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Increasing the operational safety of Autonomous Underwater Vehicles using the JANUS communication standard

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Abstract— **Increasing the operational safety of Autonomous Underwater Vehicles (AUVs) is necessary to fully explore their potential. Currently, AUV operations are limited by several constrains including the need to guarantee no interference with manned vessels and a safe deployment and recovery. Exclusion zones are used in many deployments to de-conflict activities but in a near-future world, populated by manned and unmanned surface and underwater vehicles, this will not be enough. In the absence of clear rules and ideal perception capabilities, one way to prevent collisions is to use acoustic communications. In this article, we propose several ways of improving the safety of AUVs and manned vehicles operations through the use of JANUS, the first standard for underwater digital communications. Other ways to communicate underwater could be explored but the usage of a standard protocol represents a landmark step to implement collision avoidance rules and to make the operations of heterogeneous AUVs safer.**

I. Introduction

Autonomous Underwater Vehicles (AUVs) are a widespread technology that has been used for decades in a variety of applications from oceanography to archaeological surveys or even in search and rescue of sunken planes [1], [2]. Autonomy algorithms and sensory capabilities are well developed, however, there are various issues preventing to exploit the full potential of AUVs such as long term endurance, safety and legal issues.

While long endurance AUVs and gliders can withstand month-long mission [3] through efficient propulsion schemes or automatic docking and charging [4]–[6], the lack of regulations for safety of operations hampers AUVs usage. Some countries require scientific institutions to have a manned vessel in the area of the AUV operation or to have a person on-board medium-size Unmanned Surface Vehicles (USVs) for safety/legal reasons. In other cases, exclusion zones of operation are required, thus limiting AUVs activities to small well-defined areas. Therefore, it is urgent to define regulations and protocols to enable truly autonomous AUVs navigating in the oceans without the need for costly ships "babysitting" them.

Looking at autonomous maritime platforms, there is a growing interest on the safe regulated operation of Autonomous Surface Vehicles (ASVs) and in particular Autonomous Ships [7]. The Convention on the International Regulations for Preventing Collisions at Sea, 1972 (COLREG) [8] is one of the instruments that has been studied for collision avoidance between ASVs and manned vessels [9]–[12]. However, at the moment there is no consensus in the literature if these rules should apply to ASVs or not. This is due to the fact that the COLREG Convention defines vessels as "every description of water craft, including non-displacement craft, WIG craft and seaplanes, used or capable of being used as a means of transportation" which may or may not encompass ASVs [13]. For what regards underwater platforms, marginal work has been devoted to AUVs, or more in general manned and Unmanned Underwater Vehicles (UUVs). Collision avoidance rules have not been yet deeply studied as UUVs spend most of their time underwater and therefore the number of potential collisions with manned vessels is lower. Nonetheless, it is important to implement water space management also underwater as demonstrated by recent examples involving highly capable underwater vessels: the incident between a Royal Navy submarine and a trawler[1] (October 2016); the collision between UK Astute-class nuclear submarine and a merchant vessel in Gibraltar[2] (July 2016); the collision between two Royal Navy and French Navy submarines [14] occurred in 2009. AUVs are way less capable than submarines and the chances of collisions are higher.

It has to be noticed that implementing collision avoidance rules in the underwater 3D space is not easy due to limited manoeuvrability and perception issues. For instance, for a non-holonomic AUV with limited sensing capabilities it may be hard to change its trajectory instantaneously when surfacing. Additionally, communicating underwater is not an easy task [15], incurring in longer delays or shorter ranges with respect to terrestrial or surface communications. All these factors may have contributed to the reduced effort in developing COLREGs for AUVs so far. However, with the advent of larger and longer endurance AUVs, increased number of units deployed and wider area missions, this becomes urgent if one wants to avoid accidents between AUVs themselves and between AUVs and manned vessels (submarines and surface). While there are Submarine Operating Authorities (SUBOPATH), there is no similar authority for AUVs. Some authors advocate for an international or national governing agency to co-ordinate and de-conflict AUV operations with Navy operations [14]. Such an agency could be extremely beneficial and could require AUV owners/operators to register their vehicles and provide info regarding their planned

[1] https://www.bbc.com/news/uk-northern-ireland-37633330
[2] https://www.bbc.co.uk/news/uk-36852365

trials in advance. Looking at other fields, one can find a parallel with the Unmanned Aerial Vehicles (UAVs) industry. UAVs, popularised as drones, had a similar issue. Their development was fast enough to prompt authorities to define new regulations specific for UAVs including registration, classification and insurance. While each country is making its own rules, recently the European Commission mandated the development of an UAV traffic management system and the full integration of drones in the European airspace[3]. This is needed to provide manufacturers legal certainty but also to diminish the risk of accidents with commercial planes. In fact, UAVs are forbidden to fly in the vicinity of airports/landing paths and their operation is heavily restricted in urban areas.

In the underwater domain, to avoid using simply exclusion zones which could hamper the research activities in cluttered environments, one should take benefit of the current AUV capabilities and communication technologies. Something similar to COLREGs should be defined/used for AUV/ASV/manned vessel interactions, even given the above mentioned difficulties. Perception issues could affect the performance of COLREG-based navigation, i.e., an AUV might not be aware of a manned vessel passing just above it or a manned shipping vessel might not be able to identify a small AUV at the surface. These perception issues could be however overcome if manned and unmanned vehicles manage to communicate easily. One way of doing that is to use acoustic communications and in particular JANUS [16], the first digital underwater communication standard which has recently been approved as a NATO Standardisation Agreement (STANAG)[4] and is freely available online [17]. Several vendors are currently working to implement JANUS on their products and the first modems equipped with JANUS are reaching the market[5]. Additionally, various papers have been presented in the recent past addressing the use of JANUS in support for different application scenarios, involving both manned and unmanned underwater and surface platforms [18]–[21].

There are several ways in which JANUS can be used for improving the operational use of AUVs. In a world populated by AUVs, ASVs, manned vehicles and oceanographic buoys, if all of them include an acoustic modem (not an unrealistic option) and use a standard communication protocol, the task of de-conflicting activities becomes much easier. The exchange of relevant information can be used not only to increase the safety of operations, by decreasing the risk of collisions, but also to ensure better mission planning and better acting in case of distressed vehicles. In the remaining of the paper, several possible scenarios will be presented as well as the basic idea of using JANUS for collision avoidance.

The scope of this article is not to define the possible COLREGs for AUVs but to show how communications (in particular via JANUS) could be used to implement these future regulations. Likewise, essential steps to be accomplished before regulations could be enforced are left out of the scope of the paper such as registration and classification of AUVs.

The rest of the paper is organised as follows. Section II describes an underwater AIS service using JANUS for the purpose of collision avoidance. Discussions on how to enhance an existing JANUS-based underwater AIS service (II-A) are presented along with possible scenarios (II-B), implementations (II-C) and experimental results (II-D). Other potential uses of JANUS for improving the safety of AUV operations are introduced in Section III. Finally, Section IV concludes the paper and presents future works.

II. Underwater/Surface AIS JANUS service for collision avoidance

The Automatic Identification System (AIS) is a service used to broadcast information such as unique identification, position, course, and speed of a given vessel to nearby vessels. It complements marine radar as a method for collision avoidance and it is mandatory for vessels above 300 tons and all passenger ships[6] according to the International Convention for the Safety of Life at Sea (SOLAS) 1974 [22]. It is also used by many other smaller boats.

The idea of using JANUS to transmit the AIS picture of the area to submarines operating at depth was proposed initially in [18] as a means to avoid collisions between submarines and surface vessels. In [20], a JANUS-based underwater AIS service was presented and testes at sea in support for submarine operations. To cope with the bandwidth limitation of underwater acoustic communications, a subset (filtered in space) of AIS contacts[7] available at the surface was compressed and broadcasted under water using JANUS. In what follows, we focus on how to expand this underwater AIS service in support for safety of unmanned vessels (AUVs and ASVs) operations.

The JANUS AIS message presented in [20] was composed by Maritime Mobile Service Identity (MMSI), Latitude, Longitude, Heading, Speed and Status information. Additionally, with respect to a common navigational AIS message, two more fields were included: Depth and Type (i.e., AUV, ASV, moored buoy, etc), where up to 16 predefined types of contacts are used. The reason for this choice was to allow submerged nodes to broadcast their identification and localisation data to any other vessels in communication range, above and below the surface. In case of surface platforms (e.g., ship, moored or drifting buoys, fixed infrastructure like wind/wave energy generators or oil & gas platforms) the depth field can be used to notify about the presence of any underwater structure (e.g., sensors, cables, fishing nets, keel depth). This contributes to reducing the probability of accidents between surface and submerged manned and

[3]https://www.easa.europa.eu/document-library/notices-of-proposed-amendment/npa-2017-05-npa-consultation-will-start-12052017

[4]https://www.nato.int/cps/en/natohq/news_143247.htm

[5]https://www.oceannews.com/news/subsea-intervention-survey/teledyne-benthos-takes-part-in-janus-interoperability-fest

[6]http://www.imo.org/en/OurWork/safety/navigation/pages/ais.aspx

[7]The JANUS-based underwater AIS service can be used to transmit any type of contacts (e.g., radar, satellite, visual) as long as the required data is provided to the transmitter(s).

unmanned assets. Table I presents the full specification of the JANUS packets employed for the Underwater AIS scenario. The implementation uses JANUS Class User ID 2, specifically defined for this application (as described in the standard specification document [23]). The information for each contact is expressed using ~ 15 Bytes.

TABLE I
SPECIFICATION OF THE JANUS PACKETS EMPLOYED IN THE UNDERWATER AIS SCENARIO

Field	Underwater AIS
Version num.	3
Mob.	1
Sch.	0
Tx/Rx	1
Rou.	1
Class User ID	2 (Underwater AIS)
App. Type	8
Rpt.	Not Used (Sch=0)
App Data Blk	<SRC ID>, 8 bits
	<DST ID>, 8 bits
	<PAYLOAD SIZE>, 9 bits
Cargo	<MMSI>, 30 bits
	<TYPE>, 4 bits (vessel, AUV, ASV, buoy, bottom node, submarine)
	<LATITUDE>, 28 bits (decimal degrees)
	<LONGITUDE>, 28 bits (decimal degrees)
	<DEPTH>, 10 bits (metres)
	<SPEED>, 8 bits (knots)
	<HEADING>, 12 bits (degrees)
	<STATUS>, 4 bits (**0** = Under way, using engine; **1** = At anchor; **2** = Not under command; **3** = Restricted manoeuvrability; **4** = Constrained by draught; **5** = Moored; **6** = Aground; **7** = Engaged in fishing; **8** = Under way, sailing; **9** = For future use; **10** = For future use; **11** = Power-driven vessel towing astern; **12** = Power-driven vessel pushing ahead; **13** = For future use; **14** = AIS-SART; **15** = Undefined/default;)
	<NUM CONTACTS>, 3 bits (integer)
	for each of the contacts appended:
	<MMSI>, 30 bits
	<TYPE>, 4 bits (vessel, AUV, ASV, buoy, bottom node, submarine)
	<LATITUDE>, 22 bits (decimal degrees, relative to the first one)
	<LONGITUDE>, 22 bits (decimal degrees, relative to the first one)
	<DEPTH>, 10 bits (metres)
	<SPEED>, 8 bits (knots)
	<HEADING>, 12 bits (degrees)
	<STATUS>, 4 bits (as above)
	<CRC>, 8/16 bits depending on cargo length

A. Enhancing the JANUS-based underwater AIS service

One of the AIS fields transmitted underwater is the <STATUS> of the contact. This field, available in traditional AIS messages, contains the status of the reporting vessel. It consists of 16 predefined values, each of them representing a possible navigational condition (the list of values is reported in Table I).

A similar approach could be explored for other types of vessels (e.g., manned/unmanned underwater nodes) to inform about their status and the type of manoeuvring they intend to perform, e.g., surfacing, diving, following a specific mobility pattern. Using the <STATUS> field in its current form, one could define up to 16 different values for each type of vessel/structure. This would make possible to provide in an easy and fast way more dynamic information to other manned/unmanned vessels without the need of high communication rates. An effective mapping of possible autonomous or unmanned vessels manoeuvring to the <STATUS> field should be addressed within the definition of related COLREGs.

Another possible way to extend this underwater AIS service in support for AUVs safety is including the report of additional information such as dimensions and capabilities (holonomic/non-holonomic) of the underwater/surface vessels. This information would be beneficial to perform different kinds of COLREGs, depending on the size and "smartness" of the other vessel(s). This information is currently available in some specific types of traditional AIS messages. It is periodically broadcasted by ships at a lower rate with respect to position updates. A similar approach could be implemented for the underwater AIS service with the periodic transmission of different types of AIS messages: one at higher frequency for position and status updates, another one at a lower frequency with additional information that does not change over time (e.g., dimension and capability). A second option could be including the additional fields to the JANUS packet defined in Table I, thus making this information immediately available in each contact, at the price of more data to be transmitted in each acoustic packet. A third option could be encoding the required information inside the <TYPE> field. Different combinations of dimension and capability could be defined to tag each contact type, e.g., small/medium/large for dimension and holonomic/non-holonomic/others for capability. This combination information can be added to the various contact types thus enlarging the number of possible mappings. This could reduce the number of bits to add to each acoustic message but may represent however a less flexible solution to use and to extend in the future.

Similarly to what is currently done for the assignment of unique identification (MMSI) to vessels, AUVs and ASVs should be registered as well (the first ASV was recently registered in the UK Ship Registry)[8]). The registration number can provide more info about the type and capability of AUVs and ASVs. Therefore, even if a vehicle does not receive the AIS message including the dimension of the contact and other details, this information could be obtained from available databases once the MMSI is known (similar to what is done nowadays for ships).

B. Collision avoidance scenarios

The JANUS-based underwater AIS service can be applied in various scenarios and configurations in support for collision avoidance. Some of these require only the capability to receive messages, others may involve active transmission of data.

A typical scenario is when underwater vehicles (manned or unmanned) need to surface. Any assets in the surfacing area represent a possible source of collision. Position and navigation data of the surface assets must be provided to the underwater vehicles (which could be passively listening for incoming messages) to prevent possible collisions. Similarly, underwater platforms could transmit their AIS data to inform the surface assets and other underwater vehicles

[8]https://www.ukshipregister.co.uk/news/uk-ship-register-signs-its-first-unmanned-vessel/

about their presence. This would enable surface platforms to adapt their current navigation accordingly. In scenarios with bidirectional communications, both underwater and surface platforms can exchange information and adapt each other navigation according to defined COLREGs.

A similar approach can be considered in the presence of fixed/semi-fixed underwater structures such as landers, oil & gas platforms, wind/wave energy generators, drifter buoys with drogues or subfloats, etc. These structures cannot move or their movement is very slow and hard to predict exactly and therefore AUVs/submarines should avoid them. Providing the information about these structures to vehicles operating at depth enables the avoidance of possible collisions. AUVs and submarines could identify the type and depth of the structure (contained in the underwater AIS data as shown in Table I) and navigate accordingly. Moreover, in the case of fixed structures that have both surface and underwater parts, these can act like underwater lighthouses and provide support for localisation and navigation of underwater vehicles. These lighthouses could be the equivalent for the underwater space of what satellites are for GPS localisation over the water. By getting a better localisation, AUVs can decrease the risk of getting lost and crash against other vehicles, structures or natural features, increasing the safety of their operations.

C. Implementations of collision avoidance scenarios

To implement the above scenarios, underwater assets will need to be equipped with JANUS-capable acoustic modems. In current operations underwater vehicles are usually equipped with acoustic modems. This is done to support the exchange of data between the user and the vehicle while operating under water, thus avoiding the need of periodic vehicle surfacing. The use of modems supporting JANUS opens to interoperability and enables interaction among different and heterogeneous acoustic modems from multiple manufacturers. This in turn can help to manage effectively the water space through the use of new underwater/surface COLREGs.

For what regards surface assets, different configurations can be explored. One option is to install acoustic modems on ASVs, buoys, ships and fixed infrastructures. However, in some cases this may not be possible due to several reasons, including costs and manoeuvrability/speed limitations (especially for ASVs and ships) imposed by the presence of equipment deployed in water. Another option is to use some surface platforms to work as gateways between the surface and underwater domains. Data collected via radio at the surface can be forwarded to the underwater domain and vice versa. Any surface platform (static or mobile) equipped with a radio receiver/transmitter[9] at surface and an acoustic modem below surface can serve as gateway. Gateway platforms can also be used to aggregate and filter (in space and time) the received data at the surface before the forwarding via JANUS. This is relevant to diminish the needed bandwidth as several AIS data from different sources can be compressed in one single acoustic message. Additionally only contacts located within a given range from the gateway node could be relevant for the transmissions. On the reception of AIS contacts from the underwater platform(s), the gateway will forward the data via radio, thus informing the other surface assets. Data aggregation and filtering could be performed again, if needed.

[9] It is normal practice to equip surface platforms with radio capability for data exchange.

D. At-sea testing

The use of the underwater JANUS-based AIS service has been tested and validated during various at-sea campaigns. Initial tests were performed during the REP15-Atlantic [24] and REP16-Atlantic trials in cooperation with the Portuguese Navy and their submarine squadron. During these tests (depicted in Fig. 1) no AUVs were deployed.

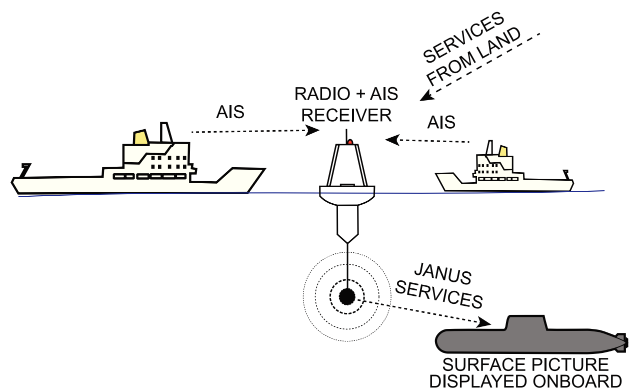

Fig. 1. JANUS-based services, delivered to underwater assets (manned or unmanned).

Fig. 2 shows a subset of the AIS contacts broadcasted by a gateway buoy (at the surface) during REP16-Atlantic. These contacts were delivered to the NRP Arpão submarine operating at depth via JANUS transmissions. To cope with the bandwidth limitation of underwater acoustic communications, up to three contacts were aggregated in each acoustic message with a transmission rate of one message every 30 seconds. Each message was carrying the most updated information about any transmitted contact. This makes possible to reduce the delay between the production and the delivery of the data to an average value of few seconds. The NRP Arpão submarine was building the AIS picture over time, receiving the information related to 53 different contacts in an area of $\sim$ 60 km $\times$ 30 km. JANUS prototype hardware, developed by CMRE, was used at the gateway buoy and on board the submarine. A maximum communication range of $\sim$ 6 km was achieved, with a sound pressure level (SPL) at the transmitted of 183 dB reμPa @1 m. It is worth to notice that this is just an indication of the achievable communication range. This value depends in fact on many environmental factors, affecting the sound propagation in water, and on the status (speed, depth, SPL) and hardware (e.g., transducer and amplifier) at the transmitter and receiver.

The AIS contacts received by the submarine were provided on a geo-referenced graphical interface ready to be used by

Fig. 2. REP16-Atlantic: Subset of the AIS contacts transmitted delivered to the NRP Arpão submarine operating at depth via JANUS transmissions. Area $\sim$ 60 km $\times$ 30 km

an operator. The feedback from the submariners was very positive.

Additional tests were then conducted during the REP17-Atlantic trial in cooperation with the Portuguese Navy and the FEUP team at the University of Porto, Portugal. This time two AUVs, provided by FEUP, were added to the deployed network. Each AUV was transmitting/receiving AIS data. The submarine operating at depth was provided with live AIS contacts of the surface vessels and underwater vehicles. Similarly, the AUVs were receiving the surface and underwater AIS picture, thus enhancing their situational awareness for water space management.

This scenario was then further extended during REP18-Atlantic with the addition of a SPARUS AUV and two ASVs. All the underwater and surface vessels were able to collect the information about the the presence and status of the other assets operating in the area through acoustic communications. A better JANUS receiver was used on board the submarine extending the reception of AIS contacts up to $\sim$ 7.5 km. Given the typical speed of AUVs and ASVs, this system can provide the required information quite in advance to plan and take the required actions. A gateway buoy was used to receive and aggregate the surface and underwater contacts and to report them to an operator on board the control ship. The operator was in charge of implementing collision avoidance measures. Knowing the position and navigation status of the surface and underwater assets, alarms can be triggered when two or multiple vehicles start approaching each other. Actions could be therefore taken by the operator to change ASVs navigation (via radio/satellite messages) or AUVs navigation (via acoustic transmissions), when possible. The next step is of course to define and implement underwater COLREGs to autonomously avoid collisions of surface and underwater vessels without the need of human intervention. It has to be noticed that given the challenge of obtaining reliable and robust underwater communications, the definition of any regulations based on the exchange of acoustic data will need to cope with possible loss of communications. This is an important aspect to be considered but it remains out of the scope of this paper.

III. Other relevant JANUS services for safe AUV operations

JANUS as an acoustic communication protocol can be used for a myriad of applications. In this section, we give two examples of other JANUS-based services that are relevant for the safety of AUVs operations. In particular, the support for distressed AUVs and the transmission of meteorological and oceanographic (METOC) data. The first one is important as AUVs in distress is something not very uncommon during intensive long term experimental campaigns or during the development of prototypes. In the latter case, the availability of METOC data while operating at depth could help in the planning/execution of the assigned tasks.

A. Distressed AUVs

The support for distressed submarine operations using JANUS as an alternative to the Underwater Telephone has been demonstrated during operational exercises [20]. In the case of AUVs, there is obviously no Underwater Telephone and a simple pinger at a known frequency and with a known pulse (for the AUV operator) is commonly used. The alternative here would be to transmit distress messages using JANUS. This would allow virtually any other ASV/AUV/manned vessel with JANUS decoding capabilities to listen to that message and to possibly find the distressed AUV or relay the message to the appropriate authorities/operator.

The use of JANUS as a communication protocol would increase the complexity with respect to a simple pinger. But at the same time, it would enlarge the possibilities of recovery of a distressed AUV. The JANUS emergency message should include the MMSI of the AUV for vehicle identification. Eventually, if possible, and for non-catastrophic failures, essential information such as status, location and depth (possibly including heading, pitch, roll) should be sent as well. The availability of this relevant data can help during the planning and execution of the rescue operations, similar to AIS-SART radio devices for distressed surface vessels.

B. Oceanographic data for better planning and increased safety

Finally, the presence of a gateway platform forwarding data from the surface to AUVs (and vice versa) opens a wide range of possibilities on the type of information AUVs can get/provide in real time. Besides AIS or other situational awareness data, gateways could also be used to transmit

METOC information. This information can be collected locally, using the sensors on board the platform, or received via radio/satellite referring to the gateway deployment area. This is especially relevant for gliders (subset of AUVs typically used for oceanographic sampling) which are required to periodically surface in order to offload some of the data and collect new tasks. Gliders operating at depth could therefore use the received METOC information to improve the safety of the operations, e.g., avoiding to surface during heavy storms, and to perform online re-planning. This online re-planning could be performed in accordance to the assigned task and the received METOC data. For instance, information regarding currents and wind could be compressed in JANUS packets and sent over to a glider. Once the environmental data is received and the glider has increased its awareness, an online re-plan of the mission could be performed to achieve a better sampling of the phenomena of interest. Additionally, the glider could update its current environmental model and correct its heading getting a more precise navigation and sampling. A similar service has been tested tested in [20] where live wind maps were transmitted to a submerged submarine.

IV. Conclusions and Future Works

In this work, we have presented several ways of using JANUS to improve the safety of AUV operations when interacting with other heterogeneous assets (manned/unmanned, surface/underwater, fixed/moving). The most important one is its use as a way of implementing underwater/surface COLREGs for unmanned vehicles. The fact that JANUS is a standard introduces interoperability and therefore easiness of implementation across heterogeneous vehicles. Nonetheless, there are other possible JANUS-based services that are worth to mention. In particular, better localisation, planning and emergency response for AUVs through the use of lighthouses, near real-time oceanographic data and standard emergency messages can also improve the safety at sea. These services have been already tested in real scenarios for communications and situational awareness purposes and its effectiveness has been assessed by end users (Portuguese Navy). Future works aim at proposing underwater/surface manned/unmanned interaction COLREGs that would then be implemented and tested using JANUS.

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Title

Increasing the operational safety of Autonomous Underwater Vehicles using the JANUS communication standard

Abstract

Increasing the operational safety of Autonomous Underwater Vehicles (AUVs) is necessary to fully explore their potential. Currently, AUV operations are limited by several constrains including the need to guarantee no interference with manned vessels and a safe deployment and recovery. Exclusion zones are used in many deployments to de-conflict activities but in a near-future world, populated by manned and unmanned surface and underwater vehicles, this will not be enough. In the absence of clear rules and ideal perception capabilities, one way to prevent collisions is to use acoustic communications. In this article, we propose several ways of improving the safety of AUVs and manned vehicles operations through the use of JANUS, the first standard for underwater digital communications. Other ways to communicate underwater could be explored but the usage of a standard protocol represents a landmark step to implement collision avoidance rules and to make the operations of heterogeneous AUVs safer.

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