Assessing a UAS for Maritime Firefighting and Rescue on Ro-Ro Ships

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Abstract

This paper details the development and onboard evaluation of an Unmanned Aerial System (UAS) specifically designed for maritime firefighting and rescue operations on roll-on/roll-off (ro-ro) ships. Emphasizing the use of open hardware and software, the study focuses on the operational practicality and legal fesibility of a UAS prototype. The assessment of the UASs performance is multifaceted, incorporating expert surveys and a SWOT analysis. Key findings demonstrate the significant potential of UASs in augmenting maritime safety and emergency response capabilities. The paper provides insights into broader opportunities for integrating UAS technology in maritime operations, highlighting its role in enhancing the efficiency and effectiveness of critical maritime functions.

Figure 1: Visual and thermal image of DFDS Petunia Seaways by the UAS prototype (height cropped). Bunker tank visible on left end of thermal image.

1. Introduction

The development of automated systems for emergency fire situations is a key element in reducing response time, improving the safety of humans and assets, and reducing intervention costs [1, 2]. The use of Unmanned Aerial Vehicles (UAVs) provides several advantages in hard to reach areas, surveillance, and supporting humans during fires by monitoring with a free line-of-sight. However, using these systems in maritime environments poses unique challenges due to adverse weather conditions and high-risk scenarios like fires or emergencies at sea. Conventional methods for surveillance, firefighting, and rescue operations show limitations in terms of accessibility and response time. The advent of Unmanned Aerial Systems (UASs) technology offers a promising enhancement, providing extended capabilities for rapid response, real-time surveillance, and effective resource management. In this context, integration of UASs into maritime operations can significantly augment safety protocols and operational efficiency.

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The utilization of UASs in maritime operations represents a paradigm shift in addressing complex and critical missions. Within the LASH FIRE EU project [3], an international research initiative on reducing the risk of fires on board roll-on/roll-off (ro-ro) ships, the possibility of adding a UAS as part of the fire and rescue arsenal was studied. The primary objective of this research is the prototyping and evaluation of a UAS tailored to the maritime environment, capable of performing automated fire patrols, aiding in fire resource management, and executing search and rescue missions. Thus, a UAS was designed and eventually tested onboard the DFDS Petunia Seaways to patrol the ship and support with identifying abnormal temperatures. Figure 1 shows a snapshot of the visual and thermal image of the ship during testing. This paper briefly introduces the high-level technical design of the UAS and the use cases' technical feasibility. The main focus lies on a usefulness assessment and SWOT analysis, thus, we present the following contributions:

- Assessment of an open UAS design for maritime use[1].
- Expert survey on UAS usefulness.
- Analysis of legal compliance and SWOT analysis.

1.1. Related Work

UASs in maritime operations have been explored for enhancing safety and efficiency, particularly in fire management and search and rescue missions. Jeong et al. (2022) presented an Unmanned Aerial Vehicle (UAV) with a robotic arm for firefighting, featuring enhanced operational capabilities such as payload delivery and high-altitude worker assistance [4]. UAV applications in hazardous environments have been expanded by Irimia et al. (2019), who showcased their utility in augmenting rescue team safety [5]. Kardasz et al. (2016) discussed UAVs in public services, outlining their practicality and associated risks [6].

Yanmaz et al. (2018) emphasized the potential of UAV networks in coordinated disaster relief [7], while Zaw et al. (2017) focused on marine UAVs' wireless communication in offshore settings [8]. The concept of maritime UAS services ecosystem was explored by Muhammad and Gregersen (2022), identifying its contributions and challenges [9].

Queralta et al. (2020) proposed the AutoSOS platform, utilizing edge computing and AI for maritime search and rescue, enhancing the operational scope of UASs [10].

The presented work further explores the use of UASs for the maritime use cases defined in the following section by introducing a UAS prototype for feasibility and usefulness assessment. Through practical on-ship demonstrations and a SWOT analysis, our research aims to provide strategic insights into UAS deployment in maritime settings, addressing gaps in field validation and user-centered evaluations.

2. Use Cases and Requirements

2.1. Fire Patrol

The primary use case for the UAS aboard a ship within this study is for fire patrol. This use case is critical given the complex and hazardous environment of maritime settings, where traditional fire detection and control methods can be challenging due to limited view and accessibility. The UAV is designed to periodically and automatically patrol the weather deck of the ship, utilizing its visual and thermal camera to detect signs of fire. In the event of a fire, the UAV can quickly relay precise location data to the bridge, enabling swift action to control and extinguish the fire.

[1]Software available online: https://github.com/RISE-Dependable-Transport-Systems/ControlTower

2.2. Fire Resource Management

In the second use case, the UAS plays a pivotal role in fire resource management. Once a fire is detected, the UAS assists in assessing the situation and providing real-time data, which is crucial for strategizing firefighting efforts. This includes evaluating the fire's spread, effectiveness of firefighting measures, and identifying safe routes for firefighting personnel. This real-time assessment helps in optimizing the allocation of resources and personnel, thereby enhancing the efficiency and effectiveness of firefighting operations.

2.3. Search and Rescue Missions

The third use case involves search and rescue missions, where the UAS's capabilities can significantly impact the success of these operations. In maritime disasters, time is of the essence, and the UAS's ability to quickly survey large areas of the ship or surrounding water can be life-saving. While this use case is not the focus of this study, the UAS can identify individuals in need of rescue with its thermal camera and relay their locations to rescue teams. This capability not only speeds up the rescue process but also increases the safety of rescue personnel by providing them with critical information about hazardous areas or conditions.

3. UAS Development and Feasibility for Maritime Operations

Our development of a UAS for maritime operations focused on enhancing safety and operational efficiency on roll-on/roll-off ships. The UAS was designed using open hardware and software based on the Pixhawk ecosystem [11] to support fire patrols, resource management, and search and rescue missions under the stringent requirements posed by the maritime environment. Key requirements include precise positioning, reliable long-range communication, and the ability to operate in adverse weather conditions up to Beaufort force 6 "strong breeze" and 7 "near gale", while ensuring high-quality imaging for both visual and thermal cameras. The technical considerations are presented very concisely in the following, the full details are described in our project report [12].

The system architecture integrates an "Acecore Zoe" [13] quadcopter with GNSS-based navigational capabilities and the "HereLink" [14] communication system, ensuring robust control and video links in the 2.4 GHz ISM band even under electromagnetic interference from ship systems (e.g., radar). The quadcopter is equipped with a combined visual and thermal camera system for comprehensive imaging, mounted on a gimbal for stable, high-quality data capture. The UAS employs a ground station "ControlTower" that serves as the control hub, ensuring high data throughput and real-time operational control, critical for tasks like automated fire detection and coordinating rescue missions. It utilizes MAVSDK [15] and our open-source prototyping library WayWise [16] to control the UAV to fulfill the use cases presented in Section 2.

Technical feasibility assessments confirm that the UAS meets the necessary operational capabilities, including precise positioning and path following relative to the ship. However, further developments are required in automated take-off and landing systems to ensure reliability on moving ships. Initial field tests have demonstrated the system's potential, yet highlight the need for long-term evaluation of automation and weather resilience to meet all operational requirements. Our approach not only considers stringent maritime safety standards but also leverages open hardware and software to ensure adaptability and ease of integration with existing ship systems. The ongoing development and testing aim to refine the UAS's capabilities, focusing on robustness, crew interaction minimization, and operational reliability in challenging maritime conditions.

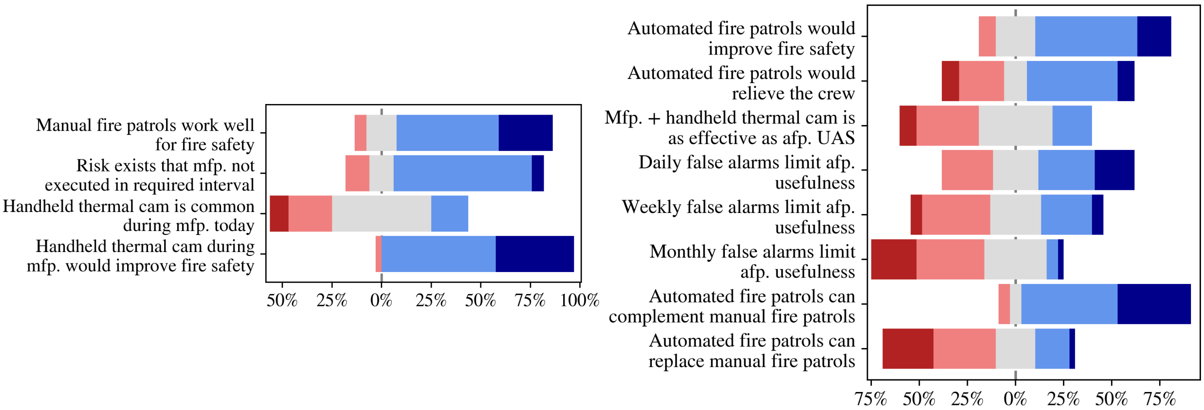

Figure 2: Likert results on manual fire patrols (mfp.) and automated fire patrols (afp.)

4. Assessment of Usefulness

This section presents a detailed assessment of the usefulness of the developed UAS prototype for maritime fire patrol, fire resource management and rescue operations. The assessment is based on a survey conducted among LASH FIRE partners, the Swedish Maritime Administration, and maritime experts within RISE Research Institutes of Sweden. Participants partly represented the potential customers and partly potential providers of such a system. The survey aimed to capture insights into the perceived effectiveness, practicality, and potential impacts of the UAS in maritime settings.

The survey was designed to collect both qualitative and quantitative data from a diverse group of respondents, including maritime professionals, researchers, and managers. The survey contained Likert scale questions ranging from 'strongly disagree' (represented by dark red in Figures 2 to 5) to 'strongly agree' (dark blue), with varying shades indicating degrees of agreement or disagreement, including neutral (grey). Further included were open-ended responses, visual aids such as videos showing UAV take off and landing on ship, visual and thermal camera recordings taken by the UAS, and screenshots of the ControlTower interface. Questions are presented in slightly shortened form for brevity, the full survey including videos is available online[2].

The survey collected responses from 34 participants, providing a varied perspective on the system's potential. Their professional backgrounds spanned across maritime operations and UAS technology, offering a broad spectrum of insights into the applicability of the UAS in maritime environments.

4.1. Use Case Analysis

For each use case presented in Section 2, the survey presented a section that introduced the UAS's role in textual and video format. Each of the three videos gave an impression of how the system might look like when used on ship.

4.1.1. Fire Patrols

For this use case, first manual fire patrols were assessed, followed by the potential of automating them (with a UAS as one option). Results indicate mixed views on the effectiveness of manual fire patrols, see Figure 2. Although a significant majority (approx. 79%) acknowledge their safety benefits, an almost equal proportion (approx. 76%) raises concerns regarding inconsistent execution. Notably, nearly all respondents (approx. 97%) see the potential enhancement of patrols with handheld thermal cameras, yet their current use is limited, with only 19% reporting

[2]https://forms.office.com/r/e9gSAGA3m9

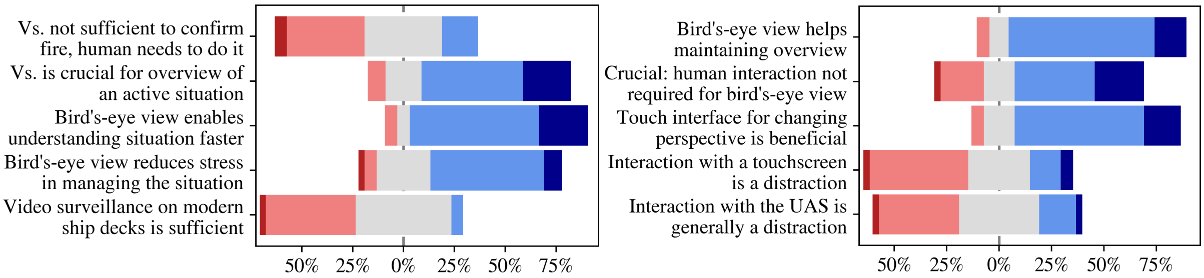

Figure 3: Likert results on video surveillance (vs.) and controlling the UAS in fire resource management

common usage. Comments left by half of the participants highlight the varied implementation of fire patrols, often encompassing broader safety checks. However, risks such as human error and insufficient coverage due to suboptimal routes or complacency were also mentioned.

Results regarding automated fire patrols indicate general endorsement (see Figure 2), with a substantial majority (71%) recognizing the potential to enhance fire safety on the weather deck. Opinions on the ability to alleviate crew workload were mixed, with 56% of participants agreeing, while 32% disagreed. Interestingly, the majority of respondents (41%) did not believe that manual fire rounds using handheld thermal cameras could perform as effectively as automated fire patrols, a notable 38% remained neutral, about 21% considered both approaches equally effective. False warnings by the automated system were seen critical in perceived usefulness. While 59% agreed that monthly false warnings would not significantly impact the system's utility, this tolerance decreased with increased frequency of false alarms, as 50% agreed that daily false warnings would undermine the system's effectiveness (24% neutral). Most respondents (88%) agreed that automated fire patrols can be a complement to manual patrols, rather than a complete replacement, which was met with skepticism, indicated by 59% negative responses.

Additional comments from 14 participants, emphasized the value of automated fire patrols as a complement rather than a replacement for manual patrols. This perspective was underpinned by the perceived necessity of retaining human oversight and the importance of direct communication among crew members. While acknowledging the current limitations of technology, there was an underlying optimism about the potential of automation to reduce human error, with the anticipation of ongoing technological advancements.

4.1.2. Fire Resource Management

The fire resource management section paralleled the fire patrol section's structure, starting with textual and video introductions, followed by two Likert scale-rated statements. The first set of statements addressed managing active situations through video surveillance, while the second focused on UAS control.

Video surveillance on ships received generally positive feedback (see Figure 3), with approx. 74% of participants agreeing on its crucial role in providing an overview of active situations. Approx. 88% believed that a birds-eye view could expedite understanding and manage situations, though nearly half (approx. 47%) felt that current video surveillance is insufficient on modern ships. A considerable number of participants (approx. 18%) thought that a human needs to confirm a fire and that video surveillance is not sufficient, while 44% disagreed with this statement. Comments from thirteen participants suggested that the UAS offers a beneficial perspective in emergencies, potentially improving the chances of winning the battle. However, concerns were raised regarding its operation under adverse weather conditions. Additionally, there were doubts about its effectiveness in monitoring closed decks, where fires often originate from.

Most participants (approx. 62%) emphasized the importance of minimizing human interaction with the UAS in active situations (see Figure 3). A substantial majority (approx. 79%) viewed

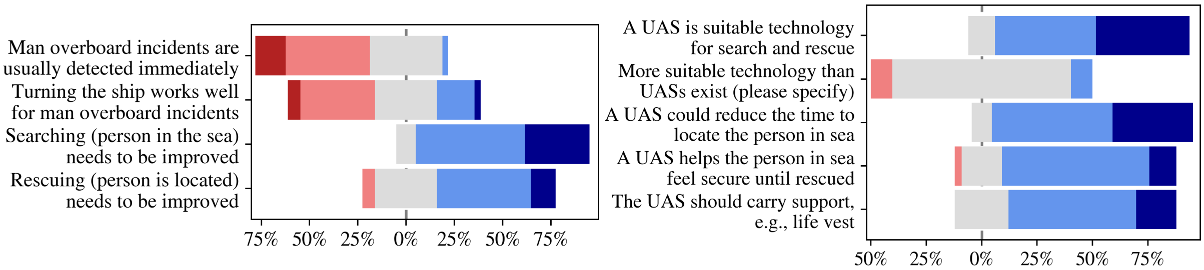

Figure 4: Likert results on the current state of search and rescue missions and the use of drones

the simple touch interface for controlling the UAS's perspective positively. However, opinions on a touchscreen's potential to distract the crew were mixed, with half of the participants not considering it a distraction, while about 21% did. A similar percentage viewed the UAS as a potential distraction overall. Comments from twelve participants highlighted that ease of use and benefits of the UAS's control vary with the crew's training and familiarity. Concerns were also raised about the UAS being perceived as a distraction or toy if the crew is not accustomed to it.

4.1.3. Search and Rescue Missions

The same pattern of the previous two sections of the survey focusing on the fire patrol and fire resource management use cases, was also used for the section on the final use case of search and rescue missions. In the first set of statements on the current state of search and rescue missions, the survey revealed that 59% of participants disagreed that that the detection of man-overboard incidents is immediate, with approx. 38% remaining neutral (see Figure 4). The effectiveness of ship maneuvers like turning during such incidents received mixed responses: 23% found them effective, while 45% did not. A significant majority (90%) agreed on the need for improved search methods for missing persons, with a similar proportion (approx. 61%) advocating for better rescue techniques. Neutral responses comprised about 32% for this need and approx. 7% disagreed. 14 participants commented the challenges in locating individuals at sea, pointing out factors like weather conditions and time of day, and the need for technological advancements in these operations.

The survey results indicated strong support for using a UAS in search and rescue missions, with 88% of respondents considering them suitable for this application. While approx. 81% remained neutral on whether UASs were the most suitable technology, approx. 10% of participants either agreed or disagreed with this statement. The comments from participants suggested that the UAV can be complemented with other technology, e.g., enabling the UAV to drop a life vest or including location devices and accelerators that could detect a fall from height in the crew members equipment. Over 76% of participants agreed that UASs could reduce search time, provide security to persons in the sea until rescue, and should carry supportive equipment like inflatable life vests. Participants also noted that man overboard incidents, often exacerbated by strong winds, could pose challenges to UAS operations. However, the presence of a UAV might offer reassurance to individuals awaiting rescue, signaling that the crew is aware of the situation.

4.2. General questions on use of a UAS on deck

The final survey section compared the use cases and evaluated the UAS using various question types. Ranking the use cases, the majority (75%) selected search and rescue as the most promising use case, followed by fire patrol (approx. 18%) and fire resource management (approx. 6%). Both fire patrol and resource management were similarly ranked as the second most promising. Further potential use cases mentioned in comments are checking for cargo shifts during strong weather and observation of evacuation situations.

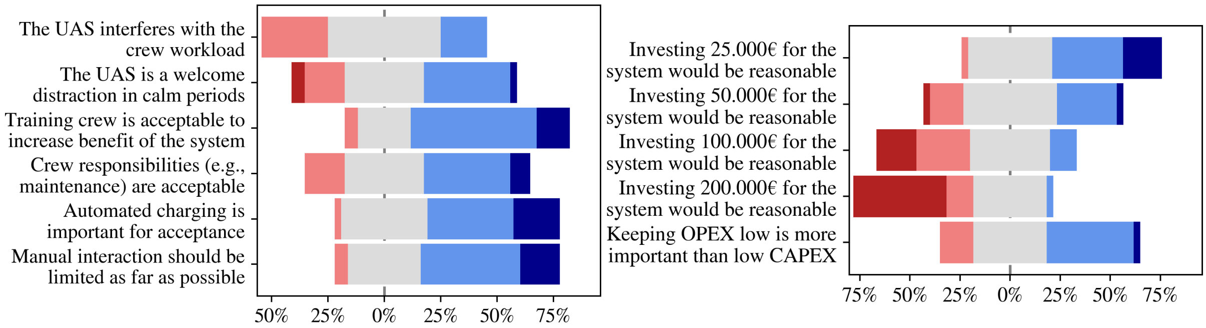

Figure 5: Likert results on time allocation and expenditures for a UAS

4.2.1. Technical and Operational Challenges

Regarding time allocation for the UAS (see Figure 5), approx. 30% of participants anticipated it would impact the crews workload, with approx. 21% disagreeing and half remaining neutral. Around 41% viewed the UAS as a potential welcome distraction, yet approx. 24% disagreed. Training for the crew to enhance system benefits received strong support (approx. 71% agreement), while additional responsibilities elicited mixed responses (approx. 47% agreement, 18% disagreement). Limiting manual interaction was favored by approx. 62%, emphasizing the need for automation. Automated charging, rather than manual battery swaps, was considered important by approx. 59%.

Trust in the UAS hinges on reliability under adverse conditions, with participants highlighting the importance of minimizing false alarms, weather resistance, ease of use, and a high level of cybersecurity in their comments. Crew acceptance, facilitated by their involvement in the adoption process, was also deemed essential for building trust in the system.

4.2.2. Cost Considerations and Market Potential

In assessing UAS expenditures (in price points 2022, see Figure 5), participants expressed varying levels of acceptance towards different investments. While approx. 55% found investing EUR 25,000 reasonable, only 3% deemed it unreasonable. The acceptance decreased with higher amounts, with approx. 33% agreeing to EUR 50,000, but 20% finding it unreasonable. A significant majority, approx. 47%, considered EUR 100,000 unreasonable, and for EUR 200,000, 60% disagreed with the investment.

Nearly half of the participants (approx. 45%) prioritized keeping operational expenditures low over initial investment costs, with approx. 17% disagreeing. Comments highlighted challenges in estimating a reasonable cost, emphasizing the need for clear benefits to justify investments, especially given the regulatory risks and uncertainties surrounding UASs in maritime contexts.

4.2.3. Net Promoter Score (NPS)

Finally, the participants rated the likeliness of UASs playing a role in improving safety on ship within the next 5 to 10 years on a scale of 1 to 10. On average, the likeliness was rated at 6.97.

The NPS, a market research tool that tries to estimate business growth as a result of customer experience [17]. It is calculated by grouping the received ratings into Detractors (rating 1 to 6), Passives (rating 7 to 8) and Promoters (rating 9 to 10). The percentage of Detractors is then subtracted from the percentage of Promoters. Usually, the result is compared to competitors, but in our case, there were no obvious competitors. The results was -20%, suggesting that when relying on the impression of the UAS on the participants of this questionnaire, the business of UASs for improving safety on a ship as presented would not grow, because there are too few people promoting their use and too many having a sceptical or negative opinion.

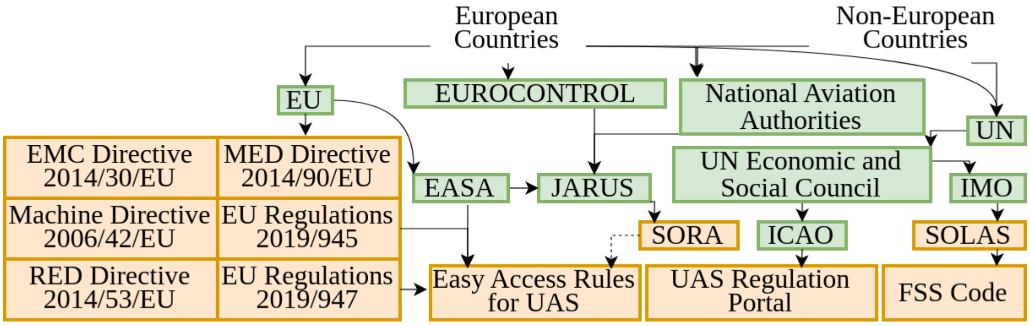

Figure 6: Regulatory framework for UASs in maritime applications. Regulation bodies and organisations in green, regulations and rules in yellow.

4.3. Key Insights

The questionnaire results reveal a practical outlook on the UAS. Key insights include:

- Fire Patrols: UASs are valued for complementing manual fire patrols, with a need to reduce false alarms and enhance trust in the system.
- Fire Resource Management: Improved video surveillance with UASs can speed up situational response, necessitating minimal manual intervention.
- Search and Rescue: This emerged as the most promising use case, with UASs potentially speeding up person localization and providing immediate assistance.

Effective crew training and system familiarization are essential for seamless UAS integration. Weather-related concerns and cost factors are notable, with a suggested price cap of EUR 50,000 for a certified system. Building trust with ship operators and crew is crucial, focusing on robustness, usability, and extended operational capabilities.

Overall, despite cost and trust challenges, the UAS is regarded as a beneficial asset for maritime safety, suggesting favorable market acceptance regardless of its negative NPS.

5. Legal Feasibility and Regulations

The deployment of UASs for maritime applications, particularly for fire prevention and firefighting on ships, falls under a complex regulatory framework. Figure 6 outlines the regulatory framework from an EU context. The Regulations 2019/947 and 2019/945 establish a framework for the safe operation of UASs within EU airspace. These are covered in EASA's "Easy Access Rules for UAS" [18] together with related acceptable means of compliance and guidance material. Further, the EU directives on machinery (2006/42/EC)[3], electromagnetic compatibility (EMC 2014/30/EU), and radio equipment (RED 2014/53/EU), mandate compliance for CE-marking, ensuring health, safety, and interoperability.

The Marine Equipment Directive (MED 2014/90/EU), and the International Convention for the Safety of Life at Sea (SOLAS) [19] along with the International Code for Fire Safety Systems (FSS code) [20], prescribe performance and testing standards for marine equipment including UASs deployed on ships. The MED demands that marine equipment meets specified safety and performance standards. The UAS may interface with a decision management system, provided it meets compatibility requirements and maintains the fire detection system's integrity.

EU Regulation 2019/947 defines three categories of civil UAV operations: the open, the specific and the certified category. Automated UAVs, as well as UAVs heavier than 4 kg operating

[3]The directive 2006/42/EC is to be replaced by Regulation (EU) 2023/1230 applying from 20 January 2027 with some articles applying earlier.

close to people, fall into the 'specific' category [21] and require authorization from the National Aviation Authority (NAA) via a Predefined Risk Assessment (PDRA) or Specific Operations Risk Assessment (SORA). Exceptions occur if a European Standard Scenario (STS) is applicable or if the operator holds an appropriate Light UAS operator Certificate (LUC). Geographical zones may impose additional restrictions requiring authority approval. While EU airspace extends over territorial waters, regulations for international waters differ and must be considered.

In conclusion, while the legal operation of UASs in the EU appears feasible, obtaining operational authorization is a complex process. A collaborative approach with ship operators and classification societies is recommended to navigate the regulatory landscape effectively and advance the practical deployment of UASs for maritime safety applications.

6. SWOT Analysis

This SWOT analysis, derived from the feasibility and usefulness assessments presented in the previous sections, evaluates the internal and external factors influencing the UAS designed for maritime firefighting and rescue operations. The analysis also considers current market trends to identify opportunities and threats as presented in Table 1.

Table 1
SWOT analysis of a UAS for improving safety on ship for the presented use cases

STRENGTHS	WEAKNESSES
1. **Unique Bird's-Eye View:** Provides a powerful feature in various situations, crucial for rapid localization and situational assessment. 2. **Life-Saving Capabilities:** Enhances the speed of localizing missing persons and fire detection, potentially saving lives and protecting property. 3. **Reduction of Human Error:** Helps avoid human errors in existing safety procedures. 4. **Technical Feasibility:** Achievable using off-the-shelf components and open standards. 5. **Maintenance Integration:** Can be combined with other scheduled maintenance activities. 6. **Versatility for Additional Use Cases:** Applicable in various scenarios like evacuation management, inspections, and aiding in navigation. 7. **Adaptability:** Suitable for offshore contexts, extendable to onshore applications.	1. **Considerable Investment:** Requires significant financial resources for development and integration. 2. **Regulatory and Integration Challenges:** Time-consuming and complex processes involved in regulation compliance and system integration. 3. **Safety Risks:** Particularly associated with take-off, landing, and charging operations. 4. **Weather Dependence:** Performance is subject to weather conditions; weather resistance is a cost factor. 5. **Limited Monitoring:** Primarily effective on open decks, with reduced utility in enclosed spaces. 6. **Flight Time Limitations:** Restricted operational duration, further reduced in adverse weather conditions. 7. **Usability and Training Needs:** High usability demands comprehensive crew training. 8. **Manual Interaction:** Essential to keep manual interaction minimal, promoting automation. 9. **False Alarm Minimization:** Necessitates reduction of false positives to enhance system credibility.
OPPORTUNITIES	**THREATS**
1. **Expanding UAS Market:** Drives down costs, leads to improved products. 2. **Growing UAS Services:** Emergence of servicing and repair markets helps in maintaining low operational expenses. 3. **Developing Airspace Regulations:** Evolving regulations facilitate the integration of UAV-based services. 4. **Maritime Digitization and Automation:** Trend towards increased digital and automated solutions in the maritime industry.	1. **Regulatory Influences:** Revised maritime regulations, like SOLAS, could significantly affect the system's adoption. 2. **Trust and Perception:** Public perception and trust in the system are crucial but can be easily undermined by adverse events.

Strengths: UAS offers a unique birds-eye view, unachievable with traditional surveillance, enhancing safety in search and rescue, fire detection, and resource management. Constructed from off-the-shelf components and open standards, it promises technical feasibility, versatility and adaptability.

Weaknesses: The development of a fully certified UAS faces time and cost challenges, compounded by the need for rigorous safety testing, especially for critical operations like take-off, landing, and charging. Limited to open-space operations, the UAS faces constraints in flight duration, particularly under adverse weather conditions. Crew trust and minimal false alarms are crucial for effective deployment, necessitating comprehensive training and limited manual intervention.

Opportunities: The rapidly growing UAS market suggests declining costs and technological advancements, enhancing product safety and performance. The expansion of UAV servicing markets aids in reducing operational costs. Evolving airspace regulations and the maritime industry's shift towards digitization and automation create conductive environments for the integration of UAS-based services.

Threats: Changes in maritime safety standards, like SOLAS, could impact the UAS's relevance and adoption. The fragility of trust in emerging UAS technologies, susceptible to negative incidents, underscores the need for testing and adherence to regulations.

In summary, the SWOT analysis highlights the UAS's potential in enhancing maritime safety and operational efficiency, but also underscores the challenges in investment, regulation, and trust. Successfully navigating these factors is critical for the system's adoption and effectiveness in maritime applications.

7. Conclusion

This study assesses a UAS prototype for maritime operations on ro-ro ships, targeting fire patrol, fire resource management, and search and rescue. Developed using open standards and software, the UAS demonstrates technical feasibility through limited onboard tests, highlighting needs for further development in automated landing and weather resistance.

The legal feasibility analysis within the EU suggests partnering with ship owners and classification societies for operational authorization. A survey with maritime experts shows positive reception, particularly for search and rescue, but identifies challenges in cost and trust.

The SWOT analysis summarizes these insights for strategic planning by potential UAS providers. Conclusively, the UAS shows promise in enhancing maritime safety, but future work includes extensive testing and collaboration for technology validation and trust building in the maritime industry.

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