DOI 10.52171/herald253
UDC 622.276

Automated Systems for Applying Reagents for Oil Spill Elimination

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Abstract

The article discusses the development and application of an automated oil spill response system using drones and autonomous underwater vehicles (AUVs). The system is based on mathematical models for optimizing drone trajectories and reagent dosage, as well as machine learning algorithms for adapting the system's actions in real time depending on sensor data and the spread of the oil slick. This allows for increased spill response efficiency, reduced reagent consumption, and minimized impact on the ecosystem. The article highlights the technological features of the system, including the use of GPS and infrared sensors, as well as machine learning methods for predicting the spread of pollution and dynamically adjusting the system's actions**.**

Keywords: automation, oil spills, drones, autonomous underwater vehicles, mathematical modeling, reagents, environmental safety.

Submetted *11 Nov 2024*
Published *17 Mar 2025*

For citation:
V.A. Kuznetsov, S.H. Gasimov
[Automated Systems for Applying Reagents for Oil Spill Elimination]
Herald of the Azerbaijan Engineering Academy, 2025, vol. 17, №1, pp. 129-136

Neft dağılmalarına cavab üçün reagentlərin tətbiqi avtomatlaşdırılmış sistemleri

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Xülasə

Məqalədə dronlardan və avtonom sualtı nəqliyyat vasitələrindən (AUVs) istifadə edərək neft dağılmalarına cavab üçün bir metod hazırlanıb və adaptiv sistem tətbiq edlib. Sistem dronların trayektoriyalarını və reagentlərin dozasını optimallaşdırmaq üçün riyazi modellərə, həmçinin sensor məlumatlarından və neft dağılmalarının yayılmasından asılı olaraq sistemin hərəkətlərini ilk anda uyğunlaşdırmaq üçün maşın öyrənmə alqoritmlərinə əsaslanır. Bu, dağılmalara cavab tədbirlərinin səmərəliliyini artırmağa, reagentlərin istehlakını azaltmağa və ekosistemə təsirini minimuma endirməyə imkan verir. Məqalədə, həmçinin sistemin texnoloji xüsusiyyətləri, o cümlədən GPS və infraqırmızı sensorların istifadəsi, həmçinin çirklənmənin yayılmasının proqnozlaşdırılması və sistem hərəkətlərinin dinamik tənzimlənməsi üçün maşın öyrənmə üsulları haqda məlumatlar əks olunub.

Açar sözlər: avtomatlaşdırma, neft dağılmaları, dronlar, avtonom sualtı nəqliyyat vasitələri, riyazi modelləşdirmə, reagentlər, ekoloji təhlükəsizlik.

Автоматизированные системы нанесения реагентов для ликвидации разливов нефти

В.А. Кузнецов, С.Г. Гасымов

Аннотация

В статье рассматривается разработка и применение автоматизированной системы реагирования на разливы нефти с использованием дронов и автономных подводных аппаратов (АПА). В основе системы лежат математические модели для оптимизации траекторий дронов и дозировки реагентов, а также алгоритмы машинного обучения для адаптации действий системы в реальном времени в зависимости от данных с датчиков и распространения нефтяного пятна. Это позволяет повысить эффективность ликвидации разливов, снизить расход реагентов и минимизировать воздействие на экосистему. Освещены технологические особенности системы, включая использование GPS и инфракрасных датчиков, а также методы машинного обучения для предсказания распространения загрязнения и динамической корректировки действий системы.

Ключевые слова: автоматизация, разливы нефти, дроны, автономные подводные аппараты, математическое моделирование, реагенты, экологическая безопасность.

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2025, vol. 17, № 1, pp. 129-136
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Introduction

Automated systems for oil spill response are becoming increasingly popular due to their accuracy and high efficiency. Oil spills pose a serious threat to the marine ecosystem, and their prompt elimination requires the use of advanced technologies. This paper discusses the OSAD system, which integrates drones and autonomous underwater vehicles (AUVs) to distribute reagents such as dispersants and sorbents. These unmanned devices are equipped with GPS systems, optical and infrared cameras, and sensors that allow you to accurately determine the spill boundaries and control the supply of reagents [1].

The use of mathematical models to calculate the trajectory of drones and adaptive dosing of reagents increases the efficiency of cleaning and reduces the burden on the environment [2]. The OSAD system is an innovative solution that combines environmental safety, precise resource management, and the ability to quickly adapt to spill conditions.

Purpose of the work

The aim of this work is to develop mathematical models for an automated oil spill response system (OSAD) utilizing drones and autonomous underwater vehicles (AUVs) to optimize flight trajectories of drones and the dosage of reagents for oil spill remediation. The task is to ensure the precise, cost-effective, and environmentally safe distribution of reagents in contaminated waters, which will improve system efficiency and minimize environmental impact. To achieve this goal, algorithms need to be developed that consider oil concentration, contamination parameters, and dynamically adaptive control methods based on sensor data, enabling real-time system adjustments. The proposed methods will contribute to more accurate and efficient reagent distribution, minimize reagent consumption, and accelerate contamination remediation, which is especially important in remote and hard-to-reach areas.

Problem statement

The objective of this work is to develop mathematical models for an automated OSAD system using drones and AUVs to optimize the trajectories and dosage of reagents for oil spill response. The objective is to ensure accurate, cost-effective and environmentally friendly distribution of reagents in contaminated waters [3, 4].

Research methods

To achieve this goal, mathematical modeling and algorithmic analysis methods are used. Equations have been developed to calculate drone trajectories and reagent dosage taking into account oil concentration. Machine learning algorithms are used to adapt parameters in real time, as well as sensor data to control reagent distribution [1].

Scientific novelty

The scientific novelty of the work lies in the development and implementation of adaptive mathematical models for managing autonomous systems used in oil spill response. For the first time, algorithms for optimizing drone trajectories and reagent dosage have been integrated, allowing for minimizing resource consumption and increasing distribution accuracy. In addition, the use of machine learning algorithms for dynamically

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predicting the spread of oil slicks and adjusting the actions of drones and AUVs based on sensor data in real time is proposed [2, 3]. These innovations are aimed at ensuring environmental safety and increasing the efficiency of cleaning, which allows expanding the capabilities of existing technologies for use in complex and hard-to-reach areas [4].

Research and Discussion

The OSAD system study included simulations and field tests to evaluate the accuracy of reagent distribution and adaptive control in real oil spill conditions. The developed mathematical models allowed optimizing the trajectories of drones and autonomous underwater vehicles (AUVs) taking into account the area of the contaminated zone and oil density [5]. The use of hydrocarbon concentration sensors and machine learning algorithms provided effective adaptive control of reagent dosage depending on changes in the contamination level. Optimization of UAV flight routes for oil spill monitoring is an important task to ensure maximum coverage and minimize flight time. Optimization of UAV flight routes for oil spill monitoring involves taking into account many factors, such as the size of the study area, spill characteristics, meteorological conditions, and the features of the unmanned aerial vehicle itself. First of all, it is necessary to assess the geographic location of the spill using geographic information systems (GIS) to accurately calculate the size of the area requiring monitoring. It is also important to consider the impact of weather conditions such as wind and waves, which can affect the flight path, speed and energy consumption. For example, strong winds may require route adjustments to maintain optimal speed and accuracy [6].

Given the characteristics of the drone itself, such as maximum speed, range and flight duration, it is important to integrate these parameters into the route model to ensure maximum coverage and minimize flight time. To optimize the trajectory, methods such as genetic algorithms or the nearest neighbor method are used, which help calculate the route with minimal energy consumption [7].

In addition, real-time data analysis systems can be used to adjust the route depending on changes in weather conditions and spill characteristics. These systems allow the flight path to be dynamically adapted and ensure maximum efficiency in oil spill monitoring [8].

Figure shows an unmanned aerial vehicle (UAV) designed to monitor and eliminate oil spills at sea.

Figure – UAV for oil spill response

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The device is made in an aerodynamic shape, which allows the drone to have greater maneuverability and stability in flight, especially in wind and wave conditions. The body of the device contains cameras and sensors for collecting data on the spill, including water temperature, hydrocarbon content and other important parameters.

The propeller system located on the base of the drone provides vertical takeoff and landing, which is convenient for working in confined spaces and hard-to-reach areas. Additional sensors for analyzing the state of the water or even specialized devices for spraying chemical reagents to neutralize oil pollution are installed on the bottom of the device [9].

In addition, the unmanned aerial vehicle (UAV) is equipped with an OSAD system, which allows real-time data transmission for monitoring and analyzing the situation from ground stations or from a ship [10]. A powerful battery or solar panel system ensures a long flight, which is especially important when conducting long-term operations to monitor and treat large oil spill areas. To develop the OSAD system, a mathematical model of automated reagent application was created, including the following stages:

Trajectory optimization stages:

<u>1. Determining the coverage area and the trajectory grid</u>. The drone coverage area for one pass is defined as:

$$S = W \cdot d$$

where W is the width of the coverage strip for one pass, and d is the distance traveled by the drone per unit of time.

<u>2. The problem of minimizing the coverage time</u>. Let the drone speed be *v*. Then the total coverage time to cover the entire area of the slick *A* is defined as:

$$T_{total} = \frac{A}{v \cdot S}$$

<u>3. The wave tracing method.</u> The wave tracing method is used to minimize the coverage time. At each step, the algorithm plots the drone's trajectory from the center of the slick to the boundaries, covering areas with the maximum concentration of oil in stages. The grid area *A* is divided into small elements, and the algorithm determines which elements need to be covered first.

For each element i of the slick area, the time it takes the drone to reach the element from the current position is determined:

$$T_i = \frac{d_i}{v}$$

where d_i is the distance from the current position of the drone to element iii.

<u>4. Calculating the time of complete coverage</u>. The algorithm estimates the sum of the Topt time for all elements i, optimizing their coverage in such a way as to minimize

T_{Total}:

$$T_{opt} = \sum_{i-1}^{n} T_i = \sum_{i-1}^{n} \frac{d_i}{v}$$

where n is the number of passes required to cover the entire area of the slick.

<u>5. Selecting the optimal trajectory</u>. The optimal trajectory is selected when Topt reaches a minimum value, ensuring maximum efficiency of covering the entire area of the slick:

$$T_{\min} = \min(\sum_{i-1}^{n} \frac{d_i}{v})$$

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Thus, the wave tracing method minimizes the time of complete coverage of the slick by choosing the shortest path between elements with a high concentration of oil, ensuring efficient distribution of reagents on the contaminated surface.

6. Calculation of the concentration and spray rate of the reagent. To ensure the effectiveness of oil slick neutralization, the concentration of the reagent Creg per unit area must be sufficient. The mass of the reagent Mreg required to cover the area A is calculated as:

$$C_{reg} = \frac{M_{reg}}{A}$$

To maintain a certain concentration Ctarget, the reagent flow rate Q is determined by the formula:

$$Q = C_{reg} \cdot v \cdot W$$

where W is the width of the drone coverage strip.

7. Optimization of the dosage based on sensor data. For adaptive control of the reagent supply, sensors are used that determine the concentration of oil Coil in the spill area. The dosage adaptation algorithm can be described as follows:

$$R = \alpha \cdot (C_{oil} - C_{reg}) + \beta$$

where α and β are adjustment coefficients that determine the accuracy and sensitivity of the system. This approach allows you to adapt the reagent dosage in real time, increasing the cleaning efficiency.

8. Chemical reaction model. Oil neutralization can be described as a first-order reaction:

$$\frac{dC_{oil}}{dt} = -k \cdot C_{oil} \cdot C_{reg}$$

where k is the reaction rate constant. This equation allows us to predict the change in oil concentration over time and calculate the time required to reach an environmentally safe level.

Research results

The study assessed the efficiency and accuracy of the automated reagent application system (OSAD), and compared it with traditional oil spill response methods (tables 1-3).

Table 1 – Indicators of reagent distribution accuracy and efficiency

Parameter	**Drone speed (m/s)**	**Coverage time (min)**	**Number of reagent doses (l)**	**Coverage area (m²)**	**Distribution accuracy (%)**
Initial conditions	5	20	50	200	85
Optimized trajectory	7	15	40	200	95
Increased speed	10	10	35	200	90
Additional sensors	5	18	42	200	98

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Table 2 – Comparison of reagent costs between traditional and OSAD methods

Method	Coverage area (m²)	Reagent amount (l)	Reagent savings (%)
Traditional methods	200	60	-
OSAD system	200	40	33
Traditional methods	500	150	-
OSAD system	500	100	33

Table 3 – Results of path optimization using wave tracing

Spill scale (m²)	Coverage time without optimization (min)	Coverage time with optimization (min))	Time reduction (%)
200	20	15	25
500	45	30	33
1000	70	50	29
1500	120	80	33

These tables demonstrate the efficiency and accuracy of the OSAD system in reagent distribution, showing a significant reduction in resource consumption and coverage time compared to traditional methods.

The results show that the use of an optimized drone trajectory taking into account the wave tracing method can significantly improve the accuracy of reagent distribution (table 1). Compared to the initial conditions, with the trajectory optimization, the accuracy of reagent distribution increased from 85% to 95%, which confirms the high efficiency of the OSAD system in oil spill response. Also, due to the improved trajectory and the use of additional sensors, it is possible to ensure greater coverage accuracy even in hard-to-reach places.

According to the analysis of reagent consumption, the OSAD system demonstrated significant savings compared to traditional methods (table 2). For an area of 200 m², the reagent savings were 33%, which is also observed with an increase in the scale of the spill. The system requires less reagent for effective coverage, which reduces both economic costs and the impact on the environment.

The use of the wave tracing method made it possible to significantly reduce the time to cover the spill (table 3). For a spill of 200 m², the coverage time was reduced by 25%, for a spill of 500 m² - by 33%. This indicates a significant reduction in response time and an increase in the efficiency of the system, which is extremely important in conditions of a rapidly spreading spill. Thus, the study confirmed the high efficiency of the OSAD system, ensuring accuracy, saving resources and reducing the time of oil spill response, which makes it a promising technology for the protection of the marine ecosystem.

Environmental safety and development prospects

One of the advantages of the OSAD system is the minimization of the environmental impact on the marine environment. The system's autonomous vehicles and drones operate on energy-efficient batteries, which reduces the carbon footprint. The use of biodegradable reagent

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tanks also helps reduce the load on the ecosystem. The use of mathematical modeling to optimize dosage and trajectories, as well as the ability to analyze sensor data in real time, not only improve current spill response methods, but also create a basis for further research and technology development

Conclusion

The OSAD (Oil Spill Aerial Deployment) system is a complex that combines unmanned aerial vehicles and AUVs with modules for spraying reagents. The main components of the system include. Drones with a GPS system and spraying modules that allow precise control of the coverage area and reagent dosage. Sensors and cameras that collect data on the state of the slick and transmit information to the control platform. Autonomous underwater vehicles used to treat subsurface layers where oil could penetrate to depth. A centralized control platform that optimizes trajectories and dosage based on machine learning algorithms.

These elements allow the system to function effectively even in difficult weather conditions, providing a quick response to changing conditions and minimizing reagent consumption.

Conflict of interests

The authors declare there is no conflict of interests related to the publication of this article.

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