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COLREG and Autonomous Collision Avoidance Development: An analytical review

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Abstract:
Maritime Autonomous Surface Ships (MASS) face regulatory challenges, evident by that the current ship anti-collision regulations (e.g. COLREG) are not appliable for autonomous navigation systems. While academic research has focused on developing autonomous collision avoidance (CA), these studies have produced inconsistent outcomes compared to conventional navigation practices. This study aims to identify trends and weaknesses in recent academic studies on CA by reviewing and analysing the contents of selected papers. The conventional collision avoidance process (CCAP), which benchmarks human driven modern ship's capacity for CA compliance with COLREG and industry requirements, was used to disintegrate into 53 fragmented functions under eight main functions. 32 papers were selected by filtering based on keywords, period of publication, language, and relevance. The autonomy development content was then grouped under appropriate CCAP codes. Statistical and graphical interpretations were generated using the collected literature content data and evaluated statistics of the existing digital contribution of CCAP. The study reveals significant trends, inconsistency, and weaknesses of CA regulations to guide future scholarly studies toward comprehensive CA solutions.

Keywords: COLREG, MASS, collision avoidance

1. Introduction

The International Maritime Organization (IMO) introduced the concept of Maritime Autonomous Surface Ship (MASS) with four degrees of autonomy. Since then, many organisations in the maritime sector have taken steps to regulate the integration of autonomy on ships. For instance, IMO (2021) regulatory scoping exercise, classification society guidelines (DNV.GL, 2018; ABS, 2020), and initiatives from major industrial players like Rolls-Royce have all collaborated to update maritime regulations and standards to give recognition to the potential instrumentation, design, construction and operation of MASS.

One of the main challenges of the development of MASS is the avoidance of collision. International regulations for the avoidance of collision at sea "COLREG" (IMO, 2002) is the underpinning regime which defines collision avoidance standards to be followed by seagoing vessels. With the emergence of MASS, disruption incurred as how it is going to fit into the conventional means of navigation of vessels. Therefore, it is important to identify regulatory barriers and find means to address them to bridge the gap between conventional ship functions and autonomous ship functions. In that view, there must be a universally interacting mechanism and standard to enable ships to acquire and share information electronically to facilitate collision avoidance manoeuvres performed by each other. This would require the COLREG as well as other decision supporting attributes such as information conveyed through linguistic formats like digital publications and radio broadcasts, to work in a single platform to synchronise with innovative cyber solutions.

In the advent of MASS, there are a considerable amount of research studies have been and being performed by numerous scholars to develop an autonomous collision avoidance decision-making system on ships, but these studies seem to be scattered over the conventional process of addressing a CA situation by a prudent navigator. For instance, IMO (2002) Collision Regulation (CR) describes the aspect of detecting a target, then determining it for existence of risk of collision, identifying the situation followed by the suitable manoeuvre, execute the action and monitor until situation is cleared. These sequential steps are differently addressed in academic studies making lags in the development of holistic autonomous coverage of CA process. Therefore, to develop a comprehensive autonomous decision-making system, there are many measures needed to be addressed in terms of bringing the CA autonomy into a reality. Hence, it would be beneficial for both research community and maritime community to have an overview of research trends and possible lags in the academic studies performed in the recent past with the emergence of enthusiastic curiosity in MASS. With a better comprehension of the Conventional Collision Avoidance Process (CCAP) practiced by a prudent human navigator, as required by the CR and other local requirements, it would deliver a sensible ability to analyse comparatively, the extent of withdrawal of human intervention achieved by proposed artificial or digital autonomy. This comparative analyses based on conventional practice seem to be the most convincing mean to justify the potential and, importantly, to organise goal based targets on the development of a conflict free MASS operation with respect to CA. Evaluating recent academic research studies for its' attainments in CA autonomies, potentially enabling the withdrawal of human participation those are being recognized in CCAP, would showcase the lapses, intensities and trends of scholarly studies. This analytical study would benefit the scholars to understand the true scope of CA at sea and how to achieve a holistic decision-making autonomy convincingly by replacing each human oriented conventional CA practice.

The main aim of this paper is to identify the academic research trends and gaps in the development of comprehensive CA autonomy for MASS in the recent five years (i.e., 2018- 2022). Mapping the Conventional Collision Avoidance Process (CCAP) adhering to CR and other navigational attributes, human interventions are recognised for each CA function. Through that, potential and viable technological and conceptual demonstrations in the academic research literature are assessed for the potential withdrawal of each human intervention in CCAP.

2. Literature review

2.1 Digital interpretation of COLREG, Navigation Data and e-Navigation

The emphasis of digital interpretation of CR found to be a main zeroed-in interest in many research discussions. Modern ships, navigated by human, are substantially equipped with technologies to both support and enhance the safety of navigation compared to the ships operated a few decades ago. Integrated Navigation System (INS), which combines almost every navigation equipment including main propulsion controls, serves a stand-alone operability of the ship for modern navigators. For a considerable period, navigators have been using geometric techniques (i.e., Radar Plotting) to identify dangerous targets in vicinity. Closest point of approach (CPA), Time to CPA (TCPA), Bow crossing Range (BCR), Bow Crossing Time (BCT) and Relative Bearing (RBRG) are frequently used parameters in deciding the risk of collisions (Olindersson and Janson, 2015). These terms are however not defined or presented in COLREG (IMO, 2002) but being widely used as decisive metrics by professional navigators, vessel traffic services (VTS) as well as in Electronic Navigation systems (i.e. Automatic Radar Plotting Aid, ARPA; Automatic Identification System, AIS; Electronic Chart Display and Information System, ECDIS) to represent the relative behaviour of targets around the ship and, to detect and determine the existence of risk of collision as required by CR. In light of these long stood parametric usage, there is realistic potential to develop a comprehensive autonomous collision avoidance system with further AI based integrations to human oriented functions.

For this point, Papageorgiou et al. (2019) modelled an autonomous decision support framework for ships with existing systems and potential innovative advancements. However, in his study there are a few vital elements being overlooked that needed to be addressed in terms of decision-making process. Integration of ship specific data, manoeuvring characteristics, regional or local restrictions required to observe by transiting ships, good seamanship practices are some of the missing elements which are critical in dealing with collision avoidance. Bakdi and Vanem (2022) addressed COLREG linguistic and vague provisions by codifying them to develop a decision-making model for MASS. Gil et al. (2022) used big data analytics to determine the BCR of a ship. Nonetheless, digital representation of certain COLREG provisions seems already in place. They are being immensely used by navigators and VTS to identify collision dangers and plan safe passages. Consequently, developing a universal autonomous CA platform would be a necessity in future mainly due to the potential of adopting MASS-DoA1 by a modern human driven ship is not too far for the technology it possesses at present. Such approach would eliminate the communication gap likely be created in dealing with CA situation between MASS and human driven ship.

2.2 Identification of collision avoidance functions

As for the requirement of CR (IMO, 2002), CA can be identified as a sequential process. It implies the importance of situational awareness and adaptation to the sailing area in reference to the ship's capabilities and limitations. It seems a complex process but with long term experience and developed skills by traditional navigators, structured procedural process is followed adopting the CR demands. In general, ship's safety margins (SSM) and Danger Identifying Parameters (DIP) are adapted depending on the limitation of the navigable sea area by the ship for its draught, density of traffic in proximity, navigational dangers, and local sanctions. Then, for detection of targets in the vicinity, area is continuously screened with the aid of proper lookout and all available means including RADAR, AIS, etc (Cockcroft and Lameijer, 2012). Then each target will be assessed to determine any development of risk of collision (Dangerous Targets). Once danger targets are identified, developing situation (i.e., Overtaking or Crossing or Head-on or keep out of the way) is determined as per rules 13, 14, 15 and 18 of CR, respectively. Rule 18 provides responsibility between ships having different navigation status, encounter each other in Collision Danger situation. Having transmitted the navigation status through AIS or other means, ship required to keep out of the way (the give way ship) will be ascertained.

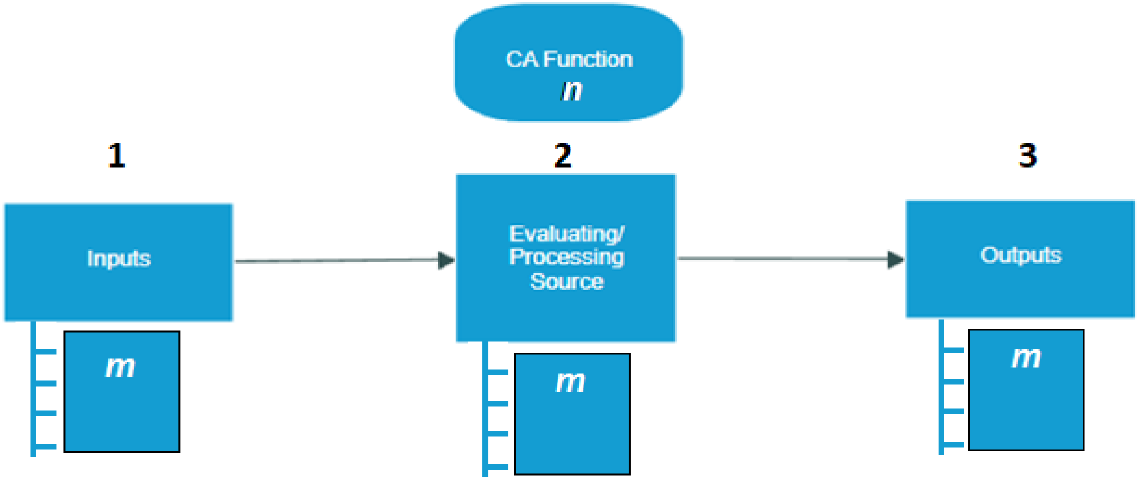
Once, situation is determined, available sea room (ASR) for the ship to safely manoeuvre around the position of CPA is assessed. Then, suitable action, either alteration of course or speed or by both, is decided considering the general provisions of "Actions to avoid collision" laid in CR rule No.8 and executed to avoid danger. Once execution takes place, monitoring will be followed until the danger is past and clear (IMO, 2002; Cockcroft and Lameijer, 2012; Olindersson and Janson, 2015). Assessment phase and before action phase consist of detection and determination functions. Manoeuvre represents the execution function; the after action phase resembles the monitoring function and the safe situation is where danger of collision is Past and clear.

3. Methodology

3.1 Detailed Mapping of CCAP

COLREG and “A guide to the collision avoidance rule international regulations for preventing collisions at sea (Guide)” (Cockcroft and Lameijer, 2012) are closely referred to, along with industry and academic literature for the mapping of CCAP. Individual CCAP function has been scrutinized further with the aid of generic outline illustrated in Figure 1. Having “n” number of “Main Functions” and “m_i” number of “fragmental data or functions” under each standard sub-groups of “Inputs (i = 1)”, “Evaluation/ Processing (i = 2)” and “Outputs (i = 3).

Figure 1- CCAP coding



(1) Inputs
In each main CA function, “Inputs” represents the information or data required to process the object of the function to deliver “Outputs”. Crucial data demand for each function is listed and coded as a fragmented function under the main CA function. During the review of literature, these input data are recognised through a close investigation of the CA practice required to be followed by a navigator.
(2) Evaluating/ Processing
This explores the required evaluations and/ or processes as per objective of the main CA function are identified under this segment. In fact, this would be the first aspect identified in each main CA function whilst constructing the CCAP and then, aforementioned input data is identified. Depending on the scope of the CA function, single or multiple evaluations and processes under Main function are recognised and fragmented. Evaluating source or mean of processing is also observed to assess the contribution of digital autonomy and human navigator.
(3) Outputs
These are the outcomes of the main CA function. These outcomes are listed according to the objectives and, presented in the form of data units as well. Eventually, almost every output data become inputs to subsequent CA functions. Similarly, as performed under Inputs, sources of outputs will also be assessed for the extent of digital contribution. In case where output source becomes fully digitalized with the aid of INS and independent from navigator involvement, it is assumed that such data can be easily transferred as input data into the next CA function.

In general, capabilities of existing marine electronic navigation systems and their limitations are investigated, identified, and considered here to recognize and demonstrate the availability of digital contribution to withdraw onboard human intervention when dealing with a CA situation as per CCAP. It is mainly focused on identifying prevailing capabilities in data managing, such as means of data (or information) collection from available sources, data feed and sharing through integration of different navigation systems (i.e., INS) and task-oriented processing/ evaluating means that can be either sole human based or completely digital or blend of both. Whenever there are fragmented CA functions that consist of both human and digital sources, most predominant source would be taking the charge of the function. For instance, if a data input function is solely independent from the onboard human involvement, it will be awarded with "Digital Autonomy" status. In case there is human involvement, but digital contribution alone possesses the capability to suffice the objective of the function in general, without exceptional circumstances, then it will be also awarded with "Digital Autonomy" status and vice versa if the process accomplishment depends on human contribution and become "Human" dependent status.

3.2 Fragmenting and Codification of CCAP

A CA process is in nature a human oriented activity onboard classical manned ships that had been evolved over the time with technology. Due to the complexity of the human oriented procedures with decision-making, in the scope of developing autonomous CA system for MASS, CCAP breakdown would facilitate to identify segmental and sequential thinking and actions followed by a prudent navigator in coping up with a CA situation with the assistance of modern equipment and systems. This would cater to demonstrate the degree of digital contribution available in modern day ship navigation and eventually provide means to codify the whole CCAP for the collection of literature content of CA autonomy development.

Simplified functional and data-oriented breakdown of each function of CCAP mapping has been modelled to streamline the qualitative literature data collection by codification. The fragmented CCAP will be allocated with a code. Then with these codes, it is expected to collect, group the explore autonomy development content of each selected academic paper under these codes. For instance, if one academic study manages to provide its content to cover all the codes of CCAP, it is expected to have identified the holistic functionality of CA to develop an autonomous CA system.

3.3 Academic literature and data collection

The academic literature is searched primarily through the Scopus database using keywords {(MASS) OR (Autonomous Ships) AND (COLREG) AND (Collision Avoidance)}. The search is limited to the following selecting criteria, 1) content: title, abstracts, scope of the study, (2) language: only published in English, (3) type of publications: only journal and conference papers, (4) period of publications: 2018 to June 2022. Literature contents that possess interests, proposals, and endeavours to devise novel CA autonomies and technologies to discontinue onboard human intervention, are harnessed through a thorough segmental review of individual abstracts, methods, outcomes, and conclusions. Inconsistency of terminology will be closely scrutinized and referenced under the most appropriate code. Nvivo software is used for efficient analysis and segregation of the linguistic data under each CA function.

3.4 Scopes of analyses

3.4.1 CCAP analysis for existing Human and Digital contribution

Initial analysis is performed after generating statistics of the outcome of CCAP mapping to identify the existing levels of human intervention and the contribution of digital technologies. CCAP codification will be utilized for the tabulation of data in "Excel." This analysis outcome will be used as a baseline for the comparative discussion of the outcomes of the subsequent academic literature data analysis.

3.4.2 Analyses of Academic Literature in CA autonomy development

Once reference data of academic literature is collected, it will be imported to Excel from Nvivo to produce statistics. By organizing the imported data in with the aid of "Data Analysis" facility provided in Excel, analyses will be conducted to demonstrate the levels of autonomy development achieved individually and wholly by selected scholarly studies. Outcomes of these analyses will be used to identify research trends and lapses as well as probable causes for such disproportions with the comparison of CCAP analysis outcome. In addition to above main two analyses, the novel concepts and theories adopted by individual study will be collected and, methods of trialling and testing will also be presented.

4. Data collection

In this research first primary objective of mapping the CCAP of a modern ship has managed to showcase the existing state of the CA process in terms of human dependency and AI oriented autonomy (digital autonomy). It also helps to witness the details of fragmental functional areas under main functions of CCAP that require further technology integration to attain complete autonomous capability. Furthermore, constructive mapping of CCAP immensely facilitated to organize and codify CA functions to collect literature contents conveniently. It eventually served the capability to generate suitable charts and tables to identify trends, consistencies, and lags of recent academic research in terms of their interests and understanding in developing an autonomous CA decision making model in relation to the conventional CA practice. The collection of literature content also managed to identify and analyse the base theories and trialling methods used by scholars.

4.1 Main CA functions

Eight main CA functions are derived from CCAP mapping in the scope of simplifying the complex cascading processes.

1. Adaptation

This is the first step and the most diversified information appraisal in CCAP. This is somewhat a continually followed activity by a prudent navigator in the aspect of conducting safe navigation in any sea area, but generally, the intensity of the information demand rises when a ship approaches towards landfall where topography generally creates clustering or bottlenecking of traffic. The main objective of this function is to anticipate and prepare the ship for upcoming traffic conditions, observing all appropriate information (i.e., limitations, restrictions, and special procedures) that is available to conduct safe navigation.

2. Target Detection

This represent the first active step of CA functionality where, locating of targets (vessels in the vicinity) is performed. In addition to locating the targets, identification also being enabled with modern navigation systems such as AIS. Overlaying of ARPA target data as well as AIS target data on ECDIS through data integration provides better spotting of targets in the vicinity.

3. Determination of Dangerous Targets

This is the important function of CA where dangerous targets are filtered from rest of the detected targets. By feeding threshold safety parameters (i.e., DIP values of CPA/TCPA/BCR/BCT) into systems such as ARPA and AIS based ECDIS, automatically the infringements will be triggered, and warning alerts or alarms will be emanated to gain the heed for the developing risk of collision.

4. Determination of Situation & Rule

After detecting dangerous targets, next key factor is to identify the developing situation. For instance, whether it is one of either Head-on or Over-taking or Crossing or Keep-out-of-the-way scenarios. This is crucial for the adoption of correct COLREG rule for understanding the options available for CA manoeuvre.

5. Determination of Available Sea-Room

Having recognized the applicable rule and available CA options pertaining to developing situation, it is important to estimate the available safe navigable waters at the location where both ships get dangerously closer (i.e., at geographical location where CPA occurs). If the sea-room is inadequate or restricted in terms of the width and/or depth of the available waters to avoid risk of collision by alteration of course alone, it would necessitate a speed alteration as well, to execute the CA manoeuvre effectively and safely without running into another danger.

6. Collision Avoidance Action Selection

At this stage, all optional collision evasive actions are evaluated, and optimal action is selected either by Alteration of course (AoC) or Alteration of speed (AoS) or a blend of both.

7. Action Execution

This is the stage where required alterations of either course or speed or both are applied to evade the developing danger of collision. On ships, these two functions are involved with heavy machinery, for instance, Main Engine for speed control and Steering gear system for course alteration. Sophisticated automations (automated functions developed for specific machinery tasks with set limitations) are already in place for these machinery operations and human intervention is required only to select the responsive values through the engine speed controller (e.g., Telegraph) and require wheel order or course to steer in Autopilot. However, in congested waters where large course-alterations take place frequently, engaging human helmsman (Manual Steering) in lieu of autopilot is a compulsory standard.

8. Action Monitoring

After the execution of the CA manoeuvre, it is paramount to check the effectiveness of the initiated action. This function shall ensure that the dangerous targets are away from threshold DIP values and ascertain the safe clearance from ship's domain of safety, so the ship can resume its original route.

4.2 Descriptive classification of fragmented functions

To map CCAP, this paper adapted the concept of Cockcroft and Lameijer (2012) and validated by a maritime expert who has work experience with more than 20 years on board, a detailed classification is generated and presented in Table 1. Each fragmented function (breakdown functions) of CCAP is briefly clarified for better comprehension and reference throughout the study. In this, the highlighted breakdown functions (bolded texts) are identified as human dependent and require further digital integration to achieve complete human withdrawal. These are the focal areas that are expected to identify in autonomy development outcomes of academic papers. In deciding the human and digital contribution of individual fragmented functions, own seafaring experience on modern ship navigation systems is utilized supported by literature review and common industry practices and usages.

Table 1- CCAP classification

No	Code	CA Function	Brief Explanatory Remark
	1	Adaptation	
	1.1	Inputs	

No	Code	CA Function	Brief Explanatory Remark
1	1.1.1	Ship Dynamic Data	Comprises values of Course Over Ground, Speed Over Ground, Heading of the vessel, speed log, position, Rate of Turn, etc., that change with ship motion
2	1.1.2	Ship Static Data	Comprises Ship Dimensions, Unique Identities (i.e., Name, Maritime Mobile Service Identity No, IMO No), etc., inherent to the ship
3	***1.1.3***	***Voyage Data***	Comprises information of Draught, Destination, Estimated Time of Arrival, Type of Cargo, etc., particular for the current voyage
4	***1.1.4***	***Ship Status***	Contains Navigation status of the ship at present (i.e., Power Driven Vessel / vessel Not Under Command / vessel Restricted In her Ability to Manoeuvre / Sailing Vessel)
5	***1.1.5***	***VTS Data***	Provides local communication means, speed limits, Traffic info, mandatory and dynamic traffic requirements
6	***1.1.6***	***Chart Update Data***	Electronic Navigation Chart updates, these are crucial amendments on operating area for safe navigation
7	***1.1.7***	***Tidal and sea current data***	Crucial for evaluating dynamic effects on ship's manoeuvrability and safe navigable depths
8	***1.1.8***	***Notices to Mariners Data***	Consists of crucial information to adopt, avoid, or consider for safe navigation in the area
9	***1.1.9***	***Sailing Direction Data***	Provides specific vital information including safer routes, and navigational dangers in coastal region
10	***1.1.10***	***Meteorological and Weather Data***	Provides regional weather prognosis, surface analysis data. (i.e., Wind force/ direction, sea state, wave height, visibility, precipitation, etc.)
	1.2	Evaluation/ Processing	
11	***1.2.1***	***DIP values***	Predetermining threshold safety parameters (i.e., CPA, TCPA, BCR, BCT to detect dangerous targets)
12	***1.2.2***	***SSM values***	Predetermining safety zones to maintain the ship within, to avoid running into navigational dangers other than traffic. (i.e., channel limits, safety depths, Look-ahead limits, etc.)
13	1.2.3	Safe Navigable Area Identification	Process of screening the operating area on electronic navigation charts for charted dangers and highlighting unsafe regions as per safety depth.
14	***1.2.4***	***Safe Route***	Process of selecting the safe path in respect to existing navigational hazards and avoiding dense traffic
	1.3	Outputs	
15	***1.3.1***	***DIP Data***	Limits of CPA, TCPA, BCR, BCT (Use to detect dangerous targets)
16	***1.3.2***	***SSM Data***	Safety Channel Margins, look ahead zones, Guard Zones, etc., Use to detect charted navigational hazards other than ships. Crucial for dynamic detection topographical dangers

No	Code	CA Function	Brief Explanatory Remark
17	1.3.3	Safe Navigable Area Data	Referred during selection of avoidance action in respect to available sea room for manoeuvre
18	***1.3.4***	***Safe Route Data***	Use to navigate the ship safely with minimal risks to the intended destination
	2	Target Detection	
	2.1	Inputs	
19	2.1.1	Heading of the vessel	Provides Direction of ship motion
20	2.1.2	Speed of Ship	Provides speed of the ship
21	2.1.3	Position of Ship	Provides position of the ship
	2.2	Evaluations/ Processing	
22	2.2.1	Detecting Targets in the Vicinity	Process of locating and identifying the target in the ship's vicinity
23	2.2.2	Evaluating Status of Targets	Acquiring the navigation status of the targets
24	2.2.3	Evaluating/ Acquiring Target motion Data	Evaluating the position, ID, true and relative CO, speed, and CPA, TCPA, BCR, BCT, RB of targets
	2.3	Outputs	
25	2.3.1	Target Data	Target ID, position, True/ Rel. Course, speed, CPA, TCPA, BCR, BCT, RB
	3	Determination of Danger targets	
	3.1	Inputs	
26	3.1.1	Target Data	Target ID, position, True/ Rel. Course, speed, CPA, TCPA, BCR, BCT, RB
27	***3.1.2***	***DIP Data***	Limits of CPA, TCPA, BCR, BCT (Use to detect dangerous targets)
28	***3.1.3***	***SSM Data***	Channel Margins, Look ahead zones, Guard Zones, etc.
	3.2	Evaluation/ Processing	
29	3.2.1	Identifying Dangerous targets	Process of identifying targets infringing the safety threshold limits (DIP) of the ship
	3.3	Outputs	
30	3.3.1	dangerous target Data	dangerous targets ID, position, True/ Rel. Course, speed, CPA, TCPA, BCR, BCT, RB
	4	Determination of situation and rule	
	4.1	Inputs	
31	4.1.1	dangerous targets Data	dangerous targets ID, position, True/ Rel. Course, speed, CPA, TCPA, BCR, BCT, RB
	4.2	Evaluation/ Processing	

No	Code	CA Function	Brief Explanatory Remark
32	***4.2.1***	***Identification of Collision Danger Situation***	Process of identifying developing situation according to COLREG or Local regulations
	4.3	Outputs	
33	***4.3.1***	***Collision Danger Situation Data (CDSD)***	Head-on/ Crossing/ Overtaking/ Keep-out-of-the-way
	5	Determination of Available Sea Room	
	5.1	Inputs	
34	***5.1.1***	***CPA Position Data***	Estimated geographical positions of the own ship and dangerous targets at CPA occurrence
35	5.1.2	Ship Safety Margins Data	Channel Margins, Look ahead zones, Guard Zones, etc.
36	5.1.3	Safe Navigable Area Data	Referred during selection of avoidance-action in respect to available sea room for manoeuvre
	5.2	Evaluation/ Processing	
37	***5.2.1***	***Evaluation of ASR at CPA***	Process of evaluating sufficiency of the sea area for CA manoeuvre
	5.3	Outputs	
38	***5.3.1***	***ASR Data***	Extents of available sea area on the chart display
	6	CA Action Selection	
	6.1	Inputs	
39	***6.1.1***	***ASR Data***	Extents of available sea area on the chart display
40	***6.1.2***	***CDSD***	Head-on/ Crossing/ Overtaking/ Keep-out-of-the-way
41	***6.1.3***	***SMD (Ship Manoeuvring Data)***	Max/Min Speed, Critical Revs, stopping distances, turning circles for Laden and Ballast conditions
	6.2	Evaluation/Processing	
42	***6.2.1***	***Selection of Avoiding Action Manoeuvre***	Best option of action determining either AoC or AoS or blend of both
	6.3	Outputs	
43	***6.3.1***	***AoC Data***	Heading of the vessel Value
44	***6.3.2***	***AoS Data***	Speed value
	7	Action Execution	
	7.1	Inputs	
45	7.1.1	AoC Data	required Heading of the vessel Value
46	7.1.2	AoS Data	required speed value
	7.2	Evaluation/Processing	

No	Code	CA Function	Brief Explanatory Remark
47	7.2.1	Processing AoC Manoeuvre	Turning of the ship by the steering gear control system
48	7.2.2	Processing of AoS manoeuvre	Adjustment of the speed by ME speed control system
	7.3	Outputs	
49	7.3.1	New Course	New Course Over Ground value
50	7.3.1	New Speed	New Speed Over Ground value
	8	Action Monitoring	
	8.1	Inputs	
51	8.1.1	Dangerous target Data	dangerous target ID, position, True/ Rel. Course, Speed, CPA, TCPA, BCR, BCT
	8.2	Evaluation/Processing	
52	8.2.1	Identify Danger is Past and Clear	Process of confirming the exit from collision danger. For dangerous targets passing astern of the own ship (OS), negative TCPA confirms safe clearance but for dangerous targets passing ahead of the OS consider negative BCT for safe clearance.
	8.3	Outputs	
53	8.3.1	Collision Danger Exit Confirmation Data	TCPA, BCT, negative time-values constitute historical events thus the resembling events (i.e., CPA and BCR) ca be confirmed as past and clear.

4.3 Outcome of academic literature and content data collection

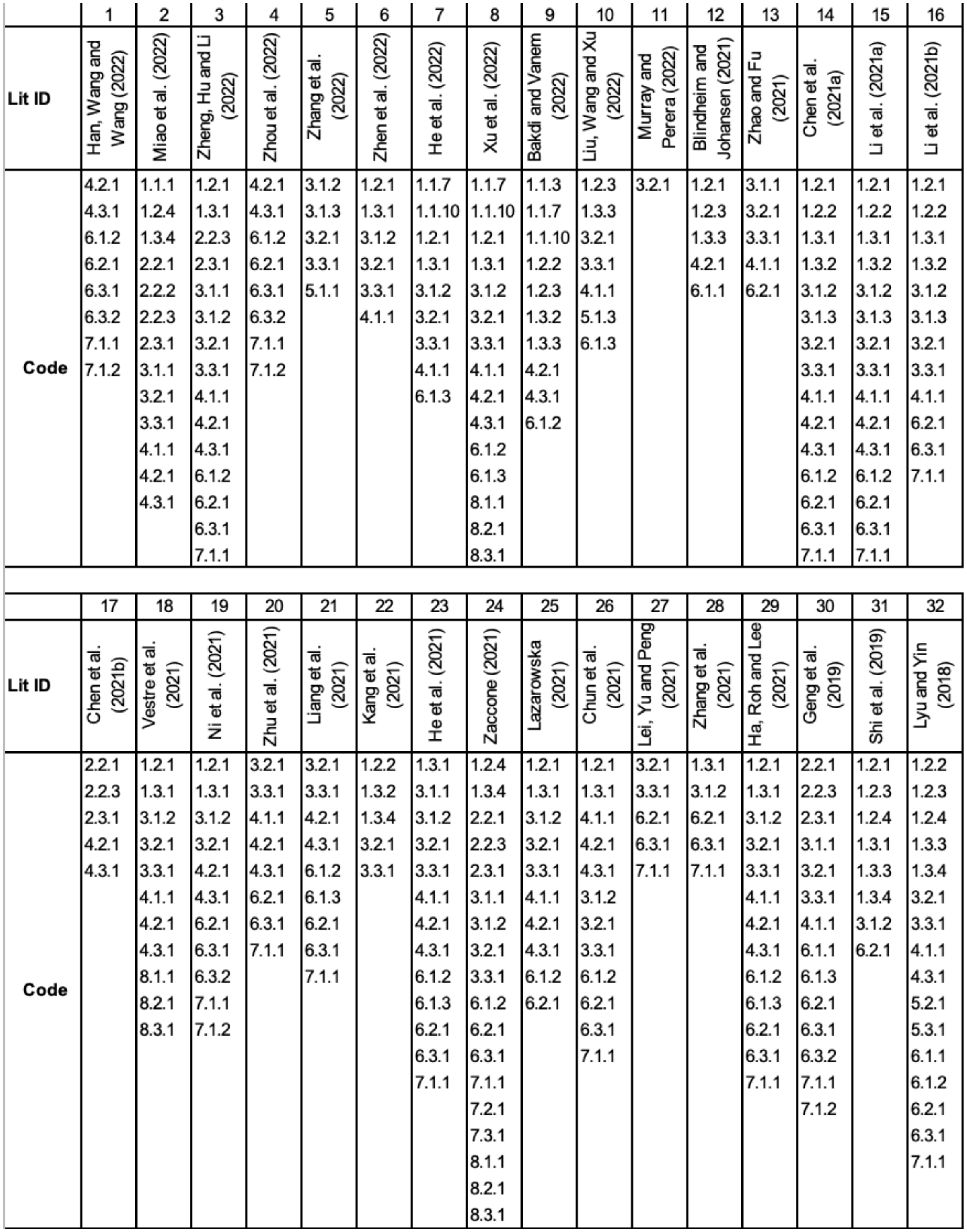
4.3.1 Filtration outcome of academic literature

With the selected keywords, predetermined time frame and language as English (see Section 3.3), 168 academic papers were filtered from Scopus data base. Having further carefully examined the applicability through the content of title, abstract and scope of research, only 32 papers were condensed for further progress of the research.

4.3.2 Literature content data (references)

With the aid of Nvivo, each paper was closely examined for contents of CA autonomy development. Through codification, the identified literature content was grouped under the applicable codes out of the 53 codes. Table 2 presents the derived outcome of Nvivo codification.

Table 2 Coded representation of autonomy development content data



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Lit ID	Han, Wang and Wang (2022)	Miao et al. (2022)	Zheng, Hu and Li (2022)	Zhou et al. (2022)	Zhang et al. (2022)	Zhen et al. (2022)	He et al. (2022)	Xu et al. (2022)	Bakdi and Vanem (2022)	Liu, Wang and Xu (2022)	Murray and Perera (2022)	Blindheim and Johansen (2021)	Zhao and Fu (2021)	Chen et al. (2021a)	Li et al. (2021a)	Li et al. (2021b)
Code	4.2.1 4.3.1 6.1.2 6.2.1 6.3.1 6.3.2 7.1.1 7.1.2	1.1.1 1.2.4 1.3.4 2.2.1 2.2.2 2.2.3 2.3.1 3.1.1 3.2.1 3.3.1 4.1.1 4.2.1 4.3.1	1.2.1 1.3.1 2.2.3 2.3.1 3.1.1 3.1.2 3.2.1 3.3.1 4.1.1 4.2.1 4.3.1 6.1.2 6.2.1 6.3.1 7.1.1	4.2.1 4.3.1 6.1.2 6.2.1 6.3.1 6.3.2 7.1.1 7.1.2	3.1.2 3.1.3 3.2.1 3.3.1 5.1.1	1.2.1 1.3.1 3.1.2 3.2.1 3.3.1 4.1.1	1.1.7 1.1.10 1.2.1 1.3.1 3.1.2 3.2.1 3.3.1 4.1.1 6.1.3	1.1.7 1.1.10 1.2.1 1.3.1 3.1.2 3.2.1 3.3.1 4.1.1 4.2.1 4.3.1 6.1.2 6.1.3 8.1.1 8.2.1 8.3.1	1.1.3 1.1.7 1.1.10 1.2.2 1.2.3 1.3.2 1.3.3 4.2.1 4.3.1 6.1.2	1.2.3 1.3.3 3.2.1 3.3.1 4.1.1 5.1.3 6.1.3	3.2.1	1.2.1 1.2.3 1.3.3 4.2.1 6.1.1	3.1.1 3.2.1 3.3.1 4.1.1 6.2.1	1.2.1 1.2.2 1.3.1 1.3.2 3.1.2 3.1.3 3.2.1 3.3.1 4.1.1 4.2.1 4.3.1 6.1.2 6.2.1 6.3.1 7.1.1	1.2.1 1.2.2 1.3.1 1.3.2 3.1.2 3.1.3 3.2.1 3.3.1 4.1.1 4.2.1 4.3.1 6.1.2 6.2.1 6.3.1 7.1.1	1.2.1 1.2.2 1.3.1 1.3.2 3.1.2 3.1.3 3.2.1 3.3.1 4.1.1 6.2.1 6.3.1 7.1.1

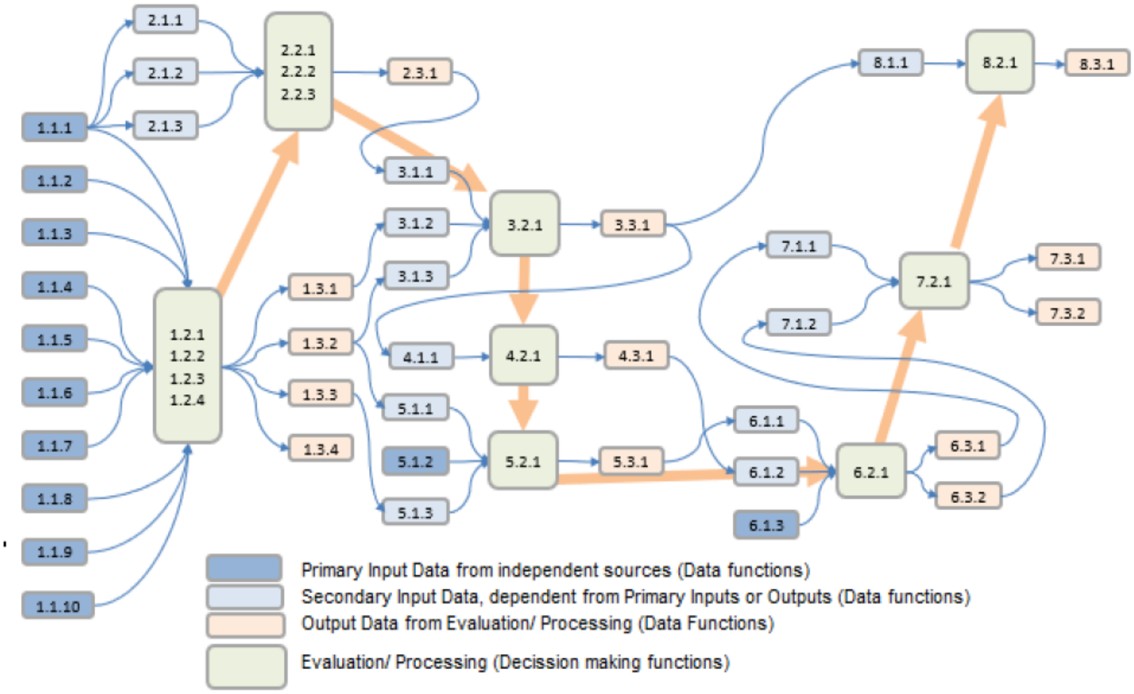
	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Lit ID	Chen et al. (2021b)	Vestre et al. (2021)	Ni et al. (2021)	Zhu et al. (2021)	Liang et al. (2021)	Kang et al. (2021)	He et al. (2021)	Zaccone (2021)	Lazarowska (2021)	Chun et al. (2021)	Lei, Yu and Peng (2021)	Zhang et al. (2021)	Ha, Roh and Lee (2021)	Geng et al. (2019)	Shi et al. (2019)	Lyu and Yin (2018)
Code	2.2.1 2.2.3 2.3.1 4.2.1 4.3.1	1.2.1 1.3.1 3.1.2 3.2.1 3.3.1 4.1.1 4.2.1 4.3.1 8.1.1 8.2.1 8.3.1	1.2.1 1.3.1 3.1.2 3.2.1 4.2.1 4.3.1 6.2.1 6.3.1 6.3.2 7.1.1 7.1.2	3.2.1 3.3.1 4.1.1 4.2.1 4.3.1 6.2.1 6.3.1 7.1.1	3.2.1 3.3.1 4.2.1 4.3.1 6.1.2 6.1.3 6.2.1 6.3.1 7.1.1	1.2.2 1.3.2 1.3.4 3.2.1 3.3.1	1.3.1 3.1.1 3.1.2 3.2.1 3.3.1 4.1.1 4.2.1 4.3.1 6.1.2 6.1.3 6.2.1 6.3.1 7.1.1	1.2.4 1.3.4 2.2.1 2.2.3 2.3.1 3.1.1 3.1.2 3.2.1 3.3.1 6.1.2 6.2.1 6.3.1 7.1.1 7.2.1 7.3.1 8.1.1 8.2.1 8.3.1	1.2.1 1.3.1 3.1.2 3.2.1 3.3.1 4.1.1 4.2.1 4.3.1 6.1.2 6.2.1	1.2.1 1.3.1 4.1.1 4.2.1 4.3.1 3.1.2 3.2.1 3.3.1 6.1.2 6.2.1 6.3.1 7.1.1	3.2.1 3.3.1 6.2.1 6.3.1 7.1.1	1.3.1 3.1.2 6.2.1 6.3.1 7.1.1	1.2.1 1.3.1 3.1.2 3.2.1 3.3.1 4.1.1 4.2.1 4.3.1 6.1.2 6.1.3 6.2.1 6.3.1 7.1.1	2.2.1 2.2.3 2.3.1 3.1.1 3.2.1 3.3.1 4.1.1 6.1.1 6.1.3 6.2.1 6.3.1 6.3.2 7.1.1 7.1.2	1.2.1 1.2.3 1.2.4 1.3.1 1.3.3 1.3.4 3.1.2 6.2.1	1.2.2 1.2.3 1.2.4 1.3.3 1.3.4 3.2.1 3.3.1 4.1.1 4.3.1 5.2.1 5.3.1 6.1.1 6.1.2 6.2.1 6.3.1 7.1.1

5. Results

5.1 Function flow mapping of CCAP

To generate a graphical overview of the CCAP, code-oriented function flow map is produced (Figure 2) using the unique array of codes adopted in CCAP. This aids to develop a clear notion of the sequential process, and reliance of preceding functions for the process continuation towards subsequent functions in CCAP. It highlights two types of input data used in CCAP. Primary inputs are the type of data being acquired from independent sources such as equipment, sensors, and information from publications and manuals. Secondary inputs are either reliant of primary inputs or outputs of a preceding function. The advantage of this flow map is that it could assist readers to overview the whole CA process in a systematic way throughout this study. Also, it allows to distinguish the primary data and secondary data demand in each main CA function.

Figure 2 Data oriented function – flow map of CCAP



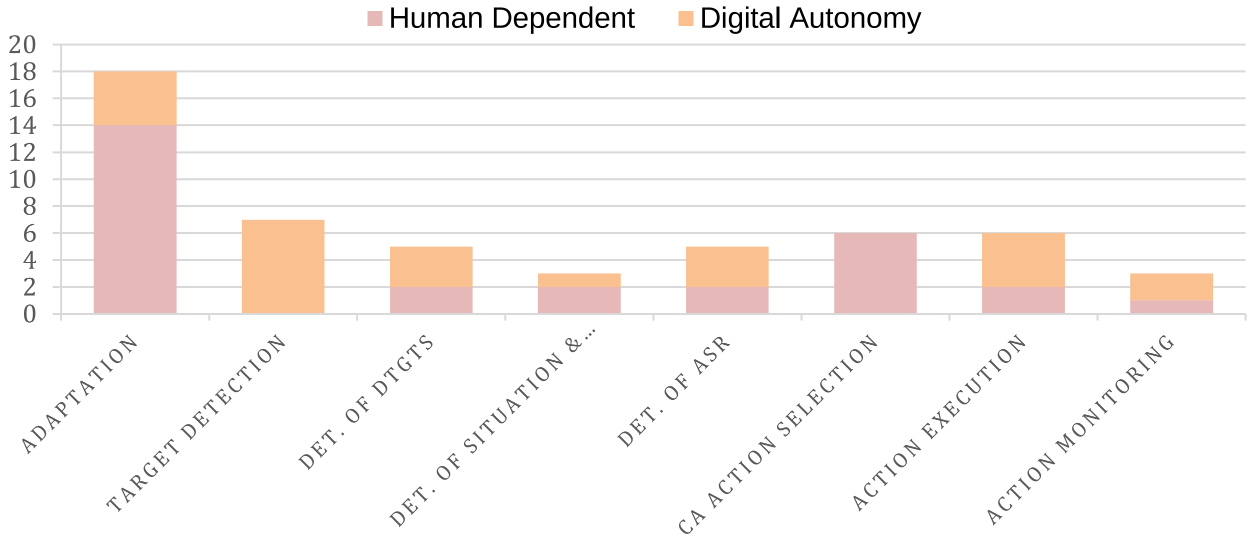
In the scope of achieving autonomous decision-making status, developing digital platforms to extract the Primary Input Data seems essential. Some of these data are sensor based on shipborne instrumentation (e.g., GYRO, LOG, GPS, etc.) where digital contribution is almost hundred percent. In contrary, where the data is dependent on dynamic status of the ship (e.g., Ship status, etc.) require AI integration to process or recognise physical status of the vessel operability as per COLREG. When the data is more informative (e.g., Sailing direction data, tidal and current data, VTS data, Meteorological data, etc.), generated externally and conveyed to the ship via different means (i.e., Digital publications, Radio Broadcasts, linguistic data, etc.), it would require extreme digitalization to produce digitally recognisable common data platforms to operate autonomously. However, to some extent, ECDIS platform seems to have managed to produce universal mean to collect some primary input data (e.g., Chart update data, notice to mariners data, etc) with minimal human intervention by only prompting the function, where the exchange and application of data take place automatically.

5.2 Analysis of existing digital contribution in CCAP

This analysis is performed to evaluate the existing status of main CA functions to develop a point of reference for the main analyses planned on academic literature.

Existing status of Human and Digital contribution in each fragmented function has been examined in consideration with existing modern capabilities. Then each code is rated either to denote “human dependent” or “digital autonomy” (independent from human), to provide comprehension of the autonomous functional state at present. Hence, in this study, it is assumed conceptually, that once every fragmental function identified during CCAP mapping, is fully independent from on board human intervention, the main function is full autonomy capable. In contrary, if a single functional attribute remains human dependent (onboard), then the system is not considered fully autonomous. Figure 3 represents the graphical representation of the extent of human dependent status of each main CA function according to the number of codes. It produced sensible insight of individual status of main CA functions with respect to the level human involvement.

Figure 3 - Analysis of existing status of fragmented functions of CCAP



- Analysis of Adaptation

“Adaptation” endures the highest number of codes due to the numerous input data and multiple decisive outputs thus represented as the tallest column. Considerable amount of the input data is from independent sources such as digital publications, that could not be fully integrated into INS systems due to limited digitization. Thus, human intervention still requires interpreting these data and evaluate outputs. For instance, DIPs (CPA, TCPA, etc.) are still evaluated by the navigator with its personal judgement and experience supported by the collected data.

- Analysis of Target Detection

However, the only independent function of CCAP has become the “Target Detection.” It is due to the existing instrumentation, basically the Radar and AIS, targets are detected automatically without human involvement. It should be noted that, here the assumption was made, for that, these instrumentations operate at its best level of performance to negate the encounters of operational flaws, which is out of the scope of this study. Continuous monitoring is done by navigator for each navigation equipment. However, such elements are not applicable in the scope of this study. Another significance was the status.

- Analysis of CA Action Selection

This is the only main function that appeared as entirely human dependent. Here the COLREG digital interpretation sets as a barrier where, there have not yet been a system developed to evaluate this process. Since modern ships are continuously staffed at navigation control area (the

Bridge), apparently, there have not been any system or a decision supporting mechanism developed. In the rise of MASS, this could be a hot topic in working out for a digital autonomy.

5.3 Autonomy contribution chart

Table 3 maps individual literature (Lit. ID) to their study outcomes by two tone colour mapping (white and grey) of the codes they addressed. In each row, grey segments represent the attempted CA functions, whereas white zones indicate omissions. This provides a clear graphical overview of individual coverage of autonomy development attempted over the 53 codes and the diversities and concurrences of the outcomes of 32 studies. The study's contribution coverage over CCAP codes is charted statistically and graphically using two tone colour bars and excel analytical tools (Green scale bars) on the right-hand end of Table 3. Two types of graphs are used to present illustrative analyses: (1) grey scale colour bar charts what shows spectrum of literature density, and (2) a combo chart (line and column) that demonstrates numerical and proportional representation of the number of literatures under CCAP codes.

Table 3 - Autonomy contribution chart

No	Lit. ID	# Code Ref	Ref%
1	Han, Wang and Wang (2022)	8	15.1%
2	Miao et al. (2022)	13	24.5%
3	Zheng, Hu and Li (2022)	15	28.3%
4	Zhou et al. (2022)	8	15.1%
5	Zhang et al. (2022)	5	9.4%
6	Zhen et al. (2022)	6	11.3%
7	He et al. (2022)	9	17.0%
8	Xu et al. (2022)	15	28.3%
9	Bakdi and Vanem (2022)	10	18.9%
10	Liu, Wang and Xu (2022)	7	13.2%
11	Murray and Perera (2022)	1	1.9%
12	Blindheim and Johansen (2021)	5	9.4%
13	Zhao and Fu (2021)	5	9.4%
14	Chen et al. (2021a)	15	28.3%
15	Li et al. (2021a)	15	28.3%
16	Li et al. (2021b)	12	22.6%
17	Chen et al. (2021b)	5	9.4%
18	Vestre et al. (2021)	11	20.8%
19	Ni et al. (2021)	11	20.8%
20	Zhu et al. (2021)	8	15.1%
21	Liang et al. (2021)	9	17.0%
22	Kang et al. (2021)	5	9.4%
23	He et al. (2021)	13	24.5%
24	Zaccone (2021)	18	34.0%
25	Lazarowska (2021)	10	18.9%
26	Chun et al. (2021)	12	22.6%
27	Lei, Yu and Peng (2021)	5	9.4%
28	Zhang et al. (2021)	5	9.4%
29	Ha, Roh and Lee (2021)	13	24.5%
30	Geng et al. (2019)	14	26.4%
31	Shi et al. (2019)	8	15.1%
32	Lyu and Yin (2018)	16	30.2%

Colour-bar analyses of Number of	# Code Ref
2022	97
2021	172
2019	22
2018	16
Overall	307

When analysing the grey scale spectrums, darker regions in the intensity analysis represent the CCAP codes with high concentration for autonomy establishment. Research published in 2021 and 2022 shows concentrated efforts to deliver solutions in the inputs, evaluation/process and outputs of Determination of dangerous targets (No.3) and Determination of Situation & Rule (No.4), and CA Action Selection (No. 6) (i.e., cover from 3.1.2 to 4.3.1 and 6.1.2 to 7.1.1). However, some of these codes (especially No 6) lie within the white zones of the “Existing Digital Contribution” (i.e., green bar chart), indicating a vacuum in existing digital contribution. On the contrary, efforts towards addressing autonomy demand in Adaptation (No.1) seems minimal, with many codes being white patches. In addition, although Determination of ASR (No.5) has three codes covered by existing digital contribution, the rest of two (i.e., 5.2.1 and 5.3.1) have limited research addressing these two codes (less than 2 papers from 2018). This indicates significant lags in recent studies. The only productive endeavour toward prevailing autonomy demand was covered by Lyu and Yin (2018).

6. Conclusion

This study constructed baseline reference of CCAP to analyse academic research content of human withdrawal solutions was effective in collecting, organizing, and analysing the literature content data. Through CCAP, discrete eight main functions were introduced that could be universally adopted in future academic studies to demarcate the area of interest in CA autonomy development adhering to COLREG, including adaption, target detection, determination of dangerous targets, determination of situation and rule, determination of available sea room, collision avoidance action selection, action execution and action monitoring. With reviewing 32 papers, a total of 53 CCAP codes are identified, and the digital autonomy status of each code is also determined.

The content of this research has the potential to cater and guide the academic researchers to recognise the trends of recent scholarly studies and adapt to the prudent navigating rationales to incorporate into their future studies of autonomy development in maritime collision avoidance. It is also expected to produce an overview of recent studies for its inclinations, omissions, as well as range of base theories utilized. This CCAP concept could be developed further by expanding it to simplify to a greater extent, whereby, it may facilitate and encourage scholars to improvise more comprehensive and productive studies.

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References

ABS (2020) *ABS ADVISORY ON AUTONOMOUS FUNCTIONALITY.* Available at: https://maritimesafetyinnovationlab.org/wp-content/uploads/2020/09/ABS-Advisory-on-Autonomous-Functionality.pdf

Bakdi, A. and Vanem, E. (2022) Fullest COLREGs Evaluation Using Fuzzy Logic for Collaborative Decision-Making Analysis of Autonomous Ships in Complex Situations. *IEEE Transactions on Intelligent Transportation Systems*, 1-13.

Blindheim, S., & Johansen, T. A. (2021). Electronic navigational charts for visualization, simulation, and autonomous ship control. *IEEE Access*, *10*, 3716-3737.

Chang, C. H., Kontovas, C., Yu, Q., & Yang, Z. (2021). Risk assessment of the operations of maritime autonomous surface ships. *Reliability Engineering & System Safety*, *207*, 107324.

Chen, C., Ma, F., Xu, X., Chen, Y., & Wang, J. (2021a). A novel ship collision avoidance awareness approach for cooperating ships using multi-agent deep reinforcement learning. *Journal of Marine Science and Engineering*, *9*(10), 1056.

Chen, X., Liu, Y., Achuthan, K., Zhang, X., & Chen, J. (2021b). A semi-supervised deep learning model for ship encounter situation classification. *Ocean Engineering*, *239*, 109824.

Chun, D. H., Roh, M. I., Lee, H. W., Ha, J., & Yu, D. (2021). Deep reinforcement learning-based collision avoidance for an autonomous ship. *Ocean Engineering*, *234*, 109216.

Cockcroft, A.N. and Lameijer, J.N.F. (2012) *A guide to the collision avoidance rules international regulations for preventing collisions at sea*. 7th ed. Oxford: Elsevier.

DNV.GL (2018) *Autonomous and remotely operated ships.* Available at: https://maritimesafetyinnovationlab.org/wp-content/uploads/2020/09/DNVGL-CG-0264-Autonomous-and-remotely-operated-ships.pdf

Geng, X., Wang, Y., Wang, P., & Zhang, B. (2019). Motion plan of maritime autonomous surface ships by dynamic programming for collision avoidance and speed optimization. *Sensors*, *19*(2), 434.

Gil, M., Kozioł, P., Wróbel, K. and Montewka, J. (2022) Know your safety indicator – A determination of merchant vessels Bow Crossing Range based on big data analytics. *Reliability Engineering and System Safety*, 220, 1-14.

Han, S., Wang, L., & Wang, Y. (2022). A COLREGs-compliant guidance strategy for an underactuated unmanned surface vehicle combining potential field with grid map. *Ocean Engineering*, *255*, 111355.

He, Y., Li, Z., Mou, J., Hu, W., Li, L., & Wang, B. (2021). Collision-avoidance path planning for multi-ship encounters considering ship manoeuvrability and COLREGs. *Transportation safety and environment*, *3*(2), 103-113.

He, Y., Liu, X., Zhang, K., Mou, J., Liang, Y., Zhao, X., ... & Huang, L. (2022). Dynamic adaptive intelligent navigation decision making method for multi-object situation in open water. Ocean Engineering, 253, 111238.

IMO (2002) *COLREG : Convention on the International Regulations for Preventing Collisions at Sea, 1972*. Organization, I. M. London: International Maritime Organization**:** 1-28.

IMO (2021) *Outcome Of The Regulatory Scoping Exercise For The Use Of Maritime Autonomous Surface Ships (MASS)*. IMO. London: International Maritime Organization. MSC.1/Circ.1638**:** 1-103.

Kang, Y. T., Chen, W. J., Zhu, D. Q., & Wang, J. H. (2021). Collision avoidance path planning in multi-ship encounter situations. *Journal of Marine Science and Technology*, 1-12.

Ha, J., Roh, M. I., & Lee, H. W. (2021). Quantitative calculation method of the collision risk for collision avoidance in ship navigation using the CPA and ship domain. Journal of Computational Design and Engineering, 8(3), 894-909.

Lazarowska, A. (2021). Review of collision avoidance and path planning methods for ships utilizing radar remote sensing. *Remote Sensing*, *13*(16), 3265.

Lei, P. R., Yu, P. R., & Peng, W. C. (2021, September). Learning for Prediction of Maritime Collision Avoidance Behavior from AIS Network. In *2021 22nd Asia-Pacific Network Operations and Management Symposium (APNOMS)* (pp. 222-225). IEEE.

Li, L., Wu, D., Huang, Y., & Yuan, Z. M. (2021a). A path planning strategy unified with a COLREGS collision avoidance function based on deep reinforcement learning and artificial potential field. *Applied Ocean Research*, *113*, 102759.

Li, M., Mou, J., Chen, L., He, Y. and Huang, Y. (2021b) A rule-aware time-varying conflict risk measure for MASS considering maritime practice. *Reliability Engineering and System Safety*, 215, 1-13.

Liang, C., Zhang, X., Watanabe, Y., & Deng, Y. (2021). Autonomous collision avoidance of unmanned surface vehicles based on improved A star and minimum course alteration algorithms. *Applied Ocean Research*, *113*, 102755.

Liu, Y., Wang, T. & Xu, H. 2022. PE-A∗ Algorithm for Ship Route Planning Based on Field Theory. IEEE Access, 10, 36490-36504.

Lyu, H. and Yin, Y. (2018) Fast path planning for autonomous ships in restricted waters. *Applied Sciences (Switzerland)*, 8 (12), 1-24.

Miao, T., El Amam, E., Slaets, P., & Pissoort, D. (2022). An improved real-time collision-avoidance algorithm based on Hybrid A* in a multi-object-encountering scenario for autonomous surface vessels. *Ocean Engineering*, *255*, 111406.

Murray, B., & Perera, L. P. (2022). Ship behavior prediction via trajectory extraction-based clustering for maritime situation awareness. *Journal of Ocean Engineering and Science*, *7*(1), 1-13.

Ni, S., Liu, Z., Huang, D., Cai, Y., Wang, X., & Gao, S. (2021). An application-orientated anti-collision path planning algorithm for unmanned surface vehicles. *Ocean Engineering*, *235*, 109298.

Olindersson, F. and Janson, C. (2015) Development of a software to identify and analyse marine traffic situations. *MARSIM 2015*, 1-14

Papageorgiou, D., Blanke, M., Lützen, M., Bennedsen, M., Mogensen, J. and Hansen, S. (2019) Parallel Automaton Representation of Marine Crafts' COLREGs-based Manoeuvering Behaviours C3 - IFAC-PapersOnLine. *12th IFAC Conference on Control Applications in Marine Systems, Robotics, and Vehicles CAMS 2019*of Conference.

Shi, B., Su, Y., Wang, C., Wan, L., & Luo, Y. (2019). Study on intelligent collision avoidance and recovery path planning system for the waterjet-propelled unmanned surface vehicle. *Ocean Engineering*, *182*, 489-498.

Vestre, A., Bakdi, A., Vanem, E., & Engelhardtsen, Ø. (2021). AIS-based near-collision database generation and analysis of real collision avoidance manoeuvres. *The Journal of Navigation*, *74*(5), 985-1008.

Xu, X., Lu, Y., Liu, G., Cai, P., & Zhang, W. (2022). COLREGs-abiding hybrid collision avoidance algorithm based on deep reinforcement learning for USVs. *Ocean Engineering*, *247*, 110749.

Zaccone, R. (2021). COLREG-compliant optimal path planning for real-time guidance and control of autonomous ships. *Journal of Marine Science and Engineering*, *9*(4), 405.

Zhang, W., Deng, Y., Du, L., Liu, Q., Lu, L., & Chen, F. (2022). A method of performing real-time ship conflict probability ranking in open waters based on AIS data. *Ocean Engineering*, *255*, 111480.

Zhang, W., Yan, C., Lyu, H., Wang, P., Xue, Z., Li, Z., & Xiao, B. (2021). COLREGS-based path planning for ships at sea using velocity obstacles. *IEEE Access*, *9*, 32613-32626.

Zhao, L., & Fu, X. (2021). A novel index for real-time ship collision risk assessment based on velocity obstacle considering dimension data from AIS. *Ocean Engineering*, *240*, 109913.

Zhen, R., Shi, Z., Liu, J., & Shao, Z. (2022). A novel arena-based regional collision risk assessment method of multi-ship encounter situation in complex waters. *Ocean Engineering*, *246*, 110531.

Zheng, J., Hu, J., & Li, Y. (2022). Codesign of dynamic collision avoidance and trajectory tracking for autonomous surface vessels with nonlinear model predictive control. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, *236*(4), 938-952.

Zhou, H., Ren, Z., Marley, M., & Skjetne, R. (2022). A guidance and maneuvering control system design with anti-collision using stream functions with vortex flows for autonomous marine vessels. *IEEE Transactions on Control Systems Technology*, *30*(6), 2630-2645.

Zhu, Z., Lyu, H., Zhang, J., & Yin, Y. (2022). An efficient ship automatic collision avoidance method based on modified artificial potential field. *Journal of Marine Science and Engineering*, *10*(1), 3.