A Systematic Mapping Study on Edge Computing Approaches for Maritime Applications

Morariu, Andrei-Raoul; Ashraf, Adnan; Björkqvist, Jerker

Published in:
Proceedings - 2021 47th Euromicro Conference on Software Engineering and Advanced Applications, SEAA 2021

DOI:
10.1109/SEAA53835.2021.00014

Published: 01/09/2021

A Systematic Mapping Study on Edge Computing Approaches for Maritime Applications

Andrei-Raoul Morariu*, Adnan Ashraf†, Jerker Björkqvist*
*Faculty of Science and Engineering, Åbo Akademi University
Vesilinnantie 3, 20500 Turku, Finland
†Interdisciplinary Centre for Security, Reliability and Trust, University of Luxembourg
29 Avenue John F. Kennedy, 1855 Luxembourg
andrei-raoul.morariu@abo.fi, adnan.ashraf@uni.lu, jerker.bjorkqvist@abo.fi

***Abstract*—Background: The edge computing paradigm allows to reduce latency and response time of applications by bringing computations and data storage closer to the locations where they are needed. Edge computing is used in different kinds of Internet of Things (IoT) applications. Maritime represents an important application domain for IoT applications and edge computing solutions. Modern vessels employ many different types of sensors, which produce a massive amount of data. Edge computing allows to perform computations and data analyses on-board a vessel or at the edge of the network.**

Objective: To present a comprehensive, unbiased overview of the state-of-the-art on edge computing approaches for maritime applications.

Method: A Systematic Mapping Study (SMS) of the existing edge computing approaches for maritime applications.

Results: A taxonomy of 17 papers on edge computing approaches for maritime applications.

Conclusion: The results of the study show that there is a small number of existing edge computing approaches for maritime applications. Most of the existing approaches focus mainly on monitoring and communication functions in vessels. Moreover, several research gaps exist with respect to the types of edge computing approaches, the purposes of using edge computing on vessels, and the data analysis techniques used for edge computing on vessels.

***Index terms*—** Edge computing; vessels; maritime applications; systematic mapping study; taxonomy

I. INTRODUCTION

Modern vessels feature a range of sensors, which produce a massive amount of data. These include Global Positioning System (GPS), inertial navigation system, optical and infrared cameras, radar, lidar, high-resolution sonar, microphones, level sensors, tank level indicators, and wind and pressure sensors. Maritime Internet of Things (IoT) applications use data produced by the sensors to perform various analytics. Due to the near real-time nature of maritime applications, fast processing of data and low communication latency are two essential requirements for the successful operation of maritime applications.

Cloud computing provides theoretically infinite amount of computing and storage resources that can be provisioned in an on-demand, pay-as-you-go fashion and leveraged for fast processing and storage of massive amounts of data [13]. Cloud computing solutions are highly suitable for big data applications. However, they are not suitable for real-time analytics of instant data produced by sensors and IoT applications [20]. Moreover, due to bandwidth limitations on vessels, it is often not feasible to send large amounts of maritime data for fast processing and storage in the cloud. Moreover, for vessels in the open sea, maritime communication network presents a challenge for remote processing and storage of instant data [26]. Data analytics cannot be performed in the cloud when an internet connection for sending data packages to land does not exist.

Edge computing has emerged as a new computing paradigm, which allows lower latency and response time of real-time applications by bringing computations and data storage closer to the sources of data and IoT applications [16]. In the maritime domain, edge computing allows to perform computations and data analytics on-board a vessel or at the edge of the network. Therefore, edge computing solutions can be used to provide a highly suitable solution for real-time analytics of instant data in maritime IoT applications. Edge computing comes with the benefit of performing data analytics in a close proximity of the crew which can be notified in case of unexpected events.

There is a growing interest on edge computing solutions for maritime applications both in academia and the maritime industry. However, to the best of our knowledge, there are no existing literature reviews on this topic. A comprehensive review and taxonomy of the topic will help the research community and maritime industry to study and evaluate the state-of-the-art to identify gaps and direct the focus of future research and development work in the area.

In this paper, we present a Systematic Mapping Study (SMS) [3], [17], [18] on the existing edge computing approaches for maritime applications. The objective is to present a comprehensive, unbiased overview of the state-of-the-art. A SMS follows the same principled process as a Systematic Literature Review (SLR), but: (1) it has a broader scope, (2) it uses different criteria for inclusions/exclusions and quality assessments, and (3) its data collection and synthesis tend to be more qualitative than for a SLR [23]. It helps to map-out previous research on a certain topic and to identify research gaps [3].

We proceed as follows. Section II presents the design and schedule of our study. The results of the SMS are presented in Section III. In Section IV, we discuss major threats to the validity of the results presented in this paper. Finally, we present our conclusions in Section V.

II. Study Design

A SMS follows an unbiased and repeatable process, which is documented as a review protocol. In this section, we present the most important parts of our review protocol. The protocol is adapted from [2].

A. Research Questions

The Research Questions (RQs) are as follows:

- RQ1: What approaches (methods, algorithms, techniques, frameworks) exist for edge computing or edge analytics on vessels?
- RQ2: What are the purposes of using edge computing on vessels?
- RQ3: What is the level and scope of implementation of edge computing approaches on vessels?
- RQ4: What types of data are used for edge computing on vessels?
- RQ5: What data analysis techniques are used for edge computing on vessels?
- RQ6: What standards, regulations, and protocols apply for edge computing on vessels?
- RQ7: How are the existing edge computing approaches on vessels evaluated?

B. Search Strategy for Primary Studies

This section presents our search strategy. It is based on the SLR guidelines in [14], [23].

1) Search Terms: Table I lists the search terms used at the initial stage of inquiry for the research. We derived the search terms from the RQs.

TABLE I
Search terms

#	Search term	Alternate spellings
1	"Edge Computing"	None
2	"Edge Analytics"	None
3	Vessel	None
4	Ship*	Ships, Shipping
5	Boat	None
6	Ferr*	Ferries, Ferryboat
7	Maritime	None
8	Waterborne	None
9	Sea	None

2) Databases: The search was performed in the following seven Digital Librarys (DLs).

- Institute of Electrical and Electronics Engineers (IEEE) Xplore
- Association for Computing Machinery (ACM) DL
- ScienceDirect
- SpringerLink
- Scopus
- Wiley Online Library
- Web of Science

The search was performed in the metadata of the publications, which includes publication title, abstract, and indexing terms or keywords.

3) Search Strings: The search terms in Table I were combined into a search string for use in the seven DLs. The general form of the search string is presented in Table II. The general form worked as it is in all DLs except ScienceDirect, because ScienceDirect does not support the use of the asterisk (*) wildcard. Therefore, the general form was customized for ScienceDirect, which resulted in three additional search strings as presented in Table III. Using multiple DLs creates duplicates in the search results. Therefore, the search results were analyzed to identify and remove duplicates.

TABLE II
General form of the search string

("edge computing" OR "edge analytics") AND (vessel OR ship* OR boat OR ferr*) AND (maritime AND waterborne AND sea)

TABLE III
Search strings for ScienceDirect

#	Search string
1	("edge computing" OR "edge analytics") AND (vessel OR shipping OR boat OR ferry) AND (maritime AND waterborne AND sea)
2	("edge computing" OR "edge analytics") AND (vessel OR ship OR boat OR ferryboat) AND (maritime AND waterborne AND sea)
3	("edge computing" OR "edge analytics") AND (vessel OR ships OR boat OR ferry) AND (maritime AND waterborne AND sea)

C. Study Selection Criteria

This section presents our inclusion and exclusion criteria for primary studies.

1) Inclusion Criteria: The inclusion criteria for primary studies are as follows:

- Edge computing or edge analytics *AND*
- Approach or method or algorithm or technique or framework *AND*
- For vessel or ship or ferry or boat *AND*
- In the context of maritime or waterborne or sea *AND*
- Written in English *AND*
- Published in a peer-reviewed journal, book chapter, conference, or workshop of computer science, computer engineering, or software engineering

In addition, if several papers presented the same approach, only the most recent paper was included.

2) Exclusion Criteria: Similarly, the exclusion criteria for primary studies are as follows:

- Not for edge computing or edge analytics *OR*
- Not an approach or method or algorithm or technique or framework *OR*
- Not for vessel or ship or ferry or boat *OR*
- Not in the context of maritime or waterborne or sea *OR*

- Not written in English *OR*
- Not published in a peer-reviewed journal, book chapter, conference, or workshop of computer science, computer engineering, or software engineering

If several papers presented the same approach, all except the most recent paper were excluded.

D. Study Selection Procedure

The study selection procedure comprised three phases namely (A) title and abstract level screening, (B) full-text level screening, and (C) backward and forward snowball sampling.

1) Title and Abstract Level Screening: In this phase, the inclusion/exclusion criteria in Section II-C was applied to publication title and abstract. To minimize researcher bias, two researchers (Andrei-Raoul Morariu and Adnan Ashraf) independently screened the search results. The results were compared and disagreements were resolved through discussions and consensus meetings [6].

2) Full-text Level Screening: In this phase, the selected studies from the first phase were further analyzed on the basis of full-text. Two researchers (Andrei-Raoul Morariu and Adnan Ashraf) independently applied the inclusion/exclusion criteria on the full-text papers. In this phase, the researchers also documented a reason for each excluded study [22]. The results were compared in a similar way as in the first phase and disagreements were resolved through discussions and consensus meetings.

3) Backward and Forward Snowball Sampling: After the full-text screening phase, backward and forward snowball sampling [12], [18] was used in order to complement the electronic searches in the seven DLs. Two researchers (Andrei-Raoul Morariu and Adnan Ashraf) independently performed backward and forward snowball sampling. The results were compared and disagreements were resolved in a consensus meeting.

E. Study Quality Assessment Checklist and Procedure

The selected primary studies were assessed for their quality. Two researchers (Andrei-Raoul Morariu and Adnan Ashraf) independently assessed the quality of the selected studies. Studies not meeting the minimum quality requirements were excluded from the final set of primary studies.

Table IV presents the checklist for study quality assessment. For each question in the checklist, a three-level, numeric scale was used [22]. The levels were: yes (2 points), no (0 point), and partial (1 point). Each study scored a maximum of 16 points. The two independent scores from the two researchers were aggregated by computing arithmetic mean. We used the first quartile ($16/4 = 4$) as the cutoff point for the inclusion of studies. Therefore, if a study scored less than 4 points, it was excluded. The researchers documented the scores of each included/excluded study.

F. Data Extraction Strategy

Table V presents the data extraction form. Two researchers (Andrei-Raoul Morariu and Adnan Ashraf)) independently extracted data from each primary study. Studies that presented multiple edge computing approaches were placed under multiple categories [3]. Differences in data extraction is a recurring topic in mapping studies [3]. The extracted data were compared and differences were harmonized in a consensus meeting and by referring back to the original papers [6].

TABLE IV
STUDY QUALITY ASSESSMENT CHECKLIST

#	Question
Theoretical contribution	
1	Is the edge computing approach clearly described?
2	Is the underlying theory/algorithm clearly described?
3	Are the assumptions clearly stated?
Experimental evaluation	
4	Is the evaluation method clearly described?
5	Is a simulation or a prototype implementation presented?
6	Is the experimental design and setup clearly described?
7	Are results from multiple different experiments included?
8	Are the experimental results compared with other state-of-the-art approaches?

TABLE V
DATA EXTRACTION FORM

Data item	Value	Notes
General		
Data extractor name		
Data extraction date		
Study identifier (S1, S2, S3, ...)		
Bibliographic reference (title, authors, year, publication venue name)		
Author affiliations and countries		
Publication type (journal, book chapter, conference, or workshop)		
Edge computing on vessels related		
RQ1 Proposed approach (method, algorithm, framework, technique)		
RQ1 Online or offline implementation		
RQ2 Purpose of using edge computing		
RQ3 Level and scope of implementation		
RQ4 Type of data		
RQ5 Data analysis technique		
RQ6 Applicable standards, regulations, and protocols		
RQ7 Evaluation method		

G. Synthesis of the Extracted Data

The most important result of a mapping study is a systematic map that allows to identify research gaps to direct the focus of future research [14]. The extracted data from the primary studies were synthesized to construct a systematic map comprising several tables (Table IX to XVI) and plots (Figure 1 to 4) [18].

H. Schedule of the Study

The schedule of the study is presented in Table VI. The estimated time for title and abstract level screening was based on approximately 40 abstracts a day. Similarly, the estimated time for full-text level screening was based on approximately 5 full-text papers a day. The schedule implicitly includes approximately 10% additional time for consensus meetings.

TABLE VI
SCHEDULE OF THE STUDY

#	Activity	Days	Due date
1	Protocol review and revision	10	27.10.2020
2	Search for primary studies	1	28.10.2020
3	Title and abstract level screening	3	03.11.2020
4	Full-text downloading	2	10.11.2020
5	Full-text level screening	6	20.11.2020
6	Backwards snowball sampling	2	25.11.2020
7	Forward snowball sampling	2	27.11.2020
8	Quality assessment	2	02.12.2020
9	Data extraction	5	10.12.2020
10	Data synthesis	9	23.12.2020
11	First draft of paper	10	12.01.2021

III. RESULTS

In this section, we present the results of the SMS. Table VII presents the papers in different stages of the research. The initial search resulted in 185 papers, out of which 25 were duplicates and were subsequently removed. A substantial number of papers were related to application domains other than maritime. After performing the title and abstract screening, we included 32 studies. At the end of the full-text screening phase, a rather small number of papers (13) was included. In the snowball sampling phase, 5 additional papers (2 from backward snowball sampling and 3 from forward snowball sampling) were included. In the last phase of quality assessment, one paper was removed because its score was below the cutoff threshold. The final number of selected primary studies was 17. Table VIII presents the list of the selected primary studies along with their study identifiers (IDs).

TABLE VII
NUMBER OF PAPERS AT DIFFERENT STAGES OF THE STUDY

Phase	Number of papers
Initial search results	185
After removing duplicates	160
After title and abstract screening	32
After full text screening	13
After backward snowballing	15
After forward snowballing	18
After quality assessment	17

Figure 1 shows that 10 out of 17 primary studies were published in 2020. Moreover, most of the studies published in 2020 were published in journals. The remaining 7 studies were published in 2017-2019. We consider that the years of publications of the selected studies are expected as the edge *way of thinking* emerged in 2016 [20]. Therefore, the research into maritime domain is still rather sparse.

A. Types of Edge Computing Approaches (RQ1)

Table IX shows the types of approaches used in the primary studies. Most of the primary studies proposed edge computing system/technology or network approaches (S7, S10, S13,

TABLE VIII
STUDY IDS AND REFERENCES OF THE SELECTED STUDIES

ID	Reference	ID	Reference
S1	[30]	S10	[15]
S2	[29]	S11	[4]
S3	[24]	S12	[27]
S4	[25]	S13	[8]
S5	[5]	S14	[28]
S6	[7]	S15	[1]
S7	[10]	S16	[11]
S8	[19]	S17	[9]
S9	[21]		

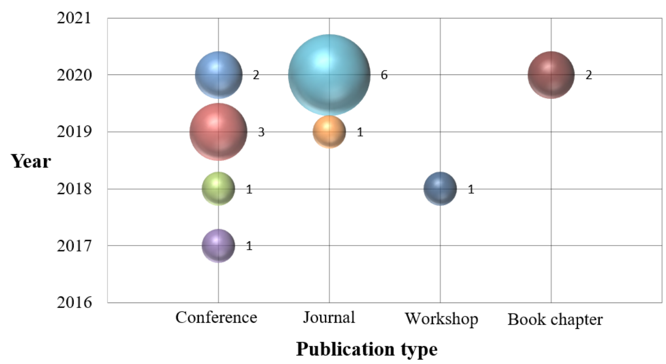

Fig. 1. Primary studies sorted by publication year and type

S14, S15) or path finding, escorting and collision avoidance approaches (S3, S9, S12, S17). Other notable types include edge computing approaches for vessel monitoring (S1, S6, S7) and computation offloading (S4, S13, S14).

TABLE IX
TYPES OF APPROACHES

Approach	Study IDs	Count
Edge computing system/technology or network	S7, S10, S13, S14, S15	5
Path finding, escorting and collision avoidance	S3, S9, S12, S17	4
Computation offloading	S4, S13, S14	3
Edge-based vessel monitoring	S1, S6, S7	3
On-line data reduction algorithm	S1, S7	2
Evolutionary algorithms	S2	1
Linear regression	S8	1
Deep learning	S5	1
Power line communications	S16	1
Fog-to-cloud platform for smart boats	S11	1

Table X presents synthesized data on whether the primary studies proposed an online/real-time implementation or an offline implementation. The results show that 11 out of 17 studies presented an online implementation. This is an important result as it shows that most of the maritime applications use edge computing solutions for analytics on real-time (instant) data. These applications have low latency and low response time requirements. Therefore, such analytics must be performed in a close proximity of the sources of data and maritime IoT applications.

TABLE X

ONLINE OR OFFLINE IMPLEMENTATION

Online or offline	Study IDs	Count
Online	S1, S6, S7, S10-S17	11
Offline	S2-S5, S8, S9	6

B. Purposes of Using Edge Computing on Vessels (RQ2)

Table XI shows that most of the studies focus on network and communication functions (S1, S2, S4, S6-S9, S17). Their purposes include reducing the maritime communication costs and improving communication efficiency. Some studies have multiple purposes. Therefore, they appear in more than one category. Other notable purposes include data exchange and acquisition (S8, S15, S17) and vessel monitoring (S6, S11, S13). There are only a few studies on each of the following four purposes: anomaly and failure detection (S5, S11), on-board computing capacity (S3, S14), reducing energy consumption (S13, S14), and search and rescue operations (S12, S16).

TABLE XI

PURPOSES OF USING EDGE COMPUTING ON VESSELS

Purpose	Study IDs	Count
Network and communication	S1, S2, S4, S6-S9, S17	8
Data exchange and acquisition	S8, S15, S17	3
Vessel monitoring	S6, S11, S13	3
Anomaly and failure detection	S5, S11	2
On-board computing capacity	S3, S14	2
Reducing energy consumption	S13, S14	2
Search and rescue	S12, S16	2

Figure 2 presents a bubble plot that categorizes the selected primary studies according to the types of edge computing approaches and the purposes of using edge computing on vessels. The bubble size represents the number of primary studies in each category. Larger bubbles indicate areas where there are relatively more studies, while smaller bubbles represent areas where fewer studies exist. It can be observed that there is a lack of research on several types of approaches and purposes. Research gaps with respect to types of approaches include evolutionary algorithms, linear regression, deep learning, power line communication, and smart boat platforms. Similarly, gaps with respect to purposes include anomaly and failure detection, on-board computing capacity, energy consumption, and search and rescue operations. Furthermore, the bubble plot is sparsely populated. Most of the edge computing approaches map to only one or two purposes. Therefore, there is a need to develop and evaluate the existing edge computing approaches for more purposes in the maritime domain. Similarly, new edge computing approaches should be devised for anomaly and failure detection, on-board computing capacity, energy consumption, and search and rescue operations.

C. Level and Scope of Implementation (RQ3)

Table XII shows that most of the studies are applicable to a general level and scope in vessels. A total of 15 out of 17 studies (S1-S4, S7-S17) indicated that the edge computing approach is implemented at the vessel, ship, or boat level. Only three studies implemented edge computing at a more precise or limited level and scope. S5 implemented an edge computing approach on the engine room with the aim to detect engine failures. S6 implemented a *MONICAP* blue-box for receiving data such as position, integrity, status records, and GPS. S3 presented an implementation of edge computing on an Unmanned Surface Vehicle (USV) platform.

TABLE XII

LEVEL AND SCOPE OF IMPLEMENTATION

Level and scope	Study IDs	Count
Vessel, ship, or boat	S1-S4, S7-S17	15
Engine room	S5	1
MONICAP	S6	1
USV platform	S3	1

D. Types of Data for Edge Computing on Vessels (RQ4)

Table XIII presents the types of data used for edge computing on vessels. The results show that the most common type of data is the position, sea condition, weather sensing data (S1, S6, S7, S11, S12, S15). In addition, several types listed in the table come under one umbrella category of ship monitoring data. It includes ship speed (S9), ship navigation data (S7, S17), generic ship data (S4, S8, S13, S16), equipment condition data (S7), as well as ship-to-ship/shore communication data (S4, S10). An important remark is that most of the studies did not clearly specify the type(s) of data used for edge computing. Therefore, we inferred the types from the context in which the data were used in the studies and then grouped the studies into the most relevant categories.

TABLE XIII

TYPES OF DATA FOR EDGE COMPUTING ON VESSELS

Type of data	Study IDs	Count
Position, sea condition, weather sensing	S1, S6, S7, S11, S12, S15	6
Generic ship data	S4, S8, S13, S16	4
User tasks	S2, S14	2
Ship-to-ship/shore communication data	S4, S10	2
Ship navigation data	S7, S17	2
Equipment condition data	S7	1
Ship speed	S9	1
Crash site	S12	1
Cargo sensing	S16	1
Intercept points	S3	1

E. Data Analysis Techniques (RQ5)

The results in Table XIV show that data mining (S3, S8, S12, S16, S17) is the most common data analysis technique for edge computing on vessels. Other common techniques include task scheduling to work with position data (S1), user tasks (S2, S14) or intercept point (S3), data filtering (S6, S12, S15, S16), data analysis (S8, S15, S17), and resource allocation (S4, S9)

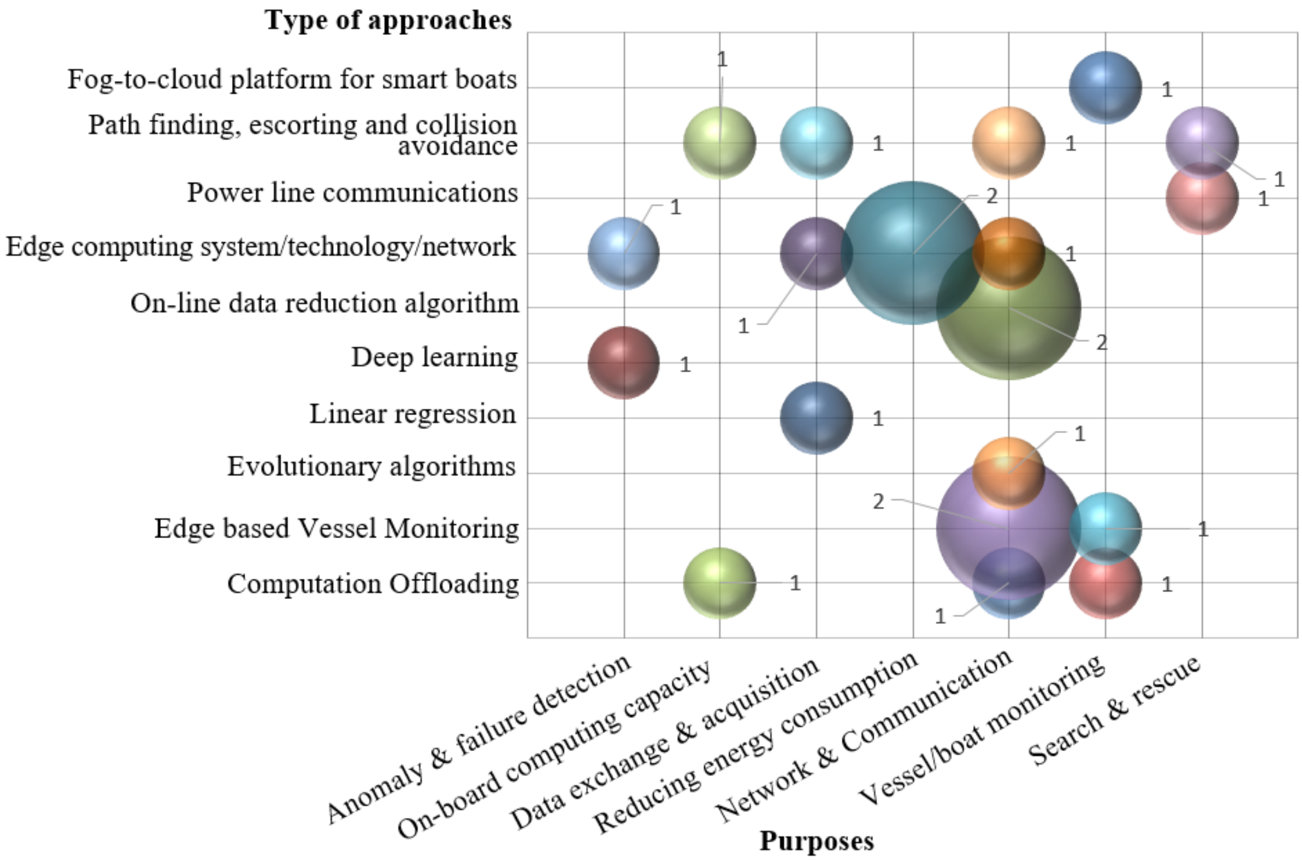

Fig. 2. Types of edge computing approaches and purposes of using edge computing on vessels

while working with ship speed or position data. Furthermore, four studies (S7, S10, S11, S13) did not specify any data analysis technique.

TABLE XIV
DATA ANALYSIS TECHNIQUES FOR EDGE COMPUTING ON VESSELS

Data analysis technique	**Study IDs**	**Count**
Data mining	S3, S8, S12, S16, S17	5
Task scheduling	S1, S2, S3, S14	4
Data filtering	S6, S12, S15, S16	4
None	S7, S10, S11, S13	4
Data analysis	S8, S15, S17	3
Resource allocation	S4, S9	2

Figure 3 shows the close connection between the data and the way it is analyzed. It can be observed that there are some commonly used techniques for different data sets, but no high-liners through the results. The bubble plot shows that there are several research gaps with respect to the types of data used for edge computing on vessels including ship speed, cargo sensing, ship-to-ship/shore communication, and equipment condition data. With respect to data analysis techniques, several studies focused on data mining and analysis. We decided to separate these two categories, even though data mining can be classified as a subset of data analysis. Studies that focused on data mining used different types of data include generic ship data (S8, S16), intercept point (S3), crash site data (S12), and ship navigation data (S17). In addition, some data analysis techniques also make use of vessel position and sea and weather data (S15). Other prominent data analysis techniques include data filtering techniques, resource allocation techniques, and task scheduling and processing techniques. One of the data filtering techniques also makes use of cargo sensing data (S16). Similarly, one of the resource allocation techniques uses ship speed data (S9). Equivalently, some task scheduling and processing techniques use user task data (S2, S14).

F. Standards, Regulations, and Protocols (RQ6)

Table XV categorizes the primary studies on the basis of standards, regulations, protocols, and conventions used in operation and experimental evaluation. The results are also graphically presented in Figure 4. Some of the regulations that we found include Regulation Number 1380/2013 - Common Fishery Policy (S6), Obligation of Using Vessel Monitoring System in Specific Countries (S7), Safety of Life at the Sea, International Convention for the Prevention of Pollution from Ships (S8), EU-MRV - Europe Union Monitoring, Reporting Verification, and NMEA 2000 Protocol (S16), among others. In addition, 9 out of 17 studies did not specify any applicable standard, regulation, protocol, or convention.

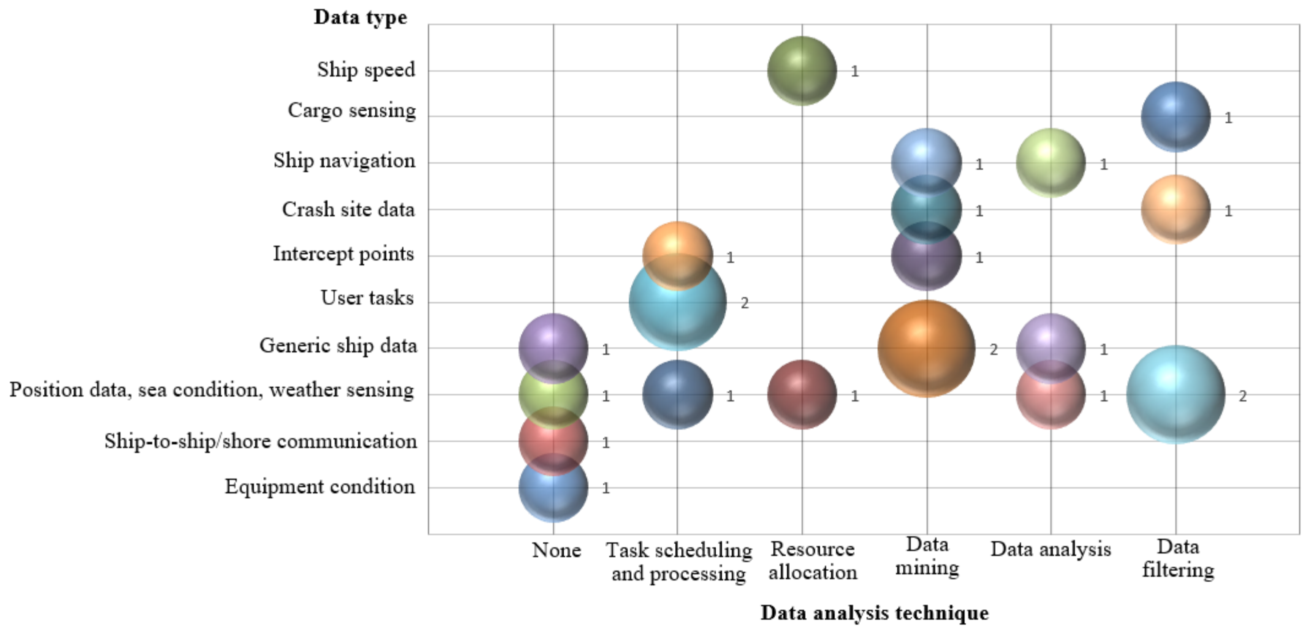

Fig. 3. Types of data and data analysis techniques

TABLE XV
STANDARDS, REGULATIONS, AND PROTOCOLS

Standard/regulation/protocol	Study IDs	Count
None	S1-S5, S9, S12-S14	9
Protocol	S7, S10, S11, S15, S16	5
Regulation	S6, S7, S15, S16	4
Convention	S8, S17	2
Standard	S8	1

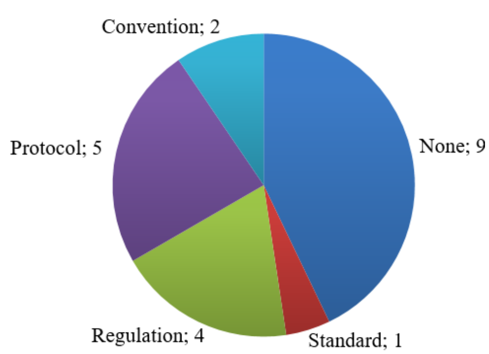

Fig. 4. Standards, regulations, or protocols related to the system setup

G. Evaluation Methods (RQ7)

We also extracted data in order to categorize the studies according to the evaluation methods they used. From the 17 studies, 14 developed simulations for the experimental evaluation, while 2 studies developed working prototypes. One study did not present any simulation or prototype implementation. Moreover, S10 used the NS 2.35 simulator, while S15 used the NS2 network simulator.

TABLE XVI
EVALUATION METHODS

Evaluation method	Study IDs	Count
Simulation	S1-S8, S10, S12-S15, S17	14
Prototype	S11, S16	2
None	S9	1

IV. VALIDITY EVALUATION

The first major threat to the validity of the results presented in this paper is related to the coverage of the relevant literature. To mitigate this threat, we designed a comprehensive search strategy based on the SLR and SMS guidelines in [14], [23]. The search terms were extracted from the RQs and the search strings were validated against a set of recent and prominent works on edge computing for maritime applications. The search was performed in seven major digital libraries.

The second threat is related to the selection of the primary studies. The results show that 128 out of 160 papers were excluded in the title and abstract level screening. It is possible that some relevant papers were erroneously excluded during the initial screening phase. To mitigate this threat, two researchers (Andrei-Raoul Morariu and Adnan Ashraf) independently screened the titles and abstracts of all papers. The results were compared and disagreements were resolved through discussions in consensus meetings [6]. A similar approach was used in the full-text level screening phase.

The third major threat is related to data extraction and classification of studies. Differences in the classification of papers is a recurring theme in SMSs [3]. To mitigate this threat, the extracted data were compared and the differences were resolved in consensus meetings and by referring back to the original papers.

V. Conclusions

The Systematic Mapping Study (SMS) shows that the area of edge computing with application on maritime is rather new, and the research is still at an incipient stage, as in this domain, there is a rather traditional way of improving or changing the present technologies. From our SMS, we came to the conclusion that there is a small number of existing edge computing approaches for maritime applications. Most of the existing approaches focus mainly on monitoring and communication functions in vessels. The research map presented in the paper shows that several research gaps exist with respect to the types of edge computing approaches, purposes of using edge computing on vessels, types of data used for edge computing purposes, and the data analysis techniques used for edge computing on vessels.

Many existing studies focus on monitoring different parts of vessels and the network and communication functions on vessels. Therefore, monitoring and communication functions on vessels represent two important research areas where a substantial amount of research is underway. Research gaps with respect to the types of edge computing approaches include evolutionary algorithms, deep learning, and smart boat platforms. Similarly, research gaps with respect to the purposes of using edge computing on vessels include anomaly and failure detection, on-board computing capacity, energy consumption, and search and rescue operations.

Acknowledgments

Part of this work was carried out while the second author Adnan Ashraf was affiliated with Åbo Akademi University. The work was sponsored by the Finnish EDGE Analytics project, funded by Business Finland.

References

[1] R. Al-Zaidi, J. Woods, M. Al-Khalidi, K. M. A. Alheeti, and K. McDonald-Maier. Next generation marine data networks in an iot environment. In *2017 Second International Conference on Fog and Mobile Edge Computing (FMEC)*, pages 50–55. IEEE, 2017.

[2] A. Ashraf, B. Byholm, and I. Porres. Distributed virtual machine consolidation: A systematic mapping study. *Computer Science Review*, 28:118 – 130, 2018.

[3] D. Budgen, M. Turner, P. Brereton, and B. Kitchenham. Using mapping studies in software engineering. In *Proceedings of PPIG 2008*, pages 195–204. Lancaster University, 2008.

[4] M. Cankar and S. Stanovnik. Maritime iot solutions in fog and cloud. In *2018 IEEE/ACM International Conference on Utility and Cloud Computing Companion (UCC Companion)*, pages 284–289. IEEE, 2018.

[5] R. Carbone, R. Montella, F. Narducci, and A. Petrosino. Deepnautilus: A deep learning based system for nautical engines' live vibration processing. In *International Conference on Computer Analysis of Images and Patterns*, pages 120–131. Springer, 2019.

[6] T. Dybå and T. Dingsøyr. Empirical studies of agile software development: A systematic review. *Information and Software Technology*, 50(9-10):833 – 859, 2008.

[7] J. C. Ferreira and A. L. Martins. Edge computing approach for vessel monitoring system. *Energies*, 12(16):3087, 2019.

[8] G. K. Gakpo, X. Su, and C. Choi. Moving intelligence of mobile edge computing to maritime network. In *Proceedings of the Conference on Research in Adaptive and Convergent Systems*, pages 189–193, 2019.

[9] C. Han, T. Yang, S. Wei, H. Feng, J. Wang, and G. Zhang. Steering machine learning mechanism based on big data integrated cooperative collision avoidance for mass. In *International Conference in Communications, Signal Processing, and Systems*, pages 2542–2549.

[10] J. Huang, J. Wan, J. Yu, F. Zhu, and Y. Ren. Edge computing-based adaptable trajectory transmission policy for vessels monitoring systems of marine fishery. *IEEE Access*, 8:50684–50695, 2020.

[11] J.-H. Huh. Reefer container monitoring system using plc-based communication technology for maritime edge computing. *The Journal of Supercomputing*, pages 1–23, 2019.

[12] S. Jalali and C. Wohlin. Systematic literature studies: Database searches vs. backward snowballing. In *Proceedings of the 2012 ACM-IEEE International Symposium on Empirical Software Engineering and Measurement*, pages 29–38, 2012.

[13] F. Jokhio, A. Ashraf, S. Lafond, I. Porres, and J. Lilius. Prediction-based dynamic resource allocation for video transcoding in cloud computing. In *2013 21st Euromicro International Conference on Parallel, Distributed, and Network-Based Processing*, pages 254–261, 2013.

[14] B. Kitchenham and S. Charters. Guidelines for performing Systematic Literature Reviews in Software Engineering (version 2.3). Technical Report EBSE-2007-01, Keele University and University of Durham, 2007.

[15] M. Liang, X. Su, X. Liu, and X. Zhang. Intelligent ocean convergence platform based on iot empowered with edge computing. *Journal of Internet Technology*, 21(1):235–244, 2020.

[16] N. Mor. Edge computing: Scaling resources within multiple administrative domains. *Queue*, 16(6):106–116, Dec. 2018.

[17] K. Petersen, R. Feldt, S. Mujtaba, and M. Mattsson. Systematic mapping studies in software engineering. In *12th International Conference on Evaluation and Assessment in Software Engineering (EASE), University of Bari, Italy*, 2008.

[18] K. Petersen, S. Vakkalanka, and L. Kuzniarz. Guidelines for conducting systematic mapping studies in software engineering: An update. *Information and Software Technology*, 64:1–18, 2015.

[19] M. Plaza-Hernández, A. B. Gil-González, S. Rodríguez-González, J. Prieto-Tejedor, and J. M. Corchado-Rodríguez. Integration of iot technologies in the maritime industry. In *International Symposium on Distributed Computing and Artificial Intelligence*, pages 107–115. Springer, 2020.

[20] W. Shi, J. Cao, Q. Zhang, Y. Li, and L. Xu. Edge computing: Vision and challenges. *IEEE internet of things journal*, 3(5):637–646, 2016.

[21] X. Su, L. Meng, and J. Huang. Intelligent maritime networking with edge services and computing capability. *IEEE Transactions on Vehicular Technology*, 69(11):13606–13620, 2020.

[22] M. Usman, E. Mendes, F. Weidt, and R. Britto. Effort estimation in agile software development: A systematic literature review. In *Proceedings of the 10th International Conference on Predictive Models in Software Engineering*, PROMISE '14, pages 82–91, New York, NY, USA, 2014. ACM.

[23] C. Wohlin, P. Runeson, M. Höst, M. C. Ohlsson, B. Regnell, and A. Wesslén. *Experimentation in Software Engineering*. Springer-Verlag Berlin Heidelberg, 1 edition, 2012.

[24] J. Xie, J. Luo, Y. Peng, S. Xie, H. Pu, X. Li, Z. Su, Y. Liu, and R. Zhou. Data driven hybrid edge computing-based hierarchical task guidance for efficient maritime escorting with multiple unmanned surface vehicles. *Peer-to-Peer Networking and Applications*, pages 1–11, 2020.

[25] F. Xu, F. Yang, C. Zhao, and S. Wu. Deep reinforcement learning based joint edge resource management in maritime network. *China Communications*, 17(5):211–222, 2020.

[26] T. Yang, H. Feng, C. Yang, Y. Wang, J. Dong, and M. Xia. Multivessel computation offloading in maritime mobile edge computing network. *IEEE Internet of Things Journal*, 6(3):4063–4073, 2018.

[27] T. Yang and X. S. Shen. Mission-critical search and rescue networking based on multi-agent cooperative communication. In *Mission-Critical Application Driven Intelligent Maritime Networks*, pages 55–76. Springer, 2020.

[28] T. Yang and X. S. Shen. Multi-vessel computation offloading in maritime mobile edge computing network. In *Mission-Critical Application Driven Intelligent Maritime Networks*, pages 37–53. Springer, 2020.

[29] T. Yang, Y. Zhang, and J. Dong. Collaborative optimization scheduling of maritime communication for mobile edge architecture. In *2018 IEEE International Conference on RFID Technology & Application (RFID-TA)*, pages 1–5. IEEE, 2018.

[30] F. Zhu, Y. Ren, J. Huang, J. Wan, and H. Zhang. An edge computing-based framework for marine fishery vessels monitoring systems. In *International Conference on Collaborative Computing: Networking, Applications and Worksharing*, pages 201–214. Springer, 2019.