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Integration of an optoelectronic surveillance system with an artillery radar station to optimise ship self-defence in mine detection

Abstract. The purpose of the study was to analyse ways to improve the efficiency and accuracy of interaction between optoelectronic systems (OES) and radar stations (RLS) on ships to improve anti-aircraft fire systems in self-defence zones. Various approaches were used approaches to analyse data integration, automate processes, and optimise communication between systems based on theoretical models and practical examples of interaction between ship systems. The study showed that the integration of OES surveillance with RLS on ships significantly increases the accuracy of target detection and the effectiveness of anti-aircraft fire systems in war zones. It was found that synchronisation of data with the OES and RLS provides faster identification of threats, especially in difficult weather conditions or with limited visibility. Data processing algorithms are analysed, which significantly improve noise filtering and the accuracy of recognising mines and other threats by improving methods for analysing signals and integrating information from various sensor systems. Automated control systems allow minimising the response time to threats, increasing the efficiency of actions. The study also found that automatic steering systems integrated with navigation and safety systems effectively reduced the risk of mine detonation through real-time manoeuvres. The methods used included dynamic positioning and automatic correction of the ship's course depending on data obtained from the OES and RLS. This contributed to a quick response to threats and increased the overall safety of ships in coastal areas. It was established that improving communication channels between systems reduces delays in data transmission, which contributes to a faster response to threats. It was found that the integration of automatic steering systems with navigation systems improves the ship's manoeuvrability and reduces the likelihood of falling into mine threat zones. The analysis showed that an integrated approach to modernising the interaction between the OES and RLS allows creating a more stable and effective ship defence system in coastal zones. The practical significance of the research lies in the potential use of the findings for the development and implementation of modern integrated ship defence systems, which contribute to enhancing ship safety in challenging conditions

Keywords: noise filtering; navigation; manoeuvrability; communication channels; coastal zone safety; automatic steering systems

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Introduction

In the modern military environment, improving the effectiveness of ship self-defence systems is an important task, especially in the context of threats from mines, missile attacks, underwater objects, and other hazards that can cause damage during navigation in coastal areas and strategically important regions. Integration of optoelectronic surveillance systems (OES) with artillery radar stations (RLS) is a key direction to achieve this goal. OES provide high-quality visual surveillance and accurate target identification, which allows detecting threats at close and medium distances. RLS, in turn, specialise in detecting objects at a long distance, including those that are under water or in conditions of limited visibility. The combination of these two technologies helps to create a comprehensive system that significantly improves the accuracy of detecting threats, such as mines. The problem of the study is the need to improve the effectiveness of interaction between the OES and RLS to improve the accuracy and speed of responding to threats in modern military conflicts. The presence of difficult weather conditions, limited visibility and risks associated with mine threats pose additional challenges to ensuring the safety of ships in coastal areas. Automation of control and data processing processes allows minimising delays and ensuring prompt response, but requires further improvement in terms of information synchronisation and integration of automatic steering and navigation systems. This requires a comprehensive approach to modernising defence systems to improve their effectiveness and security in the face of rapidly changing threats.

A study of this topic showed that a number of researchers have already explored various aspects of integrating these technologies. X. Zhou *et al*. (2021) focused on automating data processing and integrating control systems, which can significantly improve the efficiency of responding to threats. Their research has demonstrated improved accuracy due to reduced information processing time, but does not fully cover the impact of automation on integration with OES. F. Mercaldo & A. Santone (2021) explored new signal processing algorithms to reduce noise and improve the accuracy of threat recognition. Although their results showed a significant improvement in noise filtering, there are gaps in integrating these algorithms with the new sensors.

H. Bounaceur *et al*. (2022) analysed the operation of improved radars in conditions of limited visibility, which confirmed an increase in their effectiveness in detecting threats. However, aspects of RLS integration with OES were rather neglected. L. Chang *et al*. (2022) focused on control automation and its impact on response speed, but their study does not fully cover the integration of these systems into integrated defence solutions. V. Mashtalir *et al*. (2023) considered the integration of sensor systems for integrated ship protection. Their results showed the advantages of this approach, but did not consider the impact of data synchronisation on overall security under specific coastal conditions.

M. Lanza *et al*. (2022) also made significant contributions to sensor system integration research, showing the benefits of new technologies for reducing data transmission delays and improving efficiency. However, these studies do not fully cover the issues of interaction between different technologies in real-world settings. O. Melnyk *et al*. (2022a) investigated automatic steering systems and their impact on ship manoeuvrability, finding that their integration with navigation systems reduces the risk of mine strikes. E. Ali *et al*. (2021) examined the impact of new technologies on reducing data transmission delays, which is critical for timely response. J. Zhang *et al*. (2021) focused on improving signal processing algorithms and integrating information from various sensor systems, which can significantly improve the accuracy of threat detection in complex environments. The study by M. Fathi *et al*. (2022) demonstrated the advantages of new approaches to data processing in difficult weather conditions, but did not fully consider the integration of the latest sensors with existing control systems. These studies confirm the importance of integrating OES and RLS to improve defence efficiency, but also point to the need to further explore integrated solutions and integrate new technologies to achieve optimal results in real-world conditions.

The purpose of the study was to analyse methods for improving the interaction between OES and RLS on ships to improve the accuracy and effectiveness of anti-aircraft fire systems in self-defence and combat zones.

Materials and Methods

In this study, a comprehensive approach was applied to analyse methods for improving the interaction between optoelectronic systems (OES) and radars on ships, in particular in conditions typical of self-defence zones near the coast of Ukraine. Modern data processing methods were used to assess the integration of OES and RLS. In particular, noise filtering using adaptive filters was used to improve the separation of useful signals from noise. Data fusion algorithms, such as clustering and synchronisation algorithms, allowed the integration of information from different sensor systems. And the introduction of automated data processing technology helped to optimise the collection and analysis of information in real time.

Integration was carried out based on marine equipment, which are used on coastal defence ships, including:

- OES “Sarmat-2”, “Sens-2”, and “Spin”, which were developed by the State Enterprise Research Institute “Kvant” (Ukraine);
- radar system “Delta-M” by the State Enterprise Research Institute “Kvant” (Ukraine).

Special attention was paid to systems that can operate in conditions of limited visibility and complex electronic conditions.

To test the effectiveness of system integration, combat simulations were conducted using virtual reality and computer modelling technologies. This made it possible to create conditions as close to real life as possible and to assess: the accuracy of target detection and identification, the speed of system response to threats, the effectiveness of combining data from the UES and radar, and the performance of anti-aircraft fire systems in real time. The performance of the signal processing algorithms, interference immunity and ability to operate in low visibility conditions were tested in simulated conditions in coastal areas, analysing threat scenarios such as mine threats or drone attacks. The main methods for improving signal processing algorithms focused on filtering out noise that interferes with accurate determination of target coordinates, and optimising algorithms for integrating data from both systems.

The study tested a system for automatically determining safe routes in high-risk areas. It included the integration of self-driving systems with navigation systems, anti-aircraft fire control systems, information systems for collecting and processing data from the power grid and radar. The integration of these systems ensured: real-time data visualisation on interactive displays, timely detection of threats, coordination of crew actions and automated systems for rapid response to dangerous situations.

The following calculations based on equations were used in the study. The equation for calculating the synchronisation delay time of signals from two sources has the form (1):

$$t_{sync} = t_{OES} - t_{RLS}, \quad (1)$$

where: t_{sync} – time for signal synchronisation; t_{OES} – signal transmission time from the OES; t_{RLS} – time of signal transmission from the RLS.

An important stage was the introduction of an automated fire control system. The system used machine learning algorithms to quickly identify threats and classify objects. For this purpose, algorithms based on conditional probability were used according to the Bayes method (2):

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}, \quad (2)$$

where: $P(A|B)$ – probability that the threat is a mine, provided that the data obtained; B, $P(A)$ – probability of a threat; $P(A|B)$ – probability that the data reflects a mine.

The automated fire control system has reduced delays in responding to threats due to fast data processing. Autosteering systems adjusted the ship's course to avoid threats detected by the OES and RLS. Manoeuvring was provided based on the projected mine rate according to equation (3):

$$\Delta\theta = \frac{d_{min}}{\vartheta_{ship}} \cdot \cos(\alpha), \quad (3)$$

where: $\Delta\theta$ – course change angle; d_{min} – distance to the mine threat; ϑ_{ship} – ship speed; $cos(\alpha)$ – angle between the ship and the mine threat.

Results

For modern defence systems, it is important to ensure a high level of accuracy and effectiveness in detecting and neutralising threats, especially in conditions of combat operations in coastal areas. One of the key factors influencing the increase in the combat readiness of ships is the integration of the OES and RLS (Kari *et al.*, 2023). OES and RLS used on warships have various advantages and limitations. Combining their capabilities through synchronisation and collaborative data processing is a necessary step to improve the effectiveness of anti-aircraft fire systems.

OES and RLS systems play a key role in improving the effectiveness of self-defence systems of the Ukrainian naval forces. Among the main representatives of the OES are "Sarmat-2", "Sens-2", and "Spin", which were developed by the State Enterprise Research Institute "Kvant". Table 1 shows the main OES and RLS systems, their technical characteristics, advantages and disadvantages.

Table 1. Main OES and RLS systems

System name	Type	Main technical characteristics	Advantages	Disadvantages
Sarmat-2	OES	Thermal imager with cooled receiver, TV camera with varifocal lens	High sensitivity, auto-tracking ability	High cost, need for regular maintenance
Sens-2	OES (modification "Sarmat-2")	Predictor sight, manual control	Flexibility in operation, possibility of manual mode	Dependence on manual control
Spin	OES	Standard elements for integrating firepower	Easy integration with other systems	Limited features in poor visibility conditions
Delta-M	RLS	Detection of targets over long distances	High detection range, stable operation	Vulnerability to obstacles and masking goals

Source: compiled by the authors based on S. Voronkov (2020)

The "Sarmat-2" system is equipped with a thermal imager with a cooled receiver and a television camera with a varifocal lens, which provides high sensitivity and the ability to auto-track targets. It allows controlling the fire of medium-calibre artillery and increases the effectiveness of combat in conditions of limited visibility. Modification "Sens-2" has a long-angle sight and the possibility of manual control, which makes it especially useful in situations where automatic mode may not be appropriate. The "Spin" system is easy to integrate with other systems, but its capabilities are limited in conditions of poor visibility. RLS that operate based on radio wave reflection remain effective even at night or in adverse weather conditions such as fog or rain. They provide threat detection over long distances and demonstrate high stability, but may be vulnerable to masking targets. Integration of the OES with the RLS creates a comprehensive surveillance system that functions continuously, even in difficult conditions. Due to the combination of data from both systems, maximum efficiency is achieved: information from the OES can be supplemented with data from the RLS, which increases the accuracy and reliability of determining the coordinates of objects and threats (Majors & O'Neil, 2021).

An important issue in the integration of the two systems is the synchronisation of signals received from OES and RLS sensors, and the assessment of the impact of the delay in their receipt on the overall efficiency of interaction between these systems. To do this, it is important to determine specific delay time values between signals. The synchronisation delay time between the OES and RLS signals was determined using equation (1). During the study, the arrival time of the signal from the OES was 5×10^{-5} seconds, and from the RLS – 5.001×10^{-5} seconds, then:

$$t_{sync} = t_{OES} - t_{RLS} = 5 \times 10^{-5} - 5.001 \times 10^{-5} = -1 \times 10^{-8} \text{c}.$$

This result showed that the delay between signals was very small and was only -1 nanosecond, and therefore, the data transfer rate remained at a fairly high level. According to the research, optimising synchronisation between these systems can significantly reduce the time required to detect, identify, and target a threat, which is especially important in conditions of limited visibility, where the accuracy of threat recognition is crucial. In coastal waters where the presence of mines and small objects can lead to serious consequences, a quick and accurate system response is vital. Rapid detection of the exact location of threats allows quickly responding and use anti-aircraft fire systems with maximum efficiency. In addition, integration reduces the burden on operators responsible for monitoring and analysing threats. A system that automatically combines data from OES and RLS can provide operators with more accurate and coordinated information about potential threats, making decision-making easier (Zhang *et al.*, 2022). Therefore, the introduction of data synchronisation and co-processing methods between OES and radars is an important step to improve the accuracy of threat detection and improve the effectiveness of ship defence systems.

Automating processes in controlling artillery systems on ships can significantly improve the efficiency and speed of responding to threats (Brown *et al.*, 2021). For this purpose, it is important to implement modern algorithms that allow automatic processing of data from OES and RLS. However, to understand how accurately automated systems can identify threats, it is necessary to consider a probabilistic approach, in particular, Bayesian inference. The probability that the detected object is a mine threat can be calculated using equation (2). In particular, in the current study, the probability that an object is a mine threat before receiving a signal is 0.4 (or 40%), the probability of receiving a signal from an object if it is really a mine threat is 0.9 (or 90%), and the overall probability of receiving a signal from an object (regardless of its type) is 0.5 (or 50%), then:

$$P(A|B) = \frac{0.9 \cdot 0.4}{0.5} = 0.72.$$

Therefore, in the current study, the probability that an object is a mine threat, provided that a signal is received, is 0.72, or 72%. In general, the accuracy of object identification using OES is very high, and when using artificial intelligence, it exceeds 90%. The accuracy of OES identification depends on the resolution of cameras, infrared and thermal imaging sensors, and computer vision algorithms that allow achieving 90-95% accuracy for well-defined objects. Radar identification is limited to general categories of objects, with an accuracy of 70-80%. These systems are primarily designed to fix an object and determine its trajectories. The integration of OES and RLS allows to achieve a high level of threat identification accuracy – 95-98% in favourable conditions, reducing the likelihood of false identification, which is important for optimizing ship self-defence systems. In particular, the probability of detecting a threat if a signal is received is crucial for an effective response in coastal areas, where even small errors can lead to serious consequences. To achieve high accuracy and quality of threat detection, the technical performance of both systems is important.

High-quality OES systems provide accuracy of up to 0.01-0.05° in determining angular coordinates, depending on the resolution of sensors such as infrared, ultraviolet, or daytime cameras. OES can detect targets at distances of up to several tens of kilometres, but atmospheric conditions such as fog or rain can affect the range. The error of visual detection methods is several metres, which can affect the accuracy of threat assessment. Modern radars can determine the angular coordinates of targets with an accuracy of 0.1-1°, which depends on the frequency of operation and signal strength. Radars are capable of detecting targets at distances of up to several hundred kilometres (for large objects), and the accuracy of measuring the range can reach several metres. For ultra-high-frequency radars, the error is 5-50 metres, while for millimetre waves it can be only a few centimetres. Combining these technologies reduces the overall error rate. The RLS provides accurate distance and speed detection, while the OES improves the accuracy of angular coordinates and target recognition (Ballan *et al.*, 2024). Based on this integration, the total error can be reduced to 1-5 metres in distance and 0.01-0.1° in angle. Due to this approach, automated systems are able to better classify objects and respond more quickly to threats, which ensures a high level of ship safety in difficult conditions.

Modern autosteering systems are an important component on ships, providing automatic correction of the ship's course depending on threats detected by the OES and RLS. They can significantly reduce the risk of damage from mines or anti-aircraft fire by manoeuvring in a timely and accurate manner. Automatic course adjustment is carried out in real time, which ensures prompt response to changes in the situation around the ship. Autonomous steering systems can integrate with navigation and ship protection systems, which helps to automatically determine safe routes in areas with a high level of threat (Hanaford & Hassel, 2021). This provides an additional layer of security, as the system can process data from the OES and RLS, identify potential threats, and instantly adjust its course to avoid dangerous areas. Such integration allows the ship to manoeuvre effectively even in difficult conditions, reducing the likelihood of enemy shells hitting the ship or tripping mines. This approach significantly increases the overall effectiveness of the ship's self-defence system, ensuring a high level of safety in dangerous waters. Automated systems help to reduce the human factor in decision-making and increase the speed of response to threats, which is critical for maintaining the ship's defence capability in the face of constant risks. The characteristics of systems for improving the overall effectiveness of ship self-defence are discussed in Table 2.

Table 2. Basic control systems and their functions in ship self-defence

System	Function	Advantages
OES	Visual observation	High accuracy in the daytime and in good weather conditions
RLS	Radar detection	Can work in conditions of limited visibility
Automated control system	Control of anti-aircraft fire systems	Minimises reaction time and improves accuracy
Autosteering system	Automatic ship manoeuvring	Reduces the risk of being blown up by mines and hit by enemy shells
Navigation system	Automatic detection of safe routes	Provides security in areas with a high level of threat

Source: compiled by the authors based on G. Mander *et al.* (2023)

In general, the integration of OES, RLS, automated control systems, steering systems and navigation technologies into a single control network significantly increases the effectiveness of the ship's self-defence. This integrated system provides a timely and accurate response to a variety of threats that arise in difficult and unpredictable conditions, such as limited visibility or high levels of mine hazards. Due to this integration, management decisions are made faster, manoeuvring becomes more adaptive and accurate, and the risk of damage is significantly reduced. This creates a more stable and reliable defence system that can effectively protect the ship in all situations, increasing its survivability and efficiency in coastal waters and in areas with a high level of threat.

In modern conditions of technology development, an important aspect of improving the efficiency of OES and RLS is the improvement of signal processing algorithms. One of the key problems that arise during the interaction of OES and RLS is the influence of external interference and noise on the accuracy of systems. Noise filtering is an integral part of improving signal processing algorithms, as it can significantly reduce the impact of undesirable factors on system performance. In addition, an important step in improving algorithms is to improve the accuracy of determining the coordinates of objects. Since OES provide high-resolution visual data, and radars provide stable operation in conditions of limited visibility, the combination of these advantages helps to more accurately determine the location of targets, reducing the time to make decisions in critical situations. Algorithms for integrating data from different systems are also being improved. Modern data pooling algorithms use multisensory information processing methods, which facilitates more accurate and faster coordinate determination. Combining information with OES and RLS should consider the difference in data formats and the speed of their receipt. Table 3 shows the interaction of systems on the ship and potential directions for improving signal processing algorithms.

Table 3. Interaction of systems on the ship and improvement of signal processing algorithms

System	Main function	Data type	Data processing issues	Ways to improve algorithms
OES	Visual observation	Infrared and daytime video streams, SWIR signals, laser marking signals, analogue and digital signals (voltage, current, frequency)	Noise, interference, voltage instability, limited visibility, power consumption	Noise filtering, adaptive voltage regulation, optimisation of power consumption, improvement of image processing algorithms
RLS	Object detection and tracking	Radar signals (amplitude, phase, frequency)	Noise, interference, multi-purpose echoes, coordinate errors	Improvement of signal processing algorithms, adaptive filtering, use of artificial intelligence methods for object recognition
Management system	Decision-making, movement control	Digital signals (coordinates, speed, course)	Data transfer delays, data inaccuracies, conflicting commands	Optimisation of route planning algorithms, use of neural networks for real-time decision-making
Autosteering system	Steering wheel control	Digital signals (commands to change course)	Delays in executing commands, steering instability	Improvement of control algorithms, adaptive regulation, use of ship movement models

Source: compiled by the authors based on P. Xie *et al*. (2021) and I.K. Dagkinis *et al*. (2023)

Therefore, improving signal processing algorithms is crucial for improving the efficiency of OES and RLS. Improved noise filtering, coordinate accuracy, and optimisation of data pooling algorithms allow creating a more reliable and accurate threat detection system. This, in turn, increases the level of safety of ships in coastal areas and ensures timely response to potential hazards.

Making effective decisions in a dynamic combat environment requires quick access to relevant information provided by automated systems. The interfaces of these systems should be designed in such a way as to minimise the time required to analyse the situation and make a decision. Imperfect interfaces can lead to delays in decision-making and, as a result, reduce the efficiency of task execution. Therefore, the development of ergonomic interfaces is one of the priority areas in modern research in the field of human-computer interaction (Liu *et al.*, 2022).

In addition, to ensure management flexibility, operators should be able to manually interfere with the operation of automated systems. Although automated systems can operate effectively under standard operating conditions, human intervention becomes necessary in complex and unpredictable situations. For example, an operator can manually adjust the system's actions in cases where it misclassifies a threat or skips critical data. This provides an additional level of control and reliability in the decision-making process.

The effectiveness of modern ship protection systems largely depends on optimal interaction between the operator and automated threat detection systems, such as OES and RLS. Rapid exchange of information between these systems and the operator is a prerequisite for timely response to changes in the tactical situation. Automatic control systems should be integrated into the overall control system of the ship in such a way as to ensure effective performance of tasks under all conditions. This provided real-time optimised manoeuvring based on the projected mine rate, which significantly reduced the risk of a collision. The angle of change of the ship's course was calculated using the following equation (3). For example, if the distance to a mine threat was 100 metres, the ship's speed was 20 m/s, and the angle between the ship and the mine threat was 30°, then:

$$\Delta\theta = \frac{100}{20} \cdot \cos(30°) = 4.33°.$$

This result showed that to avoid the threat, the ship had to change course by 4.33°. This was especially important in high-risk conditions, when even minor manoeuvres could help to avoid a collision with a mine or other obstacles.

Operators must quickly analyse the situation and make informed decisions based on data coming from the OES and RLS (Höffmann *et al.*, 2021). For modern defence systems, it is important to ensure a high level of accuracy and effectiveness in detecting and neutralising threats, especially in conditions of combat operations in coastal areas. One of the key factors for improving the combat readiness of ships is the integration of OES and RLS. Data synchronisation between these systems can significantly improve the speed of threat identification and accurate detection, even in difficult weather conditions.

The introduction of automated control and autosteering systems that can quickly respond to threats minimises response time. Automation and improvement of signal processing algorithms play a key role in improving the accuracy of these systems, which, in turn, reduces the risk of damage to ships and increases their efficiency in difficult coastal conditions.

Discussion

The combined use of OES and RLS technologies has significantly improved the accuracy of determining the location of sea mines. OES uses highly sensitive cameras, including day, night and thermal imaging, which helps to visually identify mines on the water surface by temperature differences. Due to its high resolution, OES systems can identify even small objects with an accuracy of several metres, automating the image analysis process using machine vision and artificial intelligence algorithms. RLS, in turn, are capable of detecting both underwater and surface objects, providing high accuracy in determining their location with the possibility of penetration into the surface layers of water. This allows quickly tracking moving mines, significantly expanding the detection area. Integration of OES and radar provides more efficient solutions to mine detection problems. First, the radar quickly detects suspicious objects at a long distance, then the OES clarifies identification, reducing the likelihood of false positives and allowing the crew to make decisions more quickly. Automated object recognition, based on data from both systems, increases situational awareness and helps to clearly classify threats. Due to the integration of these technologies, the response time was optimised, and the overall level of safety of ships was significantly increased.

This was also investigated by M. Zhang *et al.* (2021), where the results confirmed that data processing and integration between OES and RLS is critical to improving the effectiveness of air defence. The introduction of synchronisation and collaborative data processing methods allows combining information from both systems to quickly identify threats and improve the accuracy of determining target coordinates. Data synchronisation helps to avoid delays and errors that may occur when using individual systems, and provides a faster and more accurate response to threats.

G. Wu *et al.* (2021) also showed that the integration of OES and RLS can effectively combine the advantages of both technologies. OES provides high resolution and accuracy in conditions of good visibility, which contributes to clear identification of targets. In turn, radars demonstrate high efficiency in difficult weather conditions, such as fog or night darkness, where visibility is limited. Based on this integration, a significant improvement in target detection and maintenance is achieved, which is crucial for ensuring reliable protection in difficult conditions. It is worth noting that the integration of OES and RLS combines the advantages of both technologies: OES provide high resolution with good visibility, and RS are effective in conditions of limited visibility, such as fog or night. This significantly improves target detection and tracking.

The integration of these systems requires proper crew training and the development of intuitive interfaces for rapid information analysis. In addition, it is critical to ensure data security and stability of communication between systems, since the risks of cyber-attacks can significantly affect efficiency. Integration of OES and RLS is a strategic step in the development of the fleet's defence capability, but its implementation requires a comprehensive approach and careful analysis of possible challenges. The study showed that OES provided more detailed information about targets, which allowed reducing the load on the RLS. Thus, the crews were able to respond to threats in a timely manner, relying on visual information, which significantly improved the quality of operational management. This synergy between the two systems has significantly improved the detection of underwater objects, providing more detailed information about the situation around the ship.

The results of this study are consistent with the conclusions given in the paper by X. Wu *et al*. (2021), as improvements in algorithms for detecting small objects in coastal areas significantly improve the accuracy of threat detection, and reduce the likelihood of errors, which makes systems more efficient and efficient in responding.

The results of the study open up a broad discussion about the importance of integrating modern technologies in military operations. As threats in the marine environment become more complex, it is important to adapt control systems to new challenges. Integration of OES and RLS can significantly improve detection capabilities, but continuous improvement of data processing algorithms is necessary to achieve optimal results. The analysis of the data obtained highlights the importance of combining OES surveillance with artillery radars to improve the self-defence of ships, in particular, when searching for mines. This integration of technologies opens up new opportunities for improving the security of naval operations, requiring continuous improvement of systems to ensure their effectiveness in modern military conflicts. It is also worth noting that the results obtained confirmed the possibility of improving the efficiency of defence systems by simultaneously using OES and RLS. This integration significantly reduced the time required to respond to threats, which had a positive impact on the overall safety of ships when performing tasks in difficult conditions.

The study by H. Cui *et al*. (2021) found that improving signal processing algorithms is key to effectively integrating data with OES and RLS, as these systems use different types of information. Improved noise filtering reduces the impact of extraneous signals that can distort the results, while improving the accuracy of determining the coordinates of objects provides more accurate target detection. Optimising algorithms for combining data from both systems provides more comprehensive and reliable analysis, which is crucial for improving the overall efficiency of the system in the face of real threats.

In turn, E. Chiou & J. Lee (2023) concluded that improving interaction between operators and automated systems is a critical aspect for ensuring efficiency in complex air defence systems. It is necessary not only to automate processes, but also to ensure that operators have access to intuitive interfaces that provide quick access to the most important data from the OES and RLS. This helps to reduce delays in decision-making and increase the efficiency of responding to threats.

The results show that the simultaneous use of these technologies not only reduces the burden on the crew, but also optimises decision-making processes, which is crucial in difficult combat conditions. However, the implementation of these integration solutions requires further improvement of signal processing algorithms to ensure accuracy and reliability in detecting threats. An important aspect is also the need to provide intuitive interfaces for operators, as this will reduce delays in decision-making and increase the speed of responding to threats. Thus, success in implementing the integration of OES and RLS depends not only on technological improvements, but also on the readiness of crews to work with new systems. This comprehensive strategy can significantly improve the overall safety of ships in difficult operating conditions, highlighting the need for further research in this area.

An important aspect of the study was the need to adapt systems to the specific conditions in which they operate. The results showed that a variety of mine search scenarios required the configuration of integrated systems to meet specific environmental conditions. This highlighted the need for further research that would allow for a deeper study of the various situations in which systems can be optimised.

M. Del Giudice *et al*. (2022) also conducted a study, the results of which confirmed that interfaces should be user-friendly and clearly structured, which allows operators to quickly analyse information and make decisions based on data from systems. Operators should be able to intervene manually if necessary to adjust automated actions or respond to unforeseen situations. This approach provides a balance between automation and human control, which is critical for effective management in the face of rapidly changing threats.

S. Krile *et al*. (2021) also found that the modernisation of communication and network interaction is an important step to ensure the efficient operation of the OES, RLS, and other systems of the ship. The introduction of high-speed data channels will facilitate rapid exchange of information between these systems in real time, which is crucial for timely response to threats. In addition to speed, special attention should be paid to the security of networks to prevent cyber-attacks and unauthorised access that could disrupt the operation of systems.

The variety of scenarios that can occur when searching for mines requires a deeper understanding of environmental conditions and adaptation of systems to these conditions. It is also important to note that user-friendly and clearly structured interfaces for operators are critical, as they allow quickly analysing data and making informed decisions. A balance between automation and human control is essential for responding to unforeseen situations, which can be key in the context of rapidly changing threats. Modernisation of communication tools and the introduction of high-speed data channels also play an important role in ensuring the efficiency of these systems, since the speed of information exchange is crucial for timely response. However, network security is critical to preventing cyber-attacks, which can significantly threaten the security of systems. Therefore, further research in this area is needed to develop optimal solutions that ensure the reliability and effectiveness of integrated defence systems.

Analysis of the results confirmed the importance of integrating OES surveillance with RLS to optimise the self-defence of ships when searching for mines. This combination of technologies opens up new opportunities for improving the safety of naval operations, requiring further development and improvement of these systems to ensure their effectiveness in war conditions.

O. Melnyk *et al*. (2022b) found that integrating upgraded communications equipment into the overall network of the ship's combat control system is also a priority. This will ensure synchronisation between the OES, RLS, and other important elements of the ship's defence, such as fire support and missile defence systems. The coordinated operation of all these systems will improve the overall defence capability and increase the effectiveness of protecting the ship in combat conditions.

It should be noted that the modernisation of communication and network interaction is a necessary condition for improving the effectiveness of ship defence systems. Fast and secure data transmission between OES and RLS can significantly reduce the time spent on information processing and decision-making, which is critically important in real combat operations. Synchronisation of all elements through a single network increases the reliability and efficiency of responding to threats, improving the overall level of protection of the ship.

In general, the results obtained confirmed the potential of integration of OES and RLS in improving the safety of naval operations and the requirements for further development of these technologies in modern combat operations.

Conclusions

The study confirmed the effectiveness of integrating OES surveillance with artillery radars to optimise the self-defence of ships when searching for mines. Synchronisation of data between these systems has improved the accuracy of threat detection in difficult conditions, such as limited visibility or worse weather conditions. The use of OES helped to reduce the response time to potential hazards, since improving the efficiency in processing and transmitting information made it possible to minimise delays. Automation of control processes in combination with integrated automatic steering systems increases the manoeuvrability of ships, which reduces the risk of falling into mine threat zones. Improved coordination systems between various defence subsystems have increased the effectiveness of air defence in coastal zones of Ukraine. This integration allowed for more reliable self-defence of ships, reducing overall vulnerability to external threats. A comprehensive approach to modernising the ships' defence systems has shown significant potential in improving their security. Improved interaction between the radar and OES made it possible to optimise the functioning of anti-aircraft fire systems, which increased the speed and accuracy of responding to threats, thereby reducing risks for ships in high-risk areas.

Thus, the results of the study indicate a high efficiency of integrating OES surveillance with artillery radars to improve the safety of ships when performing tasks in minefields. The data obtained confirm the need for further development and improvement of technologies for integrating surveillance and defence systems to ensure more reliable protection of ships from modern threats, in particular, unmanned aerial vehicles, cruise missiles, underwater sabotage forces, and conventional air and sea attacks. In the face of growing security challenges, particularly in coastal areas, it is important to ensure synchronisation and effective interaction between OES and RLS. Such integration will help to quickly identify threats, increase the accuracy of target detection and speed of response, which are critical aspects for the successful implementation of combat missions. Systematic improvement of these technologies will contribute to strengthening the defence capabilities of naval forces and improving the level of security in areas of potential conflict.

To further improve the integration of OES surveillance with artillery RLS, it is necessary to investigate their effectiveness in real combat operations, in particular, when countering dynamic threats and sudden changes in the tactical situation.

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Conflict of Interest

None.

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Інтеграція оптико-електронної системи спостереження з артилерійською радіолокаційною станцією для оптимізації самооборони кораблів при пошуку мін

Анотація. Метою дослідження було проаналізувати способи підвищення ефективності та точності взаємодії між оптико-електронними системами (ОЕС) і радіолокаційними станціями (РЛС) на кораблях для вдосконалення зенітно-вогневих систем у зонах самооборони. Були проаналізовані процеси інтеграції даних, автоматизації і оптимізації комунікації між системами на основі теоретичних моделей і практичних прикладів взаємодії корабельних систем. Дослідження показало, що інтеграція ОЕС спостереження з РЛС на кораблях значно підвищує точність виявлення цілей і ефективність зенітно-вогневих систем у зонах бойових дій. Встановлено, що синхронізація даних з ОЕС та РЛС забезпечує швидшу ідентифікацію загроз, особливо у складних погодних умовах або при обмеженій видимості. Проаналізовані алгоритми обробки даних, які значно покращують фільтрацію шумів і точність розпізнавання мін та інших загроз завдяки вдосконаленню методів аналізу сигналів і інтеграції інформації з різних сенсорних систем. Автоматизовані системи керування дозволяють мінімізувати час реакції на загрози, підвищуючи оперативність дій. Дослідження також виявило, що автоматичні рульові системи, інтегровані з навігаційними системами та системами захисту, ефективно зменшували ризик підриву на мінах завдяки маневрам, оптимізованим у реальному часі. Використані методи включали динамічне позиціонування та автоматичне коригування курсу корабля залежно від даних, отриманих від ОЕС і РЛС. Це сприяло швидкому реагуванню на загрози та підвищувало загальну безпеку кораблів у прибережних зонах. Встановлено, що удосконалення комунікаційних каналів між системами забезпечує зниження затримок у передачі даних, що сприяє оперативнішому реагуванню на загрози. Виявлено, що інтеграція автоматичних рульових систем з навігаційними системами покращує маневреність корабля і знижує ймовірність потрапляння в зони мінних загроз. Аналіз показав, що комплексний підхід до модернізації взаємодії між ОЕС та РЛС дозволяє створити більш стійку і ефективну систему оборони кораблів у прибережних зонах. Практична цінність дослідження полягає у можливості використання отриманих результатів для розробки та впровадження сучасних інтегрованих систем оборони кораблів, що сприяють підвищенню рівня безпеки кораблів у складних умовах

Ключові слова: фільтрація шумів; навігація; маневреність; комунікаційні канали; безпека прибережних зон; автоматичні рульові системи