

A survey of crowd evacuation on passenger ships: Recent advances and future challenges

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ABSTRACT

During ship emergencies, a reliable and efficient evacuation system is able to guide passengers to the appropriate muster stations as quickly as possible. The majority of the existing indoor evacuation systems provide emergency guidance for people trapped in general buildings. However, those systems fail to consider the unique challenges of ship passenger evacuation, such as the effect of ship motion on pedestrian motion and the feedback of pedestrian motion on ship inclination state. Consequently, evacuation guidance provided by these schemes may not always be optimal or may even make the evacuation worse due to the differences in the critical factors influencing emergency guiding between land-based buildings and passenger ships. This paper presents a systematic literature overview of recent advances in building evacuation, followed by a description of the challenges unique to evacuating passengers on vessels. Furthermore, the existing ship evacuation research is reviewed from three aspects, i.e., passenger behavior study, ship evacuation optimization, and evaluation of evacuation on passenger ships. A discussion of land-based evacuation schemes and prospects for ship evacuation is also presented.

1. Introduction

Over the past few years, passenger ships have become one of the most popular means of marine transportation and tourism (Fowler and Sorgaard, 2000; Yang et al., 2020). According to the data from Cruise Lines International Association (CLIA), the worldwide ocean cruise passenger capacity had a compound annual growth rate of 6.6% from 1990 to 2021 (Chiou et al., 2021). Fig. 1 shows the worldwide passengers carried from 1990 to 2021. Although modern cruise ships have made continuous progress in their structural designs, operating practices, marine technologies, and regulations in the past 20 years, passenger ship accidents still occurred with catastrophic consequences, e.g., the Costa Concordia disaster in 2012, which leads to 32 passengers/crew dead and more than 4,000 injured (Mileski et al., 2014; Liu et al., 2022). According to Lloyds Register accident statistics, there were close to a hundred thousand deaths and injuries of vessels worldwide from 2000 to 2020, of which more than 5% were associated with inappropriate evacuation (Wang et al., 2022; Statistics, 2020). Therefore, an efficient evacuation scheme should be a favorable measure to reduce the losses of human lives in such catastrophes.

The existing evacuation works focus on designing land-based evacuation schemes (Li et al., 2019). As shown in Fig. 2, there are four kinds of guidance systems for evacuation in buildings on the land: 1) Signage-based evacuation scheme, 2) Leader-based evacuation scheme, 3) Mobile equipment (ME)-based evacuation scheme, and 4) Wireless Sensor Network (WSN)-based evacuation scheme. Earlier studies focused on the design of evacuation signage, including fixed and variable signage. The former is predetermined and does not respond to environmental dynamics, while the latter can adapt to changing hazard status or pedestrian flow to guide occupants (Chu et al., 2017). People may panic in emergency situation, especially when they are unfamiliar with the environment, leading to a poor understanding of evacuation signs, potentially resulting in a stampede and subsequent casualties. The deployment of evacuation leaders is an effective method to improve evacuation safety and efficiency. There are two types of leaders: human and robotic leaders. A mobile robot plays a role similar to that of a human leader in guided crowd evacuation. Moreover, mobile robots could be more advantageous in certain emergency cases where human leaders cannot be assigned to guide people out. Rapid development in intelligent wearable devices and mobile communication technologies has made ME-based evacuation possible. ME-based schemes typically assume the location information of people is available, which may

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not always be available in many realistic situations (Fujihara and Yanagizawa, 2015; Mulloni et al., 2011; Gelenbe and Bi, 2014; Ikeda and Inoue, 2016; Iizuka and Iizuka, 2015; Wada and Takahashi, 2013; Fujihara and Miwa, 2012; Inoue et al., 2008; Chu and Wu, 2011; Chen et al., 2015; Chittaro and Nadalutti, 2008). The follow-up studies enable users to bootstrap their indoor evacuation services by themselves, avoiding the dependency on a pre-deployed localization system (Zheng et al., 2017; Shu et al., 2015; Yin et al., 2016; Dong et al., 2019; Teng et al., 2019; Li et al., 2020; Pan and Li, 2019). The ME-based systems neglect environmental dynamics, which may navigate users to hazardous areas. WSNs, capable of automatically monitoring environmental dynamics, should be incorporated into evacuation systems (Wang et al., 2014a). The WSN-assisted scheme can be divided into two categories: sensor-centric scheme, which is to find a direction for every single sensor, and user-centric scheme, which aims to provide customized guidance for each evacuee (Wu, 2017).

The above systems can effectively mitigate potential harm to building occupants in case of emergency. However, evacuating people on passenger vessels is still very challenging due to the unique characteristics of ship evacuation. For example, the impact of dynamic ship motion on pedestrian movement and the feedback of pedestrian movement on ship motion. Compared with the relatively mature land-based evacuation, the research on ship evacuation only started lately. There are mainly three kinds of research focusing on ship evacuation in terms of study intentions: 1) Investigating and analyzing the likely behavior of ship passengers in emergency situations; 2) Optimizing evacuation strategy for trapped passengers; 3) Evaluating ship evacuation performance. The first kind of research examines the characteristics of passengers (e.g., passengers' likely behavior when hearing an evacuation alarm) by conducting experiments, questionnaire surveys, or model-based simulations (Chen et al., 2016a; Wang et al., 2020; Valanto, 2006; Sun et al., 2018a). With respect to passenger evacuation optimization, most researchers focus on planning escaping routes (Ng et al., 2021), optimizing the staircase layout (Wang et al., 2022), and scheduling the time for issuing evacuation orders (Xie et al., 2020c). Ship passenger evacuation can be evaluated in two ways: advanced analyses and simplified analyses (Ni et al., 2017; Kang et al., 2019; Vilen et al., 2020; Galea et al., 2015; Wang et al., 2022; Cho et al., 2016; Sarshar et al., 2013; Xie et al., 2020b; Kana and Droste, 2019; Hifi, 2017; Vanem and Skjong, 2006). The simplified analysis considers a large passenger group as a whole. In contrast, every passenger is regarded as an individual with his/her characteristics in the advanced analysis.

This paper provides an analysis of ship passenger evacuation. The main contributions of our work are summarized as follows:

- A thorough analysis and comparison in recent advances in land-based indoor evacuation systems based on signage, leader, ME, and WSN, is presented.
- The specificities of passenger vessels, which result in the inapplicability of these land-based systems on ship passenger evacuation, are analyzed.
- The research about the evacuation on passenger vessels is reviewed from three perspectives, i.e., the likely behavior of passengers in emergency situations, the optimization of ship evacuation, and the evaluation of evacuation on passenger ships.
- Some comments on the land-based evacuation and the future research directions for the area of ship passenger evacuation are discussed.

This paper is organized as follows. Section II reviews the work pertaining to land-based evacuation with signage, leader, ME, and WSN. In Section III, the unique characteristics and the recent research efforts about ship passenger evacuation are discussed, respectively. Finally, Section IV presents our comments on the land-based evacuation schemes and the prospects for evacuating passengers on ships. The organization of our paper is illustrated in Fig. 3.

2. Land-based indoor evacuation scheme

A number of evacuation schemes for general buildings have been proposed, which can be classified into four groups, according to their guidance pattern: signage-based evacuation scheme, leader-based evacuation scheme, ME-based evacuation scheme, and WSN-based evacuation scheme (see Fig. 2). This section describes these different types of land-based indoor evacuation schemes.

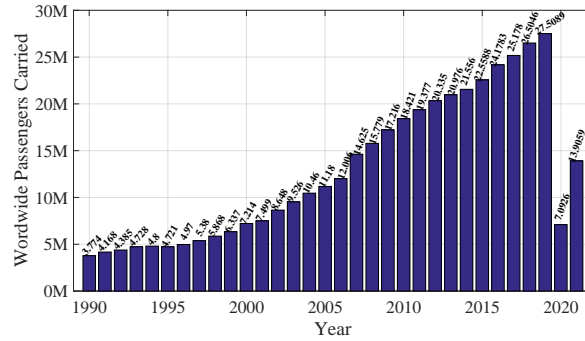


Figure 1: Worldwide passengers carried from 1990 to 2021

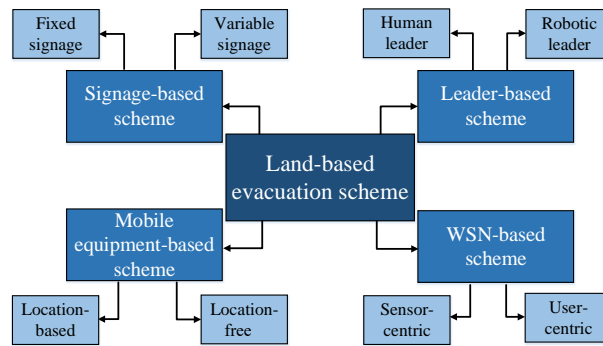


Figure 2: Different types of crowd evacuation schemes

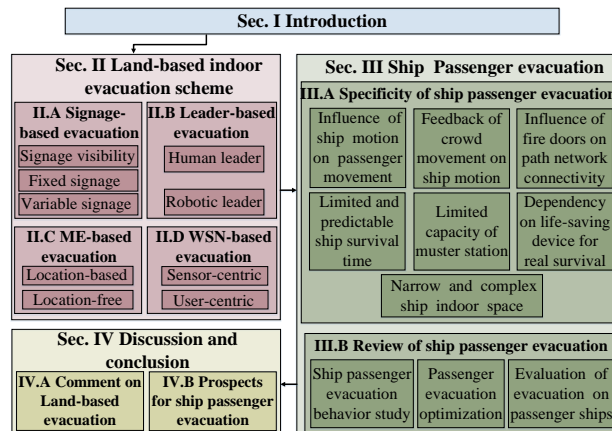


Figure 3: Organization of this paper

2.1. Signage-based evacuation scheme

Signage systems are widely applied to large buildings such as urban rail transit stations, office buildings, and supermarkets. As a sort of way-finding facility, the signage system does not only provide guidance to occupants who are unfamiliar with the layout of the building in normal situations, it also can offer safety information for evacuees in case of emergencies. Many studies have shown that the arrangement of signage is a feasible way to improve the efficiency of an emergency evacuation in most situations (Tang et al., 2009; Liu et al., 2011; Ronchi et al., 2012; Wang

Table 1
Crowd Evacuation with Static Signage

Related work	Year	Optimization objective	Technique	Algorithm/Model	Scenario
(Chen et al., 2009)	2009	Sign location	MCLP	Lagrangian relaxation algorithm	Single-floor supermarket
(Chu and Yeh, 2012)	2012	Sign location and number	MCLP with side constrains	Visibility graph	A transportation terminal
(Motamedi et al., 2017)	2017	Sign location	Simulation	Grid-based model	SenriChuo station, A 440 m ² rectangle area
(Zhou et al., 2020)	2020	Sign location	Simulation	SF model	Beijing Subway Station
(Yuan et al., 2018)	2018	Mixed layout of WS and GS	Simulation	SF model	A smoky hall

et al., 2014b; Cosma et al., 2016). Based on the response to contemporary evacuation situations, the existing signage-based evacuation system can be divided into fixed signage-based and variable signage-based guidance. The former is predetermined and cannot vary with the status of hazards and congestion, while the latter can respond to dynamic emergency conditions. This section presents a thorough review of the above-mentioned signage-based evacuation scheme.

2.1.1. Fixed signage-based evacuation scheme

The majority of existing signage-based evacuation schemes utilize static signs to provide stabilized guidance to evacuees unfamiliar with the building environment. Table 1 summarizes the previous work on crowd evacuation with static signs. Chen *et al.* formulated the location optimization for evacuation signs as a maximal-coverage location problem (MCLP) (Chen et al., 2009). Results showed that the proposed guidance arrangement scheme improved evacuation efficiency. However, it is not effective to simply optimize signage placement based on sign locations and visibility while ignoring the associated evacuation routes. Chu *et al.* found the position of signs that maximized coverage and constituted connected shortest paths by solving a maximum-coverage problem with side constraints (Chu and Yeh, 2012).

In addition, many researchers used simulations to reach efficient signage placement. Motamedi *et al.* utilized a Building Information Model (BIM) and a grid-based game engine to simulate the movement of pedestrians. Then the efficiency of the signage system design was investigated and optimized (Motamedi et al., 2017). Based on an improved social force model (SF), Yuan *et al.* proposed a mixed layout scheme of wall signs (WS) and ground signs (GS) with high evacuation efficiency in fire smoke (Yuan et al., 2018). Zhou *et al.* incorporated a perception probability model that quantified the probability pedestrians could notice and comprehend signs into a modified SF model to investigate crowd evacuation dynamics under the effects of different signage distribution schemes (Zhou et al., 2020).

2.1.2. Variable signage-based evacuation scheme

Since fixed signage cannot respond to the contemporary population density, it would more likely result in heavy congestion. Moreover, static guidance could also lead to pedestrians' frequent oscillations when hazards are on the evacuation routes predetermined by the fixed signs. Variable evacuation signage systems where signs change according to hazard status and pedestrian flow have attracted many researchers' attention in recent years (Table 2 and Table 3). A series of studies have proved the effectiveness of the dynamic signage system. Hui *et al.* conducted experimental trials to test the comprehensibility and effectiveness of variable signs (Hui et al., 2014; Galea et al., 2017b,a). Considering the high cost of field experiments, Olyazadeh *et al.* exploited virtual environments (VEs) and questionnaires to investigate and evaluate dynamic signage for emergency evacuation (Olander et al., 2017; Galea et al., 2017a; Olyazadeh, 2013; Langner and Kray, 2014; Lin et al., 2017).

Some works take into account the effect of evolving emergencies and depend on the periodic recalculation of guidance information provided by signs to keep occupants safe (Veichtlbauer and Pfeiffenberger, 2011; Wang et al., 2008; Sharma et al., 2018; Luh et al., 2012; Cho et al., 2015a). Complying with the variable guidance, pedestrians can avoid hazardous areas and go out of the building with highest probability. However, frequent change in sign indications may cause possible confusion and reduce the credibility of guidance information disseminated by the signs. Wang *et al.* proposed that guidance should only be updated when emergency status varied significantly, as determined by emergency responders' subjective judgements (Wang et al., 2009). Desmet *et al.* scheduled the dynamic pointing

Table 2
Evaluating Crowd Evacuation with Variable Signage

Related work	Year	Evaluation goal	Technique	Technique description	Scenario	Participant
(Hui et al., 2014)	2014	Comprehensibility and Detectability	Survey, Experiment	An international web based survey, Field experiment	Queen Anne building	68
(Olyazadeh, 2013)	2013	Response time to dynamic signs, Effectiveness of exit signs, Realism of VR experiment	Experiment, Questionnaire	Immersive video environment	Three back projected wall (140 degree)	10
(Lin et al., 2017)	2017	Effectiveness in evacuating through emergencies	Simulation	Agent-based model	Underground parking lot	110
(Langner and Kray, 2014)	2014	Impact on Mass Evacuation	Simulation	SF model	SC Preußen 06 e. V.	12,500
(Olander et al., 2017)	2017	Impact on effectiveness of dissuasive exit signage	Questionnaire	Theory of affordances	An egress door within a virtually simulated office	46
(Galea et al., 2017a)	2017	Effectiveness of ADSS, Most effective signage type	Experiment, Survey	An international web based survey, Field experiment	A rail station	200
(Galea et al., 2017b)	2017	Effectiveness of improved ADSS	Experiment	Field experiment	Sant Cugat station	139

Table 3
Optimizing Crowd Evacuation with Variable Signage

Related work	Optimization goal	Method	Method description	Validation
(Cho et al., 2015b)	Shortening safe egress	Dijkstra algorithm	Reverse and simplify start and end nodes of Dijkstra algorithm by adding a virtual node	Simulation
(Luh et al., 2012; Wang et al., 2008, 2009)	Mitigating blocking	Divide-and-conquer	Dynamic programming method for each group subproblem, Lagrangian relaxation framework for Inter-group coordination	Numerical example, Simulation
(Chu et al., 2017)	Reducing evacuation time	Bi-level optimization	FFCA for lower-level problem, DOT algorithm for upper-level problem	Numerical example
(Sharma et al., 2018)	Supporting real-time reactive signage, Extensible, Energy-efficient, Scalable	DSS-SL	SDN forwarding devices, LED-based visible light communication scheme	–
(Desmet and Gelenbe, 2014)	Reducing evacuation time	Capacity-reservation algorithm	CPN, CCRP	Simulation

directions of signage according to a capacity-reservation routing algorithm. Future capacity reservations can effectively forecast congestion and then assist subsequent path assignment (Desmet and Gelenbe, 2014). Chu *et al.* proposed a bi-level optimization approach to determine variable pedestrian evacuation guidance in buildings with convex polygonal interior spaces (Chu et al., 2017). The lower-level model utilized a modified floor field cellular automata model (FFCA) to predict congestion and passed the prediction to the upper-level model which used a decreased order of time (DOT) algorithm to calculate variable guidance.

2.2. Leader-based evacuation scheme

Many studies have proved that the staffing of trained evacuation leaders with complete knowledge of the layout of a building can guide evacuees to expected exits and significantly reduce the casualties (Spartalis et al., 2014; Yang et al., 2014; Wang et al., 2015b; Ma et al., 2017; Li et al., 2016; Yang et al., 2015; Vihás et al., 2012; Zhou et al., 2019b).

2.2.1. Human leader-based evacuation scheme

A trained human leader can issue guidance information and spread positive emotion. Over the past decades, several follow-the-leader evacuation models (e.g., SF model (Fig. 4a), vector field model (VF) (Fig. 4b), multi-grid model (Fig. 4c), and cellular automata model (CA) (Fig. 4d)) have been proposed, which can be used in leader effect understanding and leader distribution optimization (Table 4 and Table 5).

Utilizing an extended dynamic communication field model (DCF), Wang *et al.* found the centripetal effect of evacuation assistants (Wang et al., 2015b). Yang *et al.* proposed a modified SF model to simulate guided crowd

evacuation dynamics. Some phenomena, for example, pedestrians following the leader can escape with a faster velocity than those walking independently, were observed in the simulation results (Yang et al., 2014). Based on a CA-based model, Spartalis *et al.* discovered that a trained leader could not only trigger herding formations of crowds but activate alternative routes, which decreased congestion levels in specific passages and exits (Spartalis et al., 2014; Vihás et al., 2012). However, the effects of the staffing of guides are not always positive. Ma *et al.* found the dual effect of guides on pedestrian evacuation under limited visibility via an extended SF model (Ma et al., 2017). On the one hand, a few guides could already facilitate pedestrian evacuation when the neighbor density within the visual field was moderate. On the other hand, when the neighbors within the visual field were too many or too few, the effect of guides was usually negative.

Evacuation performance strongly correlates with the distribution and action of guiders. Yuan *et al.* proved the impact of the number of guiders on evacuation by using a CA-based model (Yuan and Tan, 2009). Hou *et al.* discovered that for evacuation under a single-exit scenario, only one or two leaders could exert a remarkable impact, while more leaders are expected for configurations with multi-exits (Hou et al., 2014). Wang *et al.* optimized the position of leaders while minimizing their number and observed that except for the distribution of leaders, other factors such as the number of evacuees guided by a leader, the visibility range of environments, and the leaders' speeds significantly affect evacuation efficiency (Wang et al., 2012; Zhang et al., 2021; Wang et al., 2015c, 2016). In addition, Cao *et al.* did not only derive the appropriate distribution of leaders but also optimized their guidance strategy (Cao et al., 2016; Zhou et al., 2019a; Yang et al., 2013).

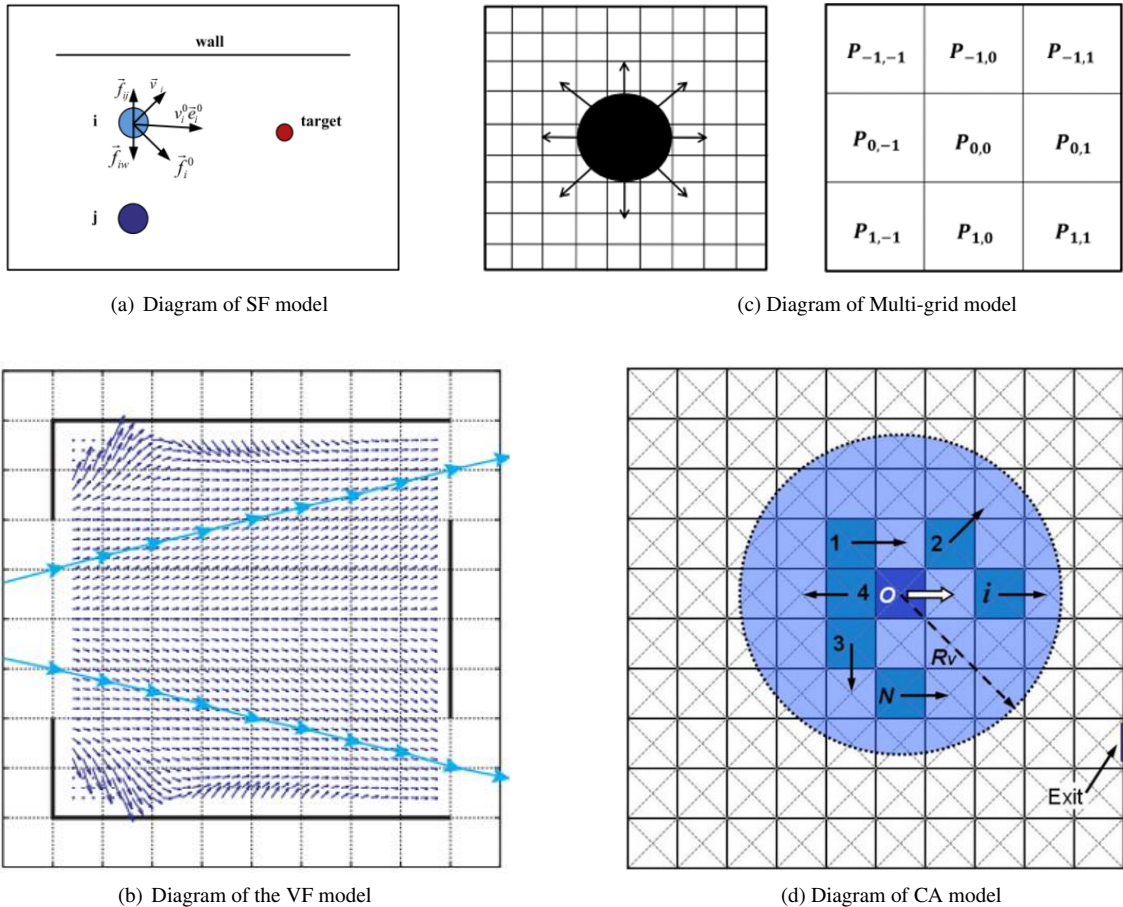


Figure 4: Diagram of classical follow-the-leader evacuation model (Yuan and Tan, 2009; Okada and Ando, 2011; Cao et al., 2016; Yang et al., 2014).

Table 4

The effect of human leader on crowd evacuation

Related work	Year	Model	Scenario	Exit number	Exit size
(Spartalis et al., 2014)	2014	CA model	20 m×30 m retirement house	Three	0.8 m, 1.2 m
(Yang et al., 2014)	2014	SF model	50 m×50 m room	One	1 m
(Li et al., 2016)	2016	Trace Model	Indoor classroom	Two	–
(Vihas et al., 2012)	2012	CA model	A two-dimensional space with 17 sectors, a cubic space with 4 sectors	–	–
(Wang et al., 2015b)	2015	Extended DCF model	26 m ×26 m room	One	0.8 m
(Ma et al., 2017)	2017	SF model	15 m×15 m room	One	4 m
(Zhou et al., 2019b)	2019	SF model	Beijing's urban rail transit station	Three	3.4 m

Table 5

The influencing factors of human leader-based evacuation

Related work	Year	Model	Influencing factor	Scenario	Exit number	Exit size
(Okada and Ando, 2011)	2011	VF model	Location, number	A room	Two	–
(Ma et al., 2016)	2016	SF model	Location, number, visibility, distribution range of evacuees	20 m×20 m room	One	1 m-20 m
(Yuan and Tan, 2009)	2009	CA model	Visibility, number	20 m × 20 m room	One	2 m
(Wang et al., 2012)	2012	CA model, CF model	Location, number	26 m ×26 m room	One	0.4 m
(Hou et al., 2014)	2014	SF model	Location, number, velocity, visibility	20 m ×20 m room	One, two, four	2 m
(Cao et al., 2016)	2016	Multi-grid model	Guidance strategy, guider type, number and distribution	20 m×10 m room	Two	1 m
(Wang et al., 2015c)	2015	CA model, CF model	Walking speed, information transmission radius	26 m ×26 m room	One	0.8 m
(Yang et al., 2015)	2015	SF model	Location, number	50 m × 50 m room	One	1 m
(Wang et al., 2016)	2016	Multi-Information CF model	Sensing radius	0.4 m×10 m T-shaped channel, 2 m×24 m T-shaped channel	Two	2 m
(Yang et al., 2013)	2013	Multi-agent model	Guiding route	80×80 area	Three	Radius 15, 10, 5
(Zhou et al., 2019a)	2019	Hybrid bi-level model	Location, number, route	Beijing's urban rail transit station	Three	3.4 m
(Zhang et al., 2021)	2021	E-AECM	Location	Spring city square of Jinan	–	–

2.2.2. Robotic leader-based evacuation scheme

Human leaders may arrive at the emergency site too late to assist crowd evacuation. In addition, they cannot be sent to guide evacuees out in some accidents like nuclear leakage because of security concerns. In such cases, the usage of robotic leaders could be attractive. Many simulators have been used to model robots and crowds to demonstrate the effectiveness of using robots for aiding emergency evacuations (Sakour and Hu, 2017).

Earlier works focused on indirectly evacuating evacuees utilizing autonomous robots, not involving human-robot interaction (Shell and Matari C., 2005; Ferranti and Trigoni, 2008). Shell *et al.* described a multi-robot-based navigational aid deployment strategy with which a network of directional audio aids can be deployed automatically following an emergency with the assistance of a team of robots (Shell and Matari C., 2005). Ferranti *et al.* devised two robot-assisted evacuation route discovery (ERD) mechanisms, namely Agent-to-Tag-ERD and Tag-to-Tag-ERD, with which robots can search for the shortest evacuation routes as soon as possible in parallel with their exploration of an unknown hazardous area (Ferranti and Trigoni, 2008).

Recently, the improvement in the trust in human-robot interaction makes it possible to guide occupants directly using emergency evacuation robots. Kim *et al.* designed a portable fire evacuation guide robot that can be thrown into fire scenes to explore the information about environmental conditions and trapped occupants, which would be transmitted to firefighters to determine a guide strategy that could be broadcast through the microphone and speaker system on the robot (Kim *et al.*, 2009). Robinette *et al.* devised robots incorporating a model of human panic behavior to navigate evacuees safely to appropriate exits (Robinette and Howard, 2011). The above-mentioned robot-assisted

evacuation systems require control and decision support from human operators. With the advance in integration techniques and computing power, robots can evacuate occupants independently. Jiang *et al.* presented an adaptive dynamic programming approach (ADP) to control the motion of a robot for a desirable collective velocity (Jiang *et al.*, 2017). Boukas *et al.* trained the intelligent emergency evacuation robots to attract evacuees heading towards saturated exits and redirect them to less blocked ones to ensure a faster and safer evacuation (Boukas *et al.*, 2015; Tang *et al.*, 2016; Wan *et al.*, 2020; Zhang and Guo, 2015; Garrell *et al.*, 2009).

2.3. ME-based evacuation scheme

Typical ME for assisting crowd evacuation includes smartphones and Augmented Reality (AR) headsets. This kind of equipment can present more useful and intuitive evacuation information than that provided by traditional techniques based on audio alarms and paper maps. In addition, with the fast development of AR and Virtual Reality (VR) technology, AR/VR-based wearable hardware such as the wireless head-mounted display (HMD) has been introduced to study human evacuation behavior and train occupants. Using HMD-based VR experiments, Feng *et al.* investigated the response of evacuees to different types of information (e.g., crowd flow and exit signs) (Feng *et al.*, 2021; Lin *et al.*, 2020). Lin *et al.* examined the effect of repeated exposures to indoor environments on people's indoor wayfinding performance (Lin *et al.*, 2019). In addition, Lovreglio *et al.* trained occupants to cope with emergencies in an earthquake or fire by using VR-based simulators (Lovreglio *et al.*, 2018; Xu *et al.*, 2014).

Based on the dependency on the pre-knowledge of user locations, the ME-based evacuation schemes are classified into two categories: location-based and location-free evacuation schemes using ME (Table 6). This section presents the review of the two schemes.

2.3.1. Location-based evacuation scheme using ME

Most of the existing ME-based evacuation schemes rely on the availability of location information on each user. Ikeda *et al.* exploited the built-in Global Positioning System (GPS) function to provide the position of smartphones (Ikeda and Inoue, 2016; Iizuka and Iizuka, 2015; Wada and Takahashi, 2013; Fujihara and Miwa, 2012). But it is challenging to receive satellite signals within a modern building. Therefore other location awareness systems become necessary for location-based indoor evacuation using ME. Chen *et al.* proposed that the location of each person can be periodically detected by his/her smartphone through signal strength-based localization or infrastructure-based positioning (e.g., radio-frequency ID (RFID) and iBeacon) (Chu, 2010; Nadalutti and Chittaro, 2008; Chittaro and Nadalutti, 2008; Chen *et al.*, 2015; Chu and Wu, 2011; Shin *et al.*, 2011). Gelenbe *et al.* identified evacuees' positions by the camera or sensors built in smartphones or AR headsets (Gelenbe and Bi, 2014; Zhang *et al.*, 2020c; Ahn and Han, 2011; Stigall and Sharma, 2017). In addition, Mulloni *et al.* exploited activity-based instructions to guide users from one info point to the next (Mulloni *et al.*, 2011). In this system, only sparse 3D localization at selected info points in a building is necessary.

2.3.2. Location-free evacuation scheme using ME

The location information may not always be available in many realistic situations where emergency guidance is needed. Zheng *et al.* designed Peer-to-Peer (P2P) navigation systems on mobile phones, which enabled efficient navigation without resorting to pre-deployed location service and the availability of indoor maps (Zheng *et al.*, 2017; Shu *et al.*, 2015; Dong *et al.*, 2019; Zhang *et al.*, 2020b; Yin *et al.*, 2016). In this kind of system, guiders recorded their traces in a variety of forms (e.g., pathway images, geomagnetic fields, or WiFi signals) and transmitted them to followers so that they could get prompt path instructions through their phones. However, P2P mode suffers from path deficiency in large complex indoor scenarios, which significantly hampers its application. Teng *et al.* merged the paths of different guiders into a global map by introducing a crowdsourcing scheme (Teng *et al.*, 2019; Li *et al.*, 2020; Pan and Li, 2019; Dong *et al.*, 2020).

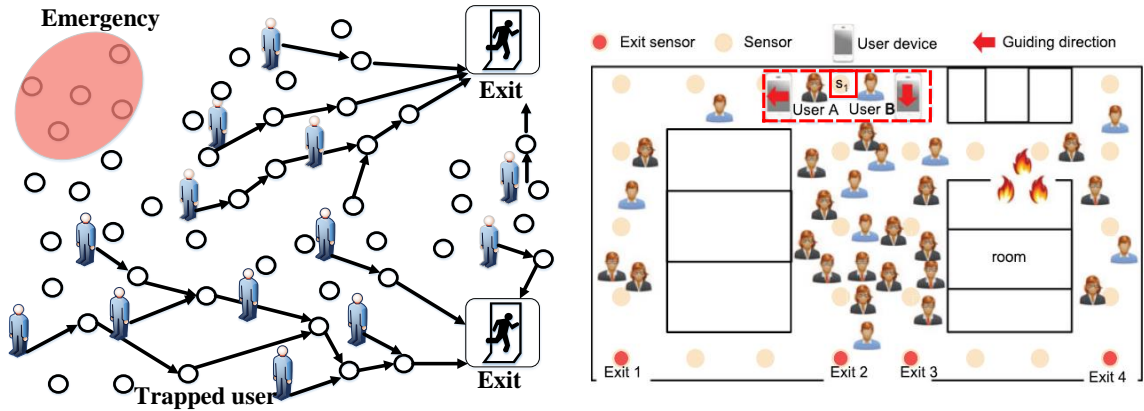
2.4. WSN-based evacuation scheme

WSN is a natural choice for supporting emergency evacuation, given the ubiquitous sensing and communication capability. Previous researches verified the effectiveness of WSN-assisted guiding mechanisms using simulations and real test-bed implementation approaches (Ahmed *et al.*, 2015; Yin, 2015; Lung *et al.*, 2016; Stigen, 2019). Fig. 5 shows the typical WSN-assisted emergency evacuation system. A number of sensor nodes are deployed in a building to monitor the time-varying environmental conditions, calculate guiding paths and send them to nearby evacuees equipped with radio modules. Existing WSN-assisted evacuation schemes can be divided into two classifications:

Table 6: Crowd evacuation with ME

Source	Location-based	Localization technique	Track-based	Tracking technique	Floor plan-based	Central sever-based	Optimization objective	Capacity aware	Clustering aware
(Iizuka and Iizuka, 2015; Wada and Takahashi, 2013)	✓	GPS	×		✓	×	Evacuation time	×	×
(Fujihara and Miwa, 2012)	✓	GPS	×		✓	×	Evacuation time	✓	×
(Ikeda and Inoue, 2016)	✓	GPS	×		✓	✓	Evacuation time	×	×
(Gelenbe and Bi, 2014)	✓	Built-in camera	×		✓	✓	Survival rate	×	✓
(Diao and Shih, 2018; Zhang et al., 2020c)	✓	Built-in camera	×		✓	✓	Evacuation time	×	×
(Stigall and Sharma, 2017)	✓	Built-in camera	×		✓	✓	Evacuation distance	×	×
(Ahn and Han, 2011)	✓	Built-in sensors	×		✓	✓	Evacuation time	×	×
(Chen and Chung, 2017; Chen and Liu, 2021)	✓	iBeacon	×		✓	✓	Evacuation time	✓	✓
(Fujihara and Yanagizawa, 2015)	✓	iBeacon	×		✓	×	True positive detection rate of guidance	×	×
(Mulloni et al., 2011)	✓	Info points	×		✓	×	Evacuation distance	×	×
(Fujihara and Miwa, 2012)	✓	Wi-Fi	×		✓	×	Evacuation time	✓	×
(Chen et al., 2015)	✓	RFID, iBeacon, RSSI-based	×		✓	✓	Evacuation time	✓	×
(Chu, 2010)	✓	NFC, RFID	×		✓	✓	Evacuation time	×	×
(Nadalutti and Chittaro, 2008; Chittaro and Nadalutti, 2008)	✓	RFID	×		✓	×	Navigation error, stops	×	×
(Chu and Wu, 2011)	✓	RFID	×		✓	✓	Distance, congestion, temperature	✓	×
(Inoue et al., 2008)	✓	Radio beacon	×		✓	✓	Evacuation distance	×	×
(Zheng et al., 2017)	×		✓	Image, IMU, WiFi	×	×	Spatial error, energy saving, path distance	×	×
(Shu et al., 2015)	×		✓	IMU	×	×	Spatial error, energy saving	×	×
(Zhang et al., 2020b; Yin et al., 2016)	×		✓	WiFi, IMU	×	×	Spatial error, deviation detection time	×	×
(Dong et al., 2019)	×		✓	Visual SLAM	×	×	Navigation success rate	×	×
(Li et al., 2020)	×		✓	WiFi, IMU	×	×	Space error	×	×
(Dong et al., 2020)	×		✓	Visual SLAM	×	✓	Navigation success rate, space error	×	×
(Pan and Li, 2019)	×		✓	IMU, iBeacon	×	✓	Navigation distance, navigation deviation, notification delay	×	×
(Teng et al., 2019)	×		✓	Point clouds, IMU	×	✓	Tracking error, navigation success rate	×	×

the sensor-centric guiding scheme (Fig. 5 (a)) and the user-centric guiding scheme (Fig. 5 (b)). This section reviews the two types of evacuation schemes.



(a) A typical sensor-centric evacuation scheme using WSN (Wang et al., 2017). (b) A typical user-centric evacuation scheme using WSN (Wu, 2017).

Figure 5: The typical sensor-centric and user-centric evacuation scheme using WSN (Wang et al., 2017). In (b), sensor s_1 can provide different guiding directions for the User A and User B even though both of them are located nearby s_1 .

2.4.1. Sensor-centric evacuation scheme

In sensor-centric scheme, all people associated with the same sensor are provided with the same direction. Table 7 summarizes previous work on evacuation with WSNs. Some research assumed the availability of global knowledge about path topology and used global exhaustive search algorithms to determine optimal guiding routes. Buragohain *et al.* carried out a Breadth-First-Search (BFS) to calculate an optimal path. In addition, in order to reduce communication expenses, an adaptive skeleton graph was constructed in a distributed fashion (Buragohain *et al.*). Filippoupolitis *et al.* used the Dijkstra algorithm to calculate the path with the minimum effective length (Filippoupolitis and Gelenbe, 2009). Wang *et al.* proposed a novel metric of path planning named Expected Number of Oscillations (ENO) to quantify the dynamics of emergency. Based on ENO information, the path minimizing the probability of oscillation was found using a global exhaustive search algorithm (Wang *et al.*, 2014a). Chen *et al.* provided the fastest routes for people to reach exits based on the evacuation time estimated by an analytical model that took into account corridor capacity and length, exit capacity, and concurrent movement and distribution of people (Chen *et al.*, 2012b). Shen *et al.* employed the dinic Algorithm to provide evacuees with navigation service, which reduced congestion and increased the evacuated ratio in a short time (Shen *et al.*, 2011).

Instead of global search, Tseng *et al.* executed path planning based on local search algorithms (Tseng *et al.*, 2006; Zhou *et al.*, 2012; Chen *et al.*, 2012a; Wang *et al.*, 2017, 2013, 2015a; Li *et al.*, 2003; Chen *et al.*, 2011, 2008; Pan *et al.*, 2006; Chen *et al.*, 2016b; Park and Corson, 1997; Pooja *et al.*, 2019). Wang *et al.* computed an artificial potential field for the corresponding state to generate optimal guiding direction (Wang *et al.*, 2017; Li *et al.*, 2003; Chen *et al.*, 2008, 2011; Pooja *et al.*, 2019). Chen *et al.* assigned sensor nodes temporally ordered sequence numbers to construct a directed navigation graph in a localized manner (Tseng *et al.*, 2006; Chen *et al.*, 2012a; Zhou *et al.*, 2012; Chen *et al.*, 2016b; Park and Corson, 1997; Pan *et al.*, 2006). Wang *et al.* sought for a global or local topological structure as a public infrastructure to provide navigation information for internal queries, through which unnecessary overhead of individually path planning is avoided (Wang *et al.*, 2015a, 2013).

2.4.2. User-centric evacuation scheme

The user-centric guiding system provides navigation directions for each individual user rather than for each sensor. As shown in Fig. 5 (b), the sensor s_1 can provide different guiding directions for User A and User B even though both of them are nearby s_1 . The user-centric evacuation scheme relaxes the constraint on the number of guiding directions provided by a single sensor, which opens up more opportunities to optimize overall evacuation time. Wu *et al.* proposed a localized user-centric guiding protocol where the overall evacuation time is minimized with the consideration of the effect of hazards and the limited capacity of a certain sensor at a certain time slot (Wu, 2017).

Table 7
Crowd evacuation with WSNs

Related work	Location-based/Location-free	Global/Local search	Method	Congestion-aware	Path metric
(Buragohain et al.)	Location-based	Global	BFS	×	Path length
(Shen et al., 2011)	Location-based	Global	Dinic algorithm	✓	Evacuation time
(Wang et al., 2014a)	Location-free	Global	OPEN	×	ENO
(Chen et al., 2012b)	Location-based	Global	TORA	✓	Evacuation time
(Pan et al., 2006; Tseng et al., 2006; Chen et al., 2012a; Park and Corson, 1997)	Location-based	Local	TORA	×	Path length
(Zhou et al., 2012; Chen et al., 2016b)	Location-based	Local	TORA	✓	Evacuation time
(Filippopolitis and Gelenbe, 2009)	Location-based	Global	Dijkstra algorithm	×	Effective length
(Li et al., 2003)	Location-free	Local	Artificial potential field	×	Distance to dangers
(Chen et al., 2008)	Location-based	Local	Artificial potential field	✓	Evacuation time
(Chen et al., 2011)	Location-free	Local	Artificial potential field	✓	Evacuation time
(Wang et al., 2017; Pooja et al., 2019)	Location-free	Local	Artificial potential field	✓	Distance to dangers
(Wang et al., 2015a)	Location-free	Local	Level set method	✓	Congestion level, Path length
(Wang et al., 2013)	Location-free	Local	Road map	×	Distance to dangers

3. Ship passenger evacuation

The consequences of an accident could be destructive for passenger ships, especially for luxury cruises. For example, thirty-two people were killed when the Costa Concordia capsized in 2012. In case of such a catastrophe, an appropriate evacuation strategy should be applied to reduce casualties. The land-based indoor evacuation approaches mentioned in Section II cannot be used directly to guide evacuees on passenger ships due to the specificities of ships' internal structure and passengers' behavior during evacuation. Compared with the mature land-based indoor evacuation, the research on evacuation on passenger ships is relatively limited and mainly focuses on three aspects from the view of intentions: 1) Investigation of the likely evacuation behavior of passengers; 2) Optimization of passenger evacuation for decreasing casualties; 3) Evaluation of evacuation on passenger ships. This section first presents the latest guideline on evacuation analysis for passenger ships, issued by International Maritime Organization (IMO), and then analyze the unique characteristics of ship passenger evacuation. Finally, a survey of existing research efforts on the evacuation of passenger ships is given.

3.1. Evaluation of the IMO guideline on ship evacuation

The international regulation "Safe Return to Port " specifies the design criteria that guarantee the return of the ship to the port when a casualty occurs. In such a case, passengers should move to the so-called Safe Areas. If the given threshold of damage is exceeded, it is necessary to abandon the ship and evacuate passengers to survival crafts. In both cases, the evacuation analysis must be performed. The latest guidelines concerning evacuation analysis for passenger ships are dictated by IMO in MSC.1/Circ.1533 (IMO, 2007). The guidelines allow evacuation analysis by either the simplified or the advanced method. The simplified analysis is based on a macroscopic model, treating passengers as the fluid that runs through corridors and stairs as if they are tubes. In this sort of analysis, the geometry of doorways, stairs and corridors, and the initial density of passengers are considered to calculate the total evacuation duration and identify the possible bottlenecks (Nasso et al., 2019). The advanced method simulates individual passengers, taking into account the particular features of passengers, such as the walking speed and the reaction time to an emergency. In this method, IMO-certified software (e.g., EVI and AENEAS), based on VR, is used to calculate the travel duration, including the response duration.

The regulations on safe return to port and evacuation analysis are of primary importance in the early stage of design for passenger ships to upgrade the intrinsic ship safety in event of casualties. In addition, these regulations provide standard scenarios and indexes for the evaluation of ship evacuation systems. The performance of a proposed ship evacuation scheme should be evaluated in day and night scenarios, in which the initial distribution of passengers on board is different. The evacuation performance of a scheme should be measured in terms of the traversal time required for passengers to arrive at the Safe Areas when it is assumed that the accident does not exceed a fixed threshold. Otherwise, it should be measured by the duration until the launch of survival crafts.

3.2. Specificity of ship passenger evacuation

Based on the analysis of maritime accident investigation reports and case studies, as well as the data collection on a real passenger ship, this section describes the specificities of the evacuation environment and crowd behaviors during the emergency evacuation on passenger ships.

3.2.1. The influence of ship motion on passenger movement

The movement pattern of passengers on board is significantly different from that on the static ground because of the effect of ship inclination and motion. Many simulations and experiments have been performed to quantify the influence of ship inclination or motion on pedestrian speed. Fig. 6 presents the speed reduction data due to ship inclination from various international research projects (i.e., Fleet Technology Limited (FTL) and Fire Safety Engineering Group (FSEG) in the University of Greenwich, Research Institute of Marine Engineering of Japan (RIME) and National Maritime Research Institute of Japan (NIMR), Korea Research Institute of Ship and Ocean Engineering (KRISO), the Netherlands Organization for Applied Scientific Research (TNO), Australian Maritime Engineering Cooperative Research Centre (AME CRC), TraffGo HT GmbH using evacuation software AENEAS, and the Skate Key Laboratory of Fire Science in the University of Science and Technology of China (SKLFS)). In addition, Valanto *et al.*, by means of evacuation software AENEAS, presented speed reduction factors in laterally and longitudinally tilted staircases as the function of ship inclination angle (see Equations (2)-(4)) (Valanto, 2006). ϕ denoted the slope angle; r_{trans} indicated the reduction factor in laterally tilted staircases; r_{longu} and r_{longd} were reduction factors when walking up and down longitudinally tilted staircases, respectively. Sun *et al.* exploited a ship corridor simulator to investigate the effect of heeling and trim on individual walking speed and group walking speed, respectively (Sun *et al.*, 2018a,b). Chen *et al.* investigated the coupled-forced pedestrian movement features as a result of ship swaying using an agent-based pedestrian model (Chen *et al.*, 2016a). Wang *et al.* carried out a series of walking experiments on a real ship to quantitatively evaluate the effect of different rolling angles on individual walking speed both on flat terrains and staircases (Wang *et al.*, 2021a).

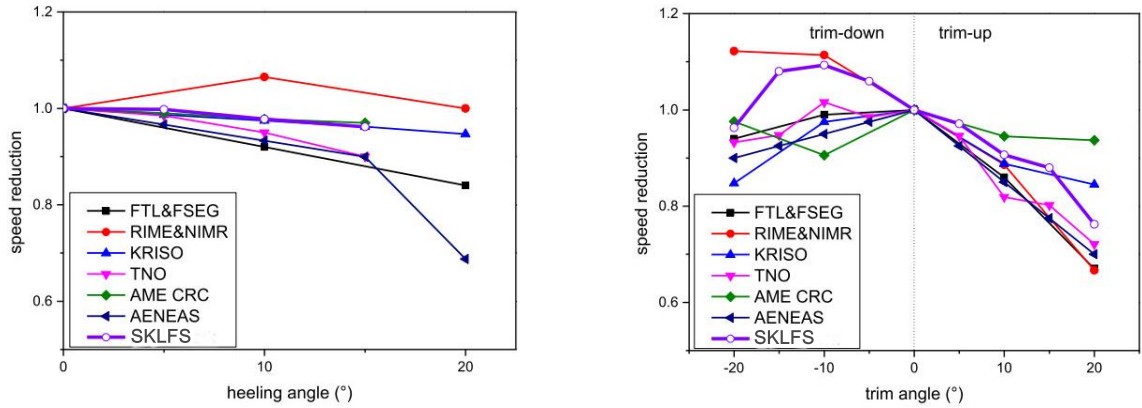
$$r_{\text{trans}} = \begin{cases} -0.005\phi + 1 & 0^\circ \leq \phi < 20^\circ \\ -0.085\phi + 2.6 & 20^\circ \leq \phi < 30^\circ \\ 0.05 & 30^\circ \leq \phi \leq 40^\circ \\ 0 & 40^\circ < \phi \end{cases} \quad (1)$$

$$r_{\text{longu}} = \begin{cases} 0 & \phi < -45^\circ \\ 0.038\phi + 1.76 & -45^\circ \leq \phi < -20^\circ \\ 1 & -20^\circ \leq \phi < 0^\circ \\ -0.015\phi + 1 & 0^\circ \leq \phi \leq 20^\circ \\ -0.065\phi + 2 & 20^\circ \leq \phi < 30^\circ \\ 0.05\phi + 2.1 & 30^\circ \leq \phi \leq 45^\circ \\ 0 & 45^\circ < \phi \end{cases} \quad (2)$$

$$r_{\text{longd}} = \begin{cases} 0 & \phi < -45^\circ \\ 0.05 & -45^\circ \leq \phi < -30^\circ \\ 0.065\phi + 2 & -30^\circ \leq \phi < -20^\circ \\ 0.015\phi + 1 & -20^\circ \leq \phi < 0^\circ \\ 1 & 0^\circ \leq \phi < 15^\circ \\ -0.032\phi + 1.48 & 15^\circ \leq \phi \leq 45^\circ \\ 0 & 45^\circ < \phi \end{cases} \quad (3)$$

3.2.2. The feedback of crowd movement on ship motion

Crowd movement, in turn, can affect the motion of a ship. On September 26, 2002, MV Le Joola capsized off the coast of The Gambia with 1,863 deaths (Rothe *et al.*, 2006). The ship was submerged in just five minutes. According to the analysis of the relative maritime accident investigation reports, it is found that lopsided crowd movement is one of



(a) Speed reduction as a function of transverse slope in a corridor (b) Speed reduction as a function of longitudinal slope in a corridor

Figure 6: Speed reduction data under different situations from various international research projects

the main reasons for such fast sinking, which dramatically decreased the allowable evacuation time. There were about five hundred passengers on the upper deck before the disaster occurred, which ascended the ship's center of gravity and thus reduced ship stability. It was, therefore, more vulnerable to severe weather and sea states. Moreover, passengers on the upper deck swarmed to the port side to avoid storms from the starboard side, which undeniably accelerated the capsizing of MV Le Joola. The sinking of Phoenix PC Diving also revealed that it was critical for an evacuation scheme to take into account the feedback of crowd movement on ship motion. When danger arose, passengers on Phoenix PC Diving stampeded to the starboard side, which sped up the ship's overturning. Within only three minutes, it sank in the ocean near Phuket, Thailand, causing 47 deaths (Chen, 2021).

3.2.3. The influence of fire doors on path network connectivity

Fire doors with different fire resistance ratings are installed to reduce the spread of fire and smoke between separate components of a passenger ship to enable safe egress from a vessel (Perez Villalonga, 2005). Certain fire doors on vessels are hidden in normal situations and can be closed in the event of a fire, which is different from the fire doors in general buildings. Once the fire door is closed, it can only be opened from one side of the door. That is to say, certain corridors on vessels are unidirectionally passable due to the existence of fire doors, which makes the evacuation scenario on a passenger ship distinguishing. In addition, it takes a certain amount of time to open the fire doors, so the calculation of the traversal time on the related passageways is different from common ones.

3.2.4. Limited and predictable ship survival time

A passenger ship is required to have sufficient hydrostatic stability to survive certain damage cases. However, the required stability cannot guarantee the survival of the ship in all cases, especially if the accident takes place in unfavorable weather conditions or sea states. In such cases, the survival time until capsizing for the ship is limited. In order to survive, passengers must flee from the damaged ship within the limited ship survival time. The value of ship survival time depends on the loading condition of a vessel, the type, location, and extent of damage, and the probable weather condition and sea state in an operation area. Valanto *et al.* determined a method to estimate the survival time (Valanto, 2006). Firstly, when the significant wave height is great than or equal to 4.5 m, the survival time can be obtained with the help of the numerical simulation of ship motion. Fig. 7 shows some typical examples of simulated ship roll motion until capsizing, where angle 30° is considered as the capsizing criterion. The estimation of the survival time for the significant wave height lower than 4.5 m using numerical simulation is very ineffective in terms of computation time. In such cases, the survival time can be extrapolated with the following formula:

$$T_c = T_s \times e^{A + \frac{B}{h^2}} \quad (4)$$

where T_c represents the survival time of a vessel. T_s and h indicate the significant wave period and height, respectively. The constants A and B can be calculated by numerical simulation for higher wave height with the same wave period.

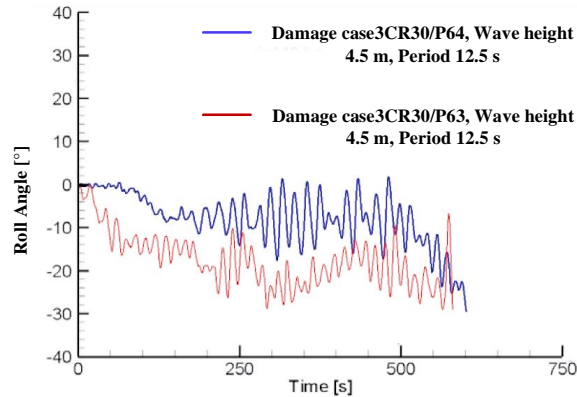


Figure 7: Typical examples of simulated ship roll motion until capsizing

3.2.5. Limited capacity of muster station

A passenger ship has multiple muster stations that are the equivalent of evacuees' destinations (Bucci et al., 2016). Different from the land building evacuation, the muster stations on passenger ships give a limitation for routing selection due to the limited number of lifeboats and rafts in the stations (Qiao et al., 2014). When the embarkation and muster stations are not coincident, the capacity of each muster station is also limited due to the space limitation, which is determined in the ship design stage. Without considering the limited capacity of muster stations, passengers are likely to be guided to the stations that have no space to accommodate more evacuees, which would lead to a reassignment to another station, and thus inevitably prolongs the period required to navigate passengers to safety. Considering the resultant longer evacuation time, it is increasingly likely that passengers will eventually miss the limited ship survival time and consequently lose their lives when abandoning the ship becomes necessary.

3.2.6. Dependency on life-saving equipment for real survival

In case the damaged ship must be abandoned, passengers will be required to arrive at boarding stations and embark on lifeboats or rafts or jump into the water (Yoshida et al., 2001). In such cases, passengers need to equip themselves with life-saving equipment such as life vests and lifebuoys, which increases passengers' feelings of safety and their chance of survival. The minimum number of different life-saving equipment is defined in Safety of Life at Sea (SOLAS) regulations based on the size and passenger capacity of the ship (Ahola et al., 2014). Specifically, there are two life jackets in each passenger room, and at other specific locations (e.g., outside decks), a certain number of lifebuoys or jackets are distributed. If a passenger is not in the room when an emergency happens, it would be vital to consider the distribution of life-saving equipment in the path planning. For example, should they return to their cabins to collect life jackets, or should they head for other locations where pertinent appliances are placed?

3.2.7. Narrow and complex ship indoor space

The internal structure of a passenger ship is very complex, especially for state-of-the-art passenger ships with theaters, shops, swimming pools, and gyms (Stefanidis et al., 2019). Moreover, the width of corridors in cruises ranges from 1 m to 3 m, only allowing one or two passengers to pass simultaneously. However, with the increase in passenger capacity, there may be thousands of passengers on a cruise ship, which gives rise to congestion points. Without considering the heavy congestion and even blocking and trampling due to capacity constraints of pathways, it is likely to aggravate the extent of injuries and casualties.

3.3. Studies of ship passenger evacuation

There are three kinds of research focusing on ship passenger evacuation from the view of intentions, i.e., evacuation behavior study, passenger evacuation optimization, and evaluation of evacuation on passenger ships. Previous research on ship passenger evacuation is summarized in Table 8.

Table 8
Ship passenger evacuation

Research intentions	Research content	Technique	Implemented in
Passenger evacuation behavior	Moving characteristic	Simulation with agent-based models, Full-scale experiment on ships, Experiment with simulators	(Valanto, 2006; Sun et al., 2018a; Chen et al., 2016a; Sun et al., 2018b; Wang et al., 2021a)
	Perception of wayfinding tools	Experiment in simulated conditions, Questionnaire survey	(Wang et al., 2020; Kwee-Meier et al., 2017; Wang et al., 2021b)
	External and internal factors affecting passengers' behaviors	Experiment in simulated conditions, Passenger ship accident investigation reports, Full-scale experiments on ships, Questionnaire survey	(Ahola et al., 2014; Nevalainen et al., 2015; Ahola and Mugge, 2017; Zhang et al., 2020a)
Passenger evacuation optimization	Effectiveness of wayfinding solutions	Simulation with SF model	(Casareale et al., 2017)
	Staircase layout optimisation	Simulation with SF model	(Wang et al., 2022)
	Optimization of issuance of passenger evacuation orders	Genetic algorithm	(Xie et al., 2020c)
Passenger evacuation evaluation	Optimization of evacuation path	BFS, Leung-Ng fast approximation scheduling algorithm	(Ni et al., 2017; Ng et al., 2021)
	Reliability of evacuation	Bayesian network parameter learning method, Risk-based methodology, K2 structure learning algorithm	(Wang et al., 2021c; Vanem and Skjong, 2006)
	Evacuation process estimation	Simulation with SF model, Modelling with Batch NHPP, Simulation with grid-based model, Dynamic Bayesian network, Markov decision process, Polynomial chaos expansion	(Kang et al., 2019; Ni et al., 2017; Hifi, 2017; Vilen et al., 2020; Galea et al., 2015; Sarshar et al., 2013; Kana and Droste, 2019; Xie et al., 2020a,b)

3.3.1. Passenger behaviors during evacuation

It is critical to study passengers' behaviors during a ship evacuation process. Valanto *et al.* investigated the moving characteristics of passengers considering the effect of ship inclination and motion (Valanto, 2006; Sun et al., 2018a; Chen et al., 2016a; Sun et al., 2018b; Wang et al., 2021a). Sun *et al.* investigated the effect of heeling and trim on individual walking speed using a ship corridor simulator (Sun et al., 2018a). Results showed that compared with trim angles, heeling angles had less impact on individual walking speed. Lu *et al.* explored the movement pattern of single file passengers under ship trim and heeling conditions (Sun et al., 2018b). Results indicated that as with individual walking speed, group speed was more vulnerable to heeling angles compared with trim angles. Moreover, the larger the inclination angle, the more the velocity between adjacent experimental subjects correlated. Chen *et al.* established an agent-based evacuation model taking into account the forced pedestrian movement pattern (Chen et al., 2016a). Simulations of single pedestrian movement indicated that pedestrian movement was significantly affected by the angle between pedestrian movement direction and ship swaying direction. Based on the primary data from a series of walking experiments on a real ship, Wang *et al.* analyzed the individual walking speed under different rolling conditions in two scenarios, i.e., flat terrains and staircases (Wang et al., 2021a). Other behaviors including cooperation with others, perception of wayfinding tools, proactive response to evacuation alarms, compliance with the crew, observation on others' actions, obedience to evacuation instructions, patient queuing, and return to the cabin when their families are left behind, were also investigated (Kwee-Meier et al., 2017; Wang et al., 2021b; Zhang et al., 2020a). In addition, Wang *et al.* addressed the demographic differences among these behaviors (Wang et al., 2020).

Some research focused on the factors affecting passengers' evacuation behaviors (Li et al., 2021). With the help of hypothesis testing, Zhang *et al.* analyzed the relationship between personnel characteristics (e.g., blood type and personality type) and evacuation behaviors (e.g., the first response to a fire alarm and the possibility of return for properties) (Zhang et al., 2020a). Ahola *et al.* conducted user studies in an authentic environment to assess the themes pertaining to passenger perception of safety (Ahola et al., 2014; Ahola and Mugge, 2017). Based on ship accident investigation reports, Nevalainen *et al.* found that both external stimuli, including alarm sound, abnormal noise, and the darkness caused by a blackout, and inner emotion could affect how passengers process and interpret environmental cues under emergencies (Nevalainen et al., 2015).

3.3.2. Passenger evacuation optimization

Regarding passenger evacuation optimization, the plan of escaping routes, the optimization of staircase layout, and the schedule of the time for issuing evacuation orders have attracted the attention of many researchers. Casareale *et al.* demonstrated the effectiveness of wayfinding systems in improving evacuation on cruise ships (Casareale *et al.*, 2017). Ni *et al.* applied a goal-driven decision-making model to create a concrete escape plan (Ni *et al.*, 2017). Ng *et al.* iteratively utilized a modification of the scheduling algorithm introduced by Leung and Ng to find a schedule for different groups at risk, which minimized the time of evacuating all people with the least total cost (Ng *et al.*, 2021). Based on a SF model, Wang *et al.* optimized the staircase layout on a Ro-Ro vessel to reduce evacuation time (Wang *et al.*, 2022). Xie proposed a surrogate-based optimization method to determine the time for issuing evacuation orders so that the assembly time could be minimized (Xie *et al.*, 2020c).

3.3.3. Evaluation of evacuation on passenger ships

The evacuation process can be analyzed in two ways: advanced analyses and simplified analyses. The advanced analysis treats each passenger as an individual with his/her characteristic and behavior. Ni *et al.* proposed an extended SF model that considered the resistance force from obstacles in cabins to govern the movement of passengers (Ni *et al.*, 2017). Kang *et al.* incorporated the psychological tendency of pedestrians to slip downhill into the SF model to simulate evacuation behaviors on inclined shipwrecks (Kang *et al.*, 2019). Vilen *et al.* evaluated two advanced evacuation analysis software packages, i.e., Evi and Pathfinder, in terms of numerical results and user experience (Vilen *et al.*, 2020). Galea *et al.* did an experimental validation of the evacuation model maritimeEXODUS using two data sets generated from semi-unannounced assembly trials on a RO-PAX ferry and a cruise ship (Galea *et al.*, 2015). Results showed that the model was capable of predicting the assembly process for the two vessels to a specified level of accuracy. In addition, Hifi *et al.* described a set of scenarios for performing advanced evacuation analysis and recommended a survey of population composition and ship familiarity before the evacuation analysis to improve analysis accuracy (Wang *et al.*, 2022; Hifi, 2017). However, the advanced analysis is very time-consuming, and thus when a fast assessment of evacuation time is needed, it is not a suitable option. Cho *et al.* developed a simplified analysis solution that took a macroscopic view of the evacuation process, treating passengers as homogeneous particles in a fluid (Cho *et al.*, 2016). Sarshar *et al.* developed a dynamic Bayesian network model that considered the most vital factors influencing congestion (e.g., panic, age, sex, and the presence of rescue personnel) to predict the probability of congestion during the entire process of an evacuation (Sarshar *et al.*, 2013). Xie *et al.* established a surrogate model using a coupling technique of nested sampling and polynomial chaos expansion method to estimate passenger travel time uncertainty with acceptable accuracy (Xie *et al.*, 2020b,a). Kana *et al.* presented a ship-centric Markov decision process model for evaluating the evacuation during the preliminary design phase of a passenger ship (Kana and Droste, 2019). The simplified analysis ignored the different elements of an evacuation process and thus could not mirror passengers' movement. Hifi *et al.* developed a parametric model that could produce a fast estimate of evacuation time while capturing the factors influencing the evacuation to satisfactory accuracy (Hifi, 2017).

The quantitative evaluation of evacuation on ships is also essential. Wang *et al.* investigated the main factors leading to evacuation failure and established a model using the K2 structure learning algorithm and the Bayesian network parameter learning method to quantify the probability of a successful evacuation (Wang *et al.*, 2021c). Vanem *et al.* developed a risk-based approach to evaluate the evacuation performance associated with a specific passenger ship using the proposed set of evacuation scenarios (Vanem and Skjong, 2006).

4. Discussion and future directions

This section evaluates the above land-based evacuation schemes and delineates our insights into the future research perspectives for ship passenger evacuation.

4.1. Comment on land-based evacuation

Significant research works on building evacuation have been carried out. Based on different types of guidance patterns, a classification of land-based evacuation schemes is proposed, including signage-based evacuation, leader-based evacuation, ME-based evacuation, and WSN-based evacuation.

In section II-A, the review of land-based indoor evacuation with fixed and variable signage is provided. The latter can respond to contemporary environmental conditions and present up-to-date guiding information. However, pedestrians may not find signs in smoky conditions. Even under clear conditions, they are likely to neglect the signs

at specific locations or cannot fully understand the content of signs during emergencies due to their anxiety and panic. In such emergencies, evacuation leaders with complete knowledge of the layout of a building can provide guiding instructions for occupants and significantly reduce casualties. Compared with human leaders, robotic leaders can be sent to guide evacuees out in several special accidents like nuclear leakage. An emergency evacuation system is requested to provide a time-critical guiding service. But for the leader-based evacuation system, it will take a significant amount of time to arrange leaders to appropriate locations. Therefore, evacuating through the equipped device (e.g., smartphone) regularly used in everyday life for all pedestrians is very attractive. However, the downsides to the three kinds of evacuation schemes are as follows: 1) Without real-time indoor environment monitoring, evacuation routes provided by these schemes are not necessarily passable due to the encroachment of hazards; 2) Passengers observing the same sign or leader or near the same beacon will escape along the same direction, which inevitably causes heavy congestions, trampling and possible injuries and casualties. The WSN-based evacuation scheme is capable of exploring dynamic environmental conditions by means of the collaborative detection of sensor nodes. But sensor-centric WSN-based evacuation scheme is only effective on the first downside mentioned above, while powerless to solve the second problem. Therefore, a user-centric WSN-based evacuation scheme will be a good choice for a modern building.

4.2. Prospects for ship passenger evacuation

Compared with the land-based evacuation, there are some specific features for passenger ship evacuation due to the uniqueness of ship structure, passenger behaviors onboard, and evacuation requirements at sea. Therefore, personalized evacuation approaches for ship passengers are indispensable. However, in contrast to the relatively mature land-based evacuation schemes, the research on ship evacuation is still in its infancy and focuses on investigating the likely behaviors of passengers. Design or optimization of evacuation routes targeting ship passengers is also critical but scarce. Drawing from the four types of land-based evacuation schemes mentioned in Section II, the prospects for the evacuation system of modern cruise ships are discussed in this section.

A WSN with functionally-separated sensors like tilt sensors, hydraulic pressure sensors, temperature sensors, and smoke sensors is deployed on a modern cruise ship. When an emergency takes place, the sensors will initiate a danger alarm and transmit the current locations and levels of hazards to a path planning server. In addition, the current position of each passenger is detected using the received strength of wireless signals on his/her smartphone, and the sensor ID with the strongest signal strength is used to determine the passenger's position in the blueprint database of sensor deployment. That is to say, the proposed scheme does not require accurate location information on each passenger. The smartphone periodically sends the determined position to the path planning server. According to the obtained information, the server will compute a dedicated escape route for each individual and broadcast it to his/her smartphone. The reason for selecting smartphones as guides during emergencies is that nowadays almost everyone has a smartphone and familiarity with their own smartphones can increase passengers' feelings of safety. Fig. 8 shows the system architecture of our proposed emergency guiding scheme for ship passengers. Red rectangles represent sensor nodes deployed at muster stations, doors, and crossing points among corridors and/or doors on a passenger ship in advance. The Wi-Fi access point is used for maintaining the communication between the smartphones and the path planning server. The following is a list of properties of evacuation routes provided to passengers:

- The path is apart from hazardous regions and through which a passenger can arrive at a specific exit before the ship capsizes under all circumstances.
- The total evacuation time of passengers should be reduced as much as possible. To realize this goal, an evacuation system has to consider not just the relative distance from the passenger to the muster station, but the movement speed on the route, the capacity of the route, and the up-to-date distribution as well as the spatial-temporal mobility of all passengers.
- The evacuation routes should be provided to passengers in a real-time manner.
- Escaping along the provided route, each passenger would have obtained a piece of saving-life equipment when arriving at the muster station.
- Following the offered direction would not speed up the ship leaning to one side.
- Passengers would not be guided to a muster station that cannot accommodate more evacuees.

- Except for guaranteeing passengers' safety, the evacuation system should also maintain the integrity of a passenger ship as much as possible.

The proposed architecture is attractive but challenging, due to the restricted battery power of low-cost sensor nodes and the ad-hoc routing protocol of a WSN in a large and complicated ship indoor space. Specifically, as the information regarding the environment is forwarded over multiple hops towards a gateway, some sensors get more congested than others, depending on their location. Therefore, they deplete their batteries quickly, shortening the overall network lifetime. In addition, considering the dynamics of the hazardous environment, the routing protocol in WSN functions poorly in the evacuation application. Because in order to ensure passengers' safety, frequent flooding is required to update the escaping paths in the rapidly changing environment, which may trigger many simultaneous bursts of broadcast packets throughout the network and thus cause a large number of packet collisions. The calculation of all routes is performed in the path planning server. So in case it malfunctions during the emergency, our evacuation system will break down. Moreover, while the potential of our proposed architecture to improve access to real-time monitoring and even intuitive and reliable navigation instruction can be provided to evacuees, concerns about personal data privacy remain. User data may be inadequately disclosed or transmitted to commercial entities by smartphone applications (apps) for ship passenger evacuation.

With the emergence of Low Power Wide Area Network (LPWAN) technologies, one type of WSN, which is designed for long-range Internet of Things (IoT) services, the above challenges from WSNs will hopefully bear solved. LPWAN IoT devices consume low transmission power but have a communication distance of several kilometers, so they can directly transmit the information pertaining to the environment to the path planning server and thus avoid the network breakdown caused by packet collisions. In addition, benefiting from the development of edge computing, in the future the distributed approach can be used to provide paths for passengers so as to reduce and even release the dependency on the path planning server. Moreover, given the negative impacts of inadequate privacy disclosures, data protection becomes particularly important. On the one hand, the anonymization technology can be adopted for the utilization of the results of analysis of the exchanged data, which includes passengers' sensitive personalized contexts (e.g., information about passengers' physical and psychological status) (Shinzaki et al., 2016). On the other hand, government regulation and up-to-date technical scrutiny are also essential for avoiding privacy leakages (Huckvale et al., 2019).

In addition, with the development of Extended Reality (XR) technology, VR-based or AR-based experiments can be introduced as an alternative method of post-emergency investigation and hypothetical survey to study passenger behavior during ship emergencies. XR-based experiments can arouse passengers' behavioral responses to virtual emergencies and thus provide the opportunity to collect evacuation behavior data with relatively high ecological validity. Taking into account passengers' behaviors, the designed evacuation system will be more effective at ensuring the safety and reliability of evacuation in reality. Moreover, it is possible to develop VR-based Serious Games (SGs) to train passengers to utilize the proposed evacuation scheme to escape, which is an effective approach to acquiring and retaining evacuation knowledge. It is also possible to substitute smartphones in the proposed architecture with AR devices that can provide more intuitive guidance for passengers.

5. Conclusion

This paper provides a survey of research efforts on crowd evacuation both in general buildings and on passenger ships. A comprehensive analysis and synthesis of different kinds of guidance patterns for evacuation in land-based buildings, including signage-based, leader-based, ME-based, and WSN-based evacuation schemes, is presented. Those schemes are not used directly for ship passenger evacuation due to the unique challenges of guiding passengers on vessels. Section III analyzes the specificities of both evacuation environment and crowd behavior during the emergency evacuation on passenger ships. In addition, the existing work on evacuation for passenger ships are reviewed. Comments on land-based evacuation schemes and future research directions on ship passenger evacuation are also discussed. In the future, more intelligent and personalized guidance systems will be designed and implemented to improve the safety and efficiency of ship passenger evacuation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

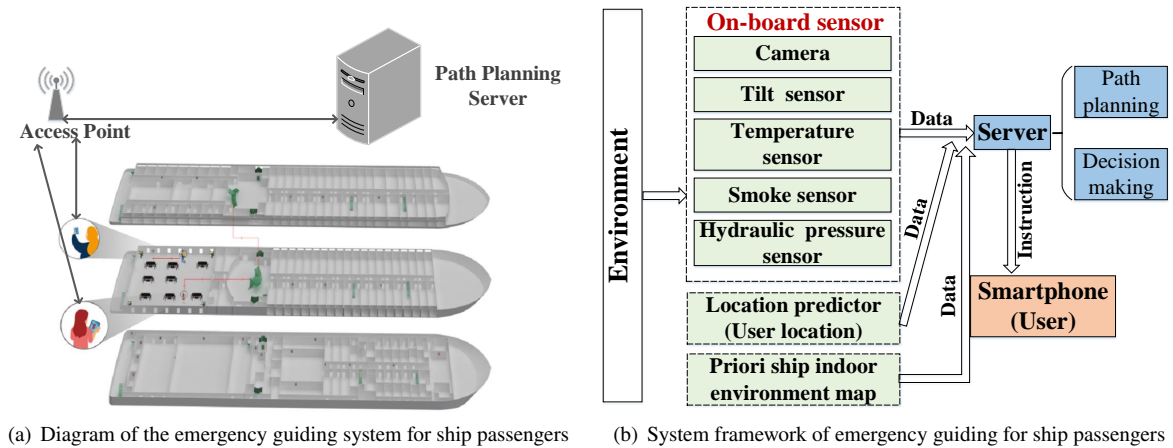


Figure 8: System architecture of the emergency guiding scheme for ship passengers

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