Comparative Review of Collision Avoidance Systems in Maritime and Aviation

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Abstract
This study provides a comparison between aviation and maritime industries in the context of collision avoidance. Thus, it focuses on the regulations, operational practices, techniques and procedures in both aeroplanes and ships for collision avoidance. Due to safety and technology advancements in the aviation industry, advancements in aviation to prevent collision avoidance can be implemented in ships, developing a better situational awareness and improved navigational watch. Generally, the Officer of the Watch (OOW) on board ships is responsible for all the decisions that need to be taken on the navigational bridge. Consequently, this requires an immense amount of data analysis; moreover, this data is located in various locations on the bridge. Yet this can cause a work overload for the OOW, potentially leading to human errors and lack of situational awareness. This study reveals the shortages in maritime industry, helping us to adopt new safety-related enhancements and technologies to reduce the risk of collision at sea, which is inspired by the aviation industry.

Keywords: Automatic collision avoidance, Navigation, COLREG, Aviation, TCAS system, Human errors, Situational awareness, Man-machine interface, Information flow

1. Introduction
Just after the expansion in the use of radar in commercial shipping, around 1960s, and the increases in traffic density, the need arose for technological support, in order to help the OOW avoid collision at sea (Szlapczynski and Szlapczynska, 2015; Tam et al., 2009) . Moreover, that led to faster ships in less sea room for manoeuvring, making the navigation tasks harder and requiring more concentration (Tam et al., 2009). Nevertheless, the OOW maintains a good level of safety when navigating the ship, but errors are still being made, contributing to accidents occurring (Statheros et al., 2008). In addition, the varying cognitive abilities of the OOW, dependent on factors such as lack of good sleep and food, workload, stress, noise levels, experience, mental health, missing home and the ergonomics of bridges, can all affect the OOW's decisions. Wrong decisions made under these conditions can cause

accidents (May, 1999). However, in order to improve the OOW's situational awareness and to reduce the human error, it is advantageous to have a decision-making support system, as a navigational aid on bridges (Perera and Soares, 2012). The decision-making support system will ensure objective decisions rather than subjective ones (Statheros et al., 2008). Moreover, that will also ensure a system fully compliant with the Role of the Road (COLREGs) (Statheros et al., 2008). The benefits of introducing the new technologies on board ships as navigational aids and decision-making support systems or automatic collision avoidance systems are reducing the workload on the OOW, reducing human error and increasing the situational awareness of the OOW (Statheros et al., 2008).

The organisation of the paper as follows; section two presents the aviation collision avoidance system and its working principles. Then, section three highlights the collision regulation (GOLREG) in marine navigation and its shortages. Section four illustrates the navigational aids and equipment. After that in section five, a comparison between the aviation and maritime industries with regard to collision avoidance is performed. Finally, the discussion is presented in section six.

2. Collision Avoidance in Aviation

In aviation, where they do not have manoeuvring regulations, the decision is left to the pilot to avoid collisions. In addition, they have the Air Traffic Control (ATC) role to allocate every aeroplane with a specific level (altitude) of flying and to ensure the separation of aeroplanes in general (Kuchar and Drumm, 2007; Williams, 2004). Also the Traffic Alert and Collision Avoidance System (TCAS) comes as last measure of collision avoidance, by alerting the pilot of any intruders in the vicinity, which could be a potential conflicting aeroplane (Burgess et al., 1994; Kuchar and Drumm, 2007). If that intruder comes in a collision course, the TCAS provide the pilot with the best avoidance action. The TCAS system has proven its reliability as collision avoidance system (Harman, 1989). However, that makes it mandatory to obey the system's decisions immediately, even if the pilot does not acquire the intruder visually, as mentioned in the International Civil Aviation Organisation ICAO (Honeywell, 2006). It could be the case that the pilot is unaware of the intruder or cannot see it visually and the TCAS system detects it and issue the avoidance decision (EUROCONTROL, 2016).

2.1. TCAS Principle

The principle of the TCAS is based on sending an interrogation to other TCAS equipped intruders and waiting for reply in order to measure the range and altitude of the intruder (EUROCONTROL, 2016; FAA, 2011; Harman, 1989; Kuchar and Drumm, 2007). As a result, the TCAS system starts communication with the intruder's system, to coordinate the avoidance manoeuvre (Honeywell, 2004). The intruder must have its altitude in its reply message, so the TCAS System can locate it accurately before issuing the avoidance manoeuvre, otherwise no avoidance manoeuvre will be issued (EUROCONTROL, 2016).

TCAS system has two types of alerts: Traffic Advisories (TA) and Resolution Advisories (RA) (Murugan and Oblah, 2010). The TA is a visual alert to the pilot, and to prepare him if needed, to avoid any risk of collision (Harman, 1989). The RA is an avoidance manoeuvre for intruders that are on the same track where the pilot must take action to avoid the collision (Honeywell, 2006). Usually the TA alert comes first and then the RA as an avoidance action. The TCAS's RAs are in vertical dimension only (climb or descend); it does not issue RA to change course (FAA, 2011). Figure 1 is an illustration of the TA and RA areas and times. Figure 2 is an example of the RA avoidance manoeuvre; with reversal RA (both airplanes are equipped with TCAS system).

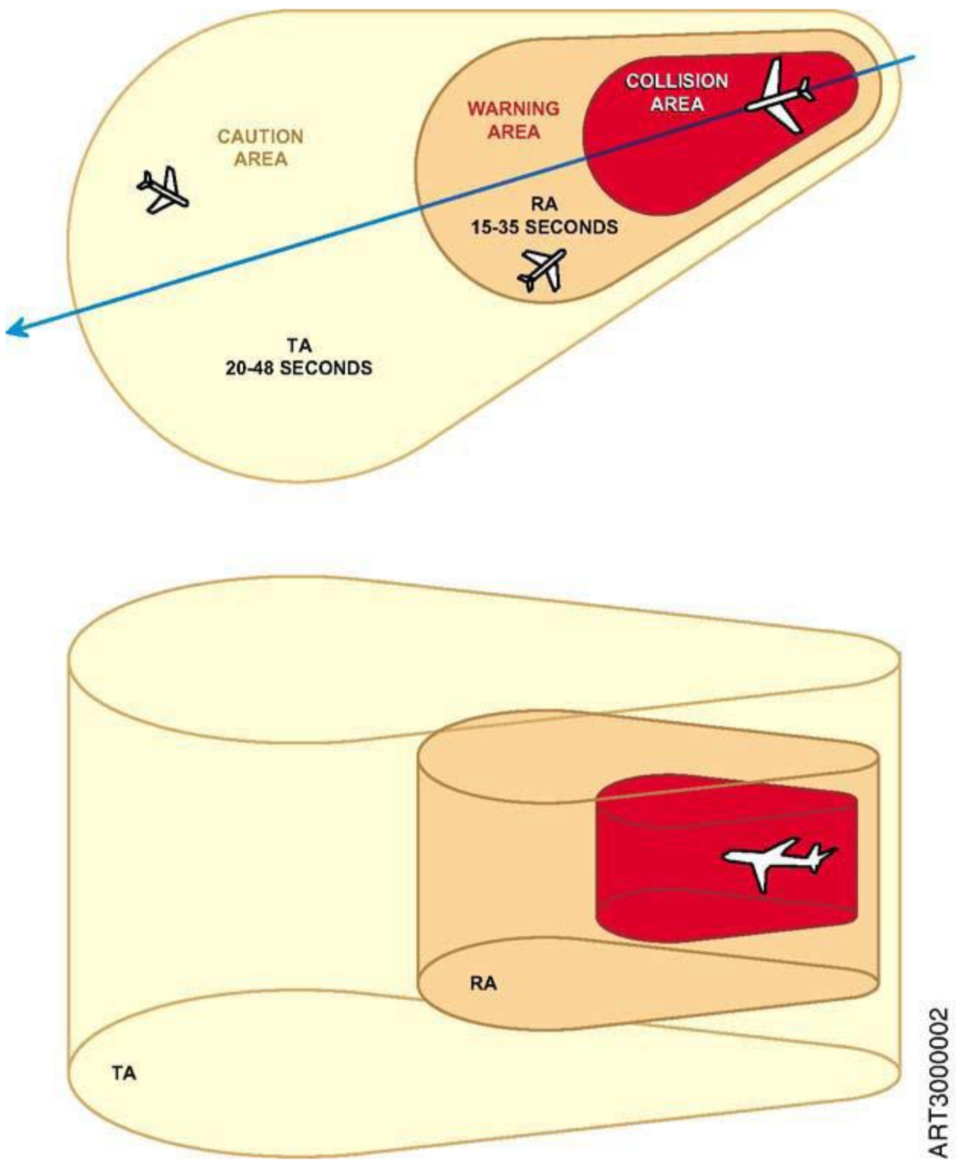

Fig. 1. TA and RA Zones (FAA, 2011)

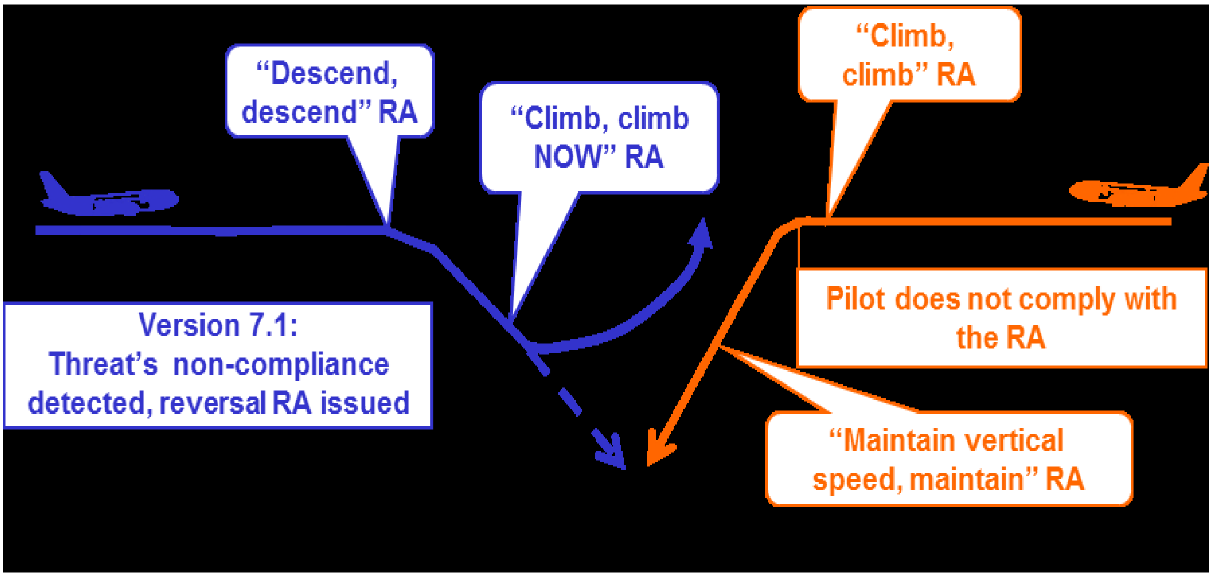

Fig. 2. TCAS RA to avoid collision (EUROCONTROL, 2016)

2.2. Collision Avoidance Logic in TCAS

The principle logic of the collision avoidance is based on the concept of Time to Closest Point of Approach (TCPA) (FAA, 2011). This means it is dependent on the time of CPA rather than the distance, to issue the TA and RA alerts (Munoz et al., 2013). The time to issue a TA is 48-20 second, and for RA is 35-15 second, before the time to CPA (EUROCONTROL, 2016).

2.3. Coordination between Two TCAS Equipped Airplanes

When two airplanes are in an encounter situation and both of them are equipped with TCAS, the TCAS systems in both airplanes coordinates the avoidance manoeuvre, in order to avoid the airplanes from selecting the same RA manoeuvre (both of them climbing or descending) (Murugan and Oblah, 2010). This coordination is known as Resolution Advisory Complement (RAC). The coordination procedure is as follows: the first airplane sees the other as a threat, selects the RA, and sends its selection to the threating airplane to restrict its selection to the opposite direction only (if the first airplane selects a climbing RA, then the other airplane must select a descending RA) (EUROCONTROL, 2016). The TCAS system keeps monitoring the execution of the avoidance manoeuvre every one second, and in case the threating intruder is not following the RA issued by his TCAS, the RA will be reversed in the obeying plane. This is known as Reversal RA (FAA, 2011). The TCAS system always selects the RA which provides the largest separation between the airplanes.

3. The International Regulation for Preventing Collision at Sea (COLREG) 1972

COLREGs are basically a set of rules that provided to the OOWs in order to help them assisting the encounter situation, such as; crossing, head-on or overtaking (Wang et al., 2010). Nevertheless, this requires full understanding and interpretation of the whole situation around the ship (Mohovic et al., 2016). However, the OOW will be able to appoint the responsibilities between vessels in encounter situation and how to avoid collision situation (Wylie, 1962). The rules guide the OOW about the suggested course of actions to avoid collision with other vessels, and give some prohibited actions that shall not be taken under any circumstances. However, these rules and its interpretation need to be well understood by the OOW to avoid any conflict situations at seas. With consideration to COLREG, three conditions of vessels conflict has been identified that covers all possible collision situation at sea (IMO, 2005). The collision situations are; Overtaking, Head-on and Crossing, however, it is important to correctly interpret the conflict situation in order to take the correct actions (Mohovic et al., 2016).

Overtaking situation / Rule 13

Any vessel approaching the other from stern is an overtaking vessel, and she shall keep clear of the vessel being overtaken (COLREG, 2017; IMO, 2005).

Head-on situation / Rule 14

Any vessel meeting the other on a reciprocal or near reciprocal course in a head-on situation, where both vessels shall alter course to starboard side so they pass port to port (COLREG, 2017; IMO, 2005)..

Crossing situation / Rule 15

Any vessel on a crossing course with another, where risk of collision exists, is in crossing situation (COLREG, 2017; IMO, 2005). The vessel seeing the other on her starboard side shall keep clear, as well as avoiding passing ahead of the other vessel if the circumstances admit it (Cockcroft and Lameijer, 2012b; IMO, 2005).

Give-way vessel / Rule 16

The vessel that is required to keep clear of another by this regulation is the Give-way vessel (COLREG, 2017; IMO, 2005).

Stand-on vessel / Rule 17

The vessel that is not the Give-way is the Stand-on one, and she shall maintain her course and speed (COLREG, 2017; IMO, 2005).

3.1. Subjectivity and uncertainty of COLREG regulation

In maritime navigation, all collision avoidance manoeuvres are made based on the Collision Regulations (the Rules of the Road) COLREG. Although these rules have helped in managing the maritime traffic and also advised every vessel about the collision avoidance manoeuvres that need to be taken in every situation, they have not stopped accidents from happening (Demirel and Bayer, 2015; Lušić and Erceg, 2008). After a deep study of the COLREG a number of issues that can cause a hassle and confusion for the OOW were identified (Belcher, 2002; Demirel and Bayer, 2015; Szlapczynski and Szlapczynska, 2015; Wylie, 1962). First of all, the subjective nature of the rules, where it does not inform the OOW about the exact action to take, instead it leaves the decision to OOW to decide (Belcher, 2002; Szlapczynski and Szlapczynska, 2015). This is clear in some phrases such as; "*If the circumstances of the case admit*" "*In ample time*" and "*If there is sufficient sea room*" all these cases are subject to the interpretation of the situation (Cockcroft and Lameijer, 2012b; Wylie, 1962). Moreover, COLREG does not inform the OOW with the magnitude, nor the time to take actions (Belcher, 2002; Wang et al., 2010). However, the judgement is left to the experience of the OOW and the good seamanship practices, which causes dangerously subjective decisions to be made (Belcher, 2002; Cockcroft and Lameijer, 2012a; Wang et al., 2010). Nevertheless, if we look at rule 15 Crossing Situation, it is clear that the ship sees the other one on her starboard side is the Give-way vessel and she should avoid the Stand-on vessel (Cockcroft and Lameijer, 2012b). whereas in rule 17 it says *"the Stand-on vessel may take action to avoid collision by her manoeuvre alone as soon as it became apparent to her that the vessel required to keep out of the way is not taking appropriate action"* (Cockcroft and Lameijer, 2012b). Again it is left to the OOW on the Stand-on vessel to decide when to take action, which are again subjective decisions (Belcher, 2002; Kunieda et al., 2015; Wang et al., 2010).

4. Navigational Aids and Equipment on Ships' bridge

Sailing started long time ago, where there were no electronic communicational methods, nor navigational systems. However, sailors depend heavily on traditional methods and experiences inherited from previous navigators and sailors. Moreover, the toughness of a sailor's life on board and the long times they used to spend in seas generated a pride and glory in themselves, which over time turned out to be an arrogance where it became the most-known trend about sailors to date. Indeed, this created a resistance from a large number of navigators to the development of new navigational technologies and techniques, claiming that they are inefficient and it is impossible to dispense with traditional techniques. In addition, the long processes and time required for adopting new technologies and systems in maritime industry by the International Maritime Organisation (IMO) lead to individual equipment introduction over long periods (Bole et al., 2014). This develops a poor bridge layout and systems' integration (Bole et al., 2014; Brigham, 1972). Consequently, the OOW is exposed to a high information flow from navigational equipment located in different areas in bridge (Pietrzykowski et al., 2016). All these navigational aids are information systems only, yet no decision support system has been developed to help the OOW in decision making (Pietrzykowski et al., 2016). Upcoming is the navigational aids and equipment on ships' bridge, which are used to assist the OOW in understanding the situation around the ship and conducting the navigational watch:

- Ship's conning display unit

- Weather monitoring unit
- Automatic Identification System (AIS)
- Radar, X and S bands / Automatic Radar Plotting Aid (ARPA)
- Electronic Chart Display and Information System (ECDIS)
- Global Positioning System (GPS)
- VHF for external communication
- Echo sounder

For collision avoidance, ARPA and ECDIS are the most utilised aids for detection, assessment and monitoring of targets, with the integration of AIS system for ships' information. Although, these systems provide the most needed information for collision assessment, but they are still information systems only. This means, the OOW must collect the information, analyse it and provide the most appropriate decision for the safety of the ship. Moreover, these systems do not warn the OOW about dangers or collision situations. However, the OOW is responsible for monitoring all these systems to detect dangerous situations and decide the best course of action to avoid them.

5. Similarity and Differences between Aviation and Maritime Collision Avoidance

Collision Avoidance Systems; Operation and Techniques

Aviation industry has succeeded in developing an automatic collision avoidance system which helped to enhance the flight safety significantly by reducing the risk of mid-air collision. The TCAS system is the last barrier of mitigating the risk of mid-air collision and it works independently without interference from ATC (Honeywell, 2004). In essence, the TCAS system alerts the pilot of any potential mid-air collision in two consequence steps: firstly, the TA alerts the pilot about any intruder in the vicinity and prepares him for avoidance manoeuvres. Secondly, the TCAS generates the RA to provide pilots with the best avoidance actions.

In maritime industry, there are no such systems which support the OOW in collision avoidance decision making. Hence it is all information systems, which means the OOW needs to collect all the navigational information, from various sources, to build up an adequate level of situational awareness (Pietrzykowski et al., 2016). As a result, the OOW should monitor various systems on different screens and locations. For collision risk assessment, the OOW extracts information from ARPA and ECDIS (two separate screens) (Hadnett, 2008; Pietrzykowski, 2010). However, he still needs to be fully aware about other important aspects, such as: Anemometer for weather conditions, Echo sounder for depth, Paper charts, GPS and GMDSS (Communication system). Constant monitoring of all this equipment is an exhausting task, especially when the devices are located away from each other (Hetherington et al., 2006). On the top of that, he still needs to assess the situation and decide the best avoidance manoeuvre, based on the COLREG rules (Belcher, 2002).

Collision Avoidance Procedures, Actions and Responses

The most significant benefit of the TCAS system is the enhancement in situational awareness by alerting about conflict traffic in vicinity and collision avoidance manoeuvres (ICAO, 2006). Hereunder are scenarios of collision situations in air and sea to make comparison between safety levels of navigation in both industries.

Scenario 1, Air collision Situation

Looking at the principle rules of separation in aviation, firstly the ATC is responsible for aeroplane control on the ground and in the controlled airspaces and as advice in non-controlled areas (EUROCONTROL, 2016). Its responsibility is to prevent collision and ensure separation between aeroplanes (EUROCONTROL, 2016). Then is the "See and Avoid" principle, where the pilot sees the other as threat, must avoid it in the best manoeuvre to avoid collision. Finally, as a last resource of collision avoidance is the TCAS system (EUROCONTROL, 2016).

The basic operation of the TCAS system starts when the TCAS issues the TA to alert the pilot about an intruder (CÎRCIU and Luchian, 2014). The TA helps the pilot in the visual acquisition of intruders, preparing him to respond to RA if risk of collision exists (FAA, 2011). Once the RA is issued, the pilot needs to respond immediately, if the given manoeuvre does not endanger the safety of the aeroplane (EUROCONTROL, 2016).

Scenario 2, Marine collision situation

In Maritime, the basic and first method of collision risk assessment is by taking a frequent visual compass bearing; if the bearing does not change that means the target ship is on a collision course. The next method is the radar, helping especially in the restricted visibility. Finally, the Automatic Radar Plotting Aid ARPA, the ARPA system makes it much easier to assess the collision situation by assessing the Closest Point of Approach (CPA) and the Time to CPA (TCPA).

In normal operation, the OOW needs to monitor the ARPA system to detect any target in the vicinity, in addition to the constant visual look out (with the support of the Look Out watch man if needed). When a target is detected, the OOW sees the target's information and parameters on ARPA (which is integrated with the AIS system), and based on the CPA he decides if a risk of collision exist. If the target ship is on a collision course, the OOW needs to evaluate the situation, based on the COLREG rules, to know which ship is the one to give way. If it is his own ship, then he/she needs to keep clear of the Stand-on vessel. On the other hand, if the other ship is to give way, the Stand-on vessel should keep her course and speed. Additionally, the water depth is an important factor in marine accidents, causing grounding. In general, the passage planning is created before the departure, and all the routes are checked to ensure a safe passage for the ship, with ship's draught in consideration all the way to the arrival point. However, in case of avoidance manoeuvres which need an alteration from the original route, the OOW must check the availability of sea room around the ship to avoid shallow water and grounding accidents.

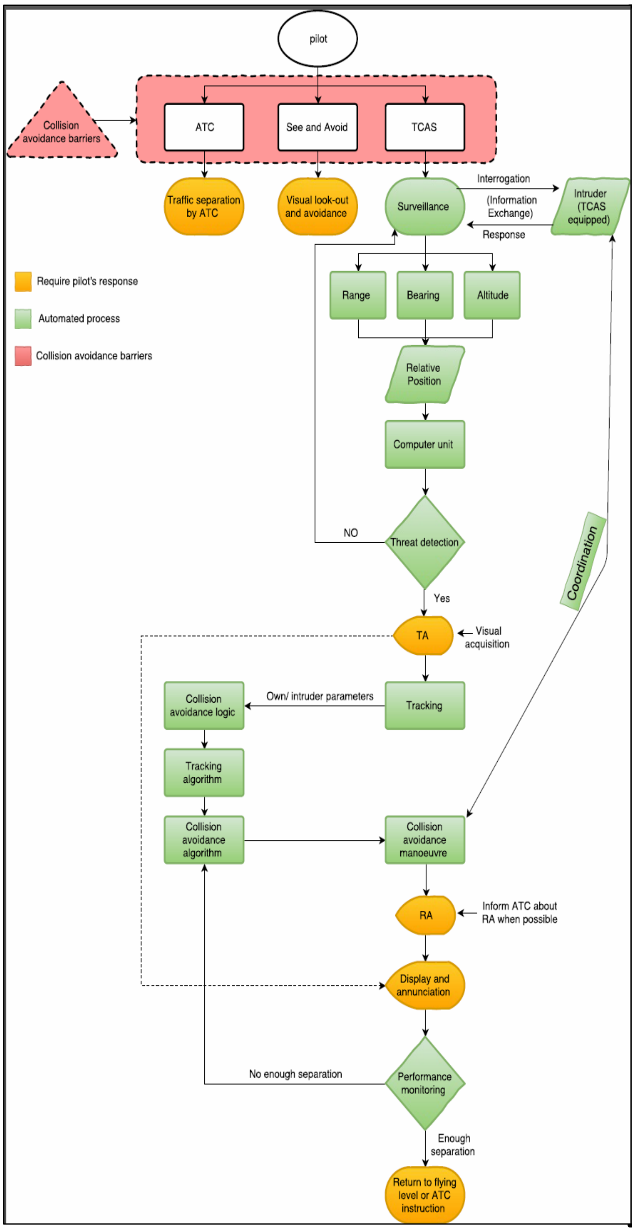

Fig. 3. Collision avoidance procedures in aviation

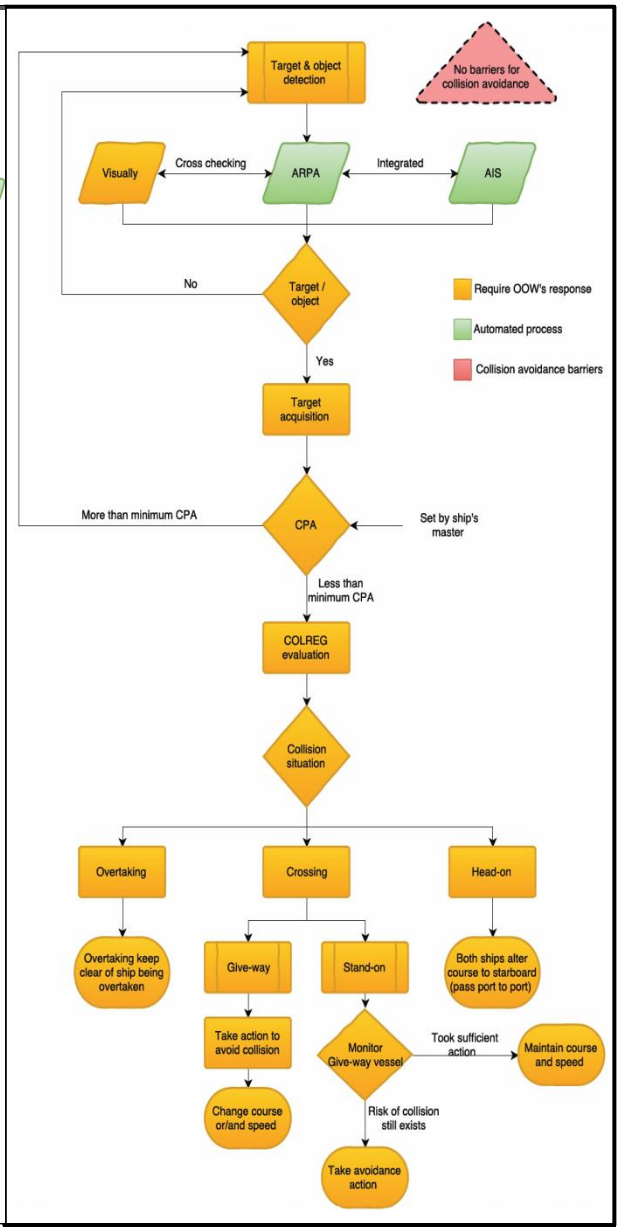

Fig. 4. Maritime collision avoidance procedures

5.1. Procedural Diagrams for Collision Avoidance in Aviation and Maritime Sectors

The comparison between the collision avoidance procedures in aviation and maritime has revealed a number of concerns in maritime sector. Still the diagrams help to spot the most important issues in the maritime procedures. However, by comparing it with the aviation procedures, a significant improvement can be achieved to enhance the situational awareness and navigational safety as well.

Starting with the aviation diagram, a three independent collision avoidance measures are available to stop mid-air collision from happening. The ATC is to control the overall aerospace and to provide separation between aeroplanes. Then the “See and Avoid” technique by the pilots to monitor the traffic in vicinity and to avoid any intruder by best actions. If these two barriers failed to prevent the collisions, then the TCAS system is in place, which is independent system that acts as the last mean of mid-air collision avoidance. On the other hand, in ships, there are no barriers for collision avoidance, it is all depend on the OOW to conduct an efficient look-out to maintain a safe navigational watch with the support of the navigational aids. Also careful monitoring of all the equipment on bridge is required as well as interaction with the ARPA system, which is used for target detection and to extract targets' information. Nevertheless, all the navigational aids, including the ARPA, provide the OOW with information that need farther process to build a decent situational awareness level. Consequently, the OOW utilise these information to realise the encounter situation, based on COLREG, then to decide the avoidance manoeuvre and responsibilities. Yet, the navigational aids do not either; warn the OOW about threats in vicinity, nor the best avoidance actions. Another important different is the automation level, in aviation the TCAS system work automatically, without any human interference, to alert the pilot about intruders in vicinity and the best action to avoid them. On the other hand, navigational aids only provide the OOW with information, and left all the analysis and decisions to him. This leads to subjective decisions based on the understanding and interpretation of the OOW to the situations around him.

6. Discussion

The above comparison has shown that the technological advancement, the collision avoidance procedures and the safety level are superior in the aviation industry.

- Information flow
- Man-machine interaction
- Automatic Coordination and Connection
- Subjectivity and objectivity of the decisions and the uncertainty of the COLREG

Hereafter are the key elements found in the aviation industry, which can be adopted by the maritime to enhance the navigational safety, especially in critical collision situations.

First, the amount of information flow in ships' bridge is immense. In such critical situations, the OOW becomes distracted by all equipment that needs to be monitored and the manoeuvrability of his ship. In order to enhance the OOW's performance, it would be better if a standardised display on one screen, presenting all the important information for critical collision decision-making procedure is available on bridge. In this case the OOW will be able to focus on decision-making without missing any other important information or tasks.

Second, the man-machine interaction: this technique will enhance the level of situational awareness on the bridge. The ordinary navigational systems are informational systems only, which present all the information and the OOW utilises what he needs. In this case, the chances of missing a key element are high and there is no method of ensuring that the OOW is fully aware about the situation. By applying the man-machine interaction technique, the system will automatically ensure the awareness of the OOW and the full utilisation of the information. Also, in order to ensure the awareness of the OWW, an alert must be issued when he is not utilising the important information on the system.

Third, the technique of automatic coordination and connection between maritime collision avoidance systems to remove the uncertainty. By adding such a technique, the OOW will be able to monitor the target ship more accurately. Moreover, it will allow the OOW and the systems to deal with the changeable parameters of target ships as well. Additionally, the feature of acknowledging the manoeuvres of both target and own ships will enhance the level of situational awareness significantly. For example, the OOW is able to monitor the target ship's changes in course and/or speed in real time. Plus if the target ship can show a means of acknowledgment to indicate its awareness of the situation, this will remove the uncertainty of the whole situation and it will indicate both ships' recognition of the situation. In such cases the Stand-on vessel in rule 17 will be sure about the Give-way vessel's action and she can act accordingly. Whether the Give-way is aware about the situation and taking the avoidance action or she needs to avoid the collision by her own actions.

Finally, the approach proposed here aims to remove the subjectivity nature of the OOW's decisions, which are based on his own perception and interpretation of the situation. This can be done by developing automatic process of information flow from different navigational systems and presenting the processed information as a warning and decision support. By enhancing his level of situational awareness through the proposed decision support based on real time information OOW should be able to make objective decisions in good time and enhance navigational safety dramatically.

In conclusion, to improve the maritime navigational safety, it is important to introduce an Automatic Collision Avoidance System, which mimics the TCAS system. The new system will enhance the collision avoidance procedures and utilisation of information on the bridge. Consequently, the navigational safety will improve by using better interpretation and perception of the OOW. In addition, this will remove the uncertainty in the COLREG and the decision-making, as well as the subjectivity of the OOW decisions.

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