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Article

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Collision-avoidance navigation systems for Maritime Autonomous Surface Ships: A state of the art survey

Xinyu Zhang [a], *, Chengbo Wang [a], *, Lingling Jiang [b], **, Lanxuan An [a], Rui Yang [c]**

[a] Navigation College, Dalian Maritime University, Dalian, 116026, China
[b] College of Environmental Sciences and Engineering, Dalian Maritime University, Dalian, 116026, China
[c] Shipping Technology Research Center, China Waterborne Transport Research Institute, Beijing, 100088, China
(E-mail: zhang.xinyu@sohu.com, wangcb@dlmu.edu.cn)

The rapid development of artificial intelligence significantly promotes collision-avoidance navigation of maritime autonomous surface ships (MASS), which in turn provides prominent services in maritime environments and enlarges the opportunity for coordinated and interconnected operations. Clearly, full autonomy of the collision-avoidance navigation for the MASS in complex environments still faces huge challenges and highly requires persistent innovations. First, we survey relevant guidance of the International Maritime Organization (IMO) and industry code of each country on MASS. Then, major advances in MASS industry R&D, and collision-avoidance navigation technologies, are thoroughly overviewed, from academic to industrial sides. Moreover, compositions of collision-avoidance navigation, brain-inspired cognitive navigation, and e-navigation technologies are analyzed to clarify the mechanism and principles efficiently systematically in typical maritime environments, whereby trends in maritime collision-avoidance navigation systems are highlighted. Finally, considering a general study of existing collision avoidance and action planning technologies, it is pointed out that collision-free navigation would significantly benefit the integration of MASS autonomy in various maritime scenarios.

Keywords

1. Collision avoidance. 2. autonomous navigation systems. 3. cognitive navigation. 4. e-navigation. 5. maritime autonomous surface ships

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1. Introduction

Research on navigation safety and shipping safety has a long history. For decades, one of the most popular ideas in ocean and maritime engineering research is that how to design more intelligent and safe collision-avoidance navigation systems. Maritime safety faces new challenges when the size and the number of ships is increasing. Based on reports received from the national accident investigation bodies of the EU, over the period 2014-2019, almost half the marine accidents were navigational in nature, including contact, loss of control, collision, and grounding stranding (EMSA, 2020). Fig. 1 shows causes of accidents to ships. On the other hand, marine accidents can lead to greater air pollution, water pollution by cargo and bunkers.

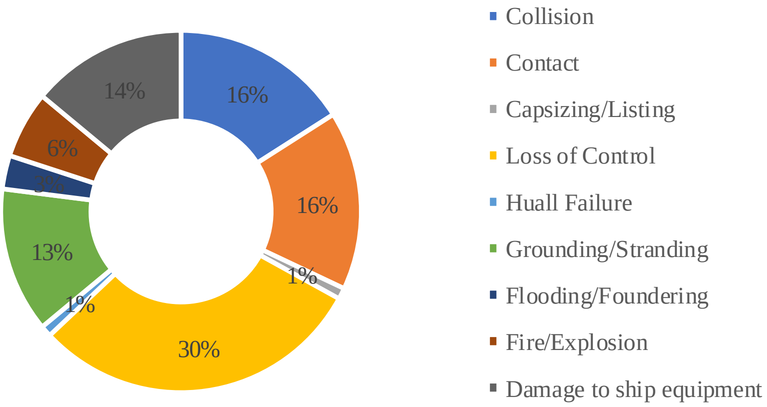


Fig. 1. Causes of accidents to ships.

The history of shipping development is the continuous improvement of navigation safety and transportation benefits. The problem of ship navigation safety has always been a hot issue in the field of marine transportation engineering, and it is also one of the main aspects that drive the growth of MASS and their technical needs. Every year, marine accidents caused by human errors or faults, such as the negligent lookout of the on-duty driver, are common. Autonomous navigation effectively replaces human pilots in ship maneuvering and cargo transportation, which greatly reduces the probability of human-induced marine accidents. At the present stage, autonomous technology is limited to applications such as unmanned surface vehicles and underwater robots, but unmanned transport cargo ships cannot yet achieve fully autonomous navigation. Collision-avoidance navigation systems use a variety of technologies and advanced research. In recent years, the research hotspots of many scholars and experts on autonomous navigation decision and planning are roughly divided into path planning, obstacle avoidance planning, trajectory planning and behavioral decision-making. Compared with path planning, collision avoidance and trajectory planning, behavioral decision-making considers time series and space constraints more. Behavioral decision-making systems are used to replace crew. Obstacle avoidance and approaching target ports are optimized goals. The behavioral decision-making is imitating the human crew's thinking activity or process of ship maneuvering. In each collision avoidance or transportation process, the optimal navigation strategy is determined from many schemes in accordance with its own behavioral constraints.

With the development of a new generation of artificial intelligence technology, the autonomy system has been widely adopted in the field of driverless vehicle, underwater vehicle, and unmanned aerial vehicle.

This work analyses current challenges and opportunities for collision avoidance and navigation planning for maritime autonomous surface ships. The following contributions are provided:

1. Summary the guidance document of IMO and industry code of each country on MASS.
2. Review of state-of-the-art MASS industry research & development and advances in collision-avoidance navigation technology.
3. Characterization of applications for maritime collision-avoidance navigation systems.
4. Overview of existing and future collision-avoidance navigation technologies.

2. State-of-the-art autonomous ship and collision-avoidance navigation technology

2.1. Advances in the MASS

There is no doubt that the development and application of autonomous ship will greatly improve the safety of maritime cargo transportation and reduce the pollution of marine environment caused by marine accidents. The Section 2.1 will review and analyze the guidance of IMO on MASS, the code of different countries on MASS, and the research and development of MASS industry.

2.1.1. The guidance of IMO on MASS

Since Maritime Safety Committee (MSC) agrees to include the issue of the autonomous ship on its agenda in January 2017 (MSC 98/20/2, 2017), MSC has been committed to guiding various countries and institutions to discuss the impact and benefits of autonomous navigation technology, research and development, testing, etc. Meanwhile, the scoping exercise is seen as a starting point. From 2017 to 2020, MSC has made great contributions to the development and application of technology of maritime autonomous surface ships, and promoted the development of technology to practical application. In the 99th session, MSC has signed the framework for regulatory scoping exercise as meeting progress, preliminary definitions of MASS, the degrees of autonomy included, as well as a methodology for conducting the regulatory scoping exercise and plan of session (MSC 99/WP.9, 2018).

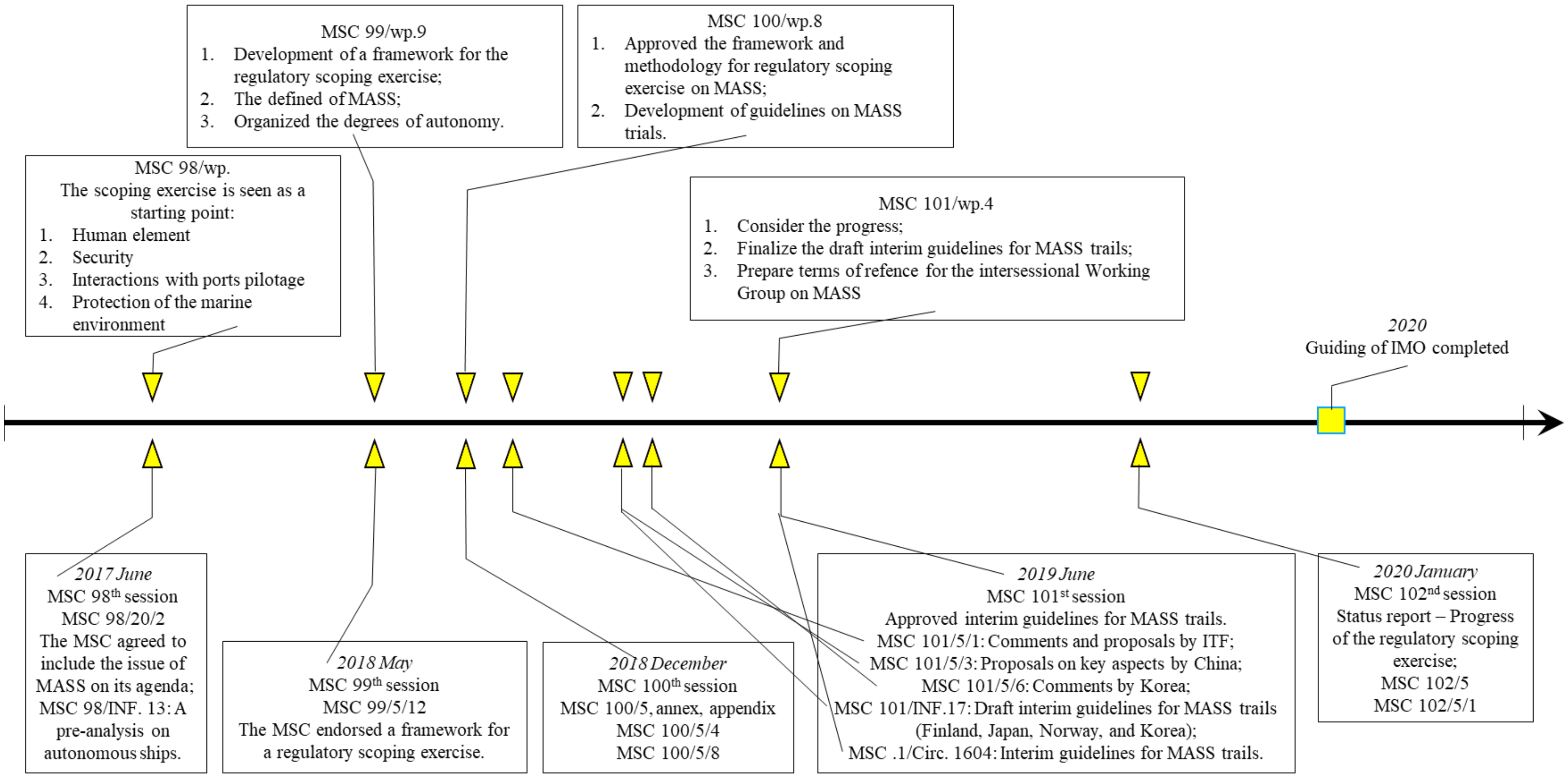
In December 2018, MSC held its 100th session, which is a milestone for maritime autonomous surface ships. The framework and methodology for regulatory scoping exercise on MASS is approved. And the degree of autonomy identified for the purpose of the scoping exercise are (MSC 100/WP.8, 2018):

1. Ship with autonomy processes and decision support;
2. Remotely controlled ship with seafarers on board;
3. Remotely controlled ship without seafarers on board;
4. Fully autonomous ship.

For the real ship test developed by the autonomous ship, MSC takes note of the proposal for the development of test criteria submitted by relevant countries and considers it a necessary work. This criterion should prevent the safety of autonomous ships and protect the environment from pollution.

In June 2019, MSC held the 101st session and approved interim guidelines for MASS trails, including the risk to safety, security and protection of the marine environment, listing the compliance mandatory instruments, manning and qualifications of personnel involved in MASS trials, human element (including monitoring infrastructure and human-system interface), infrastructure for safe conduct of trials, trial awareness, communications and data exchange, reporting requirements and information sharing, scope and objective for each individual trial and cyber risk management (MSC.1/Circ.1604, 2019). MSC 102nd session was held in January 2020, just for a status report of the progress of the regulatory scoping exercise (MSC 102/5, 2020).

Fig. 2 shows the selected proposals of each session of MSC for MASS on a timeline.



MSC 99/wp.9
1. Development of a framework for the regulatory scoping exercise;
2. The defined of MASS;
3. Organized the degrees of autonomy.

MSC 100/wp.8
1. Approved the framework and methodology for regulatory scoping exercise on MASS;
2. Development of guidelines on MASS trials.

MSC 98/wp.
The scoping exercise is seen as a starting point:
1. Human element
2. Security
3. Interactions with ports pilotage
4. Protection of the marine environment

MSC 101/wp.4
1. Consider the progress;
2. Finalize the draft interim guidelines for MASS trails;
3. Prepare terms of refence for the intersessional Working Group on MASS

2020
Guiding of IMO completed

2017 June
MSC 98th session
MSC 98/20/2
The MSC agreed to include the issue of MASS on its agenda;
MSC 98/INF. 13: A pre-analysis on autonomous ships.

2018 May
MSC 99th session
MSC 99/5/12
The MSC endorsed a framework for a regulatory scoping exercise.

2018 December
MSC 100th session
MSC 100/5, annex, appendix
MSC 100/5/4
MSC 100/5/8

2019 June
MSC 101st session
Approved interim guidelines for MASS trails.
MSC 101/5/1: Comments and proposals by ITF;
MSC 101/5/3: Proposals on key aspects by China;
MSC 101/5/6: Comments by Korea;
MSC 101/INF.17: Draft interim guidelines for MASS trails (Finland, Japan, Norway, and Korea);
MSC .1/Circ. 1604: Interim guidelines for MASS trails.

2020 January
MSC 102nd session
Status report – Progress of the regulatory scoping exercise;
MSC 102/5
MSC 102/5/1

Fig. 2. Timeline of each session of MSC for MASS, only selected proposals are indicated.

2.1.2. Industry code of MASS

Under the guidance and leadership of IMO, many countries and institutions in the world have gradually developed their own industry guidelines and codes, which include the scope and function of promoting the research and development of MASS according to the specific background and market demand of their own countries. Among them, the United Kingdom, the United States, China, and Japan have issued several industry codes related to autonomous navigation.

The UK has established the UK Maritime Autonomous Systems Regulatory Working Group (MASRWG) to develop a regulatory framework for MASS and industry-led behaviors and practices for the safe operation of MASS. The criteria, as shown in Table 1, are the classification of MASS in the United Kingdom. The second version of the code of conduct for the MASS industry was released in November 2018, the third version of the code of conduct for the MASS industry was released in November 2019, which include autonomous ships certification, registration of MASS, standards for MASS demonstration and testing areas in British waters, training, skills and qualifications and so on. Version 4 was released in November 2020, prepared in two parts, including Industry Conduct Principles and Code of Practice (Maritime, U.K., 2018, 2019, 2020).

Table 1. Class of Maritime Autonomous Surface Ship in British.

Class of MASS	Characteristic	Notes
Ultra-light	Length overall <7m and maximum speed <4kts	*Derived from MCA High-Speed Craft Code (https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/292155/hsc_2000_rev06-09_full-compall.pdf)
Light	Length overall ≥ 7m to <12m and maximum speed <7kts	
Small	Length overall ≥ 12m to <24m	
Large	Length ≥24m (and 100 GT)	
High-Speed*	Operating speed V is not less than V = 7.19 ∇1/6 knots	where ∇ = moulded displacement, in m^3, of the craft corresponding to the design waterline.

For the United States, ADVISORY ON AUTONOMOUS FUNCTIONALITY is issued by American Bureau of Shipping (ABS) in 2020. This Advisory mainly analyzes the autonomy development background, industrial demand and progress. The whole autonomous navigation is divided into smart, semi-autonomy and autonomy. The definition of each level and the role of the human in the operational decision loop are elaborated. And the functions and concepts of Remote Control (RC) and Shore Operations Centers (SOC) are described in detail (ABS, 2020). The autonomy and operational decision loop are shown in Table 2.

Table 2. Autonomy and Operational Decision Loop.

System Autonomy Levels		Integration and Application to Decision Loop			
		Monitoring	Analysis	Decision	Action
1	Smart	Machine	Machine	Human	Human
2	Semi-Autonomous	Machine	Machine	Human / Machine	Human / Machine
3	Autonomous	Machine	Machine	Machine	Machine

In 2015, China Classification Society issued the world's first intelligent ship code (2015), which proposed the concept, development path and main structure of intelligent ship (CCS, 2015). In 2018, the GUIDELINES FOR AUTONOMOUS CARGO SHIP was released, including specific requirements, objectives, functions, equipment performance, inspection and experiment of key technologies for autonomous navigation (CCS, 2018). The scope involves scene perception, navigation control, marine engine installation, mooring and anchoring, electrical equipment, communication and signal equipment, hull structure and safety, fire protection, environmental protection, ship security, remote control center, network security, inspection, and certification, etc. In 2019, according to the input of application experience, industry feedback, research results, international discussion and other aspects, the code was upgraded and revised. The new version of the Code for intelligent ships has come into effect on March 1, 2020 (CCS, 2020).

With technologies such as sensing, artificial intelligence, and internet of things having made rapid progress in various fields, the ClassNK of Japan issued the "Guidelines for Concept Design of Automated Operation/Autonomous Operation of Ships (Provisional Version)" and "Guidelines for Digital Smart Ships" in 2020. The "Guidelines for Concept Design of Automated Operation/Autonomous Operation of Ships" provide their design development, installation and operation of automated operation systems or remote operation systems (ClassNK, 2020a). The "Guidelines for Digital Smart Ships" specifies the requirements for the award of class notations to ships equipped with systems such as energy efficiency analysis, hull or machine monitoring, sloshing detection and prediction, onboard data processing and data transmission to shore, route / speed optimization and remote monitoring / operation (ClassNK, 2020b).

2.1.3. Advances in the MASS industry

Autonomy technology of MASS is the integration of numerous technologies of intelligent ships, including autonomous navigation technology (navigation situation awareness, navigation behavioral decision-making, motion control), intelligent engine room operation and maintenance, ship-shore/ship-ship communication, intelligent hull, integrated trials, and others. With the development of artificial intelligence and communication technology, the level of ship automation has been gradually enhanced. In the past several decades, some countries represented by Norway and the United States have played a constructive role in the field of research and development of unmanned surface ships and autonomous surface cargo ships, all over the words.

In recent years, the Norwegian Fraunhofer CML, as the first organization to research the demonstration related to the unmanned cargo ship, completed the project maritime unmanned navigation through intelligence in network (MUNIN) from 2012 to 2015 to verify the concept of the autonomous ship, which is defined as a ship mainly guided by the autonomous decision support system and controlled by the remote-control operator of the shore control center. The communication architecture solutions for the autonomous ship bridge, the autonomous machine room, the shore operation center, and the operators connecting the ship to shore have been developed and verified (MUNIN, 2016). Sponsorship by the Norwegian Research Council, the University of science and technology of Norway started the autonomous marine operations and systems (AMOS) project research in 2013. The architecture of AMOS is shown in Fig. 3. It is expected to complete the research on autonomous ships and robot systems in 2023, and develop the structure and operation of safer, smarter, and more environmentally-friendly ships and offshore intelligent platforms (NTNU AMOS, 2017). In October 2016, the Norwegian forum for autonomous ships (NFAS) was established to release information about international conferences and reports related to MASS, and in October 2017, under the organization of NFAS and SINTEF ocean, Norway, China, the United States and other countries established the international network for autonomous ships (INAS), marking the research of MASS has been promoted to the national level, even to the international level (NFAS, 2019; INAS, 2019). The SINTEF ocean laboratory in Trondheim, Norway, and Kongsberg, a technology company, jointly developed autonomous ship named Yara Birkeland, the first electric propulsion Unmanned Container Ship in the world. As shown in Fig. 4, the ship has a length of 70m, a width of 15m, and can carry 100-150teu. It has been tested in the water pool of SINTEF since September 29, 2017. It can use its own installed GPS, radar, and camera to avoid other ships in the channel, and realize auto-docking when arriving at the terminal point. In 2018, the autonomous navigation test from the port of Herøya in Norway to the port of Brevik has been realized for the first time. By the end of November 2020, the ship will be handed over from the Norwegian shipyard to Yara. After delivery, the vessel will undergo container loading and stability tests before sailing to port and trial sea area for further preparation for autonomous navigation (Yara Birkeland, 2020).

Fig. 3. The architecture of AMOS.

Fig. 4. Yara Birkeland.

Rolls-Royce of the UK and Stena Line AB of the Swedish ferry company will jointly develop the first intelligent ship sensing system. At the "Seminar of Un-manned Ship Technology" held in 2016, the " Development Plan of Advanced Unmanned Ship Application" was launched. It is expected that the use of remote support and specific function operations will gradually reduce the appointment of crew members in 2020; remote control of offshore MASS by 2025; remote control of ocean MASS by 2030; autonomous ocean-going MASS by 2035 (AAWA, 2017).

Other countries have also achieved excellent research results in unmanned surface vessel (USV). They have their own independently developed USV, but most of them are used in the military field, such as the United States, Israel, France, Italy, Japan, Belarus and China, the parameters of USV developed by these countries are shown in Table 3 (Richter M, 2006; Lin and Zhang, 2018; WAN J., 2014; Kumar A. and Kurmi J., 2018).

Table 3

Various types of USV parameter tables in other countries (Incomplete statistics).

Country	Ship name	Manufacturing/ application time	Size (m)	Endurance	Max speed (kn)	Research purpose and major achievements	Characteristic
USA	Spartan Scout	2001	7/11	8h/28h	50	1) Port surveillance; 2) Force protection	Light hull, shallow draft, fast maneuvering, strong endurance, and can move in very shallow waters near shore.
Israel	Sea knight	2017	11	12h	40.5	1) Surveillance and reconnaissance	It is large and capable of high-speed navigation, and is more stable in heavy winds and waves. It can sail out of the sea 500 kilometers away from the shore.
France	USV REMORINA	2017	9	——	——	1) Surveillance and reconnaissance; 2) Force protection	Autonomous decision-making and automatic obstacle avoidance.
Italy	SANDUSV	2018	16	48h	36	1) Search and rescue; 2) Environmental monitoring	Self-righting, and can work in harsh conditions.
Japan	Autonomous Ocean Observation Device (AOV)	2016	3	>24h	——	1) Environmental survey; 2) Data collection	Consists of two parts: pontoon and planning boat, connected by cables.
Belarus	Multifunctional USV	2013	6	120h(313nm)	54	——	Stealth with satellite navigation system, radar and camera.
China	ESM30 USV (Yunzhou-tech., 2020)	2015	1.15	24h	3.9	1) Environmental sampling and survey; 2) Data collection	Intelligent control terminal and real-time remote communication, automatic obstacle avoidance.
	C-38 (Smart Ocean, 2020)	2020	3.8	>7h	2	Monitoring and sampling	Multi-point selection and vertical hierarchical water sample collection.
	Skyline One (HEU, 2018)	2017	12.2	1000km	50	——	High speed, long range, independent monitoring.
	M3U (Ma and Sheng, 2018)	2017	5	——	——	1) Search and rescue	Intelligent, unmanned and three-dimensional efficient search and rescue.
	HUSTER-68 (HUST, 2018)	2018	6.8	120nm	30	Offshore patrol and supervision	Sensor equipment includes lidar, binocular camera, laser rangefinder, optical fiber combined inertial navigation, etc.
	Jinghai-1 (SHU, 2018)	2013	6.28	>130nm	10	Intelligent measurement	Independent and remote-control dual mode operation.
	DMU: Blue signal (Blue signal, 2020); Zhihai-1 (Wang et al., 2018)	2012/2018	7.02/2	——	35	1) Test platform; 2) Navigation and control systems test; 3) As sea-surface target system	It has three control modes: full autonomous, semi-autonomous and remote-control mode.

According to statistics and comparisons, USVs are used for marine environmental monitoring or military reconnaissance and strike in most countries. The military use is represented by the "Spartan Scout" in the United States. It is the earliest and most versatile. The ship is light, shallow draft, fast maneuvering, and strong endurance. For intelligence, surveillance, reconnaissance / force protection, anti-mine operations, precision strike / anti-ship operations and anti-submarine operations. Fig. 5 to Fig. 8 are USA “SPARTAN”, Israel "Sea Knight", France REMORINA and Italy SAND, respectively.

Fig. 5. USA “SPARTAN”.

Fig. 6. Israel "Sea Knight".

Fig. 7. France REMORINA.

Fig. 8. Italy SAND.

Fig. 9 to Fig. 14 are ESM30, TIANXING, HUSTER-68, JHAI No.1, LANXINHAO, and Zhihai No.1, respectively. As shown in Fig. 14, the center for Intelligent Maritime Vehicle of Dalian maritime university of China then developed a platform for "zhihai-1". The research platform consists of USV, which includes an inflatable buoy and UAV landing platform, equipment box and support erected on the buoy. The hull adopts two inflatable buoys to form a double hull structure, which enhances the navigation stability and the convenience of maintenance: the equipment boxes on both sides contain batteries to provide energy for the propulsion system. Electronic devices such as attitude sensors, GPS receivers, microprocessors and other electronic devices are placed in the equipment boxes in the middle, which can obtain GPS information, pitch angle, roll angle and heading angle, and output acceleration information in the attachment setting system, which greatly improves the measurement accuracy. The USV adopts wireless communication components, which can directly communicate with external mobile terminals and ground control stations (Wang, N., et al., 2019a). The wireless communication components communicate data through ZigBee, and implements effective data sending and receiving according to Inter-Integrated Circuit (IIC) communication protocol.

Fig. 9. ESM30.

Fig. 10. TIANXING.

Fig. 11. HUSTER-68.

Fig. 12. JHAI No.1.

Fig. 13. LANXINHAO.

Fig. 14. Zhihai No.1.

From the aspect of autonomous surface cargo ship, leading countries and research institutions are the Joint Industry Project (JIP) Autonomous Shipping of Netherlands, autonomous vessel company Masterly of Norway and action planning system project of Nippon Yusen Kaisha Line of Japan. The autonomous shipping project conducts the first autonomous ship navigation trials in the North Sea, sets the planned route, and avoids obstacles with the experience and lessons. By testing the scenarios on the North Sea, the decision-making process of an autonomous system was able to show in ensuring safe sailing and avoiding collisions with other vessels. Through the test video, we found that the system can safely avoid obstacles in simple scenarios, such as head-on scenario. It was concluded that further development of autonomous systems is needed, to cope with complex marine traffic situations in a more efficient way (Autonomous shipping, 2019). NYK has conducted the world's first MASS trial performed in accordance with the IMO's Interim Guidelines for MASS trials as the company begins tests to realize its target of manned autonomous ships for safer operations and a reduction in crew workload. During the trial, the SSR's performance in actual sea conditions was monitored as it collected information on environmental conditions around the ship from existing navigation instruments, calculated real-time collision risk, automatically determined optimal routes and speeds that were safe and economical, and then automatically navigated the ship. Through the test video, we found that the ship avoided the obstacle ship by turning right in the head-on scenario. This behavior complied with the COLREGS. NYK will analyze the data and continue to develop SSR into a more advanced navigation support system by adjusting the difference between the best course obtained by the program and the best course determined by professional officer's judgment. This trial was a big step toward realizing NYK's goal of manned autonomous ships (NYK, 2019). Comprising 22 domestic Japanese companies, such as Japan Marine Science Inc. (project leader), MTI Co., Ltd., IKOUS Corporation, NYK and so on, the Designing the Future of Full Autonomous Ship Project (DFFAS) aims to realize the trial of autonomous and unmanned navigation. The project plans to carry out a long-distance demonstration trial within 2021 in congested waters using a domestic coastal containership, efforts toward practical crewless maritime autonomous surface ships by 2025 (NYK, 2020; Weathernews, 2020). The schedule for the implementation of autonomous ships in DFFAS project is shown in Fig. 15. Kongsberg maritime and Masserly will equip and operate two zero-emission autonomous vessels for the leading Norwegian grocery distributor ASKO. All the technologies required for unmanned operation are equipped. Meanwhile, Masterly will ensure ship management and safe operation through its shore-based remote operation center (KONGSBERG, 2020).

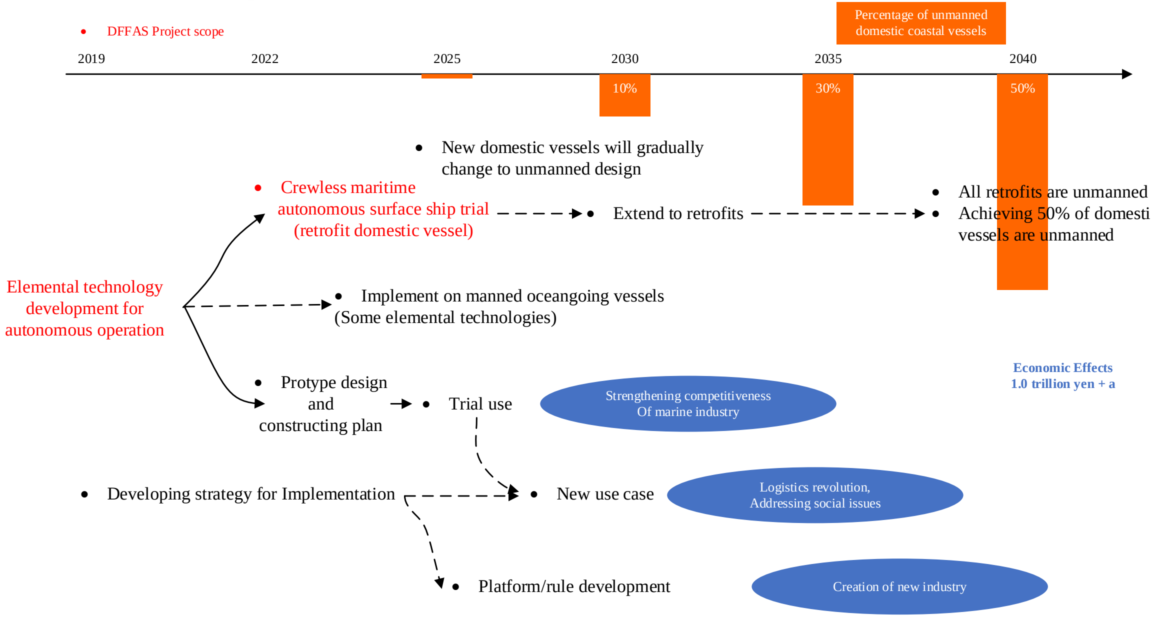


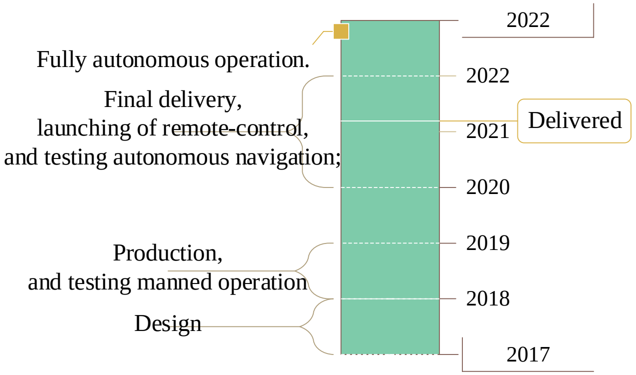
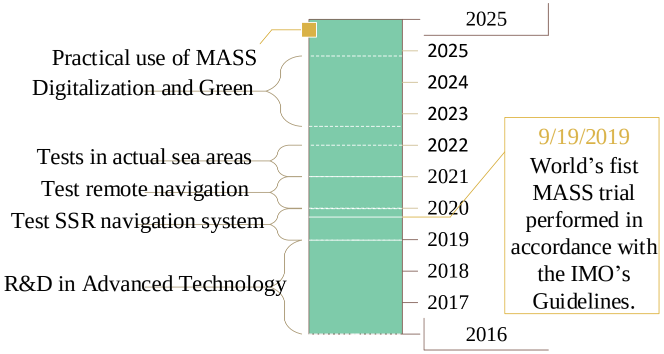
Fig. 15. Schedule for the implementation of autonomous ships in DFFAS project (Weathernews, 2020).

Other research and development projects of autonomous surface cargo ships have also achieved excellent research results all over the world. They have their own autonomous ship and trial sea area, using various algorithms and systems. Some functional tests have been implemented, such as smart support navigation, semi-autonomous, shore based remote control and so on. The detailed comparative information of MASS developed by these countries is shown in Table 4.

So current state-of-art in autonomous surface cargo ship of MASS industry is that it is possible to let a large cargo ship sail autonomously over a restricted time and nautical mile, including collision avoidance decision-making and ship maneuvering, autonomous berthing and unberthing, to realize remote control and periodicity unmanned autonomous navigation. At present, the international research and development leading projects are all entering the stage of real ship testing in specific actual sea areas.

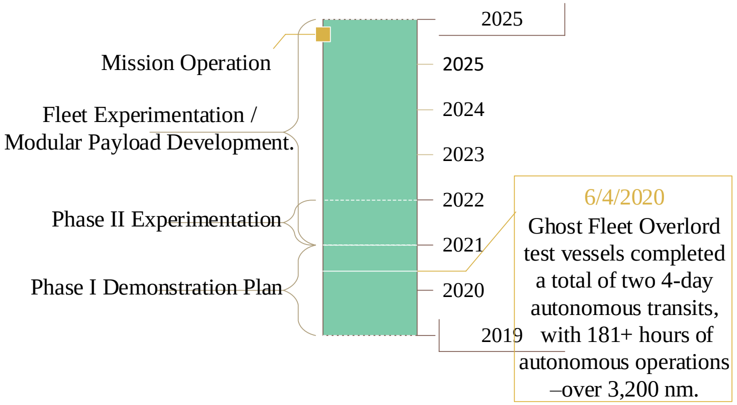
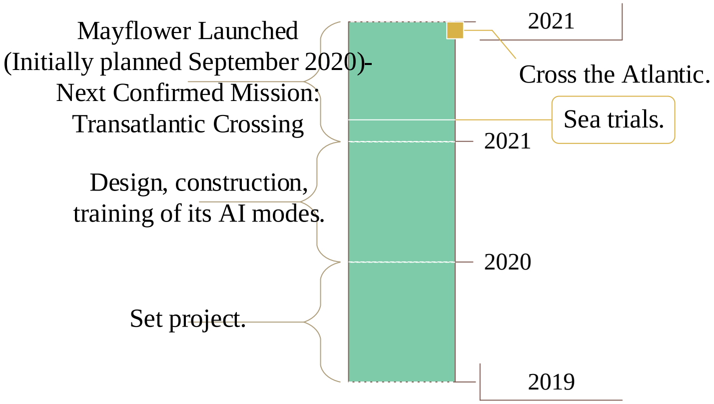
Table 4

Advances in the autonomous surface cargo ship industry.

Project	Institution	Collision- avoidance navigation system	Ship principal particulars	Proximity sensors	Timeline and status	Autonomy level*
Yara Birkeland	YARA, KONGSBERG.	K-NAV, K-BRIDGE AUTOPILOT, K-NAV AUTOPILOT.	Length:79.5m; Width mld:14.8m; Draught: full 6m, ballast 3m; Speed: Service 6knots, Max 13knots; Cargo capacity: 120TEU; Dead weight: 3200mt.	Radar; Lidar; AIS; Camera; IR camera.		L2/L3
The Designing the Future of Full Autonomous Ship Project (DFFAS)	Japan Marine Science Inc. (project leader), NYK Line, MTI Co. Ltd., et al. 22 domestic Japanese companies.	Sherpa System for Real ship (SSR) navigation system.	IRIS LEADER: Length: 199.99m; Breadth: 34.8m; DWT: 20853t; Draught: 7.9 m; Speed recorded (Max / Average): 18.7 / 17.9 knots.	Radar; ECDIS; AIS.		L2/L3, L4 (Periodicity)

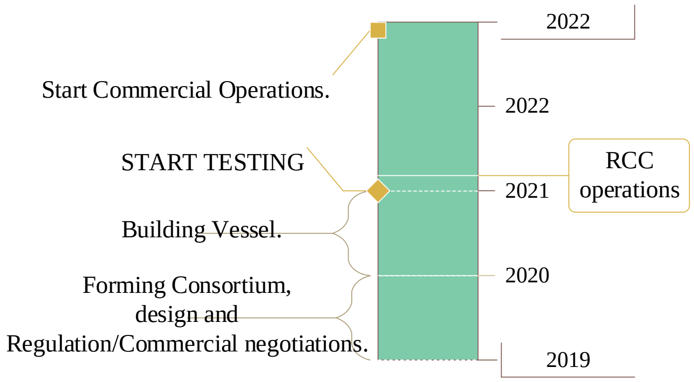
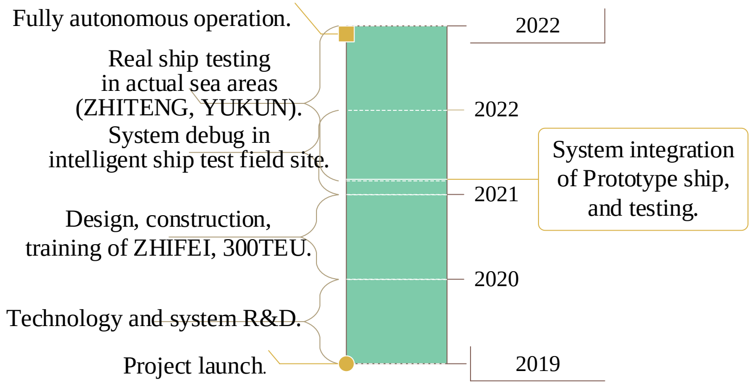
* Autonomy level refers Autonomous ships' Level defined by IMO Maritime Safety Committee.

Table 4 *(continued)*

Project	Institution	Collision-avoidance navigation system	Ship principal particulars	Proximity sensors	Timeline and status	Autonomy level[*]
OVERLORD PROGRAM & Medium / Large Unmanned Surface Vessel Plans	U.S. Navy	Command, Control and Communications (C3).	**LUSV:** Length: 200-300 feet; Full load displacements: 1000-2000t; **MUSV:** Length: 45-190 feet; Displacement of roughly 500t; Endurance of 4,500 nm or more at 19 knots transit speed or higher.	Radar; E-Optical /Infrared (EO/IR); AIS; GPS; IMU.		L3/L4 (Intermittent)
Mayflower Autonomous Ship	ProMare, IBM and a global consortium of partners.	IBM Visual Insights computer vision technology, IBM edge systems, IBM ODM.	Length: 15m; Width: 6.2m; Max speed: 10 knots; Weight: 5 tons/4535KG; Equipment capacity: 0.7 tons/700KG.	GNSS; Radar; Lidar; SATCOM; AIS; Camera; Weather station.		L3/L4 (Intermittent)

[*] Autonomy level refers Autonomous ships' Level defined by IMO Maritime Safety Committee.

Table 4 *(continued)*

Project	Institution	Collision-avoidance navigation system	Ship principal particulars	Proximity sensors	Timeline and status	Autonomy level[*]
ZULU MASS	ZULU Associates, Blue Line Logistics, Anglo Belgian Shipping Company	See AUTOSHIP Project.	Length: 90.0m; Beam mid: 15.0m; Draft mid: 5.50m; Air draft limit: 9.1m; Service Speed: 10.5 knots (85%MCR); TEU Capacity: 149+	Radar; AIS; ECDIS; RIS (River Information System); GPS.		L2/L3
Key technologies of ship intelligent navigation and control based on ship shore cooperation Project	China WTRI (project leader), DMU, WHUT, CSIC 704, HEU, BRINAV, et al. 21 domestic China companies.	Manned, remote control, unmanned autonomous navigation.	**ZHIFEI:** L: 117.15m; MB:17.32m; MD: 9.9m; Designed draft: 4.8m; Speed: 12 knots; TEU Capacity: 300.	GPS; ECDIS; AIS; G-compass; Log; VDR; MF/VHF; Radar; Lidar; Camera.		L2/L3, L4 (Periodicity)

[*] Autonomy level refers Autonomous ships' Level defined by IMO Maritime Safety Committee.

2.2. Advances in collision-avoidance navigation technology

Collision-avoidance navigation system plays the role of copilot in the whole autonomous surface ship system. The problem to be solved is to determine the obstacle avoidance strategy and collision-avoidance path through perceiving and learning the maritime safety information of the MASS. Safe and efficient maritime transportation of autonomous surface cargo ships depends heavily on intelligent navigation systems with perception, collision-avoidance decision-making, and control capabilities. Thus, the research on the technology of collision-avoidance navigation for MASS is mainly divided into perception, collision avoidance, motion control, and communication.

2.2.1. Perception

For the perception, the current shipboard perceived equipment includes high-definition cameras (HD camera), shipborne radar, millimeter wave radar (MMW radar), ECDIS, lidar, Automatic Identification System (AIS), etc. (Liu, Zhixiang, 2016). However, for maritime autonomous surface ships, intelligent perception technology may have reached the pilot or higher application stage. The problems to be solved include ship identification, static obstacles perception, visibility impact, speed perception, distance perception, viewing angle and cost. Cui, Z., et al., (2019) proposed a novel multi-scale ship detection method based on a dense attention pyramid network (DAPN) in SAR images, to detect multi-scale ships in different scenarios with extremely high accuracy. However, radar is typical sensing equipment used to detect ships and obstacles, but the radar echo cannot scan the shape and appearance of the target, which affects the ability of collision-avoidance navigation decision-making. Thus, in the early stage of research on intelligent perception, many scholars transferred learn perception technology of unmanned car, to realized maritime obstacle perception using video images and HD cameras. Knébel (2020) designed a monocular camera-based system, to detect obstacles in open sea scenarios and estimate surrounding ship's distance and bearing. Liu, B., et al., (2019) trained many ship video datasets based on deep learning framework and cross-layer jump connection policy, to realize automatically recognizing and tracking dynamic targets. At present, environmental perception is undoubtedly one of the first tasks facing the research of maritime autonomous unmanned systems. Especially under poor visibility conditions such as rain, snow, and fog, it will be very difficult for collision-avoidance navigation system to achieve accurate and rapid environmental perception. As for this problem, Wright, R. G., (2019) explored the use of machine learning and artificial intelligence techniques as a tool to combine multiple sensor equipment with collision-avoidance navigation system. The complementary advantages of multiple sensors are used to reduce the impact of environmental conditions on the ability of perception. Han, J., et al., (2020) put radar, lidar and cameras together to build a new mixed sensor fusion framework. An object ship detection algorithm had been applied to the mixed sensor platform, to estimate the encounter information. Finally, they planned the collision-avoidance navigation behavior and controlled the ship motion by trained this information with the international regulations for preventing collisions at sea (COLREGs). The identification of small moving targets at sea is an important issue in ship navigation, especially for MASS, it is necessary to introduce new means to make up for the lack of radar and AIS in detecting small moving targets at sea. Chen, Z., et al., (2020) combined a modified Generative Adversarial Network (GAN) and a Convolutional Neural Network (CNN)-based detection approach, to design a novel hybrid deep learning method. Specifically, they generate sufficient informative artificial samples of small ships based on the zero-sum game between a generator and a discriminator for training and learning.

2.2.2. Collision avoidance

From the 1990s, it is roughly divided into four parts: geometric method, optimization algorithm and bionic algorithm, virtual vector and field theory, artificial intelligence method. Fig. 16 shows the classification of MASS collision avoidance with respect to methods.

In the first stage, the autonomous collision avoidance navigation designs the model and research method according to the ship pilot's avoidance operation process, completely. That is, geometric methods and mathematical models. The early issues of collision avoidance at sea have been constantly discussed and studied through radar and radar plots. An anti-collision indicator was discussed in two ships encounter situation by Mitrofanov, O., (1968), reduction of speed and altering heading considered. The concept of a ship domain was first outlines by Goodwin, E. M., (1975). Davis, P. V., (1980) improved the ship domain model and first mentioned an evasion area, then he used these concepts to ship collision avoidance and running aground. Even though 1972 the International Regulations for Preventing Collisions at Sea (COLREGS) were drafted, but the Rule 8 and Rule 16's keywords, *early*, *large enough*, *substantial*, *safe distance*, are not clear the actual maneuvering for collision avoidance. Zhao-Lin, W., (1984) applied geometric analysis, through the construction of the calculation model of the target motion element, the Distance to Closet Point of Approach (DCPA) and the Time to Closet Point of Approach (TCPA), the latest rudder timing and the quantification of the implementation plan of collision avoidance decision, and initially realized the automatic generation of the collision avoidance decision of open water ships. Up to now, these geometric and mathematical models are still necessary for the most basic applications in collision avoidance problems.

In the second stage, with the development of computational intelligence, optimization algorithms and bionic algorithms are gradually applied to the field of ship obstacle avoidance. Zhao J., (2019) used a hybrid algorithm based on the combination of improved genetic algorithm and improved artificial fish swarm algorithm to realize the safe navigation of the unmanned surface vehicle (USV) in the complex and multi-static water surface environment. Taking the safety and economy of ship navigation as the objective function, Zeng Y., et al. (2020) proposed a hybrid optimization collision avoidance decision algorithm based on Particle Swam Optimization-Genetic Algorithm (PSO-GA), COLREGS of ship navigation considered. H. Liu, et al, (2016) combined the bacterial foraging algorithm and particle swarm optimization to optimize the collision avoidance path in the situation of multi-ship encounters. The avoidance route was generated through the avoidance angle and timing, which improved the global search and local convergence capabilities of the multi-objective optimization algorithm. In recent years, some scholars have also applied model predictive control algorithms to the field of ship collision avoidance trajectory optimization, which has solved the risk avoidance and path optimization in the complicated navigation situation of multiple ships meeting the COLREGS (Johansen, T. A., et al, 2016; Xie, S., et al., 2019; Eriksen, et al., 2019).

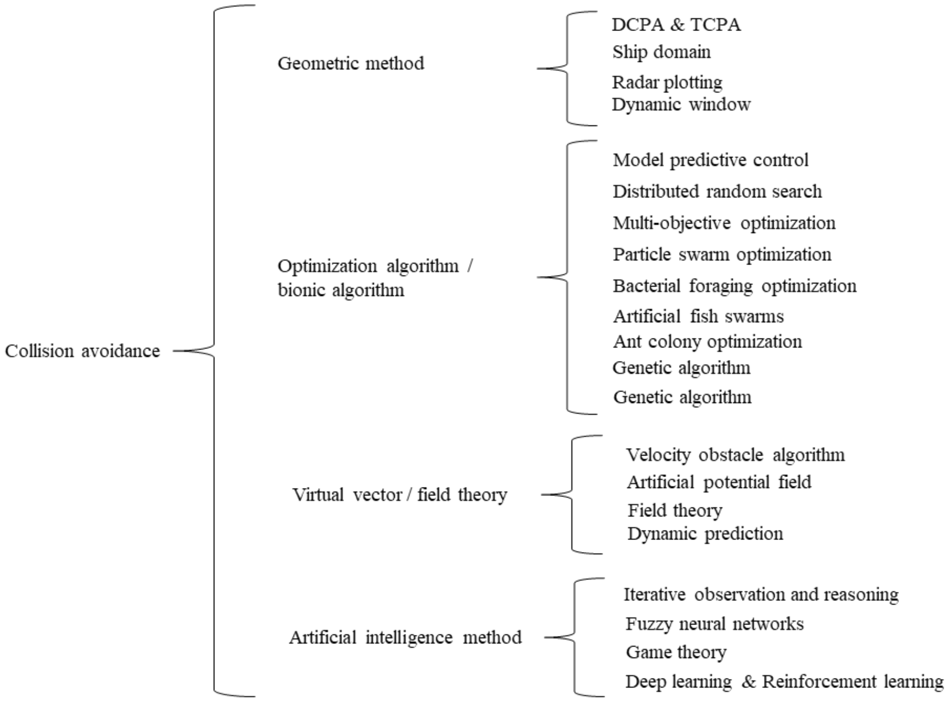


Fig. 16. Classification of MASS collision avoidance with respect to methods.

However, with the rise of driverless technology research and development, many scholars have migrated and applied key technologies of unmanned vehicles to the fields of intelligent obstacle avoidance and autonomous navigation of ships. For road unmanned driving, it has the most distinctive structural characteristics. This constitutes the third stage, virtual vector, and field theory, of collision avoidance navigation for autonomous ship. For the problem of obstacle avoidance navigation in complex and dynamic obstacle environments, Lyu, H., & Yin, Y., (2019) added security and COLREGS constraints to the corresponding virtual field strength and force, improved the artificial potential field, and constructed a real-time and deterministic obstacle avoidance path planning method. Li, Y., & Zheng, J., (2020) used field theory to abstractly simulate the trend of ship navigation, and built a collision avoidance model based on geometric derivation combined with virtual space electric field and velocity field, which solved the multi-ship avoidance problem. The last two years, velocity obstacle (VO) algorithms and the generalized velocity obstacle (GVO) algorithm are applied to the research of autonomous ship intelligent obstacle avoidance, and constructed an obstacle avoidance technology more in line with actual research and development for MASS (Huang, Y., van Gelder, et al., 2018; Huang, Y., Chen, L., et al., 2019; Shaobo, W., et al., 2020).

With the development of artificial intelligence technology, the research and development of obstacle avoidance navigation technology for MASS has also entered the fourth stage, autonomous obstacle avoidance based on artificial intelligence algorithms, such as iterative observation and inference, neural networks and fuzzy logic, deep reinforcement learning, game theory. Fan, S. and Yan, X., at al., (2020) proposed an advanced methodology for maritime accident prevention decision-making strategy formulation from human factor perspective based on Bayesian network (BN) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). It has opened a new mode of marine accident research. By fusing a hidden obstacle avoidance logic layer with an observable and predictable control layer, Wang, T., et al., (2020) constructed a two-layer human-like collision avoidance decision-making process, which improved the success rate of obstacle avoidance of multi-ship encounter scenarios without a coordination center. Ahn, J. H., et al., (2012) combined the fuzzy inference system and the expert system to the ship collision avoidance system, in which the membership functions of DCPA and TCPA were determined, and the neural network was used to evaluate the collision risk, madding up for the deficiency of fuzzy logic. In order to improve the autonomous and intelligent level of adaptive guidance for MASS, deep learning and reinforcement learning are used more to build autonomous navigation systems, to deal with multi-ship collision avoidance (Wang, C., et al., 2019; Zhao, L., & Roh, M. I., 2019; Zhang, X.; et al., 2019; Woo, J., & Kim, N., 2020). For collisions avoidance of MASS, more human-like intelligence will also be developed, and more scholars will transfer game theory to the field of autonomous navigation.

2.2.3. Motion control

Motion control systems for maritime surface ships, including ship steering and closed-loop control, have been an active topic of research since the first mechanical autopilot was constructed by Elmer Sperry in 1911 (Allensworth, T., 1999). The autopilot was referred to as the “Metal Mike”, which obtain much of the ship maneuvering behavior of a pilot or a navigator. This device did reduce heading error for various complex sea states using feedback control and automatic gain adjustments (Roberts, G. N., 2008). Later in 1922, three-term control was proposed by Nicholas Minorsky, through the analysis of a position feedback control system, that is Proportion Integral Differential (PID) control (Minorsky, N., 1922). In the 1960s, thrusters and propellers were applied to control the horizontal motion of ships, such as surge, sway, and yaw, with three decoupled PID-controller. This was named and known as dynamic positioning (DP) systems. The successful use of Linear Quadratic Gaussian (LQG) controllers in ship autopilots and DP systems, and the availability of more accurate navigation systems like GPS resulted in a growing interest in way-point tracking control systems (Holzhüter, T., 1997). Since 2000, modern control systems were based on a variety of design techniques such as sliding mode (Zhang, R., et al., 2000), H infinite control (Sheng, L., et al., 2006), PID control (Fang, M. C., Zhuo, Y. Z., and Lee, Z. Y., 2010; Fang, M. C., et al., 2012) and neural networks (Sun, M., et al., 2018), to mention only some.

In the past two years, for the study on motion control and trajectory tracking control of ships, to effectively deal with the extremely strong unmodeled dynamics, model uncertainty and unknown external interference of the USV, an intelligent self-structured robust adaptive waypoint track tracking control strategy independent of the model is proposed by Ning Wang and Hamid Reza Karimi (2020), realized a new method of precise track tracking control of the surface ship under the un-known time-varying complex sea conditions, and then proposed a limited time tracking control strategy of the USV, accurately suppress and cancel external interference and system uncertainty (Ning Wang, Xinxiang Pan, 2019; Wang, N., et al., 2019a; 2019b). To further support such a cooperative and coordinated manner for USVs, a new intelligent multi-task allocation and path planning algorithm has been proposed based upon the self-organizing map (SOM) and the fast-marching method (FMM) by Liu Y., et al. (2019), Zhou, X., et al. (2019), and Tan, G., et al. (2020).

2.2.4. Communication

The "Titanic" incident in 1912 made people realize that the primary purpose of maritime radio communication should be to ensure the safety of life and property at sea. Therefore, the first International Convention for the Safety of Life at Sea (SOLAS) was formulated in 1913. One of the important achievements is the formulation of minimum requirements for ship radio stations (Nature, 1913). In the past century, radio communication technology has been widely used in the field of ship navigation, which provides a technical means for effective information exchange and communication for ship-shore and ship-ship. Since November 1899, the first time in the history of man-made radio communication has been realized in the United States, which is mainly based on the manual Morse telegraph (Daley, A. J., 1977). In the 1970s, telex, telephone, fax, and other communication methods were gradually applied to ship communication. In the 1970s and 1980s, narrowband direct printing telegraphy (NBDP) and radiotelephone (RT) technology were applied in the ground communication system, and satellite communication technology was also occasionally used. However, the Morse signal can carry the traffic is also limited, and the operation cost of large wireless telephone station is rising. By the end of the 1980s, satellite services had begun to occupy an increasing share in the ship-to-shore communication market. For these reasons, IMO passed the International Convention on Maritime Search and Rescue (SAR) in 1979, and proposed to adopt the latest technology to develop the global maritime distress and safety communication system (IMO, 1979). Finally, the global maritime distress and safety system (GMDSS) was implemented in 1992, when advanced communication technology was widely used in ship communication. Whether it is a ground communication system or a satellite communication system, at present, the communication services recognized by GMDSS are mainly telex communication, and there is also the single side-band radiotelephone (SSB) service of the ground system. These services belong to narrowband communication services (Wikipedia, 2021).

At present, the information exchanged between the ship and shore is not only limited to ship reports and some telegrams for instructions and reports, but also includes massive data information of images, pictures, voice, and various ship parameters. At the beginning of this century, Voyage data recorder (VDR) and AIS are required to be installed on ships, and various parameters and information of ships are digitized, which lays the foundation for the transition from experience navigation to digital navigation and makes it possible to transmit various parameters of ships. For the communication technology of MASS, GMDSS, AIS, and other means of communication will face new challenges in high bandwidth and low delay.

3. Maritime collision-avoidance navigation systems

Maritime autonomous navigation systems of collision avoidance can increase the safety of life at sea. The system assists the Master or officer of watch (OOW) in their analysis of encounter situations by simultaneous plotting of all targets in the declared range, to minimize the risk of collisions. Meanwhile, the safe course or speed is calculated, according to the COLREGS, aiming at passing from all targets clearly. Therefore, it is recommended to develop performance standards that will assist the shipping community in proper analysis, design, testing, and approval of such system.

This section provides a general perspective on navigation systems of collision avoidance for maritime autonomous surface ships and modules of autonomous navigation systems that are present in the future.

3.1. Challenges in collision-avoidance navigation systems in an uncertain environment

The complexity of the uncertain environments has a certain impact on the rationality and effectiveness of the autonomous navigation behavioral decision for MASS, which is mainly reflected in the closed loop of the whole voyage (Yoo, B. et al., 2018). Three uncertainties include the scene elements in the navigation situation, the space-time characteristics and status of the obstacles, the binary relationship between MASS and the obstacles effective modeling. Therefore, MASS needs effective description and modeling of behavior decision expert knowledge base (international maritime traffic rules, good seamanship) based on scene division, and intelligent collision avoidance decision and navigation decision reasoning based on self-learning of navigation situation.

In the actual voyage, the navigation behavioral decision of MASS still faces more uncertainties (Jahnke, A., et al., 2017; Roy, N., et al., 1999; Sormunen, O. V. E., et al., 2015), such as:

1. Uncertainty of marine environment (Katsanevakis, S.; & Moustakas, A., 2018). The sea is vast and infinite, and human's understanding of the sea is very limited. In the voyage, there are not complete kinds of environmental prior knowledge. Therefore, there are many uncertainties in the sea areas lacking of environmental prior knowledge, including water depth, reef and other disturbing and obstructing factors.
2. The uncertainty of navigation situation information perception (Park, J., et al., 2019). Due to the rich information, it simply includes the information obtained by the internal sensor, the information obtained by the external sensor and the information transmitted (shared) by the third party. Internal sensors refer to the platform monitoring of MASS, generally refer to the health status of command data link, the operability and health status of sensors identified as critical, the operability and health status of onboard system (such as propeller, autopilot, collision avoidance system, etc.), watertight information, residual fuel, hull integrity, pitch, roll, heave, and ship vibration dynamic. External sensors refer to GNSS, bow direction, sea condition, wind speed and direction, water depth below keel, radar target, sound signal and visual signal (other ship's light type). Data transmitted by the third party includes AIS data, meteorological forecast data and tide calendar data. Due to the different characteristics of these sensors (principle of action, sensing mechanism, data transmission), some uncertainty of sensing information will be caused.
3. There is uncertainty in the accuracy of the prediction of obstacle motion and collision trajectory (Park, J. S., et al., 2017; Johansen, T. A., et al., 2016; Patterson, A., et al., 2019; Soloperto, R., et al., 2019). The perception of all the sensors of MASS brings the space state information, and the whole decision-making process or the navigation process has distinct space-time characteristics. These sensors cannot detect or report the behavior intention and motion state of the dynamic obstacles, such as the motion direction and speed.

In an uncertain environment, the navigation decision system and algorithm should have the ability of situation assessment based multi-source heterogeneous information, the ability to infer the motion state of dynamic obstacles and the ability to generate the optimal navigation strategy, to deal with the above problems and uncertainties.

3.2. Design of maritime collision-avoidance navigation systems

Maritime collision-avoidance navigation system is a complex system (Liu, S., et al., 2017), which integrates many advanced intelligent technologies.

In this paper, the whole system is divided into five subsystems: global route optimization, navigation situation awareness, navigation behavioral decision, motion control and execution, and high-performance communication subsystem. As shown in Fig. 17, the overall system architecture of the navigation system for maritime autonomous surface ships is presented, which describes the collaborative relationship among the five sub-systems.

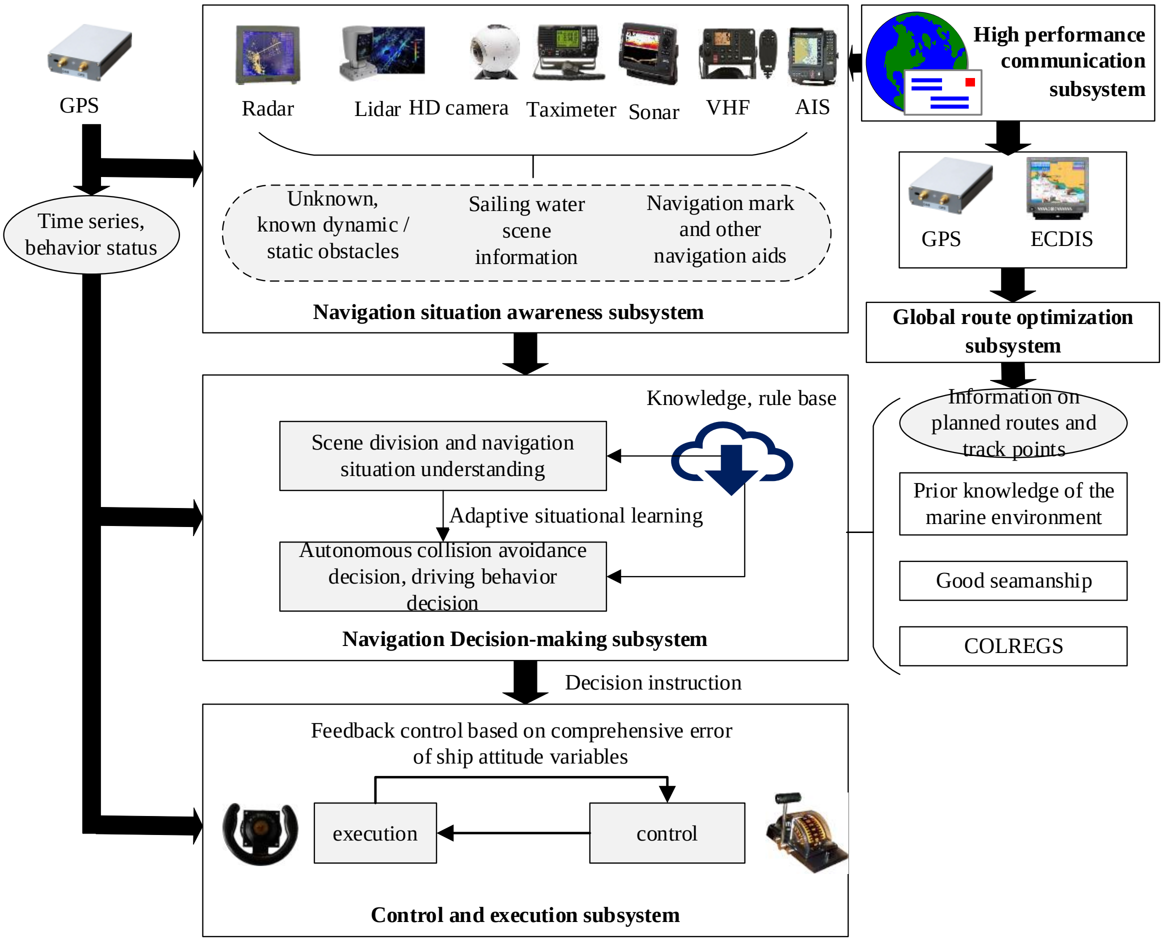


Fig. 17. The overall architecture of maritime collision-avoidance navigation system.

3.2.1. Global route optimization

The global route optimization subsystem is to set the waypoint with the help of ECDIS and GPS system in the early stage of cargo transportation for MASS, to realize the calculation and design of relatively better and safe routes for known obstacles and port-to-port (Krata, P., & Szlapczynska, J., 2018). For the whole voyage of MASS, in terms of data description, global route optimization is equivalent to optimizing the navigation strategy for global path planning. If there are obstacles or the original route is blocked in the voyage after planning, the global route optimization system will conduct quadratic programming to re-plan a reasonable and optimal global route. The commonly used algorithms are dynamic programming, a *, Dijkstra and trajectory point guidance (Zaccone, R., et al., 2017; 2018; Lee, S. M., et al., 2018; Biyela, P., & Rawatlal, R., 2019; Liu, C., et al., 2019).

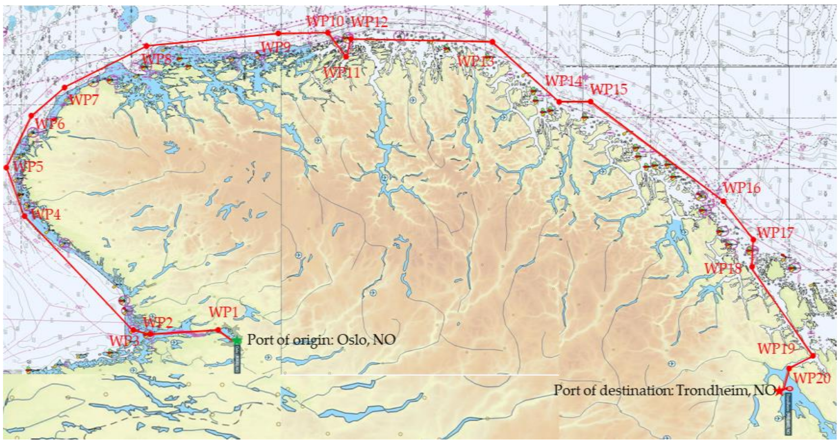


Fig. 18. Waypoint-based global route optimization from Oslo to Trondheim.

Global route optimization is to find a collision free shortest route from the known starting point to the terminal point according to the existing information under the influence of obstacles or bad weather in the marine environment. Generally, the constraints of global route optimization include time series, spatial constraints, hydrometeorology and COLREGS. In the practical calculation of global route optimization for autonomous ship, the cost setting strategy is often more important than routing planning and the shortest path selection (Wang, K., Yan, X., et al., 2020). By setting the port of origin and destination on the electronic chart, and through the calculation of route optimization and obstacle spatial constraints, multiple waypoints with cost are set to form the optimized global route. As shown in Fig. 18, it is waypoint-based global route optimization from Oslo to Trondheim of Norway.

Whether it is to determine the relationship between waypoints, establish coastal waypoint relationship database, or use various optimization algorithms to solve the shortest path, there are problems such as difficulty of establishing practical model and poor adaptability. With the development of big data technology and its wide application in the maritime field, the optimal route can be obtained by cleaning, fitting, mining, classifying, and forecasting the massive AIS trajectory data. The global optimal route generation model based on maritime big data is relatively safe and practical. Many historical trajectories are fitted to obtain recommended routes and recommended waypoints. As shown in Fig. 19, the global optimization inbound and outbound routes for Tianjin port of China are generated based on massive AIS trajectory data technology.

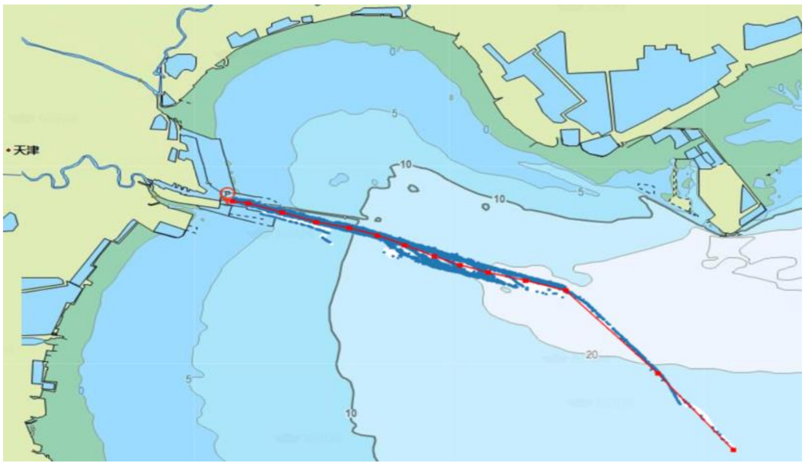


Fig. 19. Based on the massive AIS trajectory big data, inbound and outbound port routes optimization (Taking massive AIS trajectory big data of Tianjin Port of China as an example).

3.2.2. Navigation situation awareness

Navigation situation awareness system is to use a variety of onboard instruments and equipment to actively perceive the internal and external information of the ship or marine navigation environment, and receive the data transmitted by the third party (Sharma, A., & Nazir, S., 2017; Hyvönen, M., et al., 2015). Perception system is the basis of navigation behavioral decision and motion control of MASS. The accurate perception information is also an important benchmark of MASS research and development. There are many kinds of sensors and shipborne instruments in the navigation situation awareness system of MASS, such as ECDIS, radar, lidar, HD camera, sonar, AIS, etc., which can obtain high-precision position service information, maritime safety sailing information, hydrometeorological information, ship dynamic information and port information in real time (Raptodimos, Y., et al., 2016). This multi-source information is fused and processed. Static and dynamic obstacles are mapped in the ECDIS and sent to the behavioral decision system.

Generally, navigation situation awareness can be divided into three layers: navigation environment information acquisition, scenario understanding, situation assessment and prediction. For the traditional manned ship, the navigation environment information perception generally refers to the acquisition of the position, course, speed, relative direction, relative distance, hydrology and meteorology of the ship and the target ship. Scenario understanding refers to using the information obtained by ship borne navigation aids to calculate the parameters such as DCPA and TCPA. Situation assessment is the prediction and deduction of ship navigation situation in the future dynamic obstacle environment based on the situation understanding, including the prediction of other ship's trajectory and motion. However, the existing research on navigation situation awareness is simply to analyze and judge the encounter scenario based on COLREGS (Sharma A., et al., 2019).

For MASS, navigation situation awareness system realizes the navigation situation estimation and scene division with the help of the binary relationship analysis. Using ontology model and the idea of divide and conquer, the multi-source heterogeneous information obtained by the navigation situation awareness layer of MASS is clustered into different scene entities, and binary or multivariate attributes are established. Table 5 shows the attribute table of ontology model, including location attribute, data attribute and relationship attribute.

Table 5. Ontology model attribute table.

No.	*property categories*	*sub-properties*	*object properties*
1	location attribute	longitude	*hasLongitude*
		latitude	*hasLatitude*
2	data attribute	relative distance	*distToEntity*
		direction	*hasDirection*
		speed	*hasVelocity*
		current state	*currentAttribute*
		maximum	*hasMax*
		minimum	*hasMin*
3	relationship attribute	join conditions	*connectTo*
			from
			to
		incorporate relational	*has*
		orientation relation	*hasBehindLeft*
			hasBehind
			hasBehindRight
			hasFrontLeft
			hasFront
			hasFrontRight
			hasLeft
			hasRight
		position relationship	*isOn*
			isFrom

3.2.3. Decision-making

The navigation behavioral decision system is the core part of the whole MASS - navigation brain (Xinping Y., et al., 2019). The system takes the results of the perception system as input and collects all the information of the navigation situation, including not only the current position, speed, and course of the autonomous ship, but also the information of obstacles. The decision system of a maritime autonomous navigation system is to determine the route and navigation strategy of the MASS on the basis of knowing navigation safety information (Xue, J., et al., 2019; Shaobo, W.,et al., 2020).

The decision-making system takes the output of the global route optimization system as the guidance information. And gives the driving behavior instructions of the unmanned ship through the system self-learning, including longitudinal steering avoidance, such as left rudder, right rudder, etc., and lateral variable speed avoidance, such as acceleration, deceleration, parking, etc. In the future development of collision-avoidance decision making, it is found that the traditional soft computing and artificial intelligence algorithm must be combined to select the most suitable algorithm according to the needs of the scene, and adaptive collision-avoidance navigation decision-making in an uncertain environment. As shown in Fig. 20, it is the block diagram of the collision-avoidance navigation decision-making system.

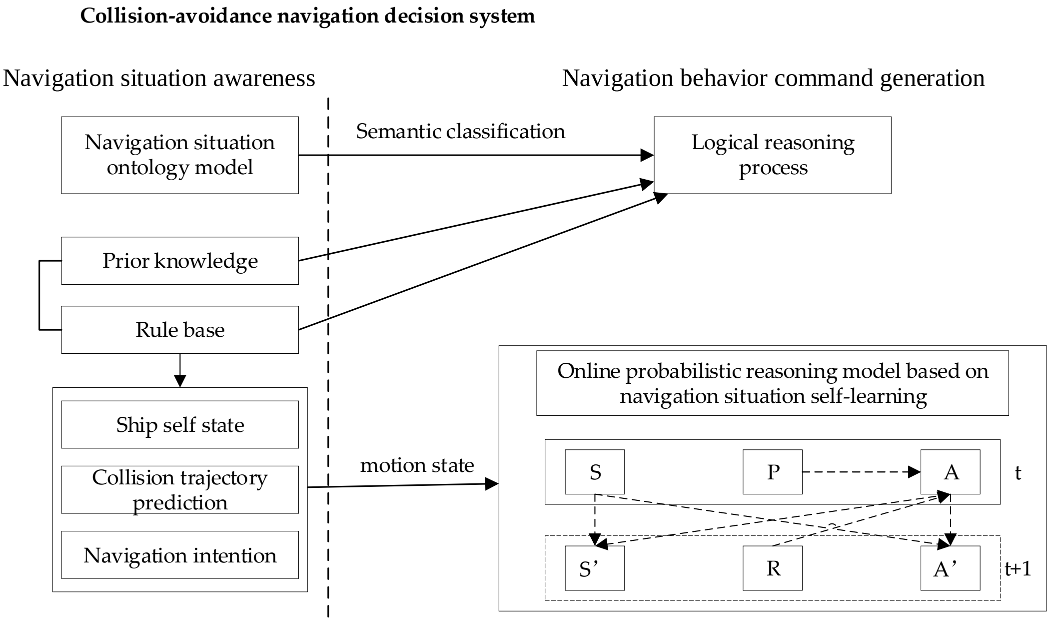


Fig. 20. Block diagram of collision-avoidance navigation decision-making system.

3.2.4. Control and execution

After the decision instruction is given by the decision system of maritime autonomous navigation system, the control and execution system of MASS will execute the instruction, mainly including speed planning and trajectory planning, corresponding to the MASS, that is, the control of the marine telegraph and rudder (Hanson, B. B., & Hanson, T. E., 2017; Huang, R., 2018). There is also a feedback control layer based on the integrated error of ship attitude variables in this subsystem. On the voyage of autonomous navigation for MASS, there are often some errors between the actual navigation and the plan due to the uncertainty of the ocean current, swell, and other environments. Therefore, the control system will be feedback controlled again based on these errors. On the one hand, the decision instructions can be adjusted in real-time for re-planning to better conform to the current navigation behavior. On the other hand, the navigation behavioral and motion can be corrected. The ship's navigation behavior can avoid uncertain risks.

From the perspective of ship attitude control, the feedback control part of MASS is not essentially different from that of ordinary ship. Both are based on a certain preset trajectory, considering the error of current ship attitude and planned route, and continuously tracking feedback control. In maneuvering, a marine craft experiences motion in 6 degrees of freedom (DOFs) (Fossen, Thor I., 2011). The MASS attitude represented by the ship model is in a three-dimensional coordinate system, and the MASS attitude can be fully described by surge, roll, sway, pitch, heave, yaw. The ship attitude represented by the ship model of MASS is shown in Fig. 21.

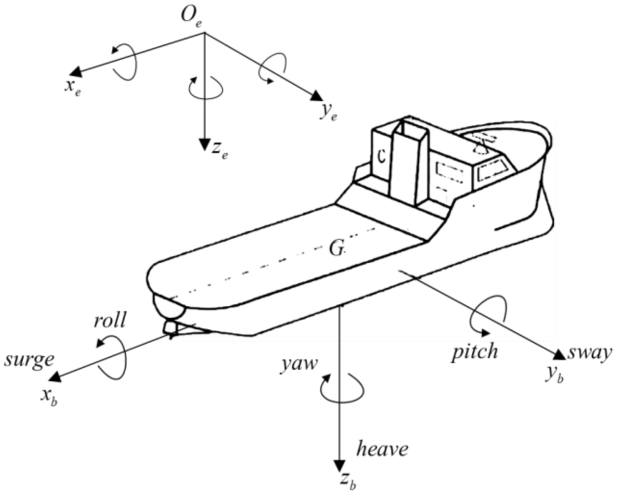


Fig. 21. The ship attitude represented by the ship model of MASS (Motion in 6 degrees of freedom (DOF), $O_e x_e y_e z_e$ is the earth-fixed coordinate system. $G x_b y_b z_b$ is the body-fixed coordinate system, and G is center of ship gravity).

As for the feedback control system of MASS, the problem we need to solve is to control the ship to follow the space-time trajectory of global route optimization and collision-avoidance navigation decision-making system as far as possible. The distinguishing feature of the PID controller is the ability to use the three control terms of proportional, integral and derivative influence on the controller output to apply accurate and optimal control. Early PID controller was developed by observing the navigation behavior of officers in maneuvering a vessel on course in the face of varying disturbance such as wind and sea state (Ma, X., et al., 2019; Zhang, Q., et al., 2020; Chen, Y. Y., et al., 2020; Wikipedia, 2020). The structure of a typical PID feedback control system is shown in Fig. 22. Where $e(t)$ represents the current tracking error, and the tracking variable error can be the longitudinal/transverse error, angle/curvature error or the comprehensive error of some attitude state variables of ship. The P controller represents the feedback to the current error, and its gain is controlled by K_P. The I and D controllers represent integral and differential terms respectively, and their gains are controlled by K_I and K_D respectively.

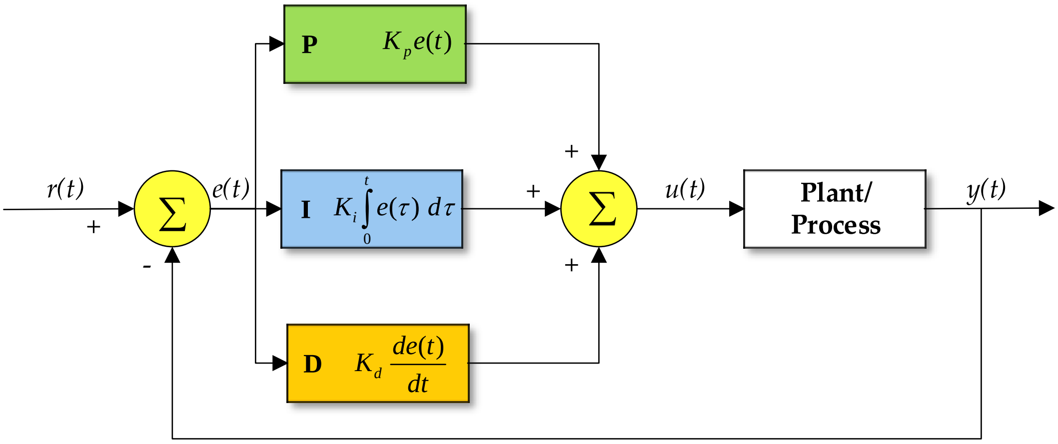


Fig. 22. A block diagram of a PID controller in a feedback loop. *r(t)* is the desired process value or setpoint (SP), and *y(t)* is the measured process value (PV). *u(t)* is the overall control function (PID controlle, 2020).

3.2.5. High-performance communication

The high-performance communication subsystem guarantees the data or safety information distribution and sharing between satellite, ship, and shore. The same as UAVs/UGVs communication, there are four types of MASS communication services: (1) MASS-to-MASS for data and control links; (2) MASS-to-Shore Control Center (SCC) for control and commands link; (3) MASS-to-Ground Wireless Nodes for MASS-aided data dissemination and collection; and (4) MASS-to-Satellite system. Due to the need to transmit many sensor information and equipment status information, as well as radar images, sea video and so on between the ship and shore, the communication volume is large. Therefore, the unmanned ships put forward high bandwidth, low delay, low cost, and other requirements for the maritime communication system.

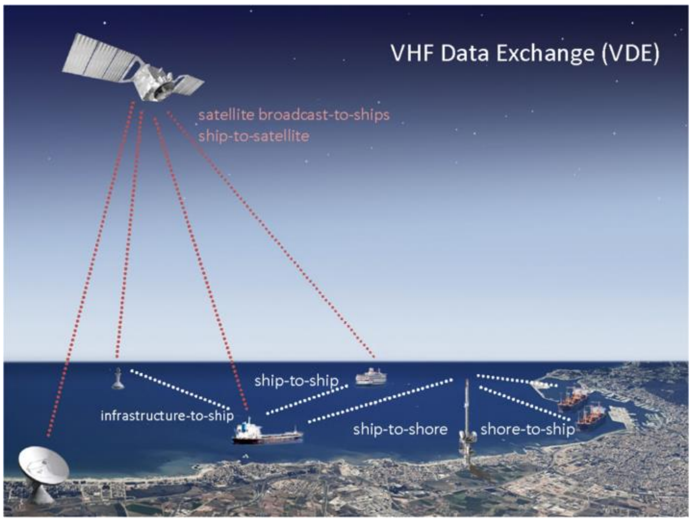


Fig. 23. VDE system concept and available communication links (Lázaro, F., et al., 2019).

As for ship collision avoidance, the high-performance communication system is particularly important. AIS, GMDSS, and other systems are mainly used for collision avoidance of ships. However, the growth in AIS has been such, that in some of the most crowded waters the system is as of today already overloaded. The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) started the work on the Very-high-frequency Data Exchange System (VDES) (Report ITU-R M.2371-0, 2015). Rather than an evolution of AIS, VDES is a communications system encompassing different communications subsystems, which including AIS and Application Specific Messages (ASM) channels. Furthermore, VDES has a third subsystem, called VDE, which allows higher rate communications, and is highly flexible to be able to support a variety of services in the future. A key characteristic of VDES is that it does not only support direct ship-to-ship and ship-to-shore communication, but it also foresees a satellite component specifically for VDE. Fig. 23 shows the VDE system concept and available communication links (Lázaro, F., et al., 2019; Golaya, A. P., & Yogeswaran, N., 2020).

With the development and support of e-navigation technology, the Maritime Connectivity Platform (MCP) has been developed and tested, which is a communication framework enabling efficient, secure, reliable, and seamless electronic information exchange between all authorized maritime stakeholders across available communication systems. AS is shown in Fig. 24, MCP has three core components, an identity registry, a service registry, and a messaging service. In general, MCP integrates the information resources of ship end and shore end, improves the level of in-depth development of information resources and comprehensive utilization of unmanned technology, promotes the deep integration of cloud computing and maritime management and services, and improves the intelligent communication technology of MASS (MCP consortium, 2019).

Fig. 24. MCP framework concept (EfficienSea2 solution, 2020).

4. Trends in maritime collision-avoidance navigation systems

4.1. Analysis on trend of maritime collision-avoidance navigation systems

There are two main types of collision-avoidance navigation systems for MASS: rule-based navigation system and learning algorithm-based navigation system. The rule-based collision-avoidance navigation system is to divide the behavior of the MASS, establish the behavior rule base according to the COLREGS, knowledge, experience, and traffic regulations, divide the ship state according to different environmental information, and determine the navigation strategy according to the rule logic. The representative methods are finite state machine and expert system. At present, the research of learning algorithm-based collision-avoidance navigation system has achieved remarkable results. According to different principles, it can be divided into deep learning-related navigation methods and machine learning-based navigation methods, such as fuzzy models.

Rules-based and learning algorithm-based collision-avoidance navigation technologies have their advantages and disadvantages. For a rule-based collision-avoidance navigation system, its advantages are the algorithm logic is clear, strong interpretability, strong stability, and easy to model. The system operation does not require high processor performance. The model has strong adjustability and expansibility, and it can realize more complex combination functions through the layering of state machine. It has advantages in the breadth traversal of function scenarios. However, the navigation behavior is incoherent due to the state cutting conditions. The trigger conditions of the behavior rule base are easy to overlap, resulting in system failure; the insufficient depth traversal of the scene makes it difficult to improve the accuracy of the system decision-making, and there is a bottleneck for the improvement of the performance of the complex condition processing and algorithm. For learning algorithm-based collision-avoidance navigation system, its advantages are it has the advantage of scene traversal depth. For a certain subdivision scene, it is easier to cover all navigation situations through the big data system. The scale of the navigation algorithm can be simplified by using the network structure. Meanwhile, some machines have self-learning performance, and the machines can refine the environmental characteristics and decision attributes by themselves, which is convenient for system optimization iteration. But it is difficult to modify the model due to the poor interpretability of the navigation decision results of the algorithm. The learning algorithm does not have the advantage of the breadth of scene traversal, and the learning models used in different scenes may be completely different. As is known, the navigation effect depends on the quality of data. Insufficient samples, poor data quality, and unreasonable network structure will lead to overlearning, under learning, and other problems.

According to the advantages and disadvantages of the two methods, the development trend of collision-avoidance navigation system for MASS can be summarized as follows:

1. The rule-based algorithm will still be widely used in a collision-avoidance navigation system. It will be used as the top-level architecture of the navigation system and the subdivision solution of some specific problems, and more hybrid structures will be used. The research focus of this method will be to solve the reasonable decision-making problem of the "gray area" of state division, and the overlapping of trigger conditions of behavior rule base of navigation.
2. The combination of rule-based methods and learning algorithm-based methods will be more used in the collision-avoidance navigation system. The top layer uses finite state machine to traverse hierarchically according to the scene. The bottom layer uses a learning algorithm to apply in modules based on the specific scene. The research focus of this method is how to connect the finite state machine and the learning algorithm model reasonably and the overfitting/underfitting problems.
3. In the wake of developments in technology that combined rule-based with learning-based, technology brain-inspired and cognitive navigation has become more capable of conquering uncertainty in complex navigation situations. It integrates perception, decision-making, planning, and control to realize the intellectualization and human-analogy of collision avoidance navigation systems.
4. E-navigation development lays a technical foundation for the construction of the autonomous collision-avoidance navigation system in the aspects of intelligent perception, intelligent navigation decision, intelligent communication, and intelligent control.

4.2. Cognitive navigation and its thought of brain-inspired realization

With the continuous development of brain, neuroscience, and artificial intelligence technology, the integration of perception, cognition, path planning and behavior decision-making inspired by the brain navigation mechanism of insects and mammals has been greatly developed. From the input of the original perception information to the direct output of collision-avoidance navigation decision, it presents the intelligent behavior of human end-to-end navigation. It has the potential to improve robustness, accuracy, real-time response, autonomous intelligence, and computational efficiency. Generally, it can be divided into brain-inspired spatial cognition layer and brain-inspired goal-directed navigation layer (Vijesh, M., et al., 2013). For intelligent ships, the concept of "navigation brain" was first proposed by academician Yan Xinping's team. "Navigation brain" system is an artificial intelligence system based on reinforcement learning, which gradually replaces the human brain with a machine brain to realize the development of ship intelligence and even unmanned. The system is an artificial intelligence system for ship intelligent navigation, which is composed of three functional spaces: perception, cognition and decision execution (Xinping Y., 2017; 2019; Xue, J., Yan, X., et al., 2019).

Brain-inspired spatial cognition can solve the self-motion information extracted from the brain-inspired perception process of environment and the analyzed environment beacon information through the self-organizing group discharge activity of brain navigation cells. The navigation information is transformed into specific navigation cell discharge activities in the brain. At the same time, the location information and beacon information are related and stored by the location cells, completed construction of cognitive map.

Through unsupervised learning, the intelligent neural connections between multiple navigation cells and multiple action cells are established by brain-inspired goal-directed navigation, in the cognitive map. Navigation cells mainly include head facing cells, position cells and boundary cells, which represent various navigation information such as orientation, position and obstacles. Action cells mainly represent a variety of navigation behaviors, such as steering, acceleration and deceleration (YANG C., et al., 2020). The intelligent behavior inspired by human navigation is realized. The brain-inspired goal-directed navigation in Fig. 25.

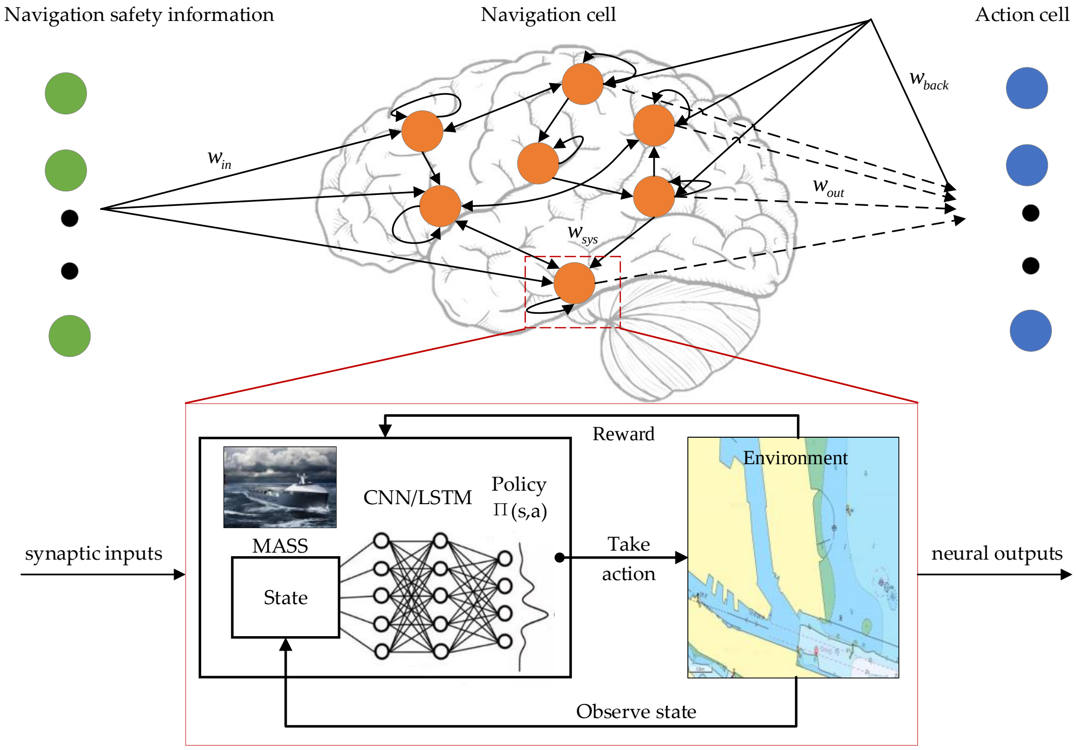


Fig. 25. Brain-inspired goal-directed navigation. w_{in} is input connection weight. W_{sys} is internal connection weight. w_{out} is output connection weight. w_{back} is feedback connection weight.

4.3. Collision-avoidance navigation based on e-Navigation

In May 2006, at the 81st meeting of the Maritime Safety Committee (MSC) of the IMO, the Seven Countries Proposal-"Development of e-Navigation Strategy" was adopted and adopted by The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA). E-navigation refers to the coordinated collection, integration, exchange, display, and analysis of maritime information onboard and onshore by electronic means to enhance the navigational capabilities of berths and other related services to improve the level of safety and security at sea and protect the marine environment (IMO MSC 81/23/10).

The e-navigation concept was put forward to meet the rapid development of autonomous navigation technology and navigation assistance methods. It aims to achieve the optimization of maritime transportation by integrating the existing navigation assistance technology and tools. The e-navigation technology framework mainly includes three elements, the ship environment, the shore-based support environment, and the communication system. Ship environment refers to supporting the collection, integration, exchange, display, and analysis of all information provided by ship-based sensors. Shore-based support environment refers to shore-based technical services that support shore-based applications, such as search and rescue, VTS, ports, and MSI (Maritime Safety Information) services, etc. Communication systems refer to the communication equipment and communication links between ships-ships, shore-ships. To this end, the overall technical architecture of e-navigation can be simply described as the three sides of the coin, as shown in Fig. 26. The front and back sides of the coin represent the ship environment and the shore-based support environment, and the side of the coin represents the link ship communication system with the shore (Wang C. B., et al., 2017).

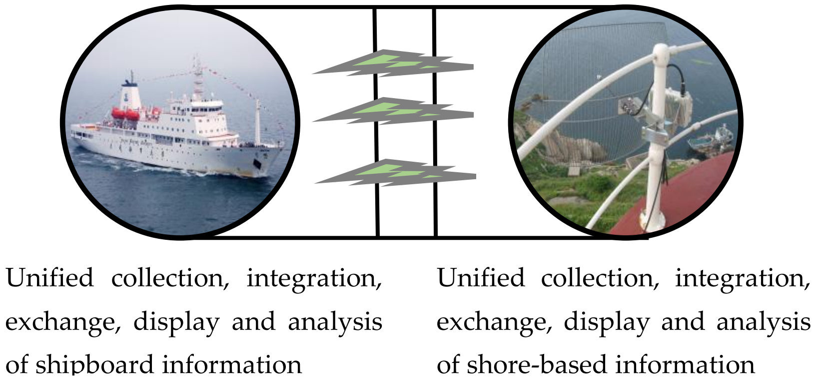


Fig. 26. E-navigation overall technical architecture.

At present, with the development of shipping industry, ships have shown the characteristics of large-scale, specialized, high-speed, and intelligent. E-navigation tries to integrate the existing navigation technology to maximize the safety of ship navigation and improve the efficiency of maritime cargo transportation. MASS combined with artificial intelligence technology greatly reduces the impact of human factors on maritime transportation safety and improves the level of ship navigation safety. The combination of e-navigation technology and maritime autonomous navigation technology can effectively promote the development of intelligent and information technology of maritime transportation and enhance the safety of navigation.

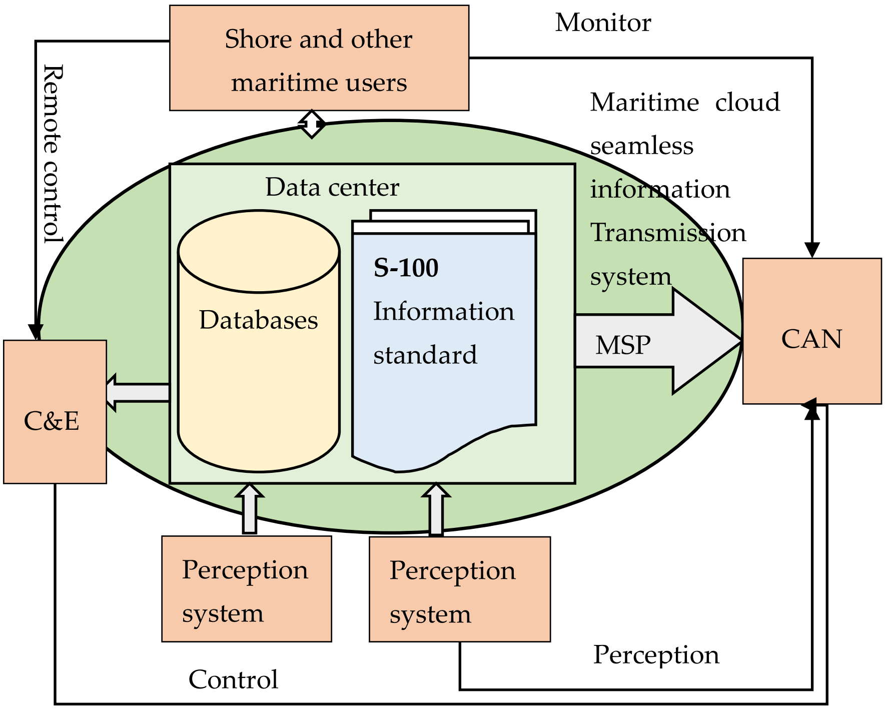


Fig. 27. Framework of autonomous navigation system based on e-Navigation. (C&E stands for control and execution center. CAN stands for collision-avoidance navigation system. MSP stands for maritime service portfolios.).

To effectively improve the safety level of maritime transportation and combine the autonomous navigation with e-navigation, the overall technical framework of the autonomous navigation system of MASS based on e-navigation is shown in Fig. 27, and autonomous navigation is developed based on the intelligent environment state information perception, intelligent navigation decision and intelligent communication of e-navigation (Gao Zongjiang, et al., 2017). The application of e-navigation technology lays a foundation for the development of autonomous navigation of MASS, and promotes the implementation of e-navigation strategy.

E-navigation relies on four major issues of perception, data, standards, and transmission, and moves from theory to practical application. The application of e-navigation technology lays a foundation for the development of autonomous navigation technology of MASS, and the development of MASS also promotes the implementation of e-navigation strategy (Im, I., et al., 2018; Porathe, T., & Rødseth, Ø. J., 2019; Ahn, J., et al., 2019; Jeong, et al., 2018). It integrates e-navigation technology and autonomous ship technology. In the data center, it establishes a database of the information sensed by the MASS based on the standard of S-100, and transmits information to the ship and the shore-based platform through the maritime cloud, to realize the autonomous navigation of MASS without collision.

The four major issues that e-navigation technology system mainly solves are perception, data, standard and transmission. From the common research of e-navigation and autonomous navigation of MASS, e-navigation development lays a technical foundation for the construction of autonomous navigation system in the aspects of intelligent perception, intelligent navigation decision, intelligent communication, and intelligent control.

5. Conclusion

The importance of maritime autonomous navigation systems is undeniable and the opportunity for coordinated and interconnected operations is clear. MASS may finish intelligent navigation through shore remote control center with long distance to the operations, so that dependence on more autonomy infrastructures, such as maritime autonomous navigation system, collision avoidance decision support systems, or motion control systems must be expected. The cost, reliability, performance, and availability of such systems are important issues.

Moreover, there is a wide variety of scenarios with different collision avoidance decision requirements with respect to data-rates, latency, and importance. These are, for instance, command and control data (telemetry), sensor data for situation awareness, payload sensor data, collision avoidance transponder broad-casts, and status information. Therefore, autonomous navigation strongly depends on the system autonomy level and situation needs.

This work reviews the major advancements in maritime collision-avoidance navigation technologies applied in several different scenarios, from transportation to scientific research. Moreover, it highlights how available technologies and systems can be composed to efficiently and effectively handling in maritime obstacle environments.

Existing and prototype maritime autonomous surface ships, collision-avoidance navigation technologies are characterized, describing their requirements and capabilities. Additionally, the design of maritime collision-avoidance navigation systems is highlighted, considering the availability and performance of different autonomy levels. The discussed are aligned with current trends in the collision-avoidance navigation system, e-navigation technologies, and brain-inspired cognitive navigation.

Author Contributions:

Xinyu Zhang: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Chengbo Wang:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing - review & editing. **Lingling Jiang:** Conceptualization, Methodology, Investigation, Writing - review & editing. **Lanxuan An:** Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Rui Yang:** Methodology, Writing – original draft, Writing - review & editing.

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