Development of a Methodology for Demonstrating Compliance with COLREGs for Autonomous & Remotely Operated Vessels

PROJECT OVERVIEW

This project took on the challenge of COLREGs compliance for autonomous & remotely operated vessels. It has led to the development of an enabling framework which supports a practical and appropriate level of compliance for autonomous vessels. It considered the specific issues posed by COLREGs and aligned them with the concepts of Sense, Perceive, Decide and Act. The work considered whether the combination of capabilities required by each COLREGs Rule were essential in all cases or whether mission planning could be used to reduce or eliminate the potential for challenging scenarios, thereby mitigating the risks. The output of this project is a consistent, scalable, and justified compliance methodology to support the autonomous maritime industry in complying with the 'spirit' of COLREGs.

The project process, findings, and areas of further work are presented in this briefing note. These are signposted and easily accessed using the contents navigation table provided below:

The outcome of this project, an enabling framework for COLREGs compliance, is available in the Australian Code of Practice for the Design, Construction, Survey and Operation of Autonomous and Remotely Operated Vessels Annex A (best printed in A3). There is a partial extract of the framework at Figure 5, showing the general format and style. An interactive digital version of the framework will soon be available in the Robotic and Autonomous Systems (RAS) gateway.

COLREGS DIGITISATION TOOL

The COLREGs digital tool is being developed to streamline the process by which COLREGs is understood and applied. This tool enables the user to input information specific to their vessel, including the vessels physical features, the navigational scenarios, and the activities undertaken. Responses to these guiding questions will then be used to classify COLREGs Rules as vessel specific, always applicable, and not applicable. An example of this classification is shown below using the demo tool, where:

- Rules where at least one Rule subcomponent is vessel specific (gold).
- Rules applicable to all vessels (blue).
- Rules which are not applicable (stricken-through, grey).

	COLREGS	
Part	Rule	Essence
Part B: Steering and sailing rules (Section 2)	Rule 11 - Application	Rules in Part B Section 2 apply to vessels in sight of one another.
	~~Rule 12 - Sailing Vessels~~	~~Where two sailing vessels are on opposite tacks the vessel on port tack shall keep clear. Where they are on the same tack the windward vessel shall keep clear.~~
	Rule 13 - Overtaking	Rules and considerations specific to an overtaking situation. The overtaking vessel shall keep clear.
	Rule 14 - Head-on situation	Where two power-driven vessels are approaching in a head-on situation, both vessels shall alter course to starboard and pass on the port side.
	Rule 15 - Crossing situation	Where two power-driven vessels are crossing, the vessel which has the other on its starboard side shall keep clear, and where feasible cross behind the other vessel.
	Rule 16 - Action by give-way vessel	Give way vessels shall take early and substantive action.
	Rule 17 - Action by stand-on vessel	Stand-on vessels shall maintain course so as not to confuse the situation, unless the give-way vessel fails to act, in which case action should be taken by the stand-on vessel in order to avoid collision.
	Rule 18 - Responsibilities between vessels	A hierarchy of vessel types which determines which vessel type generally has right of way, unless an exception is provided under Rules 9, 10 and 13.

Figure 1: Output snapshot from the COLREGs demo tool.

In addition to tailoring COLREGs, the tool also recommends the evidence type and format used to demonstrate the identified capabilities. This functionality is described later in the 'Evidence for Compliance' subsection.

This tool is designed to make it easier for operators to understand COLREGs and demonstrate compliance by gathering relevant evidence. Cross-validation using the digital tool of the supplied evidence pack can then be undertaken by the regulator during their assessment. This approach is anticipated to increase transparency and uniformity during the regulatory process, leading to higher levels of trust that autonomous vessels will operate in accordance with COLREGs.

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ABSTRACT

Autonomous vessels of various sizes, forms and speeds are already at sea, on the surface and beneath it. The International Regulations for Preventing Collisions at Sea (COLREGs) were adopted by the International Maritime Organization (IMO) in 1972, entered into force in 1977 and were last updated in 1996. COLREGs governs the 'Rules of the road' at sea. They describe the features that vessels must have to facilitate being seen and identified, define means of communication between vessels for the purposes of signalling intent, and most importantly they describe the navigational behaviours expected of vessels in proximity to one another, for the purposes of avoiding collision. It's clear from the terms and phrases used in COLREGs that the notion of navigational or operational decisions being made by computers was not considered. Consequently, the methods for an autonomous vessel to "comply" with COLREGs are not clear.

Autonomous systems technology does not replicate humans, it emulates some of their skills using a different set of "senses" and decision-making processes. This means that humans and autonomous technologies have different strengths and weaknesses.

The autonomous maritime industry has been wrestling with the challenge of 'compliance' with COLREGs for years, in terms of both understanding how it applies, and how to demonstrate compliance. The challenge for the designer or operator of an autonomous vessel is that the regulations are phrased from the underlying assumption that a human is operating the vessel. Where an autonomous control system is performing some or all of the functions a human previously would have been performing it can be difficult to work out, in a practical sense, what constitutes 'compliance' in a way that a regulator would accept. This difficulty can lead to additional costs, delay, and operations which are subject to more limitations than may be reasonable based on the actual risks presented.

Developing one-off COLREGs compliance cases for a single autonomous vessel is onerous for the designer or operator and would cause the regulator difficulty in terms of the resources required to assess the compliance case and ensure consistency in regulatory decision making.

There are significant efficiencies to be gained for designers, operators, and regulators of autonomous vessels in the development of a repeatable compliance framework that is designed to reduce these burdens.

This project was undertaken by Frazer-Nash Consultancy on behalf of Trusted Autonomous Systems (TAS) and this paper describes the development of such a framework.

PROJECT PRINCIPLES

This project addressed the COLREGs challenge by developing an enabling framework which supports a practical and appropriate level of compliance for autonomous vessels. It considered the specific risks posed by the full spectrum of autonomous vessels, thus allowing flexibility in the operator's approach to compliance. The guiding principles for the COLREGs project, were:

- **The compliance methodology will be repeatable and scalable across a broad range of autonomous vessels** – The framework developed is agnostic of Autonomous Surface Vessel (ASV) type and size. It has introduced novel ways of complying with COLREGs which should increase the number of ASVs which can comply.
- **The underpinning philosophy of the compliance methodology will be logical, reasoned and justified by argument** – The framework is supported by a precursor excel workbook which provides the detailed justification behind how the framework was developed. This paper explains the thinking and logic behind the framework.
- **The compliance methodology will be enabling rather than constraining whilst upholding the purpose and spirit of COLREGs** – The framework, in conjunction with the new Code of Practice, provides ASV designers and operators with new avenues by which COLREGs compliance can be achieved. The concepts proposed from this work will provide a starting point for the ASV industry to collaborate on the few real challenges posed by COLREGs compliance.
- **The process followed to use the compliance methodology will be simple to follow and supported by guidance** – The published framework is simple to understand. Its rollout will be supported by industry engagement. The framework is also supported by a guidance note on its use. Further options to encourage engagement are being considered.
- **The project aims to develop a methodology which can be agreed to by the regulator** – We believe that the framework has been provided with the best chance possible of being agreed to by the regulator. The previous four principles are all key to this i.e. broad applicability, clear links back to COLREGs Rules, provides a jumping off point for the industry to move forwards from, and is simple to follow.

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We believe that the burden of demonstrating compliance for an autonomous vessel can be reduced by:

1. Identifying regulations which are not applicable to an autonomous vessel based upon its physical features.
2. Identifying regulations which are not applicable to an autonomous vessel based upon the operations that are intended to be performed.
3. Where regulations are applicable for the vessel and context we will recommend:
   a) Compliance – confirming that it is feasible for an autonomous vessel to comply and therefore that compliance should be achieved.
   b) Equivalence – where it is not feasible for the autonomous vessel to comply with the wording of the regulation as is, but where it is feasible to achieve the spirit of the regulation, developing a defendable definition of equivalency.
   c) Mitigation – where it is not feasible for the autonomous system to comply with the requirement directly or through equivalence, drafting a replacement requirement which mitigates in-full or partially the risk presented by non-compliance.
   d) Limitation – where any of the above options are not feasible, assisting the operator in deriving operational limitations which will mitigate the risk presented by non-compliance

PROJECT WORKFLOW

The challenge presented by COLREGs for ASVs is that the regulations are phrased from the underlying assumption that a human being is operating the vessel. It relies on the human to understand the meaning of both the stated and unstated capabilities needed to action the applicable Rules consistently and adequately. Assisting designers and operators of ASVs to comply with COLREGs requires the capture of the elements of the existing subjective set of regulations and translating them to be objective and discrete. This approach is primarily applicable to the Rules contained within Part B, which defines the expected behaviour of vessels operating within sight of each other or in restricted visibility. Therefore, the principal focus of this project became the decomposition of COLREGs, classification of the capabilities required to comply with each Rule, and then translation of the Rules to be implementable for ASVs. The initial methodology for translating COLREGs for ASVs began as is shown below in Figure 2.

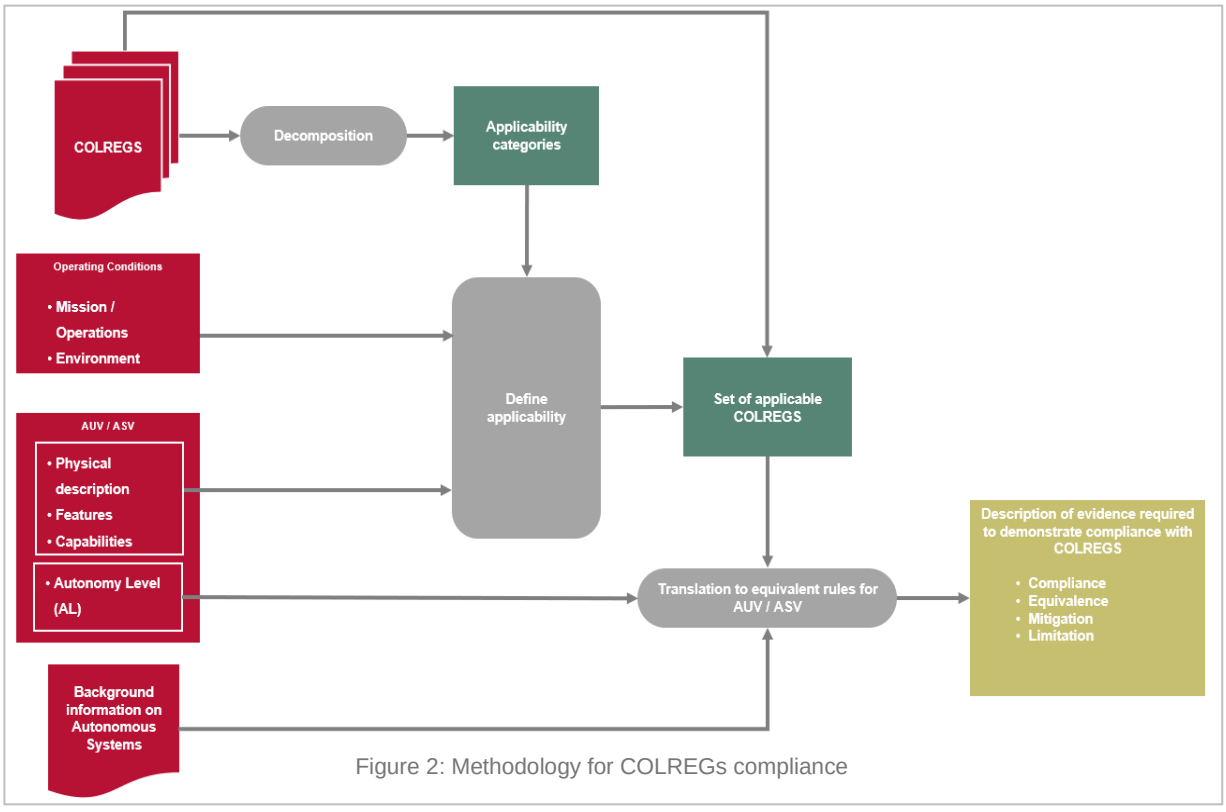

Figure 2: Methodology for COLREGs compliance

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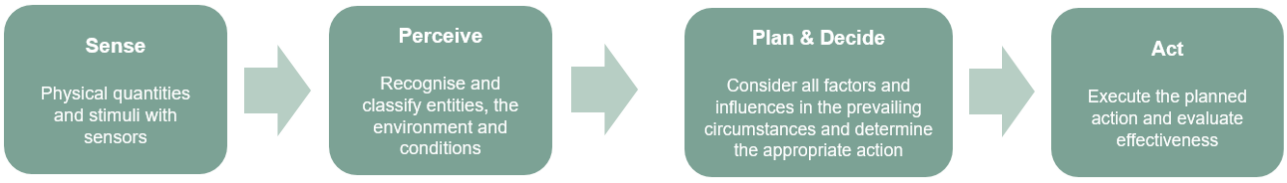

Figure 3: High level functional flow diagram for ASV decision making

DECOMPOSITION OF COLREGS BY VESSEL FEATURES

COLREGs is a broad set of Rules that was authored to cater for all surface vessels operating in a wide range of scenarios. As such, there are references to very specific vessel features, physical characteristics, and navigational circumstances. COLREGs has a native structure principally based on parts and Rules, where each Rule consists of individual statements. While this is an established and familiar structure, it does not allow for intuitive identification and down-selection of Rules and their constituents. The initial decomposition of COLREGs formed the foundation for a filter tool to down-select the vessel specific subset of applicable Rules.

The decomposition of COLREGs was intended to assist ASV manufactures and operators to concentrate their efforts on the applicable subset of COLREGs Rules specific to their vessel. Applicability of the entirety or a subset of items of each Rule within COLREGs is based on expected operating conditions, as well as the features and characteristics of the ASV under consideration. Six filter criteria based on the ASV under consideration were identified. Each of these categories, and the values possible within that category, is presented in Table 1.

Table 1: Overview of own vessel attributes to enable down selection of applicable COLREGs Rules

Length	Type	Features	Visibility	Constricted waterways	Activity
< 7m	Power-driven	Speed of less than 7 knots	Inconspicuous / partly submerged	Narrow channel	Diving operations
< 12m	Sailing	Anchor	Restricted visibility	Traffic Separation scheme	Dredging or underwater operations
< 20m	Seaplane	Operational radar			Fishing
12m ≤ L < 50m	WIG				Mine-clearance
< 50m					Pilotage
≥ 50m					Towing or pulling
> 100m					

CLASSIFICATION OF REQUIRED CAPABILITIES

For COLREGs to be interpretable and applicable to autonomous systems, translation of the human operator-focussed Rules to capabilities aligned with those of autonomous systems is necessary. A review of COLREGs in its decomposed form identified that Rules generally include references to:

- Entities and conditions that must be ascertained;
- Decisions that must be made; and
- Actions that must be taken.

This breakdown shares similarities with the high-level processes employed by autonomous systems to execute their intended functions, illustrated in Figure 3. The functional groups of Sense, Perceive, Plan & Decide and Act form the foundation of informed decision making and behaviour, and provide a logical categorisation of autonomous system requirements and capabilities. This grouping can be applied to COLREGs, establishing a capability-aligned structure for demonstrating compliance against each Rule.

Once this initial functional flow had been deduced from the Rules, the Rules were interrogated further to identify specific capabilities which were required to deliver COLREGs compliant behaviour in all conditions. These are presented in Figure 4.

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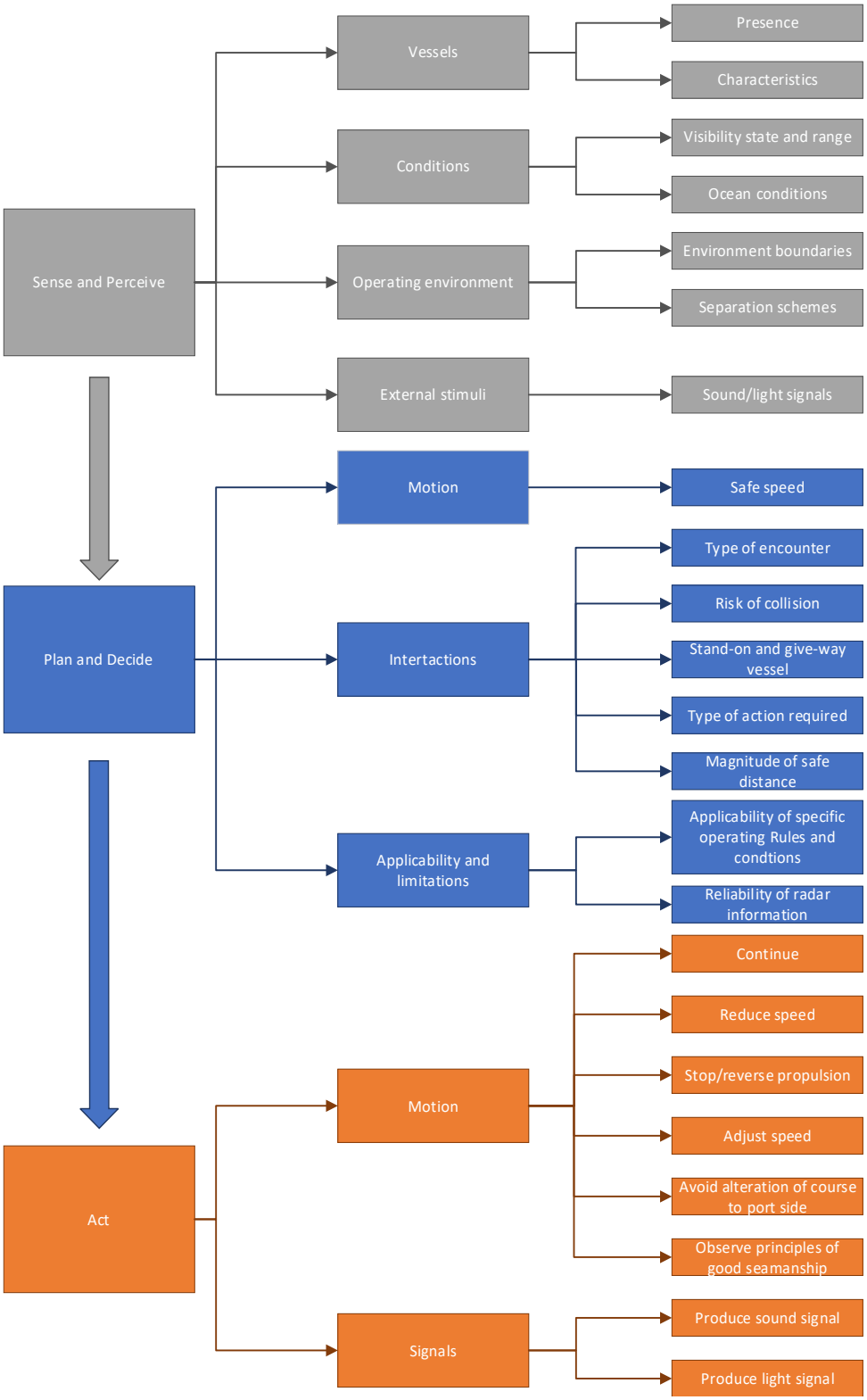

Figure 4: Summary of vessel capabilities split into: Sense and Perceive, Plan and Decide, and Act.

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Some phrases and terms used in COLREGs are not directly applicable to the capabilities of an ASV. A further exercise was then undertaken to “translate” these challenging terms into language which is more recognisable as a function, and therefore easier to apply when considering an ASV.

Table 2: Translation of COLREGs terminology

COLREGs Terminology	Framework Terminology
Prevailing circumstances	Presence and characteristics of other vessels Light/sound signals produced by other vessels Course and course change of spotted vessels over time
Visibility state and range	Time of day Weather conditions Visual obstructions
Ocean conditions	Wave height Wind speed Water depth
Environment boundaries	Traffic separation scheme/narrow channel locations Location of separation lines and zones Start and end location of traffic separation schemes
Reliability of radar information	Deconflict sensor information

EVIDENCE FOR COMPLIANCE

Verifying COLREGs compliance of an ASV, particularly from a regulator’s perspective, will require evidence. Evidence types should be system independent so as to not inhibit or constrain the ASV technology innovation process. A suitable regulatory body will need to review a body of evidence submitted by an ASV designer/operator in order to consider granting permission to operate (Certification). As this project precedes significant engagement with regulators the proposal for the evidence required to support ASV compliance against the new framework has intentionally stayed high-level. Three types of evidence are proposed for the verification of the physical features, software capabilities, and operational performance. They are broadly similar to those which would be expected to be provided for crewed ships.

1. Design record

A design record is proposed for two purposes. The first is to verify that the physical characteristics of the ASV are compliant with the lights, shapes, and sounds specifications defined within Parts C, D and the relevant Annexes of COLREGs. Where this is not possible, the ASV can consider any exemptions permitted by Codes of Practice or seek an exemption from the regulator.

The second function of the design record is to identify the type, quality, and quantity of sensors used for situational awareness and to determine how sensor information is then processed effectively to provide accurate situational awareness and inform planning. Application of this record is intended to provide an estimate of the functionality of the ASV based solely on the quantity and quality of the data it can collect, process, and action. This aspect of the record will be key to:

1. Demonstrating that all capabilities required (based on COLREGs Rule Applicability and Context) are provided;
2. Describing whether each capability is provided on-board (autonomous capability) or is provided through human oversight from a remote control centre;
3. Explaining when human oversight will need to be provided, i.e. continuous or only for specific occasions; and
4. Detailing any mission constraints which will be required due to a lack of capability.

It will be important for ASVs to comply with existing or introduced standards/specifications as they emerge. A design record, which facilitates comparison with the framework and can then act as evidence, is proposed as being both effective and efficient.

2. Decision making capability

Verification of the vessel or onshore operator to make decisions in accordance with the applicable Rules and regulations is discussed within this section. Two types of verification exist, with the type applied dependent on whether the decision-making capability is onboard or offboard the vessel.

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a. Onboard - Simulation

Simulations are a rapid, affordable, and scalable method of observing how a system behaves within a virtual environment. For this reason, simulation is proposed as the primary evidence format to observe and evaluate the situational awareness and subsequent logical decision making used to control the ASV.

b. Offboard – Testing

Decisions made offboard the vessel require the operator to have the necessary understanding of Rules and regulations. Testing of the remote operator could be conducted using existing methods or methods developed specifically for remote operators. Some work has already been undertaken to develop training and qualifications for remote operators. This facility would provide sufficient evidence that the operator has the underlying knowledge and understanding for safe and effective decision making.

3. Sea trials

Confidence that the ASV can consistently action the decisions made by the software in a timely manner, or receive the decisions made by the onshore operator, is gained via sea trials. Trials are the most time and resource intensive form of evidence. For this reason, only a subset of action-based Rule items were selected. Seventeen items spanning across multiple Rules within Part B are recommended for sea trials. The items and the Rule within which it is contained is listed below:

- Rule 6 – Safe speed
- Rule 8 – Action to avoid collision, items b, d, and e
- Rule 9 – Narrow channels, items d and e
- Rule 10 – Traffic separation scheme, items c and h
- Rule 13 – Overtaking, item a
- Rule 14 – Head-on situation, item a
- Rule 15 – Crossing situation
- Rule 16 – Action by give-way vessel
- Rule 17 – Action by stand-on vessel, item b
- Rule 18 – Responsibilities between vessels, item a
- Rule 19 – Conduct of vessels in restricted visibility, item e

Each item above was selected on the basis that it corresponds with the highest complexity requirement of that Rule. The consistent, accurate, correct, and predictable actioning of the appropriate Rule items by the ASV would constitute a successful sea trial. Successful demonstration of these items should provide confidence to ASV operators and the broader maritime industry that the ASV is COLREGs compliant. Therein helping develop the trust needed to enable the ongoing development and deployment of ASVs.

Trial planning and development of a suitable trials program that produces the required evidence to assure compliance with these Rules, was not part of this project. We propose that the issue of how to conduct ASV trials effectively and safely is discussed by ASV industry stakeholders and agreed with the relevant regulator.

CONCEPTS FOR FURTHER COLREGS COMPLIANCE

In completing the work described in previous sections it became apparent that there were a small number of concepts deployed by COLREGs which are so “human centric” that they are not amendable to translation to ASVs. This is because COLREGs often lists considerations which must inform a decision without providing specifics on how those issues should inform decisions, or the priority which should be given to each consideration. Acknowledging this, the project identified six concepts which ASVs should address in order to demonstrate COLREGs compliance. These concepts are:

- **Vessel classification:** Classifying the type, activity, and constraints of an approaching vessel is required when determining which Rules in COLREGs are applicable and which vessel must give way.
- **Encounter classification:** Applicability of Rules in Section B of COLREGs is dependent on the type of encounter between two vessels. The type of encounters e.g. crossing, overtaking are not defined further so ASVs need a common approach to allocating an encounter type.
- **Action to avoid collision:** The type of action needed to avoid collision is dependent on the encounter type, vessel type of both the approaching vessel and the own vessel, and each vessel’s ability to manoeuvre. Both a hierarchy for right of way and for the incremental escalation of actions to avoid collision is needed.
- **Definition of safe passing distance:** safe distance is subjective and dependent on a multitude of factors. These can be summarised as: range of visibility, presence and characteristics of other vessels, wind speed and direction, water depth, proximity to navigational hazards, and vessels own characteristics (length, speed, manoeuvrability).
- **Definition of safe speed:** The consideration of this concept is very similar to that of safe distance.
- **Definition of good seamanship:** Good seamanship is an inherently human centred construct, referring to the skill and acumen of the seaman. It is proposed to be broken into its constituent parts: good judgement, predictability of actions, timeliness and magnitude of actions, navigational capability, and consideration of other vessels.

In the full report the project proposed ways forward for each of the above concepts which will be used to initiate consultation with ASV industry stakeholders. There are also a range of useful academic papers describing methods which could be used as solutions to these challenges.

Undertaking this project has delivered an enabling framework which will provide a foundation from which the ASV industry can move forwards. It has also identified and defined a set of tougher challenges which will require further collaboration to overcome. We propose that industry stakeholders now collaborate on developing harmonised solutions to these challenges.

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CONCLUSION

Autonomous vessels operating on or below the surface of the ocean will gradually increase as the technology matures. Safe operating conditions for both crewed and uncrewed vessels is facilitated by the application of COLREGs. The Rules listed within COLREGs form a consistent and common understanding of the actions and considerations needed between vessels to avoid collision. Whilst COLREGs was written with the underlying assumption that a vessel would always be crewed, the essence and 'spirit' of the regulations can be distilled and defined for uncrewed vessels. Using the five defined project principles, a system agnostic, scalable, enabling, consistent framework was derived.

Decomposing COLREGs highlighted the need to define six concepts to support system agnostic consistent application of Rules. These concepts are intended to standardise the process of vessel recognition, type of encounter, determination of right of way, and the magnitude of action needed to adhere to the unwritten principles of good seamanship. Long term benefit can be realised by fostering agreement and implementation of these concepts before mass adoption of autonomous marine vessels occurs.

Findings and recommended concepts presented in this paper will need industry input and agreement before they can be finalised and implemented. Input will be sought via the review and refinement of findings, workshops with industry and Defence stakeholders.

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COLREGS			Applicability	Context	Functional Capabilities (iaw Rule Essence) (Can be on-board autonomous capability or provided by continuous or occasional human overseer dependent on risk)			Supplementary mission constraints (to enable a mission in lieu of functional capabilities)	Requiring harmonised industry solution	Proposed Evidence of functional capability (Simulation not required for human overseer)
Part	Rule	Essence			Sense & Perceive	Decide	Act		Concepts	
Part A: General	1 – Application	Definitions of when COLREGS is applicable in national and international waters.								
	2 – Responsibility	Compliance with COLREGS is the responsibility of the vessel operator.								
	3 – General definitions	Definitions of terms used within COLREGS. Primarily vessel types and situations.	At all times		• Presence and characteristics of other vessels, see Rule 5	• **Vessel type allocation**		Autonomous Marine Equipment (i.e. size & speed limitations)		
Part B: Steering and sailing rules (Section 1)	4 – Application	Rules in Part B Section 1 apply in any condition of visibility.								
	5 – Look-out	Vessels shall always maintain a look-out by sight, hearing and all available and effective means for the circumstances.			• Presence and characteristics of other vessels by imaging camera • Light signals produced by other vessels • Sound signals produced by other vessels • Presence and characteristics of other vessels by radar • Presence and characteristics of other vessels by AIS • Course and course change of spotted vessels over	• Deconflict sensor information • Type of vessel iaw Rule 3 • **Type of encounter** • Risk of collision - Apply Rule 7		Autonomous Marine Equipment (i.e. size & speed limitations)		
	6 – Safe speed	Safe speed shall be an ongoing consideration with due regard to the state of visibility, traffic density, manoeuvrability, weather and water depth. Vessels with radar shall additionally consider radar capability, range scale, interference, the possibility of undetectable hazards.			• Range of imaging camera visibility in current environmental conditions • Wave height • Wind speed and direction • Water depth • Number, range and bearing of spotted vessels • Course and course change of spotted vessels over time • Proximity of navigational hazards	• Likelihood of undetectable hazards • Likelihood of sensor interference • Traffic density • If shallow water hazard exists • Stopping distance • Turning ability • **Maximum safe speed**	• Limit speed to safe speed			
	7 – Risk of collision	Risk of collision with other vessels shall be an ongoing consideration through systematic observations with due regard to scanty information, unexpected other vessel behaviours or inaction by other give-way vessels.			• Presence and characteristics of other vessels, see Rule 5 • Proximity of navigational hazards	• **Safe passing distance** • If expected vessel paths will cross at less than safe passing distance				
	8 – Action to avoid collision	Actions taken to avoid a collision shall be effective and confirmed effective until clear. The most effective action is dependent on the situation and shall be proportional to the risk e.g. a minor course change or full-stop.			• Presence and characteristics of other vessels, see Rule 5	• Risk of collision exists, see Rule 7 • Stand-on or give way vessel determined iaw Part B • **Safe passing distance** (if give way vessel) • If stand-on vessel	*When giving way:* • Early and obvious course/speed changes • Bearing change favoured over speed change • Pass at at least safe passing distance • Monitor effectiveness of the action until the other vessel is passed *When standing-on:* • Apply Rule 17			
	9 – Narrow channels	The limitations of other vessels proceeding in a narrow channel, and constraints on situational awareness shall be considered.		Narrow channels	• Narrow channel or fairway locations • Presence and characteristics of other vessels, see Rule 5 • Other vessels within the narrow channel or fairway • Sound signals made by other vessels • Light signals made by other vessels	• Other vessels which can only operate safely within the narrow channel or fairway • If own vessel can only operate safely within the narrow channel or fairway • Risk of collision exists iaw Rule 7 • Give way vessel if <20m, sailing vessel, crossing narrow channel or fairway • If sound or light signals are iaw Rule 34(d)	• Proceed on the starboard outer limit of the narrow channel or fairway • If give way vessel apply Rule 8 • Do not anchor in a narrow channel or fairway • Respond with sound signals iaw Rule 34 (a) and optionally light signals iaw Rule 34 (b)	⚠ Avoid narrow channels of fairways and/or avoid overtaking in narrow channels or fairways.		
	10 – Traffic separation schemes	Rules and considerations specific to proceeding within or crossing traffic separation schemes.		Traffic separation schemes	• Traffic separation scheme locations • Traffic lanes and flow direction • Presence and characteristics of other vessels, see Rule 5 • Other vessels within traffic separation schemes • Sound signals made by other vessels • Light signals made by other vessels	• Other vessels following a traffic separation scheme lane	• Proceed in the appropriate lane • Keep clear of a separation line or zone • Generally join and leave at the ends • Do not anchor in a traffic separation scheme	⚠ Avoid using or approaching traffic separation schemes. ⚠ Avoid joining or leaving traffic seperation schemes anywhere but the ends. ⚠ Avoid inshore traffic zones. ⛔ Do not cross a traffic separation scheme.		

Figure 5: Extract of the COLREGs enabling framework, refer to the Australian Code of Practice for the Design, Construction, Survey and Operation of Autonomous and Remotely Operated Vessels or the COLREGs operator guidance framework.

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