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Codifying Good Seamanship into Machine Executable Rules

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ABSTRACT: Enabling unmanned surface vessels to comply with the collisions regulations is one of the most interesting challenges facing the shipping industry. The "Machine Executable Collision Regulations for Marine Autonomous Systems" (MAXCMAS project aims to develop a comprehensive capability and demonstrate satisfactory execution of marine 'rules of the road' by autonomous vessels. This is an Industry-academia Research and Technology (R&T) collaboration with Innovate UK part-funding including a contribution from the Defence Science and Technology Laboratory (**Dstl**). The project partners include Rolls-Royce, ATLAS ELEKTRONIC UK Ltd, Lloyd's Register EMEA, Queen's University of Belfast and Warsash Maritime Academy. This paper discusses how the regulations that have been written by humans for human consumption were portrayed to the researchers by the Master Mariner to enable the generation of intelligent MAXCMAS algorithms.

1 INTRODUCTION

This is an Industry-academia Research and Technology (R&T) collaboration with Innovate UK part-funding including a contribution from the Defence Science and Technology Laboratory (Dstl). Partners were Rolls-Royce, ATLAS ELECTRONIK UK Ltd, Lloyd's Register EMEA, Queen's University of Belfast and Warsash Maritime Academy. When I was asked to join this project, I wondered whether it would be easier to teach the seafarer the science, rather than the scientist the "International Regulations for the Preventing Collisions at Sea," more familiarly known as the rules of the road.

Collisions at sea result in loss of life, damage to the environment and economic loss for the ship-owner and the cargo owner and their customers. The cause of a significant number of collisions is the failure of the human element. Research has shown that mistakes are made not because of deficient or inadequate regulations, but because the education of the officer in charge of the watch is deficient or that the officer has chosen to disregard those standards and regulations (Acar, 2012). In the United Kingdom, Merchant Shipping Notice 1781 refers to the "The Merchant Shipping (Distress Signals and Prevention of Collisions) Regulations 1996," which is statutory instrument no.75 of 1996. They came into force on the 1st May 1996 and implemented the changes to the International Regulations for Preventing Collisions at Sea 1972 (as amended). These regulations commonly known as the "Collision Regulations" are a series of rules that regulate the interaction of vessels at sea.

The regulations have been written by humans for the direction of human application. So they are a series of rules to be applied to real life scenarios. Consider two vessels moving almost parallel to each

other on a slightly converging course at nearly the same speed Ref figure 1.

Figure 1. Example of vessels converging

It is entirely possible that at some time in the future the two ships may converge. Ship A may consider that Ship B is an overtaking vessel (consider B was further away and more astern than above) and therefore should give way. Whereas Ship B may consider that Ship A is a crossing vessel and therefore should give way. In both evaluations of the scenario they both consider the other vessel to be the give way vessel. This is very similar to an actual case, the Pacific Glory and the Allegro 1970. Both vessels closed to a position 1 minute before the collision, until they took action in extremis, as they attempted to turn away from each other their sterns came together (Cahill, 2002).

2 EXPLAINING THE COLLISION REGULATIONS

The author's part in the project was to then take these series of rules designed for humans and explain them in another format by the use of diagrams or tables that would enable the scientist to design a system of intelligent algorithms to guide an autonomous vessel. Step 1 was to produce a breakdown of the Rules of the Road and what the conduct of vessels are in the three conditions of visibility i.e. Any condition of visibility; in sight of one another and in restricted visibility.

An early consideration was how manoeuverable vessels actually are, using a couple of books published by the nautical institute, the author started investigating at how quickly vessels could alter in extremis. (Lee and Parker 2007, p129) say that own ship should turn through 90° in approximately 7½ ship lengths. (Knight's 1921, p333) this handbook of seamanship shows the advance and transfer of ships in turns, so this is not new. This was considered in deciding the closest point of approach for different sizes of vessels. The other factors that should be taken into consideration are made clear in Rule 6 (Safe speed) of the collision regulations. Therefore in any condition of visibility, when vessels are in sight of one another and when in or near an area of restricted visibility the collision regulations dictate what the appropriate action should be in each case. From this we decided to test MAXCMAS on two vessels with different maneuvering characteristics, a bulk carrier and a small ferry in both open waters and closed waters. MAXCMAS uses configurable TCPA and CPA limits, these limits depend upon the type of vessel the visibility and the type of encounter. In the case of a non-compliant target, MAXCMAS will wait half the set limit to before making a large alteration or will stop.

3 CONSIDER THE CONDUCT IN SIGHT OF ONE ANOTHER

As the rules have been written for human consumption, the author proposed a way of showing the scientist illustrations to demonstrate what the regulations and appropriate actions would be in various circumstances. The first diagram in Figure 3 was produced to highlight the insight sectors and the action taken when vessels entered those sectors.

The sectors are covered by the following rules:
- Yellow sector – Head on situation – Rule 14;
- Green sector – Crossing situation – Rule 15 and Action by give-way vessel – Rule 16;
- Red sector – Crossing situation – Rule 15 and Action by stand-on vessel – Rule 17;
- White sector – overtaking situation – Rule 13.

Additionally, we have also taken into account that Rule 16 mandates that the give-way vessel must take early and substantial action to keep well clear whilst Rule 17 permits the stand-on vessel to take action to avoid collision if it becomes clear that the give-way vessel is not taking appropriate action, or mandates the stand-on vessel to take action when so close that collision can no longer be avoided by the actions of the give-way vessel alone. In these latter scenarios, the stand on vessel, must then probably make a larger alteration of course or speed.

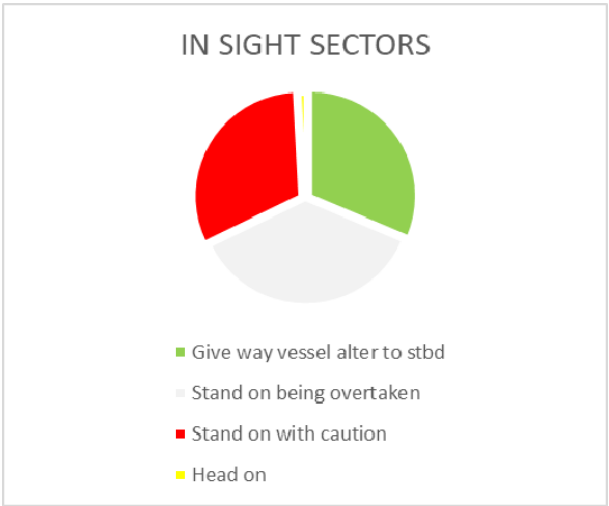

Figure 3. In Sight diagram

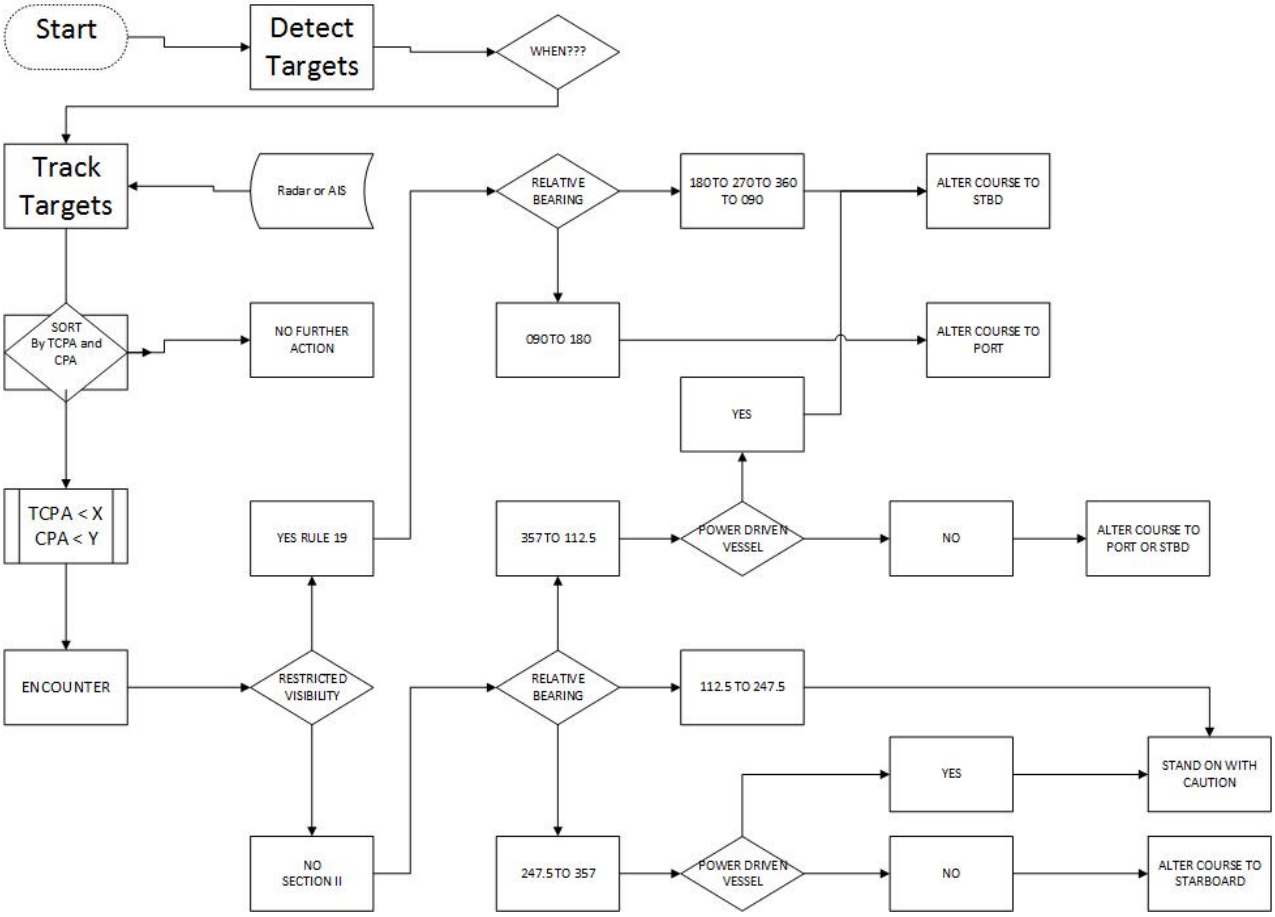

Figure 2. Basic Collision Flow Chart (Visio)

SHIP	OWN			
TARGET	Sector	Red	White	Green	Yellow
	Red	15/17/ No Risk	13 / 17	15 / 16	15 / 16
	White	13 / 16	No Risk	13 / 16	13 / 16
	Green	15 / 17	13 / 17	15/16 / No Risk	15 / 16
	Yellow	15 / 17	13 / 17	15 / 16	14 / 16

Table 1. Encounter Table

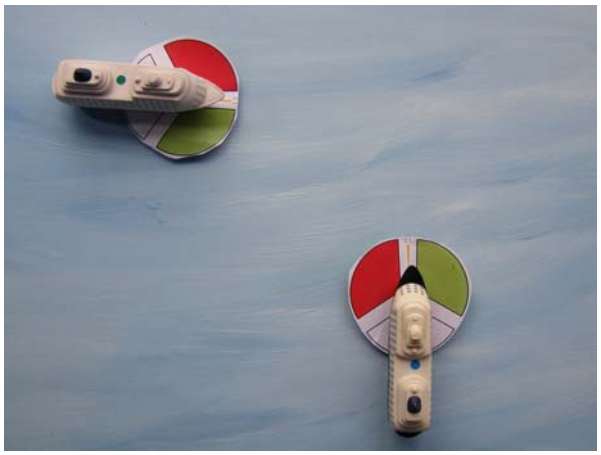

Figure 4 Green to Red Encounter

Once the rules are coded, the next stage was to test the algorithm on the simulator.

Table 4 was used to describe which rule applied to the encounter that the autonomous vessel was engaged in and was subsequently coded.

4 CONSIDER THE CONDUCT IN RESTRICTED VISIBILITY

A similar table was produced by considering the two vessels aspect to each other.

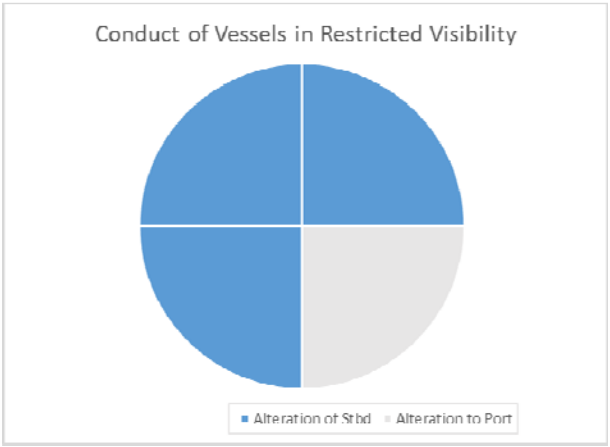

Figure 5. Restricted Visibility diagram

SHIP Rule 19	RESTRICTED VISIBILITY OWN		
TARGET	SECTOR	180-360-90 GREY	90 – 180 WHITE
	180-360-90 GREY	Alter Co to STBD	Alter Co to PORT
	90 – 180 WHITE	Alter Co to STBD	No Risk

Table 2. Restricted Visibility Encounter Table

Early on in the process we looked at some diagrams on advance and transfer so if a ship alters course using say 10 degrees of rudder, how many ship lengths before she has turned through 90 degrees? IMO manoeuvering criteria states that ships must be able to turn through 90 degrees in 4 to 5 ship lengths although this would normally be a last ditch mane. Fine lined ships such as passenger ships tend to have a larger turning circle. So ship size is a significant factor when considering a manoeuvre as well as the speed that a vessel will cover that distance in.

As an example in the "MAXCMAS" trials we used two models.

A Ferry 35.5 meters long; Speed of 22 kt.

A Bulk Carrier 215.4 meters long; Speed of 16 knots.

So using 5 ship lengths.

The Small Ferry 5 x 35.5 m = 177.5 meters at 22kt she covers 22 x 1853.2/60 = 679.5m per minute so the minimum time is 177.5m/ 679.5m = 15.7 seconds.

The Bulk Carrier 5 x 215.4 m = 1072.5 meters at 16kt she covers 16 x 1853.2/60 = 494.2m per minute so the minimum time is 1072.5m / 494.2m = 2 m 10 seconds.

In MAXCMAS the bulk carrier will begin its manoeuvre before the small ferry.

However ships do not tend to alter at the last second with maximum rudder they tend to alter with less rudder at much greater distances, to reduce the load on the engine and to increase the comfort of the passengers, but to keep the desired effect. So the next thing to take into consideration was the closing speed of the two vessels. For example two ships approaching on a reciprocal course at 15knots means a closing speed of 30 knots, therefore at 6 nautical miles apart they will hit each other in 12 minutes. In the case of our small ferries that's a closing speed of 44 knots so at 6 miles that's time to contact of 8 minutes 11 seconds. So detecting ships at adequate range and making an alteration in good time becomes paramount.

The responsibility of vessels so when two vessels meet whose responsibility is it to alter course. In some cases it depends on the aspect of the other vessel and its position relative to you, it might depend upon whether you can see the other vessel or not, or it can depend on what type of vessels are encountering each other. This is where Rule 18 comes into play as Tables 7 and 8 seek to illustrate and to a lesser extent Rule 12.

SHIP Rule 18	OWN					
NUC TARGET	Sector	Red	White Port	White Stbd	Green	Yellow
	Red	18/ a/c to stbd	18 / a/c to port	18/ a/c to port	18/ a/c to port	18/ a/c to stbd or if needed to port
	White Port	18/ a/c to port	No Risk	No risk	18/ a/c to port	18/ a/c to stbd or port
	White Stbd	18/ a/c to stbd	No Risk	No Risk	18/ a/c to stbd	18/ a/c to stbd or port
	Green	18/ a/c to stbd if sea room a/c to port	18 / A/c to stbd	18/ a/c to stbd	18/ a/c to port	18/ a/c to stbd or port
	Yellow	18/ a/c to stbd	18 / A/c to port	18/ a/c to stbd	18/ a/c to port	18/ a/c to stbd or port

Table 3. Further Encounter Table Not Under Command

It is good seamanship to avoid passing ahead if possible but that depends on the sea room available for manoeuvre.

The idea of a White port and White stbd may be odd just think of the White sector bisected in two.

SHIP Rule 18	OWN					
Vessel restricted in her ability to manoeuvre A Vessel engaged in Fishing A Sailing Vessel	Sector	Red	White Port	White Stbd	Green	Yellow
	Red	18/ a/c to stbd	18 / a/c to port	18/ a/c to port	18/ a/c to port	18/ a/c to stbd or if needed to port
	White Port	18/ a/c to port	No Risk	No risk	18/ a/c to port	18/ a/c to stbd or port
	White Stbd	18/ a/c to stbd	No Risk	No Risk	18/ a/c to stbd	18/ a/c to stbd or port
	Green	18/ a/c to stbd if sea room a/c to port	18 / A/c to stbd	18/ a/c to stbd	18/ a/c to port	18/ a/c to stbd or port
	Yellow	18/ a/c to stbd	18 / A/c to port	18/ a/c to stbd	18/ a/c to port	18/ a/c to stbd or port

Table 4 . Encounter table for Rule 18 ships.

The next consideration for codifying the regulations was the possibility of specifying which rules take precedence over the other rules. As stated above the Rules set out the criteria for making the decision as to the responsibility between vessels. That depends upon the vessel type, its aspect to you in relation to you and whether you can see it or not. In the United Kingdom MGN 369 (M+F) has clarified the position of the conduct of vessels in restricted visibility to say "If you cannot see the other vessel visually, then Rule 19 shall apply, regardless of whether your vessel is in or near an area of restricted visibility." Considerations as to whether you need a person to see the other vessel should be left to another forum. So the priority a rule takes is described in the rules themselves. Depending upon each circumstance or scenario, different priorities may seem logical from their point of view.

Priorities were discussed at length and we tried to come up with a table similar to above (see Table 5). As mariners tended to view the table differently, the author was not sure if one table would fit all views.

As the own ship alters course to keep out of the way of the other vessel, the relative position of the other vessel will change with regard to ourselves, this should not influence which rule applies until the alteration has resolved the situation. Where the relative positon of the target vessel changes with regard to our own ship can be illustrated by Rule 13 Overtaking where section (d) says: - any subsequent alteration of the bearing between the two vessels shall not make the overtaking vessel a crossing vessel within the meaning of these Rules or relieve her of the duty of keeping clear of the overtaken vessel until she is finally past and clear. MAXCMAS uses the TCPA and when that goes negative it continues on that course until it reaches the subway point.

Priority	International Collision Regulations.	
1	RULE 2. The overriding responsibility of all vessels is to avoid collision.	
2	SECTION I: Rule 4 to 10. This section has the rules that are most commonly abused, such as Look Out and Safe Speed.	
3	Section II Rule 13 Overtaking:	Section III Rule 19 Conduct of vessels in restricted visibility.
4	Section II Rule 18 Responsibility between vessels	Section II Rule 12 Sailing Vessels
5	Section II Rule 14, 15 , 16, Head on situation Crossing situation Action by give way vessel	
6	Section II Rule 17 Action by stand-on vessel (When multiple encounters at the same time vessel occur a vessel would alter and not stand on.)	

Table 5. Contentious Priority Table

In narrow channels when a vessel is crossing the channel the crossing rule 15 applies but when vessels are navigating up and down the channel then rule 9 applies. Rule 9 (d) says, "A vessel shall not cross a narrow channel or fairway if such crossing impedes the passage of a vessel which can safely navigate only within such channel or fairway…" However what if the vessel is not hampered then it must comply with rule 15. Empire Brent-Stormont (Cockcroft, 2011, page 76). MAXCMAS produces borders within the channel that it will only cross in specific circumstances.

A pragmatic way of deciding what actions that a ships master might take, was to present that situation to a few Master Mariners in the form of a questionnaire and then compare the results for example.

The following situation was presented to a Master Mariner with the following question (Fig. 6).

The red spot is our ferry, overtaking the other ferry, having blue spot on the port bow. Q2, What action should red spot take?

If there was sufficient time and sea room and if risk of collision does not exist with yellow spot and it does not create another close quarter's situation then an alteration of course to starboard could be considered. If however that was not possible then a marked reduction in speed to allow the other vessel to pass ahead should be used.

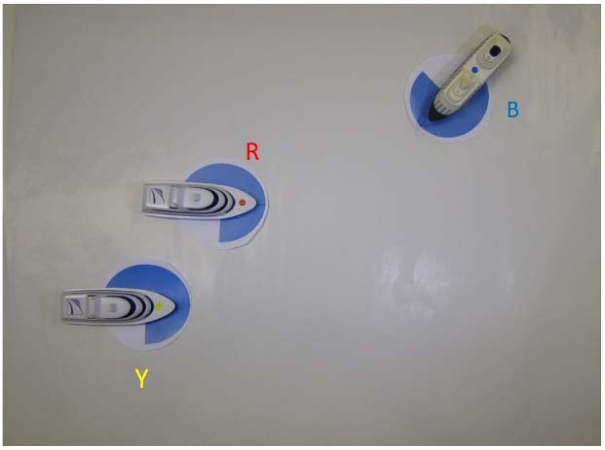

Figure 6. View of Material

For collision avoidance manoeuvres to be successful a large amount of anticipation of the situation needs to be employed well in advance. Leaving the manoeuvre to the last minute is a very risky proposition. Lee and Parker 2007 suggest on page 130 that there is a fatal zone; danger zone; high risk zone; and a risk zone depending upon the vessels TCPA and how far it travels in that time. They define a normal or planned zone as the time it takes a vessel to travel 10 ship's lengths. So if your vessel is 200 meters long that would be 2000 meters. If for calculation purposes we say 1 nautical mile equals 1852 meters. Then at 15 knots that's 27,780 meters an hour so {(2000/27780) * 60} = 4.32 minutes. The author feels that most mariners navigating vessels of approximately 200 meters in length would be altering with a TCPA of at least 12 minutes, this allows the mariner to use less rudder but achieve the same ends. The closet point of approach is the minimum estimated distance that two vessels will approach each other based upon their current course and speeds. It is used by seafarers to help rank the risk of collision when dealing with multiple targets. It is also used by masters to leave in there standing orders. Interestingly when MAXCMAS was run in human company, the humans tended to alter earlier but that can be configured into MAXCMAS by altering the TCPA.

In order to come up with what we considered to be the appropriate actions in various situations. I sent a questionnaire around to a few of my colleagues, in the form of power points using scenarios very similar to that in Figure 10. Then I collated the replies and then sent them back to the same group to come up with an agreed action plan that they would take in the various scenarios that I came up with. This also enabled us to take scenarios the algorithm had not handled well and break them down and understand exactly what was required in each case and add to or develop the understanding so that could be applied to the algorithms logic.

5 CONCLUSION

If you put six masters together and put a scenario in front of them, you can come up with seven views of what should be done. The factors that affect human decisions is an area of cognitive psychology that experts have spent lifetimes investigating. In our field you would expect that an individual's training, experience, the type of ships they normally sail on and the stress or pressure they are under will all influence their eventual decision. They may all decide to do one action but how much of an action they will take and how long they will continue an action for will vary. However it does mean that Humans will occasionally make errors.

At Warsash we did over 300 assessed collision encounters that were carefully constructed real-world scenarios including recreations of historical incidents and Navigation Aids and Equipment Simulator Training scenarios accredited by the Maritime Coastguard Agency. Some of these were one to one and some were multiple encounters in both open and restricted waters using both simulated traffic and vessels crewed by personnel in adjacent simulators.

The MAXCMAS technology, once trialed and accepted should enable ships both manned and unmanned to interact safely. The algorithm will not suffer from emotional baggage or fatigue so It should be able to follow a rule based decision system successfully all the time rather than most of the time.

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