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A Survey of Technologies for Unmanned Merchant Ships

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ABSTRACT Unmanned merchant ships are ships that carry goods and engage in commercial activities without manual operations on board. In contrast to traditional merchant ships, unmanned merchant ships have great advantages in economy, society, and safety. However, we observe that commercial applications of unmanned ships are still at an exploratory stage. We believe that unmanned merchant ships will be widely adopted and popular in the near future. There is a need to have a good survey of current technologies, foundation, and obstacles of implementation of future unmanned merchant ships. Such a survey is beneficial to ship builders, researchers, owners, and students. Therefore, in this paper, we present a comprehensive survey of ship structure and technology, navigation, automation, algorithms, communication, Internet of Things (IOT), etc. We introduce traditional ships and analyze the role of crew and navigation operations on board. We summarize classifications, benefits, and core technologies of unmanned merchant ships. We review architecture, communication standards, security, essential technologies of IOT for unmanned merchant ships. Moreover, we introduce intelligent awareness, data fusion, applications, and E-navigation for unmanned merchant ships. We also present several future research directions at the end.

INDEX TERMS Merchant ships, unmanned ships, Internet of Things (IoT), algorithms, route planning, collision avoidance, sensors, radio frequency identification (RFID), Zigbee, wireless sensor network (WSN), very high frequency (VHF), E-navigation, intelligent awareness, data fusion, communication, Ship Industry 4.0 (SI4), smart ocean, AI, big data.

I. INTRODUCTION

Merchant shipping is a general term for ships engaged in none-fishing commercial activities [1]. With 90 percent of the world trade carried by merchant ships at sea, merchant shipping is one of the most important modes of transportation [2]. A merchant ship is a watercraft that transports cargo or carries passengers for hire and is different from entertainment ships and navy ships in its use and purpose [3]. Navigation of a traditional merchant ship mainly depends on crew operation so that navigation safety is easily affected by human factors such as fatigue, attention, and emotion of the crew. The number of accidents caused by human error is in the range of 70-95% [4]. Therefore, ship owners have a strong desire for such ship types which are intelligent, green, safe, and efficient.

Unmanned ships are ships that operate on water surface without a crew [5]. We can define an unmanned merchant ship as a merchant ship without a crew on board, which use advanced methods/algorithms, intelligent awareness, data fusion, communications, Internet of Things (IOT), control technologies, and other technologies to implement automatic operation, navigation, and berthing. The ship can be intelligently operated based on navigation technologies, computer technologies, automatic control technologies during navigating, managing, maintaining, transporting cargo so that the merchant ship has more advantages in terms of safety, society, and economy.

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Unmanned merchant ships have or will have great advantages in efficiency, cost effectiveness, environmental friendliness, work safety, and family friendliness [6]. We list four major advantages of unmanned merchant ships as follows. First, merchant unmanned ships are independent of crew and are operated mainly by expert decision-making systems, artificial intelligence systems, and remote control systems in shore-based control centers to reduce the influence of human factors on safety of ship navigation. According to International Union of Marine Insurance (IUMI) [7] and the authors in [4], much of this safety improvement has to do with improvements in automation systems supporting human monitoring and decision-making. Second, unmanned merchant ships can save energy and improve economic benefits. Onboard labor costs accounts for 31-36% in the total ship operation cost [6]. The tests in [6], [8] show that slow sailing of ships can save fuel and reduce pollution emissions. Furthermore, because there are no people on unmanned ships, human cost can be reduced since people will have to do the maintenance, supervision, contingency handling, etc. On the premise of ensuring timely arrival, unmanned ships can sail slowly as much as possible to save fuel. Third, compared with traditional merchant ships, unmanned merchant ships do not need to consider all crew related facilities such as lifesaving, fire-fighting, pollution prevention and life, saving weight, space, and labor costs, and can carry more cargo [9]. Fourth, for unmanned merchant ships, pirates cannot threaten hostages so that this makes unmanned merchant ships relatively safer.

Unmanned merchant ships must be smart and autonomous to implement the goal of replacing crew handing. Several key technologies for smart ships include information sensing, communication and navigation, energy efficiency control, route planning, status monitoring and fault diagnosis, distress warning and rescue, and autonomous navigation [10]. The report [11] shows three vital elements that will make autonomous shipping a reality: sensor fusion, control algorithms, and communications. Therefore, we can see that Internet of Things (IoT), algorithms, and communication are among major factors of unmanned merchant ships with the reasons as follows. Firstly, IoT extends the Internet as the core and foundation to the information exchange and communication between any things to implement the functions of intelligent identification, location, tracking, supervision, etc [12]–[14]. The major technologies of IoT include Radio frequency identification (RFID), Zigbee, Wireless Sensor Network (WSN) [15], etc. Secondly, there are many algorithms which can find the optimal routes and avoid collisions for unmanned ships [16]–[19]. Thirdly, communications of unmanned ships include Controller Area Network(CAN) bus, WSN, Zigbee, 3G/4G/5G, satellite communication, Very high frequency (VHF), etc. These communications will connect devices of unmanned ships together.

To implement commercialized unmanned merchant ships and promote research in all aspects, there is a need to have a very systematic survey about the state of art of development and core technologies of unmanned merchant ships. Such a review will be very useful for ship builders, ship owners, researchers, and students. In this paper, we will provide such a comprehensive review of the state of art of core technologies in the field of unmanned merchant ships. The contributions of this paper are listed as follows:

- To the best of our knowledge, this paper is the first paper in the literature to present a comprehensive survey and tutorial on major factors of unmanned merchant ships.
- We survey basic structure of ships, principle of ship handing, navigation instruments, and responsibility of crew of traditional ships. This tutorial provides details of shipping technologies to the readers for their future research in these fields.
- We survey existing papers of unmanned ships combining knowledge in the field of navigation, computer science, communication, control, and automation. We classify unmanned ships and list the benefits. Furthermore, We summarize the existing core technologies for unmanned ships and analyze the advantages and disadvantages.
- We summarize intelligent awareness, data fusion, communication, IOT applications, and E-navigation for unmanned merchant ships. Although there are not many research work available in the literature about IOT for shipping, the paper shows the great and promising area of IOT for future shipping industries. Our paper is the first paper to try to survey this important aspect of IOT on shipping so that we believe that our paper will inspire many researches to work along this line.
- We discuss the challenges and further research for unmanned merchant ships from the aspects of law, communication, cyber security, IOT application onboard, intelligent auxiliary equipment, automatic control, artificial intelligence and big data, ship industry 4.0, and smart ocean.

This paper is organized as follows. Section II introduces basic information of a ship and duties of personnel on board. Section III provides an in-depth review of current research of unmanned ships. Section IV presents application of IoT and other technologies in unmanned merchant ships. Section V discusses challenges and further research of IoT for unmanned merchant ships. Finally we conclude this paper in Section VI.

II. MECHANISMS OF A MERCHANT SHIP

In order to better understand unmanned merchant ships, we first introduce general merchant ships from structure, usage, handling principles, navigation instruments, and the duties of onboard staff [20], [21]. The photos in this section were taken by us for a ship called ''Yukun'' of Dalian Maritime University. We use the ship as an example to introduce shipping functionalities with the parameters shown in Table. 1 and explained as follows:

TABLE 1. Parameters of the ship "Yukun".

Length	116.00 m
Breadth	18.00 m
Depth	11.10 m
Designed draft	5.40 m
Main engine	4440kW * 173rpm
Service speed	16.7 knots
Endurance	10000 n.miles
Complement	236 p
Classification	CSA Training Ship, Ice Class B, CSM AUT-0 SCM

- CSA - It means that the ship's structure and equipment are in full compliance with CCS (China Classification Society) specifications and are suitable for navigation in an infinite navigation area.
- CSM - It means that the manufacturing and installation of the ship's propulsion machinery and auxiliary machinery for important purposes conform to the provisions of CCS specifications and are suitable for navigation in the infinite navigation area.
- AUT-0 - The degree of automation of the engine room can be unattended during navigation.
- SCM - Propeller condition monitoring.

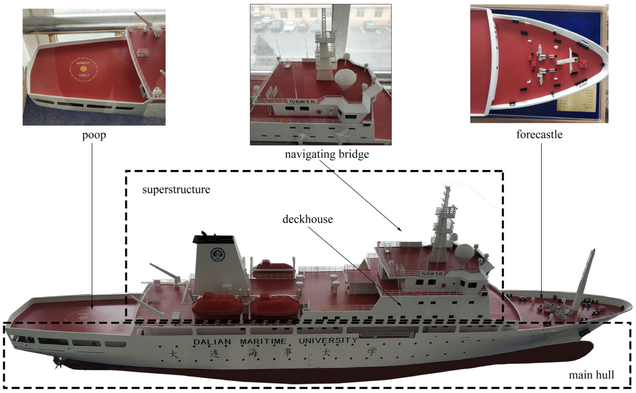


FIGURE 1. A model of navigation ship, called Yukun, Dalian Maritime University; here we show a model instead of the real ship.

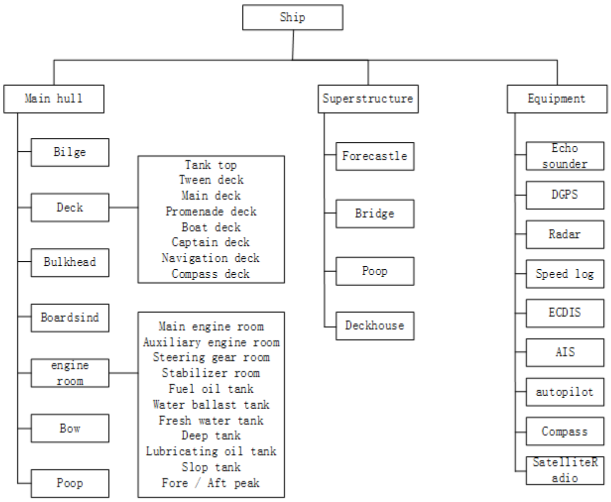


FIGURE 2. Main structure of a traditional ship.

A. BASIC STRUCTURE OF A SHIP

A merchant ship consists of a main hull, a superstructure, and various equipment, shown in Fig. 1. The main hull is a watertight hollow structure composed of upper deck, bottom, broadside, deck, fore and aft, bulkhead, etc. The superstructure includes forecastle, navigating bridge, poop and deckhouse. Apart from cabins with various functions in the superstructure, the main hull is separated into several cabins by each deck and bulkhead, including an engine room, a cargo room, a ballast tank, a deep tank, a fuel oil tank, a lubricating oil tank, a fresh water tank, a slop tank, and a caisson in this example. The basic structure of a traditional ship is shown in Fig. 2, in which there are various equipments on a traditional ship, including an echo sounder, a DGPS, a Radar, a speed log, an Electronic Chart Display and Information System (ECDIS), an Automatic Identification Systems (AIS), an autopilot, a compass, a satellite radio, etc. The shipboard equipment and navigation instruments are introduced in subsection II-C. Navigation of a merchant ship relies on supporting equipment, including a main machinery, an auxiliary machinery, auxiliary equipment, electricity, various pipes, deck equipment, safety equipment, communication equipment, navigation equipment, and living supporting equipment.

The engine room refers to the machinery spaces of a ship, where a main engine, an auxiliary engine, and other auxiliary equipments are located [22], shown in Fig. 2. According to the nature of fuel, the burning place, and the working mode, the main machinery of the ship can be classified to a steam engine, an internal combustion engine, a nuclear power engine, and motors. In the 20th century, most of ships sail on water by propelling devices of mechanical propulsion [20]. With the development of ship technologies, there are many new technologies for ship propulsion, such as water jet propulsion, azimuth propulsion, pump jet propulsion, and air cushion propulsion.

A steering gear is a main equipment to control a ship, and its function is to maintain a required course, changing original course, and carry out cyclic motion. The steering gear is usually positioned at the stern to produce a large turning moment to turn the ship, shown in Fig. 3. The steering gear are housed in the steering gear cabin on the stern peak deck platform. The control system of the steering gear is installed in the driving room, and the steering order is transmitted to the steering gear through the electric or hydraulic control system from the cab to control its action.

According to usage, piping system can be classified to bilge system, ballast pipe, ventilating system, fire extinguishing system, domestic water supply system, deck scupper system, and sanitary water system, etc.

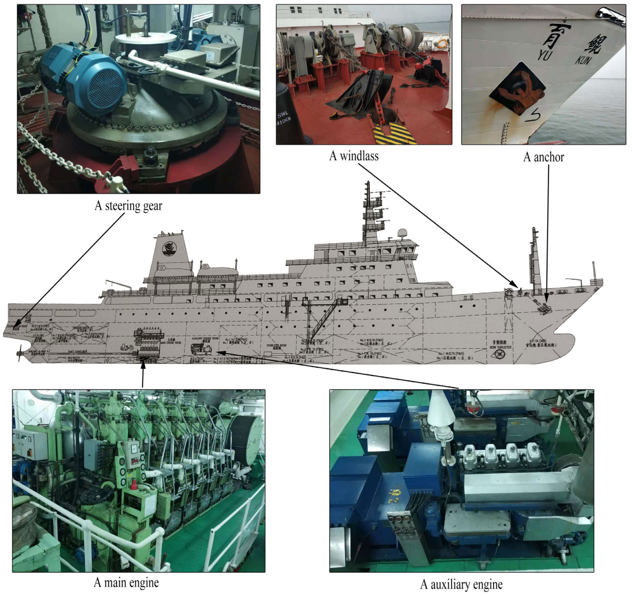


FIGURE 3. Basic structure of a ship.

An anchor equipment is an important equipment in deck equipment, which is used for ship anchoring, auxiliary control when the ship leans away from the wharf, deceleration of ship speed when sailing in narrow channel, and so on, shown in Fig. 3. An windlass is a mechanical device for dropping and heaving up an anchor, mainly an electric anchor and a hydraulic anchor, located at the bow, which can be remotely operated in the cab, shown in Fig. 3.

B. BASIC PRINCIPLES OF SHIP HANDLING

Ship handling refers to the relative motion of the hull, propeller, and rudder in water to produce hydrodynamic force to keep or change the horizontal motion of the ship. According to the helmsman's or conning officer's intention, the ship can maintain or change its speed, course, and position.

In order to reduce the work-related stress of the helmsman, it can correct the yaw in time and keep the ship on the course for a long time. Generally, a big ship at sea is installed with an automatic course-keeping control system, called autopilot. An autopilot is basically composed of main mechanisms such as automatic detection of course deviation, signal comparison, signal amplification, actuator, and feedback. When a ship is in the autopilot state, a gyrocompass can detect whether the ship is off-course.

A compass is widely used in all kinds of ships for navigation, shown in Fig. 4(a). A gyrocompass will detect the yaw angle ϕ when the ship off-course. An automatic steering transmitter outputs AC voltage proportional to a yaw angle, through phase-sensitive rectifying into different polarity DC voltage U_ϕ. The voltage signal is transmitted to a comparison circuit, which starts motors to turn the rudder left or right through an amplifier and a switch circuit. Many ships adopt adaptive autopilot (autopilot for short) to reduce the turning times and resistance of rudder, to keep the ship in the original course, and to save fuel consumption.

An automatic navigation (or navpilot) is a computer-based automatic navigation control system. It is based on autopilot and connected with the integrated navigator or ship position receiver to provide the ship with reliable and accurate course control. However, manual steering shall be adopted instead in case of severe weather or heavy traffic.

A ship must anchor while waiting for berthing, anchorage operation, and wind shelter. The handing of an anchor is usually in the charge of a chief officer. The chief officer carries out the anchoring order issued by the bridge. Meanwhile, the chief officer must reports to the bridge the status and execution of the anchor chain during anchoring.

C. NAVIGATION INSTRUMENTS

With the development of large-scale ship tonnage, high-speed movement, and intensive navigation, it is difficult to cope with complicated navigation environment with simple outlook and experience. We must use the navigational instruments widely to ensure safety of ship navigation. Several navigation instruments are widely used and described below.

As a navigation pointing instrument, the magnetic needle of a magnetic compass always points to the magnetic North Pole of the earth by the mutual attraction of geomagnetic field. A magnetic compass can indicate the course and the position of a ship, and help a ship to implement positioning and navigation functions. A magnetic compass and a gyrocompass complement each other to jointly guarantee the safe navigation of the ship. In recent years, A kind of solid-state electronic magnetic compass has been developed and a magnetic sensor is core. It uses a magnetic sensor to sense the external magnetic field and convert the induction of external magnetic field into an electric signal. At present, there are Hall compasses, flux gate compasses, magnetoresistance compasses, Giant magnetoresistive compasses, etc.

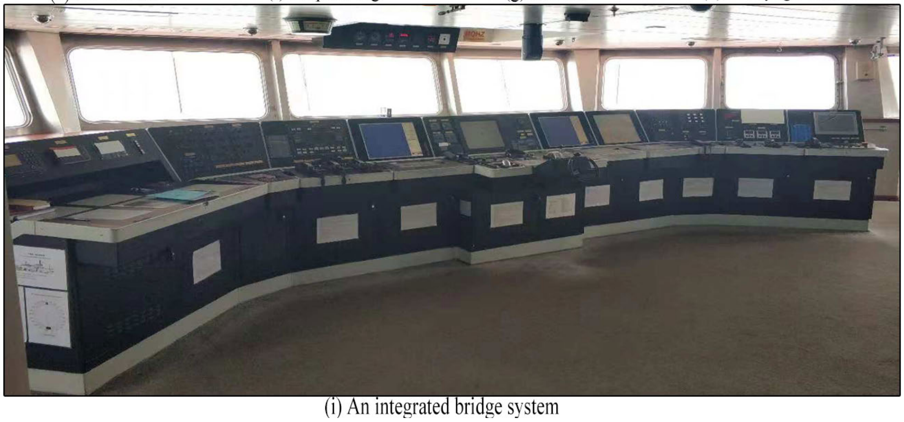
A marine echo sounder, which is a kind of acoustic navigation instrument, utilizes the physical characteristics of ultrasonic wave propagation in water for measuring water depth, shown in Fig. 4 (b). The principle of the marine echo sounder is to determine the depth of water by measuring the time interval between the ultrasonic wave emitted and the wave received after reflection from the bottom.

A speed log is a kind of navigation instrument to measure ship speed and accumulated voyage, shown in Fig. 4 (f). An electromagnetic log used the electromagnetic induction principle to measure the speed and voyage of the ship relative to the water. It is composed of an electromagnetic sensor, an amplifier, and an indicator. It has the advantages of good speed detection linearity, large range, high precision, low cost, and easy to use.

A Global Positioning System (GPS) satellite navigator is a GPS receiver specially used for positioning and navigation. Difference Global Positioning System (DGPS) is to add correction signal on the basis of GPS to improve the accuracy of GPS, shown in Fig. 4 (c). It can be used for route point

(a) A compass indicator (b) A marine echo sounder (c) A DGPS (d) A marine radar

(e) An ECDIS (f) A speed log (g) An AIS (h) A voyage data recorder



(i) An integrated bridge system

FIGURE 4. **Navigation instruments in bridge of a ship.**

navigation, route navigation, track line plotting, fixed-point navigation, alarm, etc. The Coarse/Acquisition (CA) code is more commonly used for single frequency GPS satellite navigator. It is a kind of pseudo-random noise code used to broadcast rough ranging and fast acquisition of the precise code via GPS satellite.

Radar is short for Radio detection and ranging. A marine radar is X band or S band radar on ships that detects targets by emitting electromagnetic waves and receiving the targets' reflected echo. It usually used to detect surface ships, obstacles, lands, maritime distress, and sea clutter for collision avoidance, location, and navigation [23], shown in Fig. 4(d). A radar consists of timer, transmitter, transceiver switch, antenna, receiver, display, and radar power supply. Radar/APRA (Automatic Radar Plotting Aid), Electronic Chart Display and Information System (ECDIS), GPS/DGPS, and autopilot constitute an automatic bridge system, which is currently important navigation systems on ships.

An ECDIS is an advanced nautical navigation information system used for ships [24], shown in Fig. 4 (e). It displays the position of the ship and its intended movement in relation to the navigational characteristics on the chart [5]. An ECDIS combines satellite position, GPS, sensors, radar, Navtex, Automatic Identification Systems (AIS), depth sounders, and other data with a sophisticated electronic database containing chart information for decision aid [25], where Navtex is an automated service for navigational and meteorological warnings and forecasts.

An AIS is a navigation auxiliary system which can automatically broadcast and receive the static information, dynamic information, voyage information, and safety information of the ship and surrounding ships through Very high frequency (VHF) band and Time-division multiple access (TDMA) technology. An AIS implements ship identification, monitoring, and communication, shown in Fig. 4(g). Its cores include satellite positioning technologies, digital communication technologies, information processing technologies, and computer network technologies. An AIS receives the position information from a GPS/DGPS/GNSS(Global Navigation Satellite System) receiver, the course information of a gyrocompass, and the speed information of the log through the interface circuit. The information processor processes and sends the ship's static

TABLE 2. The responsibilities of the crew on board [26].

Post	Responsibility
captain	The captain is the leader of the ship and responsible to both the ship owner (ship company) and those functions such as the safety production, navigation command, administrative management, technical business, and foreign-related work of the ship.
chief officer	The chief officer is the captain's chief assistant and the head of the deck department, in charge of the daily work of the deck department. In addition to navigation watch, he/she is in charge of cargo stowage, loading and unloading, handover and transportation management, as well as the maintenance of the deck department.
second officer	The second officer, under the leadership of the captain and the chief officer, performs the duty of navigation and berthing, and is in charge of the bridge equipment, including all kinds of radio navigational instruments, meteorological instruments, steering instruments, chronometers and ship clocks, compass, national flag, signal flag, signal lamp, model, charts, and other navigational books and materials.
third officer	The third officer shall, under the leadership of the captain and the first officer, performs the duty of navigation and berthing, and is in charge of life-saving and fire-fighting equipment.
radio operator	Under the leadership of the captain, the radio operator is on duty on time and operates all kinds of radio communication equipment correctly. The radio operator must complete the task of maintenance and communication assigned by the captain, and make records.
boatswain	The boatswain, under the chief officer, organizes and leads carpenter and crew in their work.
carpenter	The carpenter is responsible for carpentry and related work under the leadership of the chief officer and the boatswain.
cook	The cook is responsible for cooking range, warehouse, and catering.
chief engineer officer	The chief engineer, under the leadership of the captain, is the chief technical officer in charge of the mechanical, power and electrical (except radio instruments) equipment of the ship.
first engineer officer	The first engineer is the chief assistant of the chief engineer. Under the leadership of the chief engineer, the first engineer is responsible for leading the staff of the engine department to manage, operate, and overhaul electromechanical equipment to ensure the correct implementation of various rules and regulations of the engine department.
second engineer officer	The second engineer, under the leadership of the chief engineer and the first engineer, is responsible for the management of the generator and the mechanical equipment for its service, some auxiliary engines in the engine room, and other equipment designated by the chief engineer. He / She is responsible for loading fuel oil (refueling oil), measuring and recording fuel oil.
third engineer officer	Under the leadership of the chief engineer and the first engineer, the third engineer is responsible for the management of deck machinery, pump rooms, lifeboats, emergency fire pumps, air conditioners, auxiliary boilers and their auxiliary equipment, and some auxiliary machines in the engine room, as well as other auxiliary machines and equipment designated by the chief engineer. For ships without electrical engineers, the third engineer is responsible for managing the electrical equipment.
master mechanic officer	The master mechanic shall have the ability to manage, operate, and repair. Under the leadership of the first engineer, the master mechanic is responsible for organizing and arranging the shift of the machinists and the cleaning and daily maintenance of the machinery, furnace and pump compartment.
mechanic	Under the leadership of the chief engineer and the first engineer, and under the direct leadership and arrangement of the master mechanic, the mechanic shall independently conduct the overhaul, maintenance and cleaning of machinery, electricity, boiler equipment, pipe systems and valves, and is on duty within the prescribed time.

information and dynamic navigation information through a VHF transceiver. At the same time, it also receives the navigation data of surrounding ships, and displays it on the information monitor.

A ship voyage data recorder, which is an equipment in a safe and recoverable way in real time, records the information about the position, dynamics, physical condition, handing and navigation data of a ship in the period before and after the accident, shown in Fig. 4h. It includes data processor, microphone set, sensor interface and signal processing circuit, data protection module, alarm indicator, power supply, and data playback equipment.

Integrated Bridge System (IBS) bases on Integrated Navigation System (INS). IBS integrates the navigation instrument above and combines radar, electronic chart, AIS, autopilot, and various types of navigation and ship handing device, shown in Fig. 4(i). It has integrated navigation, ship handing, automatic collision avoidance, integrated information display, communication, and navigation management control functions.

D. THE RESPONSIBILITIES OF THE CREW ON BOARD

We review crew and their job responsibilities in this subsection since these are useful for unmanned merchant ships.

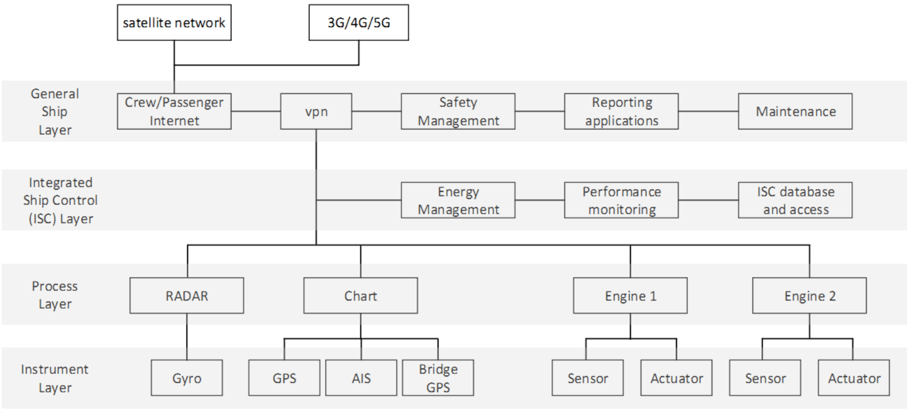


FIGURE 5. **General unmanned ship architecture [31].**

The responsibilities of these men on unmanned merchant ships are mainly replaced by mechanical, electronic, and computer technology. Besides the captain, there are also deck department and engine department personnel on board, as shown in Table 2 [26]. The deck department is mainly responsible for the navigation, hull maintenance, cargo stowage, loading and unloading equipment, and the care of cargo during the voyage. The deck department includes a chief officer, a second officer, a third officer, boatswains, carpenters, crew, helmsman, and cooks. The engine department is mainly responsible for the management, use, and maintenance of the main engine, boiler, auxiliary machinery, and various electromechanical equipment, as well as the management and maintenance of the whole ship's power system. The engine department mainly includes a chief engineer, a first engineer, a second engineer, a third engineer, a master mechanic, coppersmith, and mechanics.

In future unmanned merchant ships, most of these job responsibilities will be replaced by machines and some of them will be no loner needed, particularly for those serving crew such as cooks.

III. CURRENT STATUS OF UNMANNED SHIPS

In this section, we introduce unmanned ships. First, we classify the existing unmanned ships based on automaticity and remote control. We analyze the advantages of unmanned ships from the impacts of unmanned ship development on safety, economy, society, and environment, etc. Second, we research the history and current status of unmanned ships. At last, we summarize the core technologies of unmanned ships.

A. CLASSIFICATION AND BENEFITS OF UNMANNED SHIPS

Unmanned ships are ships that operate on the surface of the water without a crew [5]. Carderock Laboratory uses the following method of grouping Unmanned Surface Vehicles (USVs) by displacement [27]: small($<1t$), medium($<100t$), large($<1000t$), and extra large($>1000t$), where displacement refers to the total weight of a ship under a given condition and usually expressed in tonnage, abbreviated as t. We focus on large and extra large displacement USVs as unmanned ships in this paper. At present, there are many researches on small and medium USVs [28]–[30]. Research on unmanned ships can draw lessons from the existing research results of small and medium USVs.

A system architecture for an unmanned ship includes an instrument layer, a process layer, a integrated ship control layer, and a general ship layer, shown in Fig. 5 [31]. We introduce Fig. 5 in detail as follows. Generally, a gyrocompass provides compass signals for radars and an electronic chart system integrating GPS, AIS, Radar, and other information. According to sensor information, actuators perform corresponding operations on engines. Ship control system integration mainly consists of three parts: energy management, performance monitoring, and integrated ship control database and access. The general ship layer includes two parts. The first part is the network used by crew and passengers for living accommodation. The other part is the administrative network, including safety management, reporting applications, and maintenance. The communication of unmanned ships mainly uses satellite and 3G/4G/5G networks. Unmanned ships are monitored and remotely controlled by Shore Control Centers (SCCs) when necessary [32]. To minimize operators' load, unmanned ships are able to operate autonomously without operators for most of the time [31].

International Maritime Organization (IMO) classifies the automation of autonomous surface ships into several levels, shown in Table 3 [33]:

- Automated manned ships: Functional systems of ships are operated and controlled by the crew on broad. Some operations can be automated.
- Remote-control ships with crew on board: There is a certain number of crew on board. But ship's operations and decisions mainly rely on remote control through communication.
- Remote-control ships without crew on board: Control and operation of the ships take place in another place and there is no crew on board.

TABLE 3. IMO classification of the automation level of autonomous surface ships [33].

level	remote control	crew on board	autonomous
automated manned ships	no	yes	no
remote-control ships with crew on board	yes	yes	no
remote-control ships without crew on board	yes	no	no
completely unmanned automatic ships	yes	no	yes

- Completely unmanned automatic ships: Decision control systems of ships are able to make decisions, to react on automatic pilot, and to act on navigation control system independently.

An unmanned ship may have a certain number of people on board, but it does not need to be performed or supervised by the people. An unmanned ship may have operational and technical problems in crowded waters. In addition, an unmanned ship must comply with the laws of the country where the port is located. Therefore, the unmanned ship should be undertaken with a crew on board when it enters and leaves the port [31]. The crew can board and disembark via shuttle boats or helicopters after the crew has completed the operation within the specified voyage.

A remote-control ship with a certain number of crew on board has many advanced automation systems. It can perform some demanding operations without crew interaction, such as dynamic positioning or automatic berthing. A remote-control ship may need remote control operations in case of accidents or completion of operations. When a manual operation is required, the crew of Shore Control Centers (SCCs) can intervene and remotely control the unmanned ship, and the crew in the bridge can directly control it [34].

A completely unmanned automatic ship can handle all situations when it is sailing and berthing. This implies that there is no SCC or any crew in the bridge at all. However, we believe that a completely unmanned ship is not likely to be implemented in near future.

Next, we try to make a distinction between an autonomous ship and an unmanned ship. They are different in some degree. Autonomous operation and remote control are the important characteristics of unmanned ships. We can define different types of ship autonomy based on operational autonomy levels [32]. An autonomous ship can perform a series of pre-designed operations, whether or not the crew is present [32]. The report [35] shows that future advanced control systems, decision support systems, and wireless communication technologies will enable autonomous ships on SCCs to have the same monitoring and control functions as those on ships.

Many researchers work on navigation control for unmanned ships, as illustrated below. The authors in [36] design a navigation control for an unmanned ship explained as follows. The navigation control is composed of a ship's intelligent system, a Narrow Band Internet of Things (NB-IoT) based station, and a shore-based support center. The authors establish a communication link between the ship and SCCs through NB-IoT and implement a system which enables the unmanned ship of the actual track approximating the expected track. The NB-IoT communication link is supported by the SARA-N2 module with maximum speeds of 227kbps downlink and 21kbps uplink. SARA-N2 is released by u-blox, Switzerland on June 28, 2016 [37]. It is the world's first mobile wireless module following Release 13 issued by the Third GeneraTIon Partnership Project (3GPP). It has the advantages of ultra low power consumption delivering 10+ years battery life, extended temperature range of −40 to +85° C, easy migration between u-blox 2G, 3G, and 4G modules [38]. The NB-IoT based station of the telecom operator enables real-time data sharing between the ship and the shore. Users of the unmanned ship [36] can monitor the ship's position and movement in real-time and control the ship when necessary at SCCs.

Next, we explain the benefits of unmanned ships. Much of world trade depends on sea transportation. There is 90% of world trade carried by sea, worth about $375 billion [39]. Unmanned ships can reduce the operation cost, eliminate the on-board crew cost, reduce the risk associated with human errors, and reduce the threat of crew from pirates [4]. We introduce the benefits of unmanned ships from social, economic, and security aspects [40].

First of all, unmanned ships can reduce human costs. When a ship is sailing at the sea for a long time, the crew may feel lonely in a closed environment and this may reduce the attractiveness of the job. It is hard to recruit sufficient qualified crew-members. The crew may encounter natural influences such as wind, waves, fog, and typhoon, which require real-time operation and responses during the voyage. The change of geographical location causes the seasonal climate change and jet lag of voyage and this will affect the mood and psychology of the crew [41].

Secondly, unmanned ships can reduce human costs. The demand for ocean-going trades is increasing. More and more unmanned ships are needed in the future. With the increase of manpower cost, the role of unmanned ships in reducing costs is becoming more and more obvious. According to statistics, the one-day crew cost of a large container ship accounts for 44% of the total operating cost, about $3,299 [39]. Furthermore, life and life-saving equipments on the ships are for the service of the crew. Unmanned ships do not need these facilities and this can reduce weight by 5% and save 12% to 15% on fuel [9], [42].

Thirdly, navigation at sea is a high-risk industry. Maritime safety is the most important thing in ocean transportation. The main causes of marine accidents are closely related to people's sense of responsibility, skills, experience, physical and mental conditions, and strain capacity. Professionals agree that "human error" is the cause of between 70% and 95%

of shipping accidents [4]. Unmanned ships can reduce risk associated with human errors. Unmanned ships integrate the data and information of radars, High-Definition (HD) infrared cameras, and a variety of sensors, relying on artificial intelligence, remote control, and data fusion to ensure the security and accuracy of the ship operation. Furthermore, unmanned ships can effectively defend against pirates' attacks. If unmanned ships don't have easy access, pirates will have a hard time entering inside of the ships [43]. There is no hostage risk with an unmanned ship because there is no crew on board. Even boarding the ship, access to the control system is difficult. Remote control centers can allow unmanned ships to anchor or move at low speeds, making the ships easy for rescue ships to come in to help [44].

B. THE STATE OF ART OF UNMANNED SHIPS

While unmanned ships date back at least to World War II, a lot of unmanned ship projects appears in the 1990s [45]. United States Navy developed unmanned ships and they were mainly used for mine sweeping, intelligence gathering, and other dangerous tasks around the 1990s [45]. In recent years, USVs are widely used in military, environmental, and robotic research applications [29]. Next, we illustrate some practical applications of unmanned ships.

United States Navy focuses on the development of unmanned ships. In June 2003 [45], the Office of Naval Research (ONR) provided funding to the US Naval Facilities Engineering Support Center (NFESC) for developing a small USV called SeaFox. It is a semi-autonomous wire-guided mine disposal vehicle. Shore-based operators rely on video images transmitted over fiber-optic cables to remotely control SeaFox and destroy mines with integrated shaped charge [46]. Maritime Applied Physics Corporation (MARP) built a high-speed USV, which is a 10 meter hydrofoil with a top speed of more than 40 knots in a rough sea [47]. The ONR tested this high-speed USV in 2005 [47]. In May 2016 [48], United States began testing "Sea Hunter" which is the largest unmanned warship of the world at that time. Sea Hunter can travel at up to 27 knots and navigate without human intervention through the most extreme water conditions, including Sea State 5 [49].

Besides United States, several other countries also develop USVs. Japanese company Yamaha developed two USVs in 2004 [50]: UMV-H and UMV-O. The model UMV-H is a high-speed craft of 4.44m in length equipped with 90 kw and 40 knots, and the UMV-O is a displacement hull for going deep in the ocean [51], [52]. The Canadian company International Submarine Engineering Ltd (ISE) had worked on USVs for more than 35 years since 1984 [45]. They converted a manned ship into a USV using Tactical Controller (TC) Kit developed by ISE. Israeli company Elbit Systems unveiled Stingray, one USV, at the 2005 IDEF-05 exhibition in Turkey [53]. Silver Marlin developed by Elbit Systems is an autonomous and medium-sized USV featuring autonomous obstacle avoidance sensors and controllers [54]. Portuguese Dynamical Systems and Ocean Robotics Laboratory develop an autonomous USV called DELFIM, which is a twin hull ship with the advantages of safe sailing and sailing in shallow water [55].

In addition to the military role of unmanned ships, many attentions focused on industry commercialization now. Data transmission between ships and SCC is one of the core technologies for unmanned ships. In September 2015, Rolls-Royce led a new 6.6 million euro project for autonomous ships [56]. This project was built on existing ship-to-ship and ship-to-shore communication platforms and was the world's first hybrid Ka/L-band mobile satellite system. It was to provide solutions for the next generation of advanced ships and tested in 2017 [56]. In April 2017, a first remote-controlled merchant ship was developed and demonstrated jointly by Rolls-Royce and Svitzer [57].

China pays more and more attentions to the technologies of unmanned ships. In terms of scientific research, China developed the unmanned ship "Tianxiang No. 1" in 2008 which was the first unmanned meteorological detection ship in the world at the time [58]. It can monitor the environment and warn the disasters of oceans and large lakes in time. In December 2015, China classification society issued the code for smart ships, which took effect on March 1, 2016 [59]. In 2017, China classification society, Zhuhai municipal government, and Wuhan university of technology jointly launched a first small unmanned intelligent cargo ship project in China [60]. This small unmanned cargo ship named "JinDou cloud" is 500 ton of displacement with a hull length of 50 meters. It is powered by electricity, has an endurance of up to 500 nautical miles, and can sail autonomously and berth automatically [61].

C. CORE TECHNOLOGIES OF UNMANNED SHIPS

Various technologies are required to make unmanned ships a reality. Fortunately, we already have most of these technologies [56]. Especially, autonomous ship controllers and engine systems are not a hypothesis but a reality [97]. We summarize and introduce currently available core technologies of unmanned ships in detail below, shown in Table 4. Specially, state-of-the-art of core technologies and applications for unmanned ships is presented in detail in Table 5, including intelligent awareness, communication, and sensor data fusion.

Navigation is the process of planning and executing the operations from one position to another by accurately determining the position and the speed of an object relative to a known reference point [68]. There are four main methods widely used in autonomous navigation, including a satellite navigation, a dead reckoning navigation, an inertial navigation, and a multiple sensor navigation.

- Satellite navigation uses navigation satellites to navigate and locate ships on the sea. GPS navigation, Galileo navigation, and Beidou navigation are the common satellite navigation [69]. Satellite navigation has the advantages

TABLE 4. Currently available core technologies for unmanned ships [10], [11], [56], [62].

Core technologies	Description
gyroscope	Gyroscope transmits some “ship sense", which indicates average and peak roll and heave, vibrations dangerous to the hull’s structural integrity driving from slamming and taking green water on deck, to a remote officer of the watch
intelligent awareness	Intelligent awareness rely on advanced sensors on board which sense for hazard detection/avoidance and situational awareness, e.g., automated surveillance cameras, accelerator sensors, etc. It is explained in detail in Section IV.
sensor fusion	This is used to monitor, evaluate, and process individual sensor data to produce an improved output of sensors. It is explained in detail in Section IV.
route planning	Route planning of manned ship is laid by the second officer. Route planning of unmanned ship is explained in detail in this section.
avoid collision	Avoid collision of unmanned ship is explained in detail in this section.
communication	Communication of unmanned ships include HF (high frequency), VHF, satellite, 3G/4G/5G, etc. It is explained in detail in Section IV.
navigation	Unmanned ships mainly rely on GPS and DGPS for navigation.
autonomous navigation	It is explained in detail in this section.
energy efficiency control	This relies on advanced energy control algorithms.
status monitoring	Ship navigation data monitoring.
fault diagnosis	In the case of possible fault of a ship, fault diagnosis system can be used to diagnose fault timely and effectively to prevent and reduce the occurrence of accidents.
cargo supervision system	Cargo supervision system monitor standard for Identification, positioning, and management of cargo.
emergency response system	Emergency respond system can make real-time transmission of the situation of a ship when it is in danger or threatened by safety. Shore control center use computer software assesses stability, residual strength, and oil overflow of the ship.
lidar (electro-optical system)	Light detection and ranging calculate the relative distance between the target [63], according to the time of laser re-entry after encountering the obstacle.
Radar	It is explained in detail in Section II.
dynamic positioning	Dynamic positioning (DP) refers to the technology of maintaining the position of a ship or floating platform by means of an automatic propeller controlled by a shipboard computer without anchoring.
GDPS	It is explained in detail in Section II.
strain gauge	Strain gauge monitor strain of ships and equipment during navigation.
ECDIS	Electronic chart display and information system provides digital chart and its application system to assist decision-making for navigation. It is explained in detail in Section II.
iceberg tracking	Iceberg can also be detected by radar and sonar onboard.
transponder	Automatic Identification System installed on the ship can achieve automatic response.
remote human vision	SCC is important guaranteeing for the safe navigation of unmanned ships. SCC monitors unmanned ships in real time and intervenes when danger or human intervention is required.
artificial intelligence	Deep learning has a good application in path tracking and path planning of unmanned ships
cloud computing	Unmanned ships send status data and voyage data to the cloud through the network.Cloud servers use these data for training and learning to provide auxiliary support for decision-making.
edge computing	In the process of navigation, the ship needs to calculate real-time information such as speed, course and the coordinates of obstacles, so as to perform the next step of operation, deceleration, berthing and turning. This complex set of calculations must be performed in real time and with low latency. If the data is processed on a cloud server, any delay in data transfer can lead to disaster.

of all-weather, high precision, and no accumulation of errors and the disadvantages as lacking altitude information and easy to be disturbed [70].

- Dead reckoning is a method to obtain the track and the position of a ship without the aid of external navigational objects. It relies on compass, log, ship’s control factors, and air currents [71].
- An inertial navigation system uses the inertial element (accelerometer) to measure the acceleration of the carrier itself [72]. It integrates and operates the acceleration to get the speed and position of the carrier. A practical application is presented in the paper [73]. Inertial navigation’s advantages include complete autonomy, complete motion parameters, and strong anti-interference. Its disadvantages include error accumulation and high cost [70].
- A multi sensor navigation system uses radar information and integrates the data which is collected by other sensors. An application is presented in the paper [74].

Ships can use Synthetic Aperture Radar (SAR) image data to track icebergs. SAR combines high resolution with day-and-night weather-independent capability, detects and tracks most icebergs which are about 20 meters (65 feet) in size [75].

TABLE 5. **State-of-the-art of core technologies and applications for unmanned ships [64]–[67].**

Core technologies	Explanation	State-of-the-art
Intelligent awareness	An intelligent awareness system of an unmanned ship provides real time emergency warning, object detection, target recognition of severe environment and weather, assists the crew to operate safely, and reduce the risk of human error.	An intelligent awareness system enhances the situational awareness of ship surrounding. It needs advanced camera and sensor technologies support. At present, intelligent awareness system of a ship mainly consists of radar, camera, Lidar, antenna, PTZ (Pan/Tilt/Zoom), etc.
Communication	In the process of remote monitoring, the communication system only needs to send the ship's position, course, speed, and ship status flags. All flags are represented by 2 bytes. In the process of status investigation, SCC needs to query the detailed status information of the ship and the surrounding situation. The communication system needs to transmit radar images, IR and/or video images, HDTV images, and automation. The image is about 300 to 2600 kByte. In the process of indirectly remote control, SCC may need to adjust position or speed waypoints of the voyage. The communication requirements are as for status investigation. In the process of directly remote control, the SCC operators may need to access rudder and thruster controls. Although this is not very demanding in terms of bandwidth, the sensors on the ship require higher bandwidth.	The main communication channels when a ship is close to the coast include VHF, GMDSS, 3G/4G/5G, and etc. The communication has disadvantages of signal transit in short range. The communication channels of deep sea mainly use satellite communication with disadvantages of high cost, and not all satellite communication systems support global coverage and signal transit disturbance.
Sensor data fusion	There are three basic processing architectures including direct fusion of sensor data, fusion of feature vectors, and processing of each sensor to achieve high-level inferences or decision.	There are some widely-spreading data fusion architectures including Joint Directors of Laboratories (JDL), the Luo and Kay architecture, and the Dasarathy's architecture. There are also a series of challenges of data fusion including data imperfection, data inconsistency, data confliction, data alignment/registration and correlation, data type heterogeneity, fusion location, and dynamic fusion.

A transponder is a wireless communications device usually attached to a satellite [76]. The transponder is mainly used as the Automatic Identification System (AIS) transmitter/receiver in the ocean. An AIS can effectively reduce ship collision accidents. The AIS can be connected with radar, Automatic Radar Plotting Aid (ARPA), Electronic Chart Display and Information System (ECDIS), Vessel Trafc Service (VTS), and other terminal equipments [77]. According to International convention of International Maritime Organization (IMO) for the safety of life at sea, international voyaging ships with a gross tonnage of over 300 tons and all passenger ships must be equipped with an AIS [78].

The report [10] introduces that route planning is one of the key technologies of unmanned ships. The purpose of route planning algorithms is to plan a collision-free feasible path from the starting point to the target point. Next, We summarize and explain algorithms for route planning in detail below, shown in Table 6. In the paper [79], route planning for unmanned ships is classified to global route planning based on marine environmental information and local route planning based on sensor information.

- Global route planning obtains static obstacle information of the sea area through the electronic chart and uses an A star algorithm, a distance optimization Dijkstra algorithm, a genetic algorithm, and an artificial potential field method to search for collision free path from beginning to end. The description of the above algorithms are shown in Table 6.
- Local route planning is to determine the optimal route from the current route point to next by real-time detection of the surrounding environment and obstacles through sensors when the ship's environmental information is complete or partly unknown [80].

Collision avoidance at sea is fundamental to ensure the safe navigation of unmanned ships. A collision avoidance system includes obstacle detection, tracking, motion estimation, advanced algorithms, and other modules. At present, the technologies of obstacle detection, tracking, and motion estimation are very mature. We focus on collision avoidance algorithms for unmanned ships in this paper. There are many collision dangers when unmanned ships in voyage encounter other ships or other obstacles. obstacles include dynamic ships and static obstacles which are not shown on shipborne Electronic Chart Display and Information System (ECDIS). Generally, collision avoidance algorithms of unmanned ships initially compute a global optimal path. If a moving ship is detected in near proximity by sensors, the algorithms re-plan the next subpath in real-time to avoid the approaching ship [97]. In addition to above factors, the effect of sea wind, wave, and ocean current on autonomous navigation of unmanned ships should be considered in actual navigation conditions. Most of these algorithms are based on the existing navigation rules and real-time navigation information to simulate human piloting cognitive ability [98]. The route planning algorithms listed in Table 6 can avoid unmanned ships collisions. We also summarize other algorithms for collision avoidance, as shown in Table 7. Unmanned ship navigation may use efficient real-time intelligent collision avoidance algorithms to ensure navigation safety.

TABLE 6. A summary of route planning algorithms of unmanned ships.

Classification	Algorithm / Method	Description	Reference
global route planning based on marine environmental information	A star algorithm	The A star algorithm performs a Best-first search of the most probable paths leading to the goal.	[81]
	Distance optimization dijkstra algorithm	Dijkstra algorithm is an algorithm for calculating single source shortest path in a weighted directed graph [82].	[83]
	Genetic algorithm	The genetic algorithm simulates the mechanisms of natural selection and of evolution theory to search the optimal solution [84].	[85]
	Artificial potential field method	Artificial potential field method is a typical online path algorithm. It uses the idea of "water flows to low places" and can naturally understand the generation law of vehicle routing.	[86]
	Ant Colony (ACO)	ACO algorithm is a bionic optimization algorithm to simulate the intelligent behavior of ants.It has the advantages of robustness and distributed computing mechanism.	[87], [88]
local route planning based on sensor information	Flower Pollination Algorithm (FPA)	FPA is a new metaheuristic algorithm. It was developed from the characteristic of the biological flower pollination in flowering plant [89].	[90]
	Rapidly-exploring Random Trees algorithm (RRT)	RRT is a random data structure.It rapidly expand like a tree to explore most of the area of space and find a viable path.	[91]
	Fuzzy logic	Fuzzy logic has robustness and can avoid the characteristics of traditional algorithms, which are sensitive to positioning accuracy and highly dependent on environmental information	[92], [93]
	Neural network	Neural network has the abilities of large-scale parallel processing of data and strong fusion of knowledge and can implement efficient and intelligent path planning.	[94]
	Other		[95], [96]

There are many algorithms which can find the optimal routes and avoid collisions for unmanned ships. We analyze and compare typical algorithms of route planning (Table 6) and collision avoidance (Table 7) based on [16]–[19].

- An A* is an optimization algorithm with a modified best-first-search (BFS) strategy which uses heuristic cost estimations [99]. At the beginning of path planning, an A* algorithm [100] chooses a pixel with the lowest F(n) cost adjacent to the start pixel in a sonar image. The vital key to determine which pixels are chosen by the equation $F(n) = G(n) + H(n)$ [101]. G(n) is the actual cost from the begin pixel to a given pixel(n). H(n) is the estimated cost from the given pixel(n) to the goal pixel. Optimal paths are generated by repeatedly going to goal and selected the pixel with the lowest F(n) cost [101].
- A Genetic Algorithm (GA) is a stochastic optimization algorithm based on principles of natural selection and genetics [102]. The key of applying genetic algorithm to route planning of unmanned ships is a genetic representation of the path. The optimal path of unmanned ships is obtained by calculating fitness functions [85].
- In the Artificial Potential Field (APF) model, the target which produces the attraction to unmanned ships, obstacles which produce repulsion to unmanned ships [103]. The next waypoint can be computed by the steering angle of unmanned ships, step size, and current position. An artificial potential algorithm [86] finds out the direction of the resultant force by adding vectors of the forces. The disadvantages of this algorithm include the problem of local optimal solution in applications.
- An Ant Colony Algorithm (ACA) is a probabilistic algorithm that simulates the behaviour of real ants in search of food [104]. An ACA [105] divides maritime space into grids, establishes its node matrix in the navigation area, and calculates the objective function based on the routes found by each ant. The ACA deletes the nodes that are not passed and repeats this process until finding an optimal route of unmanned ships.
- A neural network is inspired by neural network in human brain and used to simulate human thinking. Back Propagation (BP) network is a widely used neural network. The BP network gives a risk degree of collision based on risk factors of ship encounter. After taking collision avoidance actions, the BP network obtains a new risk degree to evaluate the effectiveness of collision avoidance actions. A neural network algorithm [94] has strong learning ability, but it has a disadvantage of poor generalization ability.

The above algorithms and methods can implement route planning of unmanned ships and avoid collision in navigation. One or several algorithms are often used to enable unmanned ships to navigate in the optimal path and avoid collision with obstacles in practical applications.

TABLE 7. **A summary of collision avoidance methods of unmanned ships.**

Algorithm / Method	Description	Reference
Support Vector Machine(SVM)	SVM is a model which can find an optimal hyperplane to meet the requirements of classification. The hyperplane equation is defined as $\omega \cdot x + b = 0$, where ω is the normal of the hyperplane and b is the distance from the hyperplane to the origin point [106]. The characteristic parameter of multi-sensor is the environment state vector as the input of SVM, and the ship's next heading angle movement as the output of SVM. A SVM system implements real-time control for the local path planning of a ship [107]. SVM can be combined with other machine learning methods to monitor learning models, analyze collision avoidance data, and identify patterns to improve the accuracy of collision avoidance decisions.	[108], [106], [107].
Finite State Machine (FSM)	FSM is a timing Machine and divides a complex problem into several simple parts to deal with. FDM is a model which describes the sequence of states that an object experiences in its life cycle and how it responds to various events. It can be reduced to 4 elements including current state, condition, action, and secondary state [109]: the current state refers to the navigation state in real-time; the condition is used to determine the state of migration in the next cycle, such as angle deviation between real-time heading and destination; the action is related navigation operations; the second state is the next state compared with the current state.	[110], [109]
Line-of-Sight (LOS)	The core idea of LOS guidance is that the ship converges to a constant LOS heading angle between the ship and the target [97]. The LOS angle (ψ_{los}) is calculated in terms of the current (x,y) and LOS coordinates (x_{los}, y_{los}). The equation is $\psi_{los} = (y_{los} - y)/(x_{los} - x)$.	[111], [112], [97]
Multi-sensor data fusion (MSDF)	MSDF refers to the collection, processing and collaborative combination of data collected by various knowledge sources and sensors to provide auxiliary decision-making [113]. Various estimation algorithms available for MSDF include Kalman filtering based approach, hybrid multi-sensor data fusion, fuzzy logic based adaptive Kalman filter, and crisp decision algorithm [114].	[115], [113], [114]

IV. TECHNOLOGIES AND APPLICATIONS FOR FUTURE UNMANNED MERCHANT SHIPS

In the field of ships, GPS, AIS, ARPA (Automatic Radar Plotting Aid), ECDIS, and other technologies are used to enable unmanned ships to sail with information and intelligence. However, current technologies cannot fully guarantee the automatic perception and autonomous safe navigation of unmanned merchant ships. Unmanned ships monitor navigation environment, ship status, and working status of equipment through a variety of sensors and intelligent sensing equipments. The various intelligent devices on unmanned ships are integrated into a network through the ship buses or wireless networks to communicate with each other and be gathered to make decisions. Finally, the data are sent to Shore Control Center (SCC) through satellites, the Internet, and 3G/4G/5G mobile communication for monitoring status of unmanned ships in real time. Unmanned ships may need human intervention and remote management in some complex environments and dangerous situations. Next, we introduce IoT technologies, intelligent awareness, data fusion, communication, and current status of IoT for unmanned ships in detail.

A. INTERNET OF THINGS

Internet of Things (IOTs) are described as follows: every thing in the physical world is defined as a unique identity, which connects to the Internet for communicating, collecting, and exchanging data [116]. It is a bridge between the physical world and the virtual world. IoT is a world wide network of interconnected objects based on standard communication protocols [117]. It extends to the exchange of information and communication between the things in the physical world [118]. Although IOT applications in unmanned ships are still in the early stage as we survey in later subsections, we believe that IOT will be a very promising technology to apply to the unmanned ships in the near future. Therefore, next, we follow architecture, communication standards, security, essential technologies of IoT for introduction.

1) IoT ARCHITECTURE

The typical IoT architecture is 3-layer architecture [119], [120], consisting of a perception layer, a network layer, and an application layer. The authors in [121] propose a 4-layer architecture because the functions and operations in the network and application layers are complex. Based on this concept, the service layer (also known as the interface layer or the middleware layer) is developed between the network layer and the application layer. The service layer has various functions, including service discovery, service composition, service management, and service interfaces. The authors in [122], [123] divide the structure of IoT into 5 layers, including the perception layer, the network layer, the middleware layer, the application layer, the business layer. The IoT architecture is shown as Fig. 6.

2) WIRELESS COMMUNICATION STANDARDS

IoT communication technologies connect different things to provide intelligent services. When the heterogeneous things

TABLE 8. **Wireless communication technologies [119], [124]–[126].**

Technology	Protocols	Frequency Band	Data Rate	Range
Wifi	802.11	2.4 GHz and 5 GHz	1 Mb/s to 6.75 G/s	20 to 100 M
LoRa		868 and 900 MHz	0.3 Kb/s to 50 Kb/s	20 M
Z-Wave		908.42 MHz to 868.42 MHz	9.6 Kb/s	30 to 100 M
6LoWPAN	802.15.4	868/915 MHz		
NFC		13.56 MHz	424 Kb/s	
WiMax	802.16	2.4 Ghz-5 GHz	1 Mb/s-6.75 Gb/s	
BlueTooth	802.15.1	2.4 GHz	1 Mb/s to 24 Mb/s	8 to 10 M
Zigbee	802.15.4	868 MHz, 915 MHz and 2.4 GHz	250 Kb/s	1Km
Sigfox		868 MHz	4-12 B/h	30-50 KM
LR-WPAN	802.15.4	868/915 GHZ and 2.4 GHz	40 Kb/s to 250 Kb/s	15 KM
DASH7		433 MHz	167 Kb/s	2 KM

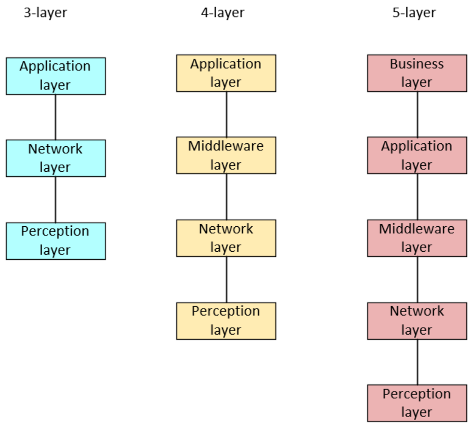


FIGURE 6. **IoT architecture [119]–[123].**

TABLE 9. **IoT Security [121].**

Layer	Security
Perception Layer	Node Capture Attacks
	Malicious code Injection Attacks
	False Data Injection Attacks
	Replay Attacks (or Freshness Attacks)
	Cryptanalysis and Side Channel Attacks
	Eavesdropping and Interference
	Sleep Deprivation Attacks
Network Layer	Denial-of-Service (DoS) Attacks
	Spoofing Attacks
	Sinkhole Attacks
	Wormhole Attacks
	Man in the Middle Attack
	Routing Information Attacks
	Sybil Attacks
	Unauthorized Access
Application Layer	Phishing Attack
	Malicious Virus/Worm
	Malicious Scripts

are connected to the same or different network, the communication needs to comply with the relevant protocols to exchange data. We summarize the major wireless communication technologies of IoT, shown in Table 8.

3) IoT SECURITY

The IoT is applied to the most important areas of the global economy, including smart gird, smart city, transportation, and health care. Therefore, security and privacy are the most important issues in IoT. There are six security features of IoT, including confidentiality, integrity, availability, identification and authentication, privacy, and trust [121]. Based on the paper [121], we summarize the security challenges in the perception layer, the network layer, and the application layer, shown in Table 9.

4) ESSENTIAL IoT TECHNOLOGIES

The Radio frequency identification (RFID) tags, sensors/actuators, Wireless Sensor Network (WSN) [127], and communication technologies are the foundation of IoT [128]. Several enabling technologies of IoT are introduced as follows:

- RFID technology was invented in 1948, but the large-scale use of RFID in commercial products appeared in the 1980s [129], [130]. It is a technology for automated identification of objects and people. An RFID system includes transponders or RFID tags, a transceiver or RFID reader, and a back-end database [131], [132]. RFID technology has two distinct advantages as unique identification and automation. In addition to acting as a pointer to a database entry, unique identifiers in RFID tags contribute to containing a large amount of transaction histories for individual items [133], [134]. RFID tags are readable at rates of hundreds per second without line-of-sight contact and without precise positioning.
- WSN is a multi-hop self-organizing network system which consists of a large number of micro sensor nodes deployed in the monitoring area and forms through wireless communication [135]–[137]. Compared with

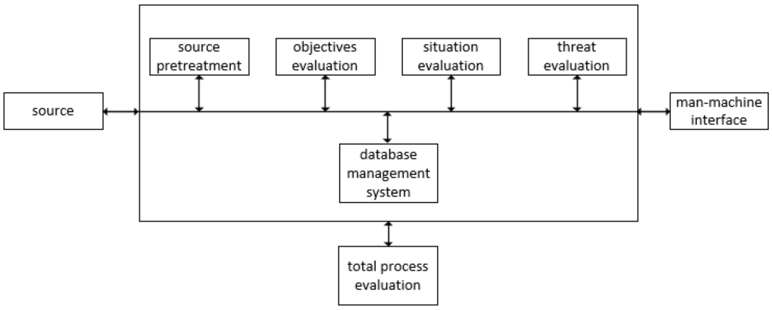


FIGURE 7. Multi-sensors information fusion processing model [146].

traditional technologies used for monitoring, WSN entails low installation and maintenance costs and enables the development of distributed collaborative applications [138]–[140].

- LPWAN (Low-Power Wide-Area Network) technologies are very popular for IOTs. The most popular LPWAN technologies are LoRa, Sigfox, and NB-IoT. These technologies are well suited for IoT applications that require little information to be transmitted over long distances. LoraWan is a derivative of chirp spread spectrum (CSS) modulation, which can operate the remote communication link in the unlicensed frequency band below 1GHz frequency band below 1GHz [141]. Sigfox uses Ultra Narrow Band (UNB) patented technology and deploys its proprietary base stations in several countries in the unauthorized sub GHz ISM frequency band (such as 868mhz in Europe, 915MHz in North America, and 433MHz in Asia) [142]. Sigfox has the advantages of low power consumption, high receiver sensitivity, and low cost. NB-IoT uses single carrier frequency division multiple access (SC-FDMA). A NB-IoT carrier uses twelve 15 kHz subcarriers for a total of 180 kHz [143]. It is widely used in LTE design.
- Fog computing is a distributed collaborative architecture [144]. In this pattern, data, processing, and applications are concentrated on devices at the edge of the network. Fog computing is characterized by low delay and position perception. It can be widely used in smart vehicle, smart grids, and smart cities, etc.

The IoT applications can be deployed various industries, such as smart city, smart grid, smart transportation, smart home, environmental monitoring, healthcare service, workplace and home support, security, and surveillance [12]. We focus on IoT applications of unmanned ships discussed in Section IV-F.

B. INTELLIGENT AWARENESS

Unmanned ships can collect data of surrounding environments, internal states of ship, and working states of equipment by applying IOT and tracking technology, such as RFID systems and intelligent sensors. We take temperature sensors [145] as an example since the exhaust temperature of engines is an extremely important parameter for the operation of unmanned ships. The exhaust temperature of engines can be obtained in real time through the temperature sensors to ensure the reliability and safety of the unmanned ships' operation. The temperature sensors carry out data acquisition for the ambient temperature signal after digital-to-analog conversion processing and data filtering and transformation. The data are sent to the central console for processing and storage through the radio frequency module. Generally, the data collected include ship sailing status and equipment data information, such as ship speed, heading, position, compass information, indoor temperature of main engines, liquid level, fuel consumption, remaining oil, concentration of warehouse smoke, temperature, and humidity, etc. Ships obtain the channel, the position of the surrounding ships, and navigation information using radar, compass, AIS, ECDIS, GPS, HD camera, and other electronic equipments. Decision-making systems of unmanned ships through a comprehensive analysis of the information make decisions for ship navigation. In addition to collecting internal status data of ships, unmanned ships also need to obtain external environment data, such as wind, wave, current, and other meteorological information, as well as water depth, velocity, and other environmental information, through sensors to ensure safe navigation.

C. MULTI-SOURCE HETEROGENEOUS DATA FUSION

Because of different types of sensors and/or data from different sensor/RFID systems, there may be redundant, conflicting, and missing. Data must be handled with uncertainties of the sources and inconsistency of multi-sensor data before using them at decision processes. This increases the credibility of the data and the ability to make decisions based on the data. Moreover, environments that ships sail at sea can be very harsh. Various sensors on board are susceptible to aging devices, bad weather, limited vision of targets, and other factors, resulting in decreased accuracy and unstable measurement data. Therefore, data fusion must be carried out to give a sufficient information support to the decision maker, so that the decision maker can make a correct decision and judgment on the state of the ship. Fig. 7 shows a multi-sensor information fusion processing model proposed by the US data fusion working group [146]. The model is composed of information source, source pretreatment, target assessment, situation assessment, threat assessment, overall process assessment, man-machine interface, and database management system module. At present, the computational intelligence methods mainly used in multi-sensor fusion include fuzzy set theory, neural network, rough set theory, wavelet analysis theory, and support vector machine, etc. By collecting multi-sensor data with fusion technologies, the unmanned ship system realizes automatic route planning, collision avoidance, and safe navigation on the water surface. The authors in [79], [147]–[151] study and improve data fusion algorithms and architecture, and improve the stability of the fusion algorithms.

D. COMMUNICATION

We classify communication of unmanned ships into internal and external communications. The internal communications of unmanned ships include CAN (Controller Area Network) bus, WSNs (Wireless Sensor Networks), Zigbee, etc. The external communications of unmanned ships include 3G/4G/5G, satellite communication, VHF, etc. The authors in [152] summarizes various use cases for communications of unmanned ship navigation, automation, and safety. Unmanned ships can adopt different communication technologies according to different requirements and types of communications.

In terms of internal communications of unmanned ships, conventional onboard monitoring systems transmit and collect data through wired networks, LANs (local area networks), fiber optic networks, and CAN buses. Unmanned ships can collect and integrate the information provided by the existing electronic navigation equipments and sensors through CAN buses or LANs to provide decision support for platform software and application software. The authors in [153], [154] study applications of shipboard monitoring system based on CAN bus technology.

TABLE 10. Wireless communication onboard [155]–[157].

Position	Environment	Transmission
Cabin	watertight doors	No
	wood doors	Yes
Stairs	no sensor nodes deployed in the stairway	No
	sensor nodes deployed in the stairway	Yes

There are many difficulties in transmitting data using traditional wired methods, such as the need to drill holes in the ship's metal plates for network wiring, resulting in additional costs and waste. WSNs have a number of advantages such as low cost, large range, flexible layout, and mobile support. WSNs can conveniently realize intelligent sensing and monitoring of ship environments. We summarize wireless communication onboard, shown in Table 10 [155]–[157].

The following is a specific application to illustrate. The authors in [158] measure the received powers of radio wave propagation on board. The measurement results show that the wireless communication depends on the distance between the transmitting antenna and the receiving antenna and position of the deck stairs. Wireless communication onboard between two Sensor Nodes (SNs) is impossible if adjacent rooms are separated by metal bulkheads and watertight doors. Each metal room is a separate network zone. Therefore, we need two types of wireless communication, including intra-zone communication and inter-zone communication. Border Nodes (BNs) are installed in every door in each room each room. Communication between SN and BN is a intra-zone communication. Gateway Nodes (GNs) are the bridges between the host system and the sensor network, which is connected to an Ethernet of the ship. The authors in [159]–[161] deploy WSNs on ships and simulated environments, and conduct relevant tests to verify that WSNs have good reliability and connectivity. In wireless communication technology for collecting sensor data, 2.4Ghz zigbee is usually adopted for wireless communication. Zigbee has the advantages of low power consumption, low cost, short delay, large network capacity, high security, and reliable data transmission. A Zigbee system is a small network with a maximum of 255 nodes per sink node. It is composed of multiple sensors, whose data are sent to the router, which then sends the acquired data to the sink node, which can access to satellite communication and the Internet.

FIGURE 8. The stair of the ship "Yukun".

Next, we take the ship ''Yukun'' as an example to introduce the wireless communication between the adjacent decks. The ship ''Yukun'' has a seven-floor deck, including a tween deck, a main deck, a promenade deck, a boat deck, a captain deck, a navigation deck, and a compass deck. The stairs from the tween deck to the main deck have a height of about 3.5 m and have steel walls with a thickness of over 20 mm, shown as Fig. 8. Therefore, wireless communication transmission between the tween deck and the main deck is very difficult. We deploy routers near the stairs, which are located in the stairway to ensure the connectivity between decks, shown

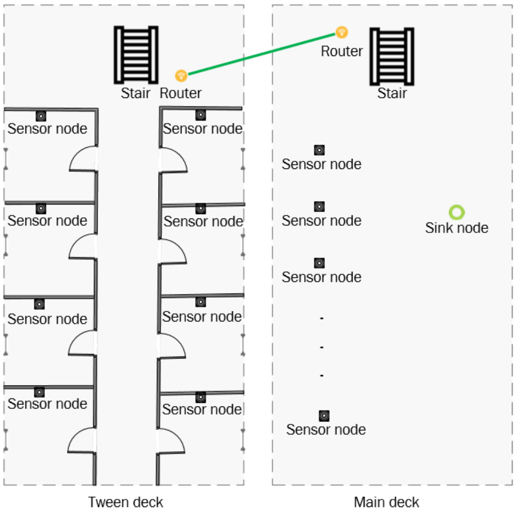


FIGURE 9. The locations of the sensor nodes, sink node, and router.

as Fig. 9, similar to [160]. The green line represents the link between the tween deck and the main deck. Meanwhile, routers are deployed near doors, which can solve the wireless communication difficulty to pass through metal walls and watertight doors.

On the other hand, in terms of external communications of unmanned ships, traditional ship communication system only relies on Automatic Identification System (AIS) to provide low data services such as position, course, heading, destination, tonnage, speed, etc [163]. When unmanned ships are closer to shore, 3G, 4G, and 5G mobile networks can be used for communication. The shore control centers (SCCs) can view the real-time data and historical data of unmanned ship operation, and make decisions based on the data. On the other hand, if unmanned ships are far away from shore, the choice of communication is limited. Satellite communication is commonly used by ships in high sea. Current satellite communication remains very expensive and impractical for most small to mid-sized ships [163]. Due to factors such as obstacles and weather, the transmission of satellite communications data may be delayed and real-time services cannot be provided [164]. Satellite communication may be not the best solution for communication of unmanned ships. In general, lower frequency bands radio is a good choice. The authors in [152], [165], [166] list the bands of the radio spectrum as defined by the International Telecommunications Union (ITU) [165]. IoT on unmanned ships is depended on Very High Frequency (VHF), Ultra High Frequency (UHF), and High Frequency (HF) radio. VHF and HF bands can provide ranges of anything between 40 nautical miles to worldwide coverage [167]. The authors in [162] propose a new communication architecture which combine Ship Ad-hoc Networks (SANETs) and multiple sensors and communicate over marine VHF radio, shown in Fig. 10.

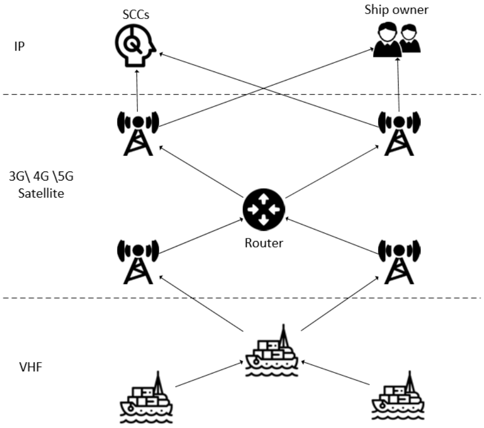


FIGURE 10. IoMat cartography network [162].

E. IoT FOR E-NAVIGATION

E-navigation implements collection, integration, exchange, display, and analysis of marine information on board and in shore control center through electronic means, so as to enhance the navigation and related services of berths for safety of the sea and the protection of the marine environment [168]. E-navigation integrates existing and new navigation tools in a holistic and systematic way. The role of E-navigation is explained as follows:

- E-navigation can improve decision support to improve navigation safety. The crew on board and managers in Shore Control Center (SCC) can acquire the relevant and real-time information of ships. E-navigation provides automatic indication and alarm to reduce human error. Moreover, E-navigation promotes the use of Electronic Chart Display and Information System (ECDIS) of consistent quality.
- E-navigation improves navigation safety, reduces the risk of collision, grounding, and the resulting leakage and pollution. At the same time, E-navigation can adopt the best route and speed to reduce emissions.
- E-navigation provides automated and standardized procedures to reduce management costs. E-navigation integration of existing systems effectively uses new equipments and meets user requirements.

IoT for E-navigation is shown Fig. 11 [169]–[172]. The perception system of e-navigation uses IOT technologies, such as sensors, RFID, WSN, zigbee, to obtain real-time information. After data fusion and processing, the information of GPS, electronic charts, and other onboard equipment is combined with an expert system and artificial intelligence technology for decision assistance and early warning.

F. IoT FOR UNMANNED SHIPS

IoT plays an important role in manufacturing, navigation, and maintenance of unmanned ships. Applications of IoT on ships simplify and optimize aspects of unmanned ship

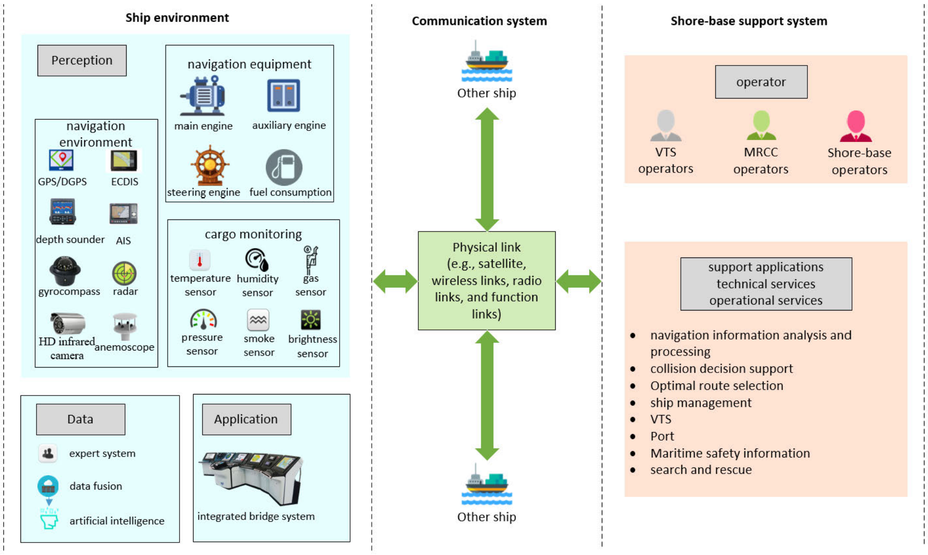


FIGURE 11. A novel IoT for E-navigation architecture [169]–[172].

operations at sea, in ports, and in formation, including ships tracking, maintenance, safety, etc. The report [173] presents key opportunities of IoT, such as transport and logistics, administrative costs, advances safety, fuel consumption, and efficiency. Therefore, we summarize applications of IoT for unmanned ships as follows:

(1) Advanced sensors and IT technology can implement real-time management and monitoring of unmanned ship navigation, as well as autonomous navigation by unmanned ship management systems. Ship owners can monitor the ship's status in real time and make decisions based on current and historical data, enabling them to operate more efficiently and save time and fuel. Furthermore, in the era of IoT, smart sensors can also be used for ships tracking or predictive maintenance on ships. By embedding important parts and equipment of the ship into sensors, various dynamic information can be monitored in real time and transmitted to Shore Control Centers (SCCs) through the network to detect the health status of the ship in real time. The data can be used as reference information for ship repair, real-time detection of defective parts, timely issuing maintenance warning, and building a ship IOT system. The authors in [174] present that IoT can cover the stages of design or production of the ship. At the same time, sensors are installed in the components that need monitoring to obtain the information about the life of the ships. In the paper [175], the authors propose an application of IoT on the ship to monitor the health in real-time sensing. The article [176] points out that IoT can enable ship owners and managers to find potential failures through real-time monitoring of ship equipment. Several applications of IoT for ship safety are shown in Table 11.

(2) According to statistics, fuel cost is usually the most expensive item in ship operation cost, accounting about 50% of ship operation voyage cost [177], [178]. Sensors and monitoring equipment onboard collect the ships' performance data and send them to Shore Control Center (SCC), which provides guidance in planning the most energy-efficient routes. After determining the optimal route, speed, and engine configuration, ships can save considerable amounts of fuel and lower carbon emission. On September 4, 2018 [179], International Maritime Satellite Organization (INMARSAT) and the company Danelec Marine jointly released fleet data, which enable owners and managers to quickly and easily identify equipment problems and failures, monitor ship performance, and fuel efficiency. Furthermore, IoT technologies were used to sense obstacles around the ship, environment, location, ocean current, and weather information. IoT provides data support for path planning to make ships run more efficiently, saving time and fuel. Moreover, the data collected by sensors are also the basis of collision avoidance and navigation decisions to avoid ship collision and leakage of environmental pollution. With today's ships becoming highly sensory, shipping management companies and owners have more data than ever about day-to-day operations of ships. Several applications of IoT for fuel consumption are shown in Table 11.

(3) IoT technology can reduce operational costs, increase efficiency, and minimize losses due to human errors. For example, IoT allows optimal placement of containers on ships to reduce offloading times. IoT can track exactly when ships arrive at ports, reducing the cost of waiting for trucks to move containers to the next station. Moreover, the IoT technology can save massive amount of human cost. With the RFID technology, active electronic tags are installed on the ships entering and leaving channel. The tags can store individual information related to the ships or cargo information. A remote reader is installed on the channel, which connects to a data server through the standard serial port RS232/485.

TABLE 11. Several applications of IoT for shipping [180], [181].

Aspects	Country	Company	Application	Detail
Safety	American	ioCurrents	An IoT processing unit capable of measuring all of the different parameters in a ship's engine.	It can enhance navigation safety and provide potential faults in time.
	United Kingdom	Green Sea Guard	A gas analysis tools measure ship's engine exhaust gas.	The gas monitor gives engineers an early warning when a ship's engine is not operating correctly. This gives engineers an early warning.
	American	Augury	Halo sensors	The sensor measure ship's engine vibration, sound, and temperature. The diagnostics platform analyzes raw data through machine learning to provide real-time alerts and health reports about in-depth view of engine health.
Fuel consumption	Finland	Wärtsilä	Dynamic Maintenance Planning (DMP)	DMP analyzes the operating conditions of the ship engines and sends it via satellite to maximize intervals between maintenance periods, thus reducing administrative costs and carbon emission.
Cost efficiency	American	Carnival Corporation	An IoT-based personalized digital concierge service.	The service makes use of near field communication (NFC) and Bluetooth Low Energy (BLE) technology to implement streamlined embarking, locking cabin doors, anytime-anywhere gaming, and easy payment.
	United Kingdom	ZS Wellness	Wearable health tracking system	The data collected can be used to create personalised wellness plans for individual crew members.
Economy and trade	American	Parsyl	A sensor which can be fitted to an individual pallet or package.	The sensor can measure temperature, humidity, light, impact, and GPS position. Moreover, the data from the sensor can across land, sea, and air. It can be used for cargo status monitoring in ocean transportation.
	Denmark	Maersk	Remote Container Management (RCM) system	The system monitors and sends data such as temperature and location to the cloud. RCM can reduce spoilage of goods, such as fresh produce.

In the area where it is difficult to place wiring, a wireless data transmission module (GPRS/CDMA) can be linked to the data server for real-time communication. The reader can identify and read the electronic tags installed on the ships at a distance of up to 80 meters, so as to implement non-stop inspection. In addition, ship owners or managers need to monitor the health of the crew in real time. The crew members wear wearable devices while on board to collect health data. The data help managers in SCC to better plan welfare provision for those on board. Several applications of IoT for cost efficiency are shown in Table 11.

(4) For cargo ships, managers need to keep track of ships' position, status, and cargo environment information at all times. Sensors on ships collect data and send them to SCC in real time via communication. Meanwhile, sensors can track temperature, humidity, light, impact, and GPS position, etc. On the other hand, for passenger ships, passengers on board can wear smart wearable devices to implement navigation, door access, payment, and other functions. Several applications of IoT for commercial trade are shown in Table 11.

(5) We think that there are also three type applications of IoT in unmanned ships including front-end data acquisition, data communication, and data storage and analysis processing. The front-end data acquisition is to collect the data of navigation parameters, navigation attitude, and surrounding environment from various types of sensors on ships. The collected data is transmitted by IoT communication technologies, including ZigBee, RFID, Bluetooth, WSN, or LPWAN. Finally, the collected data are processed and stored through cloud computing, fog computing, and cloud storage to provide decision support for the safe navigation of ships.

V. FUTURE RESEARCH DIRECTIONS

Unmanned merchant ships have the advantages of autonomous navigation, fast speed, strong mobility, good concealment, and low cost, but there are potential safety hazards such as collision, grounding, and security. For example, unmanned merchant ships cannot be converted to manual steering in case of automatic rudder failure. If there is any equipment component that needs to be replaced or repaired during the voyage of an unmanned ship, the manual treatment cannot be carried out in time, and this will endanger the voyage of the unmanned ship. In case of fire, leakage or other dangerous situations, no personnel can be organized for temporary and effective disposal. The problem of the endurance of unmanned ship is that when an unmanned ship needs energy supply, it cannot immediately learned about the unmanned ship in relation to port state legislation, and cannot automatically contact the nearby port to carry out the port supply and continue the voyage mission after supply. These problems are the urgent problems to be solved for future unmanned ships. The authors in [182] show that unmanned merchant ships have serious consequences due to non-navigational accidents (such as fire, structural damage caused by ship loss) compared with traditional merchant ships. Next, we introduce some future research directions of unmanned merchant ships from several aspects: law, communication, IoT Applications, security, onboard intelligent equipment, automatic control, Artificial Intelligence and Big Data, Ship Industry 4.0, and smart ocean.

A. IMPROVEMENT OF LAWS AND REGULATIONS CONCERNING UNMANNED SHIPS

If an unmanned ship without a captain and a crew onboard, is it still a ship? If yes, whether such an unmanned ship is governed by maritime law? If no, are there new laws that applies to unmanned ships? At present, relevant laws on unmanned ships are not perfect at present. It is one of the biggest challenges for the development of unmanned ships in the future. We summarize rules of law, including crew, navigation, rights and duties, shown as follows:

- As unmanned ships no longer need a captain or a crew, it seems that rules of law about these people will inevitably lose all relevance. These laws [183] include Manila amendment, MLC (Maritime Labour Convention), SOLAS (International Convention for Safety of Life at Sea), STCW (International Convention on Standards of Training, Certification and Watchkeeping for Seafarers), and captain's law, etc. On the other hand, there are many managers in Shore Control Center (SCC). Under special circumstances, unmanned aerial vehicles need to be controlled remotely by shore-based managers. Whether do these managers need to be restricted by relevant laws?
- International Regulations for Preventing Collisions at Sea (COLREGs) rules specify which ship is responsible for giving way to other ships and which side of the "stand-on" ship can maneuver in the case of crossing, overtaking, and head-on traffic [184]. Several researchers study the concept of COLREGS-based navigation of unmanned ships [185], [186].
- Several relevant laws [183], [187] stipulate rights and duties in connection with international shipping, including UNCLOS (United Nations Convention on the Law of the Sea), LOSC (Law of the Sea Convention), and maritime law, etc. Several researchers discuss whether the laws are applicable to unmanned merchant ships [188], [189].

The law of unmanned ship should take into consideration the navigation characteristics and functions of unmanned ships, and formulate laws and regulations fully applicable to unmanned ships, so as to facilitate the further development of unmanned ships.

B. COMMUNICATION

When unmanned ships are sailing in the high sea, 3G/4G network cannot be covered and satellite communication is expensive. Although the ships do not need the continuous control of the shore-based control center, the network security and data transmission stability of communication between the ship and the shore-based control center are very important during autonomous navigation. We have summarize following research, which can promote the development of unmanned ships. Firstly, when the ship is sailing in the deep sea, the network cannot be covered. The ship can only rely on satellite communication. However, satellite communication is expensive, which cannot guarantee the speed and stability of network transmission. For example, when the ship "Yukun" is sailing in the deep sea, it reports current position through satellite communication once a day. We believe that decrease of satellite communication cost will be beneficial to the development of unmanned ships in the future. Secondly, new communication technologies are needed with wider coverage and more convenient communications for unmanned ships at deep sea.

C. CYBER SECURITY

Communication/IoT security has become a concern for shipping. We have to consider specific risks when IoT is deployed for the unmanned ships. The use of technical and functional indicators enables the Shore Control Centers (SCCs) to monitor the status of unmanned ships with minimal operator and communications system load. Moreover, under the background of remote operation of unmanned ships, concerns on cyber security are further increased. Skilful and capable hackers may gain access to the ship control system through the network and implement the purpose of controlling the ship and changing its operation according to the destination set by the hackers. Several researchers study the concept of cyber security of unmanned ships [190], [191]. In our opinion, cyber security is one of the important issues affecting the future development of unmanned ships. In the future, a dedicated framework for specific systems, such as railway, smart grids, and nuclear power plants, will be developed to secure unmanned ships navigation. In addition to the cyber security of communication, the future unmanned merchant ships also have physical security issues, such as:

- If some hostile people (such as pirates) or ships approach or board unmanned ships, they deliberately destroy the communication equipment or interfere with the communication signal onboard. This will cause unmanned ships to lose control and be in danger. It is a problem that must be solved before the actual operations of unmanned merchant ships in the future.
- If the communication equipment is completely enclosed, it can play a protective role, but whether the communication signal can be transmitted normally needs further research and testing.

D. IoT APPLICATIONS ON SHIPS

Although a lot of IoT applications on ships have been mentioned in section IV-F, we think that there will be more iot applications on unmanned ships in the future. At present, equipments on the ship are not modular enough, and the procedures for updating the equipments are quite complex. Future equipments of unmanned ships may be modular and updated with plug-and-play functions. This requires the support of automation, control, communication, and computer technologies. Meanwhile, the development of various types of sensors can promote the development of unmanned ships, such as sensor life, data stability, and power supply, etc. Future IoT applications on ships digitize supply chains, track logistics operations, accurately predict ship arrival times, optimize navigation routes, forecast demand, and simulate complex supply networks. These future applications will greatly improve operation efficiency, improve operation control, increase maintenance reliability, and optimize operation cost.

E. INTELLIGENT AUXILIARY EQUIPMENT

Due to the high electronicalization of unmanned ships, the damage of general electronic devices will cause fatal threat to the safe navigation of unmanned ships. Therefore, unmanned ships should be equipped with related intelligent robots for daily maintenance and repair of unmanned ships in case of problems. Experts in shore-based control center make diagnosis based on the data from unmanned ships. The intelligent robots on the unmanned ship maintain and repair unmanned ships according to the solution from the shore-based control center. Experts monitor the scene of maintenance is transmitted to the shore-based control center in real time.

F. AUTOMATIC CONTROL

The shipboard equipment and navigation instruments introduced in Section II-C can use the IOT technology to connect these non automatic, semi-automatic, and fully automatic equipment to realize automatic monitoring and control in the future. Autopilot is the most typical automatic control equipment onboard. At present, many researchers study this subject. In addition, some carry out a series of researches on the next generation intelligent rudder for unmanned ships navigation [192], [193].

G. ARTIFICIAL INTELLIGENCE AND BIG DATA

Automation systems on most ships collect a large mount of data. Generally, there are hundreds of such data input or output points on a common ship. The number of modern ships may be tens of thousands. These data have three main problems. First, most of the data come from relatively independent and closed systems. Second, the quality of data cannot be guaranteed. Third, the amount of data is huge. Integrated Bridge System (IBS) mentioned in Section II-C integrates navigation system and automation system into one platform, which is convenient for comprehensive analysis and provides decision support for ship navigation. In the future, big data technology will not only store massive data, but also analyze, process, retrieve, and mine these data. Through AI (Artificial Intelligence) related technologies, such as DLS (Deep Learning System) and BLS (Broad Learning System), people and software provide guarantee for the navigation of unmanned merchant ships.

H. SHIP INDUSTRY 4.0

Ship Industry 4.0 (SI4) is a collaborative network integrating IOT, service network, data, and human. It integrates the real space and virtual space based on the virtual production system (CPPS) [194]. SI4 includes smart ship design, smart ship manufacture, and smart ship operation processes. It implements of ships industry from the design of improving energy efficiency to more intelligent and smart operation. Ship manufacture is a highly complex process involving many disciplines. Ship design is an important part before ship manufacture. Ship design generally includes four stages: conceptual design, contract design, preliminary design, and detailed design [195]. In the future, SI4 will be fully automated and directly connected to manufacturing and operating systems, designed according to market trends and customer feedback.

I. SMART OCEAN

So far, we know a relatively small area of the world's oceans. Ships are affected by environment, meteorological conditions, deep-sea communication infrastructure, and other factors. Smart ocean system collects ocean data through shore control center, island station, port, lighthouse, buoy, submarine buoy, Unmanned Aerial Vehicle (UAV), remote sensing satellite, communication satellite, etc. These data are transmitted to big data cloud server through high-speed network, providing solutions for marine ecological protection, marine prediction and disaster reduction, ship navigation, and marine engineering. In the future, unmanned commercial ships need more intelligent equipments to provide information technology support for safe navigation, resource discovery, and environmental protection.

VI. CONCLUSION

Unmanned merchant ships have the ability of autonomous planning, autonomous navigation, and autonomous environment perception. Shore-based control center can carry out real-time intervention control for unmanned ships. In the future, unmanned merchant ships will play a more important role in ocean freight transportation and military affairs. Future research of unmanned merchant ships needs more powerful sensors, perfect unmanned ship related laws and regulations, and a wider and safe network coverage.

This paper introduces the mechanisms of a merchant ship and the duties of the personnel on board from the aspects of structure, principle of ship handing, and navigation instruments. In the future, electric ships may become a better solution for unmanned ships.

We categorize Unmanned Surface Vehicles (USVs) into small, medium, large, and extra large by displacement. We focus on large and extra large displacement USVs as unmanned ships in this paper. We summarizes classification of unmanned ships as automated manned ships, remote-control ships with crew on board, remote-control ships without crew on board, and completely unmanned automatic ships according to the level of automation. We list in detail the economic, social and safety benefits of unmanned ships. We summarize the development and the state of art of unmanned ships by studying the existing unmanned ships papers and introduction. We summarize the core technologies of unmanned ships, such as intelligent awareness, sensor fusion, collision avoidance, path planning, and communication, etc. We focus on the classification and introduction of collision avoidance and path planning algorithms, compare the advantages and disadvantages of the algorithms.

We summarizes the support of IOT technologies for unmanned ships, such as intelligent awareness, sensor fusion, and communication, etc. Specially, we summarize IoT For e-navigation architecture. Furthermore, We look forward to the future of IoT for unmanned ships.

We believe that many technological breakthroughs are needed if unmanned ships implement autonomous navigation without intervention or control in the future. But unmanned ships will greatly save human and financial resources and must be the future development trend.

We realize that both unmanned ships and IOT for shipping are still in their early stages although they will have great potentials in the future. Shipping companies are reluctant to reveal their detail designs of their early products except some news reports while academia has fewer solid research publications. We hope that our paper stimulates more research in these areas so that we can see more published research papers in these areas in the near future.

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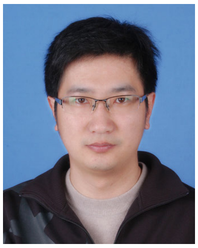

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