RIGA TECHNICAL UNIVERSITY
Faculty of Mechanical Engineering, Transport and Aeronautics
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USE OF REMOTELY PILOTED AIRCRAFTS FOR SOLVING THE TASKS OF ECOLOGICAL MONITORING OF SEA AQUATORIUM

Summary of the Doctoral Thesis

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF ENGINEERING SCIENCES

To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 30 April 2019 at the Faculty of Mechanical Engineering, Transport and Aeronautics of Riga Technical University, 8 Lauvas Str., Room 218.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Vladislavs Žavtkēvičs ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in English. It consists of Introduction; 4 chapters; Conclusions; Bibliography; 38 figures; 11 tables; 3 appendices; the total number of pages is 137. The Bibliography contains 59 titles.

TERMINOLOGY AND ACRONYMS

AMK – automated monitoring complex
ASV – automated surface vehicle
AUV – automated underwater vehicle
CEPCO – Coordinated Extended Pollution Control Operation
CSN – Clean Sea Net
EMSA – European Maritime Safety Agency
GIS – graphic information system
GPS – global positioning system
HELCOM – Helsinki Commission
IK – infrared
IMO – International Maritime Organization
LIDAR – light detection and ranging
RPA – remotely piloted aircraft
SAR – synthetic aperture radar
SLAR – side-looking airborne radar
TAS – remote aviation systems

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GENERAL DESCRIPTION OF THE THESIS

Research Topicality

The ecological status of the Baltic Sea poses serious concerns for ecologists. The main reasons are the increase in oil pollution due to the expansion of the maritime oil and gas industry and the intensity of shipping. Due to the increase in volume of transportation of oil products, the risk of oil pollution of the marine environment increases. Only in the Baltic Sea, according to the HELCOM (Helsinki Commission) statistics, there are 3 severe accidents per year leading to the leakage of oil or oil products.

The growth of oil product consumption, the production of crude oil, the creation of new transport corridors, and increased shipping traffic increase the risk of pollution of the marine aquatorium. The Baltic Sea is the most active maritime route in the world, connecting around 40 ports and terminals. According to statistics from Automatic Identification System (AIS), more than 2000 ships are routinely in the Baltic Sea. The analysis of leakage maps, the leakages detected on board of ships and shipping routes in the Baltic Sea concluded that ships are the main sources of pollution.

Shipping, including the transport of oil products, has a negative impact on the marine environment and coastal zones. In 2004, the IMO (International Maritime Organization) provisionally decided to designate the Baltic Sea as a Particularly Sensitive Sea Area (PSSA). A particularly sensitive area means that the area is particularly sensitive and endangers human activities related to shipping and maritime activities. The special status of the region at international level requires protection of the marine environment at local level. The designation of the PSSA requires that countries in the region agree on specific appropriate conservation measures to reduce environmental damage from shipping risks.

Taking into account the National Economic Development Program, which envisages to increase the turnover of ports and the volume of oil transportation, the problem of combating pollution of marine oil and oil products is one of the priorities for Latvia as well.

The solution of the problem as a whole will allow timely detection of this type of pollution using efficient marine monitoring systems.

Nowadays the operational monitoring of large areas and long districts of aquatorium for detecting pollution with oil products is being carried out using various technical equipment − satellites, seagoing ships and various aircraft. At present, the use of remotely piloted aircraft (RPA) for monitoring aquatorium is being intensively developed.

Use of remotely piloted aircraft has a number of advantages: the possibility of take-off and landing without using the aerodrome, low costs, low operating costs, no risks for pilots and the possibility of using a semi-automatic or automatic control system.

For the successful development of using RPA type airplanes and helicopters and the expansion of opportunities for monitoring marine waters, it is necessary, first of all to develop innovative methods, methodologies and tools, taking into account the technological specificities of the monitoring. Taking into account the need for automation of the monitoring procedure, special attention is also paid to optimization of RPA flight route.

AIM AND OBJECTIVES OF THE RESEARCH

Aim

The aim is to develop an innovative, unmanned aerial platform and methodology for solving the tasks of continuous monitoring of oil pollution of sea aquatorium.

Objectives

1. To perform the analysis of main tasks and methods of remote sensing monitoring of oil pollution of marine environment, and to formulate the purpose and basic tasks of the Thesis.
2. To develop a mathematical model for preparing the procedure of RPA optimal flight route during monitoring.
3. To develop an optimization algorithm of RPA flight route for performing the monitoring task and software for processing and analysis of monitoring data.
4. To develop a continuous monitoring methodology for monitoring the pollution of sea aquatorium.
5. To develop a mathematical model for the distribution of oil spill on the surface of the water.
6. To develop an unmanned aerial platform for monitoring the pollution of sea aquatorium.
7. To develop special devices and technologies for taking water samples of sea aquatorium from the remote piloted aircraft.

RESEARCH METHODS

The following methodology and research methods were used in the research:

a) analysis of sources of literature;
b) mathematical modelling;
c) mathematical programming;
d) experimental studies of oil pollution properties;
e) statistical processing of experimental results.

OBJECTS OF STUDY

- Baltic Sea aquatorium.
- Oil pollution of sea aquatorium.
- Remotely piloted aircrafts.

SCIENTIFIC NOVENTLY OF THE THESIS

Scientific novelty and the key innovations of study

As a result of the Doctoral Thesis, the following innovative solutions were developed and innovative products created:

- mathematical model for preparing the procedure of RPA optimal flight route during monitoring;
- mathematical model of distribution of oil spill on the water surface;
- continuous monitoring methodology for monitoring the pollution of sea aquatorium;
- technology for taking water samples from sea aquatorium using RPA;
- special devices for taking water samples from sea aquatorium using the remotely piloted aircraft.

THESES TO BE DEFENDED

- Mathematical model of optimal flight of RPA.
- Algorithm of RPA flight route optimization.
- Software for processing and analysis of oil pollution monitoring data of sea aquatorium.
- Mathematical model of distribution of oil spill on the water surface.
- Continuous monitoring methodology for monitoring the pollution of sea aquatorium.
- Unmanned aerial platform.
- Technology for taking water samples from sea aquatorium using RPA, and algorithm for implementing this technology.
- Special devices for taking water samples from sea aquatorium from the remotely piloted aircraft.

PRACTICAL APPLICATION OF THE RESEARCH RESULTS

The results of the Doctoral Thesis are of great practical significance and can be applied by companies and organizations responsible for water quality in sea aquatorium. Within the framework of the Thesis, a new and highly effective methodology for monitoring oil pollution of the marine environment was developed, which makes it possible to determine the characteristics of oil pollution. This methodology and the developed devices can be used for monitoring water pollution and eliminating oil spills. The developed methodology can also be used for monitoring inland waters and port waters.

APROBATION OF OBTAINED RESULTS

The main scientific and practical results of the work were presented in 5 scientific conferences.

1. 17th International Conference Transport Means, 23–24 October 2014, Kaunas, Lithuania (Urbahs, A., Zavtkevics, V. Oil pollution monitoring of sea aquatorium features with using unmanned aerial vehicles).
2. 16th International conference "Mechanika – 2011", April 8–9, 2011, Kaunas, Lithuania (Urbach A., Carjova K., Zavtkevics V., Vulans P, Ozols I. (2012) Analysis of buoyancy and design features of the underwater vehicle).
3. RTU 56th International Scientific Conference, 14−17 October 2015. Riga, Latvia (D. Goreļikovs, V. Žavtkēvičs. UAV implementation features for maritime surveillance and safety missions).
4. 21th International Conference Transport Means, 20–22 September 2017, Kaunas, Lithuania (Urbahs, A., Zavtkevics, V. Remote Piloted Aircraft Using for Sampling of Oil Spill).
5. 22th International Conference Transport Means, 03–05 October 2018, Kaunas, Lithuania (Urbahs, A., Zavtkevics, Unmanned aerial platform using for monitoring of oil pollution of sea aquatorium).

The results are published in 6 papers and 1 international patent has been received.

1. Urbahs, A., Žavtkēvičs, V. (2017) Remotely Piloted Aircraft route optimization when performing oil pollution monitoring of the sea aquatorium. Aviation, 21 (2), pp. 70−74. DOI: 10.3846/16487788.2017.1344139. (SCOPUS)
2. Urbahs, A., Zavtkevics V. (2017) Remote Piloted Aircraft Using for Sampling of Oil Spill. In: Transport Means 2017: Proceedings of the 21st International Scientific Conference, Lithuania, Kaunas, 20−22 September 2017. Kaunas: Kaunas University of Tehnology, pp.489-492. ISSN 1822-296X. (SCOPUS)
3. Urbahs, A., Zavtkevics, V. (2014) Oil pollution monitoring of sea aquatorium features with using unmanned aerial vehicles. In Book: Transport Means, ISSN 1822-296x, Proceedings of the International Conference, January 2014 January, pp. 75−78. (SCOPUS)
4. Urbahs, A., Zavtkevics V. (2018) Oil spill detection using multi Remote Piloted Aircrafts for environmental monitoring of sea aquatorium. Environmental and Climate Technologies, in print (SCOPUS)
5. Urbahs, A., Zavtkevics V. (2018) Oil spill remote monitoring by using remote piloted aircraft. Aircraft Engineering and Aerospace Technology, online publication (SCOPUS)

6. Urbahs, A., Zavtkevics, V. (2018) Unmanned aerial platform using for monitoring of oil pollution of sea aquatorium. In Book: Transport Means, ISSN 1822-296x, Proceedings of the International Conference, October 2018, pp. 1061−1064. (SCOPUS).

Patent

1. Urbahs A., Žavtkēvičs V. Unmanned aerial vehicle for collecting samples from the surface of water. Eiropas patents EP3112840 (A1), 2017-01-04 (Application No. EP20150174649 20150630, received: 05.12.2018).

The results of the Doctoral Thesis were used in one scientific project.

1. Project financed by the European Regional Development Fund "Development of an experimental long flight distance unmanned aerial vehicle prototype for multi-¬-purpose environmental monitoring (LARIDAE)". No.2DP/2.1.1.1/14/APIA/VIAA/088, participation in project implementation.

STRUCTURE OF THE THESIS

The Doctoral Thesis consists of Introduction, 4 chapters, Results and Conclusions, Bibliography and 3 appendices. The total number of pages is 137, including 38 figures and 11 tables. The Bibliography contains 59 titles.

1. ANALYSIS OF THE MAIN TASKS AND METHODS OF REMOTE SENSING FOR MONITORING OIL CONTAMINATION OF SEA ENVIRONMENT

1.1. Sea environment contamination problem analysis

Every year on average 13−14 million tons of oil products enter the World Ocean. Oil contamination is dangerous due to two reasons: first, a film appears on a water surface, which does not allow oxygen to reach to the sea flora and fauna; secondly, oil itself is toxic. If there is a dangerous oil concentration in sea water, plankton and fish kids die.

For determination the Baltic Sea oil contamination distribution conformity with the law, HELCOM annual review data of 2011−2015 about oil contaminations detected by help of remote sensing were used.

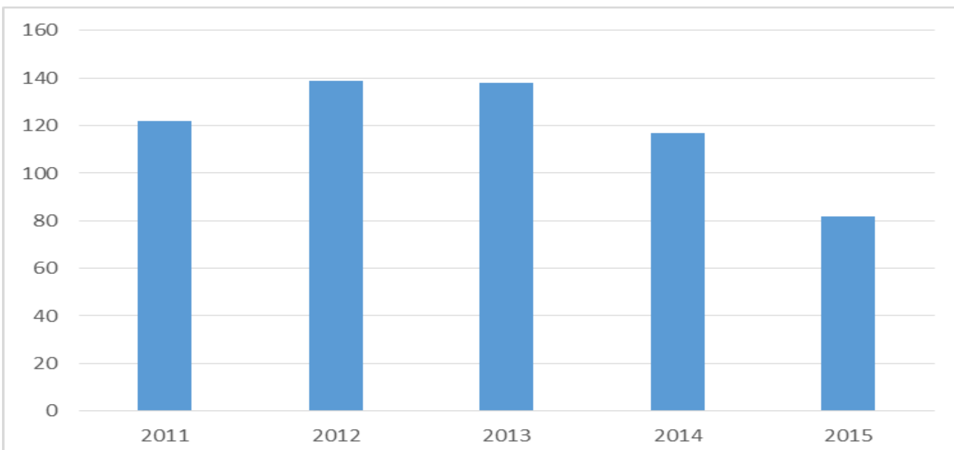

Fig. 1.1. Conformity of the Baltic Sea oil contamination distribution with law in 2011−2015.

Data, that was obtained analysing contamination cases with the help of means of remote sensing in period from 2011 to 2015, shows that the amount of oil contamination cases has decreased due to the organized monitoring.

1.2. Identification of main tasks of monitoring the sea surface oil contamination

Taking into account the situation with various sources of aquatorium contamination, the main monitoring tasks are managing of aquatorium conditions, obtaining data, and treatment. When performing oil contamination monitoring, it is necessary to collect and to accumulate information about actual parameters of the main components of the environment and to prepare prognosis of changes of their quality.

The oil contamination monitoring program should include the following tasks:

- operation of sensors during twenty-four hours, besides, the image descriptions should not be time-dependent during these twenty-four hours;
- possibility of filming irrespective of weather conditions;
- determination of the type of polluting product;
- ensuring the monitoring of the dynamics of oil spill distribution;
- sampling with the help of a specially designed RPA;
- monitoring of large areas of marine waters where there is a risk of illegal pollution;
- quantitative estimation of oil pollution according to the parameters obtained with the help of RPA sensors;
- detecting and collecting evidence of oil pollution from ships;
- provision of operational information to the responsible services in the event of an oil pollution accident;
- regular sampling of background pollution of oil products.

1.3. Analysis of the effectiveness of monitoring of marine surface pollution with existing remote sensing systems

1.3.1. Monitoring of marine surface oil pollution with satellite systems

Global oil pollution monitoring tasks are solved on the basis of satellite monitoring technologies implemented by the rapid alert systems in Norway, Canada, the United States, Finland, and others [1].

Today the implementation of tasks of oil pollution monitoring of aquatorium is not possible without the use of information obtained through the remote diagnostic devices installed on the satellites of the cosmic segment, which carry out remote sensing of the terrain [2]. Active microwave sensors such as SAR and synthetic aperture radar for the 2D image are used for monitoring oil pollution.

Satellite-based SARs today are an important oil spill monitoring tool for covering large areas, both day and night, in all weather conditions [3].

The main advantages of aerospace monitoring methods and systems are great transparency, ability to work in any hard-to-reach areas, and the availability of information on virtually any scale, with varying space and time resolution, a wide range of parameters to be recorded, high reliability and quickness of data acquisition, the ability to observe areas of research several times and work in the conditions of partial or total absence of topography, relative price of information (especially for large areas) [4].

The next negative factor is cloudiness. In addition, infrared sensors and visible and ultraviolet detectors are not able to detect oil in bad weather, such as heavy rain or fog [5]. Visible and ultraviolet radiators are commonly used to create an oil pollution chart. The successful detection of oil pollution by satellite radar is to some extent dependent on weather conditions [6]. In spite of the significant advantage compared to other observation means, satellite systems have limitations on the frequency of the reception of the same sea area (periodicity once every 3 hours, taking into account the possibility of changing the viewing angle). High definition radiolocation data is provided to responsible organizations with a delay related to the time cost of synthesizing images in terrestrial data centres and providing information to the consumer. The production of a map based on radiolocation reception data can take 1−2 days from the moment of oil pollution. These conditions for eliminating pollution lead to the need for operational monitoring by mobile means.

1.3.2. Marine oil pollution monitoring using piloted aircraft

In monitoring of marine pollution aviation observations are also widely used. In accordance with the requirements of the HELCOM (Helsinki Commission) Convention, aviation monitoring is carried out to monitor oil pollution from ships [7].

Oil pollution monitoring is carried out using airplanes, helicopters, hang gliders, and airships.

The main problem with the use of piloted aircraft is their limited use due to weather conditions (cloudiness and fog). In addition, the use of pilot-operated aircraft is characterized by a relatively long response time (up to 3 hours) and very high operating costs. The accuracy of the assessment depends on the surface fluctuation, intensity of light, observation angles. There are also a number of restrictions on flying laws due to the secrecy of the location of the coastal site (military sites, hazardous chemical storage facilities, etc.) or other prohibitions imposed by the public administration.

Long response time is very dangerous given the dynamics of oil distribution through the sea.

1.3.3. Automated complexes of oil pollution monitoring

Automatic systems are also used to control the marine pollution of the marine environment.

Most of the remote meteorological methods are ineffective. In order to eliminate the deficiencies of remote sensing, an oil spill monitoring system has been developed, whose observation module consists of fluorescent lasers and automated contact type monitoring stations. Stations may be expanded into underwater or underwater conditions. Automated complex monitoring was developed to create an early detection and monitoring system for the exploration and monitoring of oil and petroleum products without space remote sensing [8].

The marine observation system is a complex of observations from different observation platforms with unified measuring instruments on a uniform normative-methodological and legal basis [9]. This system consists of two sub-systems: surface and remote. The surface subsystem includes: the seafront hydro meteorological observation network; a vessel observation network set up by the monitoring program; oceanographic observation and works network; an automatic buoy station (anchored and drifting) network; and the national marine pollution monitoring network administration. Buoys and underwater vehicles are installed and operated in the light of maritime safety requirements, therefore information on their location is required [9]. The space sub-system consists of a group of meteorological and specialized satellites that allows to absorb the surface of the water.

1.3.4. Oil pollution monitoring by ships

The waterborne monitoring is used to validate satellite observations and to emit false alarms. Vessels equipped with fluorescence lidars make it possible to detect pollution, such as oil pollution, in large areas of water quickly and effectively [8].

With optical and digital cameras, ships equipped with lazers can analyse and monitor the dynamics of oil spill. The main disadvantage of using vessels for monitoring is low speed: the average speed is 15 miles per hour and maximum is 30 miles per hour.

Unlike remote sensing equipment, mobile marine platforms provide sampling from the surface of the water. Seagoing ships are used to collect films with glossy specimens from the surface of water and to carry out chemical analysis at the early stages of oil spills.

1.4. Analysis of pollution levels and sources of the Baltic Sea waters

The assessment of the level and source of pollution of the Baltic Sea area has been made on the basis of the analysis of annual reports of HELCOM for the period 2011−2015, based on the data fixed with oil pollution remote sensing equipment (Fig. 1.2).

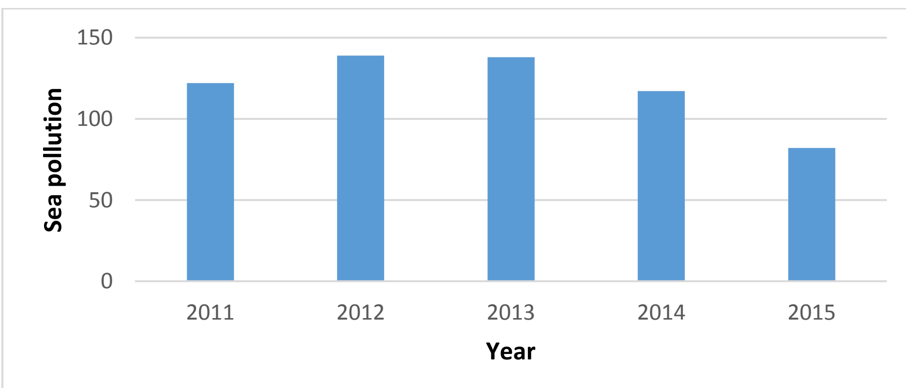

Fig. 1.2. The dynamics of oil pollution in the Baltic Sea area.

The analysis shows a significant decrease in the pollution level of the marine aquatorium due to the introduction of remote sensing equipment. As a result of the analysis of the identified oil pollution data, the Baltic Sea areas with high pollution risk have been identified over the past 10 years.

Areas with high risk of contamination are both close to the shore and at a long distance.

In order to develop specified remote sensing using remote-controlled aircraft, and complex tasks and functional capabilities, an analysis of the type of pollution product of the Baltic Sea area was carried out.

The analysis revealed three main types of contaminated products: oil, diesel and heavy fuel oil.

Thus, the mission of monitoring marine area oil pollution must cover both coastal areas and districts that are far from the coast, as well as inland waters and ports. Taking into account the monitoring of sea waters using the RPA, the specifics and the need for continuous information, as well as dynamically changing ships routing, all control areas should be divided into areas with short and long operational range. The range of the short radius area is 50−80 kilometres and the range of the long radius area is 150−200 kilometres.

Dividing of the controlled area into monitoring zones should be done taking into account the RPA, which is part of the monitoring system, and their technical characteristics.

2. REMOTELY PILOTED AIRCRAFT ROUTE OPTIMIZATION WHEN PERFORMING OIL POLLUTION MONITORING OF THE SEA AQUATORIUM

2.1. Formulation of an optimal routing task to control a remotely piloted aircraft

The main problem of sea aquatorium monitoring is the need to monitor the sea surface, covering large areas of variable geometry, and to control the large number of ships with different parameters (at variable speed, trajectory). The main task here is to develop a RPA route optimization algorithm for RPA with the ability to continuously adjust the flight parameters according to the real situation and dynamically changing control parameters.

Linear programming methods used to solve optimization tasks can be implemented only for a small number of static objects and are not suitable for the case under consideration.

The task of RPA flight routing optimization can be solved only based on a dynamic programming method, for example, using the Deikster's algorithm [10].

The generalized formulation of the routing task in the RPA conducting the oil pollution mission can be illustrated as follows. A graph is set that represents the RPA observation mission $G = (V, E)$, where V is the set of vertices of the mission route (elements), E is the set of edges (links) between the route elements. Each of the parameters of this graph has a time dependence, namely $V = \{V_i(t)\}$ $i = (\bar{\imath}, n)$, $t = (0, \mathrm{l})$ and $E = \{e_j(t)\}$ $j = (\bar{\imath}, m)$, $t = (\bar{\imath}, \mathrm{l})$. It is necessary to optimize the monitoring mission graph, for example, according to the time parameter.

For representation of the dynamical movement of ships and possibly propagated oil spills, a map with calculated target probability positions can be used [11]. Probability positions are calculated using the data obtained from the Automatic Identification System (AIS). Mission planning, integrating information from the AIS system and coastal radar surveillance systems will enable the flight missions of the monitoring mission and the RPA's operational tasks to be minimized. The main function of any marine observation system is the ability to accurately predict the trajectory of the vessel and to extrapolate the ship's trajectory over a given time period.

The following problems were defined: a set of targets with specific parameters such as target type, motion equation, positions derived from the last of the seagoing monitoring systems, display formulation (point, line, and area). An optimization of the marine pollution monitoring mission carried out by the RPA, taking into account the criteria, analyses the target matrix attendance. The next stage is the probability planning for oil pollution and targets that can lead to oil pollution monitoring. Objectives of interest are divided into high (oil tankers / chemicals and ship routes), medium (cargo ships), and small (fishing vessels) pollution levels. Successful RPA mission planning should be designed as a dynamical system with feedback on RPA and target positions. There are many types of RPA usage algorithms for monitoring and monitoring tasks with static targets at $V = 0$. When performing static target monitoring with one or more moving objects, the solution and results of these algorithms will not be optimally determined for a problem with dynamical objects. Targets in a dynamic environment can be represented as points with major parameters such as initial speed and course. The targets will be divided into four groups at a rate $V = 0$; $0 < V < 14$; $14 < V < 23$; and $23 < V$ [11]. Coordinate systems that measure the distance between RPA and observation objects will provide good results. However, it is very important to develop an automatic calculation and data collection system that performs the calculation of the RPA relative motion taking into account the effects of wind speed. In this approach, the relative motion of the two target types, the dynamical and static, is depicted in a plane with two equations: $x = RPA_N – T_N$; $Y = RPA_E – T_E$, where T_N and T_E are the target Cartesian coordinates in the plane [11].

The movement of an object, e.g. aship, is calculated by the movement parameters of a known object. In this case, the target is considered to be moving with a constant course and speed. This methodology makes it possible to find the meeting point where the RPA reaches the moving object. The following functions are used to determine the maturity point of a moving object: a function that determines the movement of an object to one of the points on a line along which the object moves, and the time; a function that determines the movement of the RPA to that point. The traversal sailing method is used to represent the motion of an object. This method allows to calculate the position of the object using the course at the next point and distance. In this case, the sea target distance from the starting point is calculated by the formula [11]

$$D = Vt, \tag{2.1}$$

where V is vessel speed in nodes from the AIS transponder information, and t is time.

Latitude φ_2 of point P_2 (φ_2, λ_2) is determined by the formula [11]

$$\varphi_2 = \varphi_1 + V \cdot t \cdot \cos Course, \tag{2.2}$$

where φ_1 – the latitude of starting point P_1,

Course – the ship's course from the AIS transponder information.

Longitude λ_2 of point P_2 is determined by the formula [11]

$$\lambda_2 = \lambda_1 + Vt \sin Course \cdot \frac{1}{\cos\frac{\phi_1+\phi_2}{2}}. \tag{2.3}$$

The main principle of controlling the RPA model in vector form is

$$x = f(x, u, t), \tag{2.4}$$

where $t \in [t_0, t_k]$, $x(t_0) = x_0$.

In this equation $x_2 = (x_1, x_2, x_3)$ is the vector of the RPA condition (the coordinate vector), $f_u = (u_1, u_2, \ldots, u_m)$ is the controlling vector, $f = (f_1, f_2, ..., f_n)$ is the vector of function of their arguments, $[t_0, t_k]$ is the time interval during which an RPA flight is performed [11].

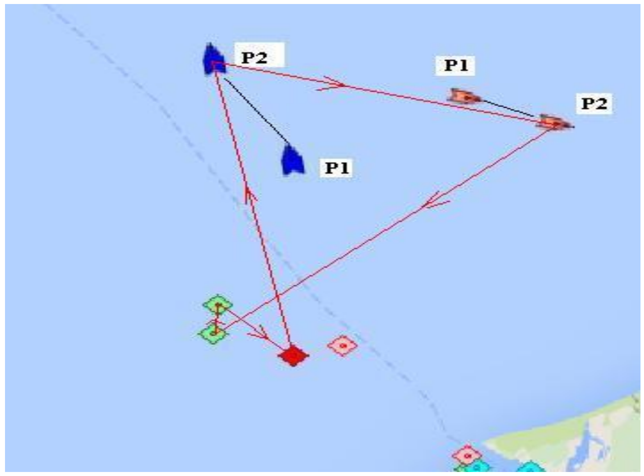

Fig. 2.1. Representation of moving objects.

To control the RPA during the mission planning, the software should take into account the restriction[11]

$$u_{\min} \le u(t) \le u_{\max}, \tag{2.5}$$

where $t \in [t_0, t_k]$.

2.2. Mathematical modelling of optimal flight route planning procedure for RPA

2.2.1. The method of dynamical programming for the task of RPA monitoring mission

In the dynamic programming method, the comparison of all possible solutions to the problem is not done at the end of the construction of all the possible variants, but at each step of the construction of the design versions [10]. The procedure for determining the optimal management (solution) is based on the analysis of the rectangular relationship [11].

$$f_{n-1}(S_l) = \text{optimum}\left[R_{l+1}(S_l, U_{l+1}) + f_{n-(l+1)}(S_{l+1})\right], \tag{2.6}$$

where $l = \overline{0, n-1}$;

$U_l = \left(u_l^1, ..., u_l^m\right)$ – the solution chosen in the lst step;

$S_l = \left(s_l^1, ..., s_l^m\right)$ – the state of the system in the 1st step;

R_l – the immediate effect achieved in the lst step;

f_{n-1} – the optimal value of the effect achieved after n steps;

n – the number of steps (stages).

The marine surveillance mission carried out by a RPA using the principle of dynamic programming can be illustrated by the following example (Fig. 2.2).

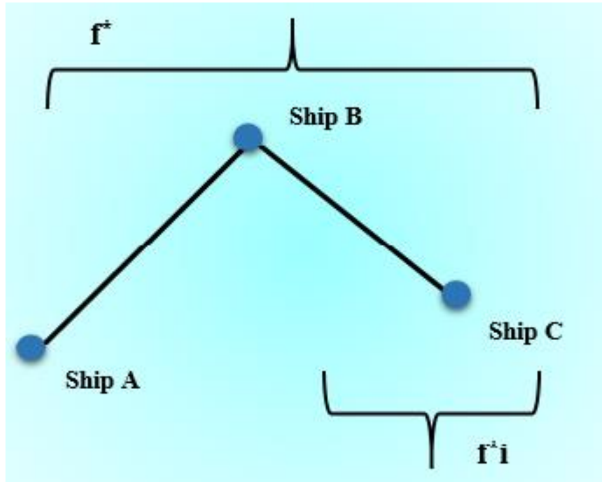

Fig. 2.2. Dynamical programming principle [11].

In the method of dynamic programming, the content of the RPA flight task algorithm in step *k* is such that the existing RPA observation route "length *k*" (which passes through the k vertices) expands to 1, a path that passes through (*k* + 1) peaks. The RPA, which performs an observation mission, takes into account the optimal route for displaying the route optimization [11]. The algorithm will analyse the section of the route that started at 0 and ended up at the vertex I, the route containing *k* intermediate vertices. If *L* is the minimum path, then the part where the connected vertices 0 and i go in a certain order along the vertices must be the minimum length. The shortest route connecting vertices 0 and i and passing only once through each *k* vertice hasthe same length.

2.2.2. The branch and border method

The mission of the monitoring for discrete optimization tasks is the final set of solutions that can theoretically be counted and the best (giving the target function minimum or maximum) set can be chosen.

The RPA route optimization problem is used by the branch and boundary method [12], [13]. One of the key principles is that it is based on the subdivision of the permissible field of the task by using the permissible set of points in the final. In each sub-area, the task is to be considered separately. In addition, the full list of permitted points is replaced by an analysis of the lower and upper assessment of the optimal value of task at the expense of this subsection. If the subcategory does not contain acceptable points or does not include solutions, it is excluded from further consideration.

2.2.3. Mathematical modelling for preparing the procedure of RPA optimal flight route during monitoring

The purpose of the section is to assess the effectiveness of the developed model of RPA route designing procedures for the implementation of oil monitoring missions based on probabilistic analysis. This mathematical modelling is an object modelling information model that takes into account the main components: object probability position model and RPA optimal movement model.

A computational experiment with the following characteristics was performed for the comparison of the offered algorithms:

1) *n* peaks were generated as points in a plane in the XOY unit squared with independent uniformly distributed coordinates;
2) part of the points was generated as moving objects with a constant course and speed;
3) the assessment of the quality of the obtained solution was calculated as the ratio of the total length of all routes to the overall assessment of the overall route at all vertices.

The optimization model was offered for the RPA route. The model examined two scenarios: in the first scenario all the coordinates of the targets were placed in the matrix, while in the second scenario some objects move at a constant course and speed [11]. An example was offered by a graph with 11 objects. It was assumed that there are 5 targets with a speed 12 knots, 3 targets with a speed of 8 knots and 3 static targets.

When comparing the solution of Scenario 2 with Scenario 1, the optimal route distance decreased by 7 %. It demonstrated objective value, the route was significantly improved [11]. For the bottom estimate, the sum of the length of minimum edges was used. To calculate the RPA route assignment for the monitoring of oil pollution, the same sequence was used in the intermediate steps of the algorithm.

The exploratory approach assumes the existence of an entry point that coincides with the starting point. This may be, for example, the location of the RPA, which performs oil pollution monitoring.

The optimization task was solved using three different methods (tree algorithm, dynamic programming, and branch and boundary method). Based on their operating speed and the accuracy of the solutions to be calculated, it was concluded that the optimum operating result is achieved by combining the dynamic programming method and the branch and boundary method. Mathematical modelling showed that the objective value for Scenario 2 significantly improved. Mathematical modelling has shown that the proposed optimisation method for RPA route planning is effective.

2.3. Development of optimal route search algorithm and programs

2.3.1. The task of assignments

When the monitoring area is divided into separate points, the task is to visit all points. In this case the task can be solved by the RPA. The task of the mission consists of designating and determining the procedure for the surveillance of objects by RPA. In addition, it is necessary to minimize the specified function, which may include the total execution time of the task, the total length, etc. The tasks of this type can be defined as the “task of assignment” [14].

There are several different approaches to solving assignments. The most popular are: tree algorithm; dynamic programming; and the branch and border method.

Since RPA is at different times from the monitoring points at any time and has an unstable energy reserve, the route can be optimality estimated using a certain optimality function.

2.3.2. Tree algorithm

The search-width algorithm [15] is the simplest algorithm for searching for a route, as the main idea is used in other algorithms. This is the basis of Dijkstra and Prim algorithms.

The drawback of such an algorithm is a complete listing of all graph vertices and paths found. The drawback of the algorithm is also that the sequence of operations in solving the problem is not oriented at once to the final vertex, but at all stages it passes all vertices.

The mission of the observation mission can be represented as the attendance of all vertices of graph $G(V, E)$, starting from the starting point and returning to the starting point. The goal is to find the optimal RPA route with the aim to visit all the objects described in the mission at the minimum possible time with minimal cost. In graph theory, this is the search for two or more vertex binding paths using optimality criteria [16]. The tree algorithm is associated with heuristic methods. In heuristic methods, the choice of elements of the solution is based on a certain recommendation of natural selection rules, a heuristic. The algorithm time is equal to $\Theta(E) = \Theta(V^2)$.

The program Pascal was written for the implementation of the algorithm.

2.3.3. Dynamic programming

Optimization solution for dynamical programming methods of the location will be carried out in two stages. Taking into account the parameters of the RPA movement and the rate parameters of the objects, the distance between the objects and the RPA is calculated. Objectives of the optimization solution for the RPA route will be mapped from the AIS electronic map, coastal radar observation systems and sea areas to the graph with vertices and edges with the weights.

The weight of edge of graph is the cost of the mission for each object. The cost in dynamic system is represented by the time function [12]. The formula for calculating the weight of edge is [11] as follows:

$$w_{ij} = t_{\text{flight\_}ij} + t_{\text{surveillance}}, \tag{2.7}$$

where $t_{\text{flight\_}ij}$ is the flight time from the previous object;

$t_{\text{surveilance}}$ is the time of the observation mission of the object.

For all objects according to the classification, the observation time should be calculated using formula [11]

$$t_{\text{surveillance}} = \frac{l_{\text{trajectory}}}{V_{\text{flight}}}, \tag{2.8}$$

where $l_{\text{trajectory}}$ is the length of the observation trajectory;

V_{flight} is the RPA speed in observation mode.

As a result of the task, we obtain the incidence matrix with shorter routes. This algorithm is based on dynamic programming.

The operating time of the Bellman–Ford algorithm is $P(F \cdot W)$, the initialization cost is $P(W)$, the test for the negative cost cycle is $P(F)$, where W is the number of graph vertices, and F is the number of graph edges.

It is more useful to use the Dijkstra's algorithm for the graph with the dynamical shift of the route, with the number of vertices higher than 15 and without negative weight values. Otherwise, if the number of vertices is less than 15 and the presence of negative weights is allowed, it is recommended to use the Bellman–Ford algorithm.

2.3.4. Branch and boundary algorithm

The branch and boundary algorithm is based on the idea of a sequential decomposition of acceptable solutions. In each stage of the method, the partition (subset) elements are analysed, or this subset of the optimal solution [17] is included. If the problem is the minimum search, the test is performed by comparing the lower limit values of the target function in these subsets with the upper limit of the function. The RPA observer mission route can be formulated as follows: $f(x) \to \min_{x \in S}$, where $f(x)$ is the real function, S is the final set of acceptable solutions, $s \subseteq S$. The function b(s), which leads to a set complying with its division into subsets $s_1, \ldots, s_N$, $N > 1$, called the branching.

The real function $H(s)$ is called the lower bound if:

1) $H(s) \le \min f(x)$; $x \in s$;

2) in the elementary element $\{x\}$ there is correct equation $H(\{x\}) = f(x)$.

The algorithm that implements the branch and boundary method consists of a sequence of one type. Each step has a known record and unsolved subtypes of solutions $t_1, t_2, \ldots, t_L$. In the first step of the algorithm $L = 1$, $t_1 = S$, x^0 is an arbitrary element of set S or an empty set (in an empty set, we define a functional value that is equal to infinity) [11].

In each step, the algorithm starts the operation of the partitioning element in order to check the set t_j. Set t_j is returned in one of two consecutive test cases:

a) if $H(t_j) \ge f(x^0)$;

b) if $H(t_j) < f(x^0)$ and where there is such element $y_j \in t_j$, that $f(y_i) = \min_{x \in t_j} f(x) = H(t_j)$;

In the event of a record change $x^0 = y_i$.

Let $t_1, t_2, \ldots, t_M$ ($M \le L$) be non-reciprocal sets (let us consider that there are the returns of sets with numbers $M + 1, \ldots, L$).

In the case of $M = 0$ the algorithm ends the operation, and takes a record of the task solution x^0.

If $M \ge 1$, a set for a new branching is selected from set $t_1, \ldots, t_M$. Let it be set t_1. Then branching $b(t_1) = (s_1, \ldots, s_N)$ is obtained. As a result, we obtain the list of sets $s_1, \ldots, s_N, t_2, \ldots, t_M$. These sets are numbered from 1 to L, and a new algorithm step begins.

The described algorithm finds optimal solution in the final steps.

In this application, the minimum route should be found. The mission plan is specified as a full directed graph $G = (V, E)$ with a plurality of vertices $V = \{1, ..., n\}$ and a plurality of edges E. For each edge $(i, j) \in E$, length $c_{ij} \geq 0$ is assigned. A simple route from i_1 to i_k is $\{i_1, \ldots, i_k\}$, and the length of the route $\{i_1, \ldots, i_n, i_1\}$ is $f(i_1, \ldots, i_n)$, taking into account that $i_1 = 1$. The subset of feasible solutions is defined as a pair of sets (I, J), where $I = \{i_1, \ldots, i_k\}$ is the partial route (a sequence of visits to first k nodes), $J = \{j_1, \ldots, j_q\} \subset V \setminus I$ is a set of restrictions on the flight to the last point i_k of the partial route I. To represent the sets of partition in $V' = V \setminus I \cup J$, an element i is chosen. If element i in V has only a single element p, the desired set $I = \{i_1, ..., i_k, i\}$, $J = \emptyset$, and $(I = \{i_1, ..., i_p, k\}, J = \emptyset)$. [11]. Next step is to find the lower boundary $H(I, J)$ for the subset (I, J). Once all the elements have been considered, the decomposition algorithm stops working and the current entry is the best solution. Otherwise, the unchecked elements will choose a set that is perspective. It is subdivided (branched). The process continues until all elements in the section are checked. This algorithm has high accuracy [11].

3. DEVELOPMENT OF CONTINUOUS MONITORING METHODOLOGY OF OIL POLLUTION OF SEA AQUATORIUM

3.1. Functional requirements for an unmanned aerial platform

3.1.1. Type and structure of unmanned aerial platform

Using two types of aerial platforms with unique capabilities and characteristics to monitor water quality and oil pollution will allow simultaneous monitoring of regions with large areas and the basis for taking water samples based on the information obtained on selected areas. The first type of monitoring aerial platform is a “fixed-wing” type remote piloted aircraft with a multifunctional payload system focused on the maximum range of observations, analysis and transmission of data in all circumstances and in all situations. The payload system for maximally accurate information about water quality allows simultaneous use of a visible near infra range (VNIR) camera, a thermal camera, and a hyperspectral or multispectral camera. The aerial platform is intended for long-term operation. The second type of aerial platform is a multi-rotor platform with vertical lifting and lowering capability, and long-time gliding and holding in a certain position. This type of platform allows to refuse from time-consuming and inefficient monitoring of pollution using mobile test stations and ships. A special algorithm allows the use of a platform for monitoring oil and bacterial contamination by taking samples from the surface of the water using a special container that allows determining the thickness of oil film. The platform is intended for monitoring and taking water samples for the purpose of pollution detection.

The platform provides taking samples of water in a certain area with a special device with 10 containers. A payload system for maximally accurate information on water quality allows simultaneous use of a VNIR camera, a thermal camera, and a hyperspectral or multispectral camera [1].

The management complex has an intelligent automatic monitoring control system that is able to receive data in real time and to decide what type of platform is necessary for the specific monitoring and sample taking in the daily mode and in an emergency situation in the surface reservoir area in order to solve the tasks. The management system will perform take off, route formation, flight on a specified route, monitoring, take-off and landing in automatic mode [1]. The control system will allow fully automatic control, react immediately to changes in the monitoring situation, allowing the transition of the priority mode to operator’s management.

3.1.2. Requirements for take-off and landing sites

The first type of carrier for monitoring the “fixed-wing” unmanned aerial vehicle was used to obtain data on water pollution in large areas and has a high operating range [18]. The given solution allows to obtain operative data on the state of the water surface, and, by using an algorithm, to estimate the deviation from clean water spectral and video image; automatically or in an operator mode a different carrier type can be used – a multi-rotor platform with the possibility of vertical lifting and lowering and prolonged obstruction with the set maintaining the position, clarifying and receiving information on the nature of pollution, using a payload multifunction module[1].

3.2. Optimal route and profile characteristics of an unmanned platform flight

The flight of the first and second type of aerial platforms consists of 3 basic phases, which are fully automatic and there is also a possibility to switch to operator control mode. The basic phases of flight are taking off and elevating, monitoring of missions and tasks performed in accordance with the flight plan and type of aerial platform and multifunctional payload system, lowering and landing. After completing a flight on a given route, the automatic system or operator implements video surveillance, thermal observation, and spectral observation mode by directing the camera to the designated water aquatorium areas or implementing the changes in the RPA flight course.

The flight route needs to be planned in such a way as to guarantee an overview of all areas under oil pollution and water control.

The water storage area is depicted as an area with objects (targets).

The optimal trajectory of the target area of the field is characterized by a minimum length between the other trajectories as well as a minimum number of turns over the target and, accordingly, a large amount of straight sections (Fig. 3.1).

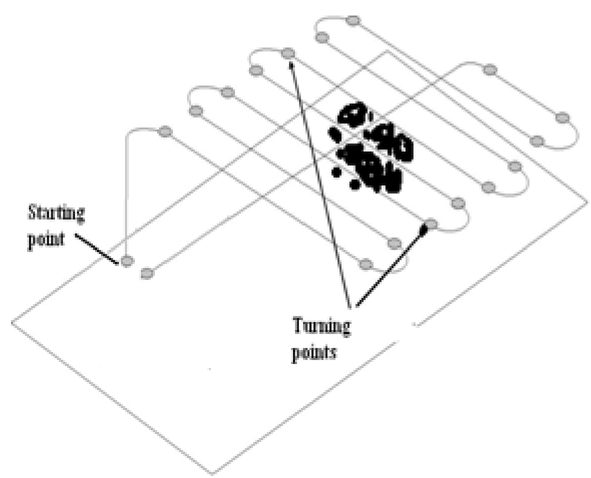

Fig. 3.1. The optimal trajectory of flight monitoring the field target.

The automatic programming system of flight provides more accurate information and compiles a digital terrain model, including 3D model, allows the application interface to be used to assign a different width of the coverage area to external factors (visibility, fog, safe flight altitude). Program algorithm, when performing calculations of the camera’s visual distance between the near-angle edges on a parallel route, is taking into account the required 15 % coverage. To complete the turning of the RPA to the required radius and proceed in straight line to the next turning point, taking into account the flight characteristics of the RPA, it adds a turning point that is equal to *X* m in electronic map scale (Fig. 3.2)

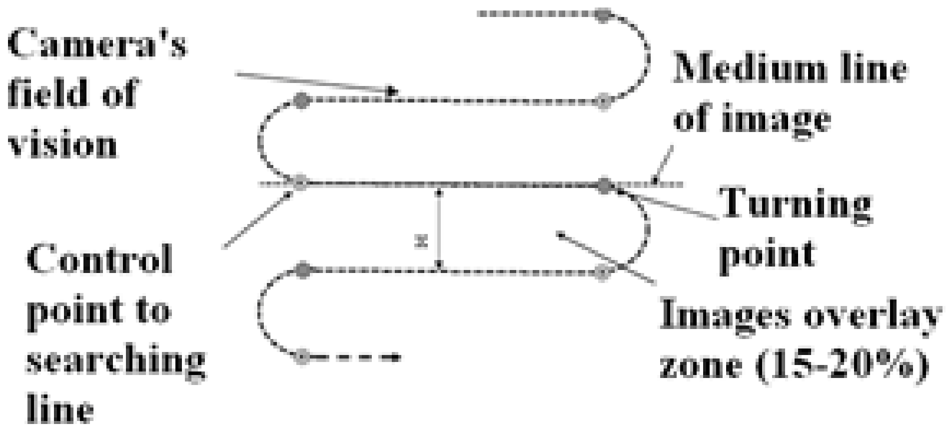

Fig. 3.2. Flight trajectory.

The automatic planning program for performing the task uses a geometric cycle of trajectories, which is indicated by a rectangle of constant width and variable length and a position applied to a region or an oil spill.

The area covered in the straight legs of the flight is determined by formula

$$\sum_{i=1}^{n(\theta)} h_i 2x, \tag{3.1}$$

where h is flight height,

x is the angle of observation of the camera.

The area covered by the turns is determined by formula

$$\sum_{i=1}^{n(\theta)} \pi 4x^2 \ . \tag{3.2}$$

3.3. Mathematical modelling of the distribution of oil pollution on the water surface

Distribution of oil spill on the surface of water is a complex process influenced by internal factors such as the type of oil product, its density, physico-chemical characteristics, temporary emission characteristics, discrete or continuous; and external factors such as oil spill drift under the influence of the stream, waves height, wind speed, water temperature, presence of oil-oxidative bacteria and salinity in aquatorium, and solar radiation.

The following model (hypothesis) of distribution of the oil spill is used in the methodology: normal distribution rate is proportional to the spot thickness.

The main indicator of oil distribution on the water surface is the dependence of the oil film radius r on time t: $r(t)$.

In the case of some localized discharges of oil in the event of a technogenous disruption of instantaneous accidents, this process can be schematically visualized as follows.

The first stage is when the oil flows on the surface of water under the influence of gravity (water density is higher than that of oil, therefore oil “rises” above the sea surface).

The second stage is the stage of force – when oil drains on the surface of the water under the force of action.

The monitoring data of the oil spot that has been received with the analytical calibration algorithm for the implementation of the motion correction is transformed into information on the map and at time intervals that were determined by the user by applying to the shape of the spot. In the case of a rupture, on some spots an ellipsis is determined for each spot in motion (speed and angle of motion at the base coordinate system) and changes in the oil range radius.

The program written in Excel performs the analysis of two cases of oil spill. First, in the absence of wind and stream the oil spread was even in all directions forming a circle whose radius changed over time. If the wind speed and stream velocity in the river or in the marine aquatorium are obtained from meteorological observation (using an anemometer), the direction of the spot drift is determined by adding superficial currents and wind direction vectors.

The resulting vector of the two complementary vectors is calculated by means of the cosine theorem:

$$V_{\mathrm{rez}} = [V_1^2 + V_2^2 - 2V_1V_2\cos(180° - \alpha)]^{1/2}, \tag{3.3}$$

where V – numerical value of the velocity vector,

α – the angle between vectors 1 and 2.

The angle between the resulting vector and one of the outgoing vectors can be calculated with the sinusoidal theorem:

$$\beta = \arcsin[V_2 \sin(180° - \alpha) / V_{\mathrm{R}}], \tag{3.4}$$

where α – the angle between the outgoing vectors.

Simplifying the creation of a mathematical model and taking into account the fact that real-time monitoring is carried out using RPA, which provides real-time basic parameters for calculating, it is assumed that the outflow of oil spill on the surface of the sea takes place under the action of forces that depend on gravity and stiff friction. The main characteristics of oil spots are the radius and thickness. Then, using the mass conservation equation for the elemental volume of the oil spot and the motion equation, the mathematical model of the process is considered in the case of a symmetric axis as a mass conservation equation:

$$\frac{\partial h}{\partial t} + \frac{1}{r}\frac{\partial (rvh)}{r} = 0, \tag{3.5}$$

Equation of motion is as follows:

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial r} = -g\delta\frac{\partial h}{\partial r} - \frac{\tau}{\rho o h}, \tag{3.6}$$

where h – the thickness of the oil film;

v – the average speed depending of the film thickness;

τ – tangential tension at the bottom border of the spot;

g – the free acceleration;

$6 = (p_w - p_0)p^{-1}$', p_w, p_0 – the water and oil density, respectively;

r – the radial coordinate;

t – the time.

The initial location of oil film instantaneous concentrated oil spills is subject to volume at the following condition: $h(r, 0) \neq 0$ at $r \neq 0$.

$$2\pi \int_0^{\infty} (h(r,0))r(d(r)) = Q_0, \tag{3.7}$$

where Q_0 is the volume of oil spills.

On the basis of the created mathematical model, in real time, the oil film has a final radius $r_k(t)$.

$$r_{\mathrm{k}}(t) = \varepsilon_0 \left(\frac{Q_0 \alpha t}{8\pi^3}\right)^{\frac{1}{8}}. \tag{3.8}$$

$$\alpha = \rho_0 \delta \frac{g}{4\mu}. \tag{3.9}$$

The constant can be written as follows:

$$\varepsilon_0 = \frac{4}{\sqrt[8]{162}}. \tag{3.10}$$

The maximum film thickness is determined by the following formula according to the time:

$$h(0,t) = \frac{\sqrt[3]{3}}{4} \left(\frac{Q_0}{2\pi\alpha t}\right)^{\frac{1}{4}} \varepsilon_0^{\frac{2}{3}}. \tag{3.11}$$

The methodology uses the calculation up to the correction moment with the help of parameters from the RPA. Potential pollution, the movement and distribution process are determined analytically. Using the data from video, multispectral, thermal and hyperspectral cameras, the size of the spot dimension and the colour code base of oil products on the surface and spectrum levels of the water and the colour code base and the thickness of the film on the surface of the water, the type of oil product is determined. Based on the data on stiffness and density, Q_0 − the initial volume of oil spills is calculated with the formula:

$$Q_0 = Sh. \tag{3.12}$$

3.4. Oil pollution monitoring algorithm

In the case of long-term emissions (the most likely case), the initial emission rate (*t*/*h*) and the emission velocity after a certain time (i.e. the gradient of speed) are determined for the implementation of monitoring of sea ports and in water areas of oil transportation terminals and areas where there is a possibility of ship accidents.

In the event of an accident, the spill parameters are included in the program, which are subject to the emission co-ordinates (geographic), the date and time of issue, the petroleum product (the user is offered to choose the necessary petroleum product from the database, which contains the physico-chemical properties of oil products, potential contaminants, the size of the spot and density of film), type of emission – continuous or instantaneous.

Until the correction moment, the calculation is made at a constant emission velocity (at two-speed equation) or at a linear rising / rising emission velocity (at a speed difference). The model is considering a case where the source of pollution continues to move. In this case, the source speed at the nodes and the direction are counted continuously until the correction moment is applied. In the case of instantaneous emissions, the amount of the emission is quoted.

Performing Phase 1 of defining the oil spill site, an automatic control system sends RPA to the water aquatorium monitoring area. Monitoring has been established for complex detection methods, which includes use of video cameras, thermal cameras and a multispectral camera. The following three complementary approaches to pollution control are used to define the oil pollution area:

- comparison of the colour of possible pollution with the colour code of clean water near the given radius;
- comparison of video observation data from the contaminated area with clean water aquatorium areas;
- estimated monitoring of changes of oil spill during the period of time *t*.

The coordinates of the shape of spots and the Dekart coordinates are determined.

Phase 2 – definition of pollution parameters.

Monitoring of oil spot and its parameters is necessary for pollution distribution planning in water aquatorium areas, and for defining the outgoing data for analytical calculation of the oil slick distribution on the surface of water and the level of operational response strategies. The percentage and thickness of a typical shape are needed to calculate the start volume.

The estimated thickness of the contamination film is estimated using the colour code table of oil spots. Using the table for the area of observation with VNIR camera allows to observe the beginning stage of the expected pollution fixation and create a slick distribution model.

Table 3.1

Colour codes

Code	Description/appearance	Thickness of layer (microns)
1	Sheen (silver/gray)	0.04–0.30
2	Rainbow	0.3–5.0
3	Metallic	5.0–50
4	Continuous true oil colour	50–200
5	Continuous true oil colour	200 and more

In order to increase the accuracy and avoid false definition of possible contamination caused by external factors, the oil thickness measurement algorithm is used with the help of multispectral images, which provides high accuracy and is universal for any area of water and various meteorological and atmospheric conditions.

Using multispectral images obtained using an RPA payload with a multispectral camera to define the oil density for multispectral classification, the results of the oil film spectre are calibrated in thickness using the data obtained by taking samples [1].

The use of a multispectral camera takes into account the ability to obtain high-accuracy results by defining low-density film and high-thickness films.

In the next stage, the evaluation and registration of relative proportions (percentage of typical spot coverage) of clean water and each colour (or thickness) above the surface of the spill area takes place. Visualization uses a graphical image of the percentage of the cover with a space of 10 % (Fig. 3.3).

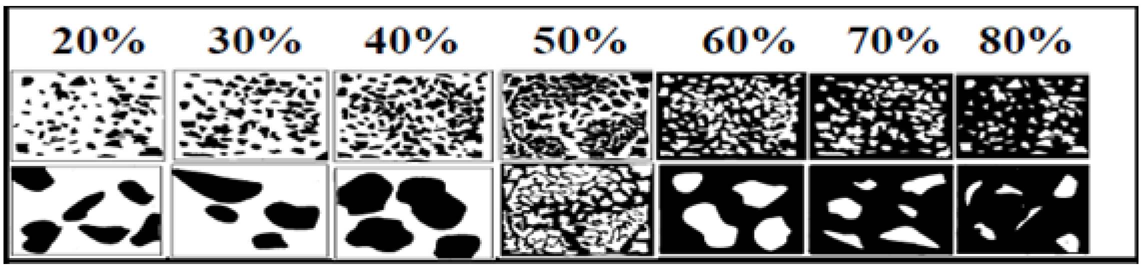

Fig. 3.3. Graphical image of percentage of cover.

For the definition of a large spot with different colour codes, the thickness methodology uses a full oil spill definition program. The spill is divided into zones. For each zone, a specific code (colour) area is calculated according to the formula

$$S_k = \%P \cdot S_{\mathrm{r}}, \tag{3.13}$$

where $\%P$ – percentage of area coverage with a specific code (colour);

S_{r} – area square.

Then, the amount of oil is calculated by multiplying the colour of each spot, area S_k is multiplied by the thickness of oil film in each colour. Calculations are performed using the EXCEL algorithm.

An analogy algorithm is used to perform a monitoring mission using thermal, multispectral and hyperspectral cameras. After an approximate determination of the volume of spilled oil, an automatic program implements the estimates of propagation of oil spills in the water surface area.

Phase 3 includes the clarification of the initial information about pollution by using RPA. The prediction of the location and distribution of oil in the water surface is dealt with analytically using wind and stream data, as these factors influence the distribution of floating oil.

At this stage, adjustments for the forecast are calculated, and the physicochemical characteristics of the oil spill are determined – parameters calculated according to real-time data received by the RPA (the oil spot radius is received with the help of payload cameras in real time mode).

After the correction of the data received from the RPA, the correction algorithm implements the conversion of volume of the oil product. The RPA payload includes a GPS receiver that detects the co-ordinates of the margin of the oil spot at the given time intervals. The radius changes Δr are automatically calculated for the time interval:

$$\Delta t = t_2 - t_1, \tag{3.14}$$

$$\Delta r = r(t_2) - r(t_1). \tag{3.15}$$

Also, the difference between the analytical prediction of the oil spot and actual radius for determining the confidence level of a forecast or the need for conversion with other parameters (stiffness, oil film thickness) is calculated.

Further, with the data received, the specified volume of oil products according to the formula is determined.

$$Q_0 = \frac{8\pi^3 \sqrt[1/8]{\frac{r_k(t)}{\varepsilon_0}}}{\alpha t}. \tag{3.16}$$

The volume obtained in an analytical way is comparable to the amount calculated from the observation results. On the basis of comparison and real data, correction and a new forecast of oil distribution on the surface of water are calculated. In the case of a particularly thin film or contamination check, if necessary, a flight plan is be created for the RPA to take samples and the aerial platform is fitted with a payload with a container to take samples. Upon completion of the flight plan, the container is sent to the laboratory and the type of oil product and the film thickness is specified.

Initial oil volume is calculated using the model and is corrected using a real database, according to formula

$$Q_0 = 2\pi\alpha t \sqrt[1/4]{\frac{4h(0,t)}{\sqrt[3]{3}\varepsilon_0^{2/3}}}. \tag{3.17}$$

When performing the monitoring of seawater in a technogenic accident, RPA transfers the coordinates of the emergency area, the end of the discharge and the oil flow to the surface of water in real time (for example, as a source of elimination, changes of speed of a ship, changes in speed and direction of spot of the oil product).

Phase 4 involves observing the motion of oil spots using RPA in real-time.

The oil spill movement is formed by the vector in the geometric centre of the oil pollution area showing the sum of currents (velocity and drift from the wind). After processing the data received by the RPA, the flight planning correction algorithm implements a real-time correction of the oil spot centre. Using the RPA's payload and the GPS device, a very important parameter is obtained, which is used for analytical calculations of the distribution of oil spot – border of spot. Thus, on the basis of information received using the RPA, which takes into account the influence of dominant winds and currents, it is possible to predict the speed and direction of flow of floating oil from the site that is known at this point and implement the predicted vector correction.

Phase 5 includes an assessment of changes and analysis of the data received in the given time intervals.

Following the results of the flight plan completed by the RPA, the criteria are set for determining the duration of the different spreading phases.

Using RPA with a valid load with different sensor types allows getting real-time information about dynamic processes in real-time.

The variation evaluation uses three methods for assessing changes that are related to each other when executing a flight monitoring plan, such as:

- comparison of data received before and after the spill;
- comparison of data from contaminated and unpolluted (control) areas;
- track changes over time.

Phase 6 involves elimination of the detection error. False clouds, cold and hot water, turbid and warm water, floating algae, and sandy shoots must be tested using the typical algorithm of potential contamination. The RPA flight task contains a sampling algorithm. Sampling process and transportation are carried out in automatic mode.

3.5. Development of monitoring technologies using the RPA group

3.5.1. Monitoring technologies using the RPA group, analysis of problem-solving methods

The main task of the RPA system is to detect and monitor the oil spill, taking into account changes in parameters over time. The main requirement – the task must be addressed in real time. Implementation of the system of RPA group allows efficient planning of resources in marine space and time constraints.

Multi-agent system has advantages over one RPA. The main advantage is the distribution of tasks among the RPA of the group. During the monitoring of a large marine area, a single RPA is not able to fulfil the mission due to the following constraints:

- there are two or more oil spills in the monitoring area;
- due to the length of the route, the flight mission must be performed using an autopilot;
- in the event that information is received on oil spill, the RPA will be sent for monitoring only in the areas covered by the surface command station;
- the duration of the oil spill monitoring mission is limited by the autonomy of the RPA;
- using one RPA allows one type of monitoring platform to be realized, which makes it impossible to use efficiently different payloads; for example, RPA with fixed wings cannot be used for oil sampling [19].

The multi-agent control method in this case is based on a multi-level management system consisting of at least two levels: high and low. The high level receives global information and information on static and dynamic objects from AIS.

The implementation of control at high level allows, after receiving the visual information from the agent, to change the position of the districts and the RPA group.

Taking into account the specificity of the mission, after the receipt of information on real-time pollution at high level, RPA group can be subdivided into efficient sub-tasks. In this case, the information from one RPA sensor is transferred to other members of the group. The oil spill propagation model allows to send RPA information for navigation to the assigned position. This position is calculated on the basis of a probabilistic approach and is corrected upon receipt of information from RPA. This strategy allows to increase the effectiveness of the RPA group. The information received from high-level RPA is used to recalculate the oil spill model. The position derived from the model of the propagation of the recalculated oil through the water surface is sent to the designated RPA group.

The system includes n RPA, $n > 1$, and a control system. A goal matrix can be represented as a set of objects using geographic coordinates. The task can be formulated as point m, which provides minimum flight time for each RPA, from the set of points N:

$$T = \min_{m<N} i \sum_{i=1}^{m} T_i, \tag{3.18}$$

where T is time.

In this context, in the framework of this work, a special algorithm was developed for multi-agent systems used to detect oil spills (see Section 3.3.2).

3.5.2. Development of monitoring technologies using the RPA group

The area of monitoring can be presented as surface area, which includes all types of targets. To perform the task, there is a set of RPA equipped by sensors and located in the points with geographic coordinates, where R is a number of all RPA, $R = \sum_{i=1} R_i$, that can be used (Fig. 3.4).

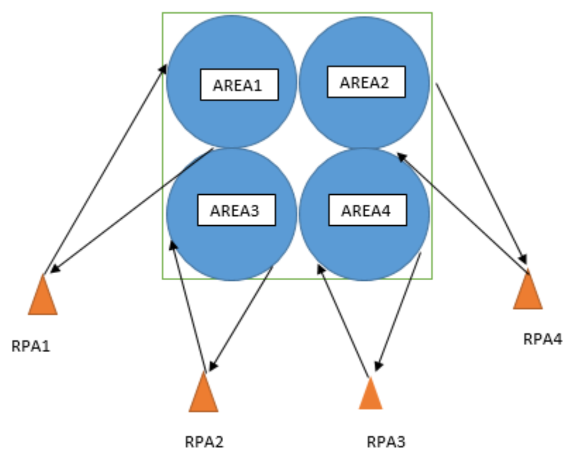

Fig. 3.4. Multi-RPA system for detecting oil spill.

To solve the problem of optimizing the route of monitoring objects using optimization criteria, time is analysed using two different methods.

The first approach is to find the optimal route using the chart of Deikster's algorithm. Many problems with the routing of static objects can be considered as a problem of travelling salesman

(TSP), which over decades has been estimated by many variants, and the solution was developed as an integrated linear programming [18] [20].

This algorithm can only be implemented for one RPA of the group because it is determined. This algorithm can be used in a multi-agent system with the condition that there are certain sets of monitoring objects, but each RPA has a distributed subset. This condition can be realized through a central monitoring system.

The second approach is to use a multi-agent system with decentralized control of agents. Usually, the system architecture is the same as in the biogenesis system, such as “spit” and others. The main advantage is the autonomy of individual RPA, the training of departments and the collective communication system. An “ant colony” algorithm is one of the most successful methods used by the “swarm” intelligence [21], [22]. There is a restriction that before implementing results for the RPA, a mathematical model has to be created and tested with a number of experiments. The ant algorithm for the RPA can be presented as set *R* of RPA:

$$R_m = \{R_1, \dots, R_m\}, \tag{3.19}$$

where *m* is the number of RPA.

The objective of the RPA is finding the optimal route. For this objective, presentation of target matrix as a graph *G*(*V*, *E*) is used. To find a solution, it is necessary to determine the value of the pheromone trail. It is taken into account that the RPA travelling on the edge of the graph E leaves some pheromone. This pheromone is connected with the optimality of choice. Pheromone left on the edge *ij* evaporates over time. Pheromone changes during time t as regularity can be presented by formula

$$\tau_{ij} \leftarrow (1-\rho)\tau_{ij}(t) + \Delta\tau_{ij}(t), \tag{3.20}$$

where

$$\tau_{ij} = \sum_{R=1}^{m} \Delta\tau_{ij}^{R}(t), \tag{3.21}$$

where *R* – each RPA;

m – the number of the RPA at each iteration;

$\rho \in (0, 1]$ is pheromone trail evaporation coefficient, defined by the intensity of activities of RPA.

The probability of flight of RPA from vertex *i* to vertex *j* can be presented by formula

$$P_{ij}(t) = \frac{\tau_{ij}(t)^{\lambda}\left(\frac{1}{t_{ij}}\right)^{\beta}}{\sum \tau_{ij}(t)^{\lambda}\left(\frac{1}{t_{ij}}\right)^{\beta}}, \tag{3.22}$$

where τ_{ij} is pheromone level;

λ, β – constants, which define the type of search for solution;

λ – the choice of object with minimal time cost;

β – the solution with pheromone level;

t_{ij} – the time cost between vertices *i* and *j*.

The time cost between vertices is proportional to pheromone quantity on the edge; this means there will be minimal time cost on the edge with maximum pheromone quantity. The main advantage is finding the best solution through a big number of experiments with optimality criteria τ. This property makes it preferable for big dynamic target matrices. The main problem is that for finding a solution, high capacity of system resources is needed. From another point of view, this approach gives an opportunity to find a rational solution.

3.5.3. Evaluation of the effectiveness of the monitoring technology algorithm

The evaluation of the algorithm of the decision tree and the ant algorithm shows that these can be implemented for the multi-RPA system. Taking into account the dynamics of the oil spill described by the mathematical model with continuously changing coordinates, an effective monitoring mission can be effectively performed by the RPA $n > 1$. The decision tree algorithm is a determined algorithm, but can be used only for one RPA. For using it, first, a centralised system where the area is split into subareas for a single RPA should be build. To implement this algorithm, a high-level system with two levels of decomposition was designed. The ant algorithm can be used in a decentralised system with time cost matrix, which includes a big number of objects.

Thus, the most effective solution for solving an effective monitoring task through the RPA group is the complex approach offered in this Thesis. In this case, an oil spill detection mission using several RPA can be scheduled using for the solution either the tree algorithm or the ant colony algorithm (Fig. 3.5).

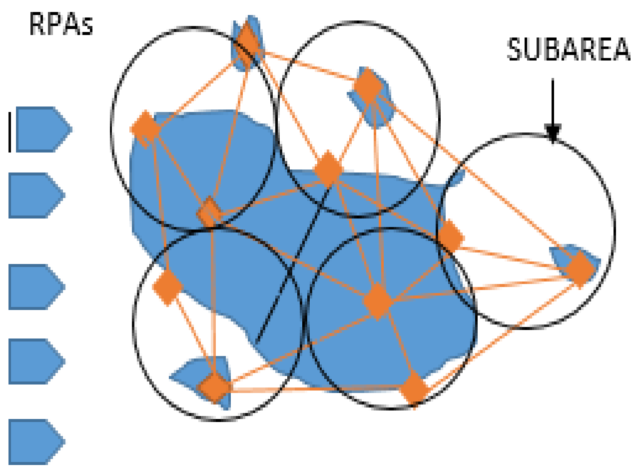

Fig. 3.5. A complex approach for detecting oil spills.

For practical implementation of oil detecting mission it is necessary to find a solution that is near to optimal in the defined probability interval. This restriction allows solving the problem of directing agents without complicated use of resources of software. This formulation of the mission task allows not using an imitation model for agents and objects. This approach allows to simplify the calculation of the length of straight lines and the time of flight for RPA. For complex approach of high-level algorithm, the matrix of time cost for all objects is calculated. This matrix is used for both centralised and ant colony algorithms. The distribution of objects among multi-RPA is performed using both algorithms. The main restriction criteria for distribution of the RPA at high level is the number of targets n. The implementation of both algorithms in multilevel system allows combining the effect at high level. Taking into account the big dimension of matrix of objects, after analysing objects and reducing dimension of matrix in dynamic system, the solution is found using heuristic algorithm for a single RPA. A centralized system, when the control centre distributes the tasks to each RPA, can give effect, when the endurance of RPA is not optimally used. Taking into account high accuracy of the decision tree algorithm, it can be used for the number of objects $n < 20$, or for the areas that are split into subareas where the number of targets $n < 20$. The oil spill dynamical changes can be calculated according to the proposed model. The solving of monitoring and detecting an oil spill by multi-autonomous agents has many solutions. At high level, an oil pollution detecting route for a group of the RPAs is created. This information is sent to the group, which includes the RPA R_i. The optimal solution can be obtained with an algorithm where both the decision tree and the ants colony algorithms are used. In this algorithm, two scenarios are realised. In the first scenario the distribution of monitoring targets is computed solving the graph of dynamic time cost matrix objects. In this scenario, the set of monitoring objects can be split into subsets. In order to design a swarm behaviour, a mathematical model must be provided for both individual agents and the whole swarm [23].

In the second scenario, the ant colony algorithm is used for distributing the dynamic time cost matrix between the RPA. In this algorithm, a restriction for evaporation of pheromone can be implemented. In this approach, the amount of pheromone depends on the number of RPA using the straight line on the graph. In a short time gap, the evaporation of pheromone can be taken into account. This option gives an opportunity to implement a new recalculated matrix at high level if the situation is changed in real time. The solutions obtained in both scenarios are compared. The difficulty criteria are used for comparison. The difficulty criteria can be presented as a result of Scenario 2 divided by the result of Scenario 1. If the difficulty criteria is > 1, the solution obtained by Scenario 1 is used as the optimal route for multi-RPA.

This approach allows using the strength options of both algorithms and eliminating weak options. The possibility to switch from one algorithm to another allows obtaining a solution according to the dimension of the mission task and minimising the time of solving the problem.

4. DEVELOPMENT OF UNMANNED AERIAL PLATFORM FOR MONITORING OIL POLLUTION OF SEA AQUATORIUM

4.1. Formulation of monitoring tasks and requirements for the unmanned platform

4.1.1. Formulation of monitoring tasks

The automatic system using RPA ensures that the following tasks are resolved:

- surveillance of large marine areas;
- continuous monitoring of marine ecosystems;
- monitoring the spread of oil spill in dynamics;
- sampling using specially designed RPA for pollution identification;
- determination of the type of contamination product;
- finding and collecting evidence of oil pollution from ships;
- providing operational information to the responsible services in the event of an oil pollution accident.

4.1.2. Requirements for the creation of unmanned flying platform

When choosing RPA's naval missions, the following principles should be taken into consideration: reliability, compliance with maritime observation requirements, simplicity of management and, finally, price [24].

In developing the requirements for the composition of an RPA complex, the following key parameters were taken into account in order to carry out a marine oil pollution monitoring mission in the offshore oil pollution monitoring.

1. Flight speed and distance of the RPA, taking into account the wide range of monitoring. For monitoring performance, the RPA speed must be in a range from 0 km/h to 180 km/h. According to the analysis of HELCOM statistical data, the largest amount of accidents and unauthorized oil spill occur near the coast. Use of the operational range of 95 km solves the monitoring problem. In addition, the use of opportunities for RPA to take off from ships increases their operational mobility.
2. The ability to monitor relatively independently of weather and environmental conditions. Wind speed or sea waves should not have a significant effect on the detection of oil pollution. It should be possible for the RPA to perform monitoring missions with wind speeds up to 15 m/s in rain and fog conditions [1]. The RPA must have equipment that is resistant to aggressive environment, i.e. salty sea water.
3. RPA facilities must be able to take samples from the surface of water in flight mode. In order to control the dynamics of pollution, it is necessary to determine the thickness of oil film and to control its changes during time.

4. Possibility of transferring information on monitoring results in real time (on-line) mode. The communication system must be able to read the oil spill propagation dynamics monitoring data in real time. In addition, data transmission channels are exposed to various disturbances. Accordingly, it is important to determine the configuration and management of data transmission channels in order to enhance the ability to withstand interference [25].

4.2. Functional capabilities and technical characteristics of unmanned platform components

The use of each particular RPA for monitoring of oil pollution, taking into account external factors, requires various combinations of payloads. One of the main problems is that the RPA has already been designed taking into account general requirements. As a result, the selection of the equipment that should solve the problem with a high probability of detection was a difficult task.

When solving a problem, it is necessary to determine the payload weight for multi-functional use at the RPA's development stage. In this case, the effective solution to the problem is the creation of a separate module for the useful load. The module must be able to install the necessary equipment and sensors in accordance with the technical specification of RPA. The sensors in the module must be installed taking into account the specific requirements of monitoring mission [26].

The analysis of RPA's payloads shows that an integrated payload must be developed. During the analysis it was determined that detection methods should be developed to improve the detection and false alert. The SWOT analysis determined, that only one sensor could not provide the information required by the oil spill monitoring program.

In developing the integrated payload, the following requirements were formulated:

- the possibility of using multiple sensors to prevent false alarms;
- to extend the observation time to 24 hours (day and night);
- to collect oil samples using a special device.

For the optimization of use of RPA during the implementation of oil pollution monitoring mission, an integrated payload has been developed with multispectral thermal sensor and a sampler.

4.3. Development devices and technology for taking samples from remotely piloted aircraft

4.3.1. Formulation of main objectives of taking samples during performing oil pollution monitoring of sea aquatorium with assistance of RPA

National environmental protection legislation includes the requirements for oil pollution control and the sequencing programs. The main objective is to observe the current oil spill to determine the source of environmental pollution and the impact on the marine environment. In the case of oil pollution, it is necessary, in accordance with international requirements, to carry out laboratory analyses and to determine the ship or object of pollution. Laboratory studies can identify the difference between the types of petroleum products and the connection of the blended petroleum product with the source.

Oil pollution is a casual phenomenon, and in this context external factors must be taken into account when establishing a sampling program.

In order to carry out effective monitoring, it is necessary to develop a theory-based and practically feasible methodology that allows to solve the following tasks:

- initial taking of samples and registration of parameters of each sample;
- provisional secondary sampling for the precision of the border of oil spill and extended laboratory analysis.

The application of the methodology in practice will allow responsible organizations to ensure the control and rapid liquidation of oil pollution.

4.3.2. Analysis of deficiencies of oil pollution monitoring programs using remote sensing equipment

Performing of the oil spill monitoring program requires observation at any time.

Measuring the oil film thickness on the surface of the water can provide information on the amount of oil and, if the area of the spill surface is known, based on this information, calculate the total oil volume. In case chemicals and retention systems are used, they should be used on thicker parts of the oil spill. The use of sampling devices can provide information on relative thickness of oil spill and assistance in establishing a methodology for oil pollution clearance. All of the above conditions indicate the need to develop an RPA with a device for collecting samples of oil pollution from the surface of water. The RPA is used for the high actuality of the data obtained for the fulfilment of various environmental monitoring tasks.

4.3.3. Requirements to existing remotely piloted aircraft for taking samples

When monitoring the oil spill to determine the severity of the contamination, it is necessary to use a sampling program to assess the overall environmental impact. The samples have to be taken in spatial areas with coordinates given for the entire contamination sector.

The IMO has drafted a special paper with recommendations on taking samples in case of oil pollution. There are two main sampling methods [19]:

- removal of oil film with a sampling bottle;
- taking samples using a special teflon small mesh.

The use of RPA for obtaining visual data on an oil polluted area provides initial information for the development of a new monitoring and sampling point program. Taking into account the specifics of the RPA oil spill detection mission, the weight of the sampling device should be included in the RPA equilibrium equation. Due to this, the main requirement for the payload is a small weight of the sampler.

In addition, RPA used for flying over water must be fitted with a special emergency landing device [19].

During the analysis, external factors were identified, which may impede the operation of RPA taking oil. These factors are wind speed and wave height. The use of RPA for taking oil samples is limited by wind speeds above 14 m/s and wave height over 2 meters [19].

Compared to autonomous surface and underwater vehicles with sample devices, RPA additionally provides aerial photography.

The payload to take a sample should be fitted to the lower part of hull of the RPA with a special emergency release device [19].

4.3.4. The development of water sampling device and technology for remotely piloted aircraft

Elimination of deficiencies and compliance with the contemporary requirements for monitoring system are possible by implementing RPA. This solution is complex and allows detection of contamination with the aim to confirm the results.

Two types of sampling devices were developed on the basis of SWOT analysis for different marine areas. The first type is intended for use in the case of one sample taken in a particular area and for visual observation approval. The equipment of this type can be installed on the airplane and in the hull of the helicopter type RPA [19].

In order to implement the operational monitoring and prevention program of the existing problems, a method and device for controlling oil pollution of marine waters and internal waters was developed in the research process [19].

The total payload of an RPA depends on the power it can provide. Consequently, the possibilities for taking oil pollution samples are limited. Taking into account the requirements for the flight radius, an RPA with fixed wings solves the problem of remote sensing for areas with long distance from coast.

The device schematically displayed in Fig 4.1 contains a fixed wing RPA equipped with a special sampling device, that is to be executed in the form of a metal holder, a sampling device installed in the hull of the RPA, and a sampler (1) mounted on the holder [27].

Innovative solutions were used in the development of the sampling device. In order to ensure proximity and possible immediate detection of oil pollution, a device with a sensor for detecting pollution was developed in its body. In order to provide high-quality information on the state of water, it is envisaged to take samples from a variety of levels. The construction of the sampling device includes a cylindrical sampler with a solenoid valve with a spring (2) connected to rod (3) with a sleeve with pistons (5) of the sampler’s chamber. In the cylindrical body of sampler, holes were made for receiving water during the sample taking. Inside the upper section in the sampler’s upper piston, a photoelectric cell (4) was mounted and in the lower piston – a lighting led (6).This solution provides the possibility to make water control on the presence of petroleum products and contamination after sampling. The photoelectric cell consisting of a photocell and a diode in the case of presence of petroleum products (optical changes are recorded) sends signals to the RPA electronic control module (ECM) and further, using communication system, to the control centre [27].

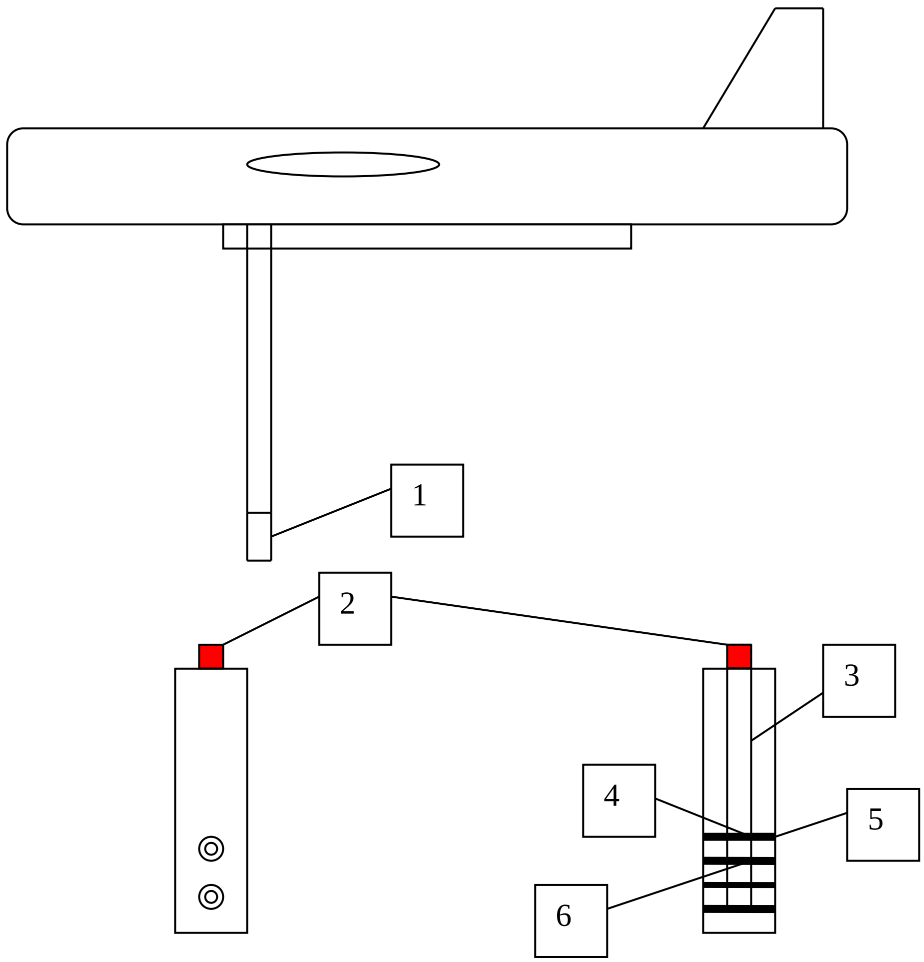

Fig. 4.1. RPA with fixed wings equipped with a special sampling device.

The technical result of the detection of spillage of oil or oil products on the seawater surface is the increase in the rate of detection of oil spills on the surface of water areas and the rapidity of collection, the accuracy of determination of oil or oil product spill coordinates, prediction of spill propagation of oil or petroleum products over short and long time period, the ability to work in all climatic conditions and independence from the day/night.

This solution allows using the coordinates in which the RPA has taken the samples to display the dynamics of the spread of pollution in multi-level electronic cartographic system.

The second type of device is designed to ensure permanent sample taking in designated marine areas. During the development of the device, the task was to take samples of thin films and identify contaminants. In order to ensure the monitoring requirements of the program, an innovative solution was developed for lowering the container to the surface and returning to the housing compartment using micro winch [28].

The invention relates to methods and devices for oil pollution control of both sea aquatorium and inland waters. The method and device, according to the invention, provides water surface sampling to analyse the collected samples for the presence of oil contaminants in the defined water aquatorium. The method includes taking a water surface sample; preparing the sample for transportation; and delivering the sample to the point of destination by means of an RPA.

For taking samples in coastal areas, during the research process a device was developed consisting of a vertical take-off and landing of RPA equipped with a special device for taking samples (Fig. 4.2), constructed as plastic containers with positive buoyancy. Container structure includes metal mesh and special teflon mesh. The container is designed to carry out the procedure of taking samples of oil from the surface of water [28]. The RPA complex performs the sample taking from the surface of oil spill. Lowering and lifting of the container to and from the surface to the special compartment of RPA is performed using a compact winch. The container with positive buoyancy provides for sample taking from water surface in any sea state and wave height. After taking water sample from the surface and lifting the container to the RPA hull, it is placed in a sealed compartment intended for placing one or more containers.

The RPA sealing compartment is equipped with shutters, which close or open automatically or with a remote control, and are sealed with teflon seal.

Sampling and transportation is carried out automatically. After landing of RPA at the base station (onshore or on ship), the container is transferred to the laboratory for sample analysis. If according the monitoring plan it is necessary to take samples from a series of points, several independent modules with containers are installed in the RPA compartment. Unlike existing probe methods, the RPA of vertical take-off and landing is equipped with a special compact winch. The presence of a winch allows remote sampling to be carried out regardless of weather conditions. An innovative solution is that the sampling device is executed in the form of a plastic container with positive buoyancy and is equipped with a special teflon mesh with small cells for obtaining samples from the surface of water. The method of using RPA with containers placed in the hermetic compartment allows the fulfilment of legal requirements for oil pollution incidents. The analysis of methods and means of detecting existing oil pollution was carried out during the research. The main advantages of the developed device are as follows.

RPA cannot be contaminated with oil products or oil product films during the collection of oil from the oil spills. Samples taken in accordance with the IMO standards and the Bonn Agreement can be used for analyses.

This probe device can be used for taking samples from oil spill areas and taking water with a thin oil film (“rainbow gloss”, “blue gloss”, “silvery gloss”).

The analysis shows that the payload with the sampling device has great advantages. There is only one restriction for this type of use – very bad weather conditions.

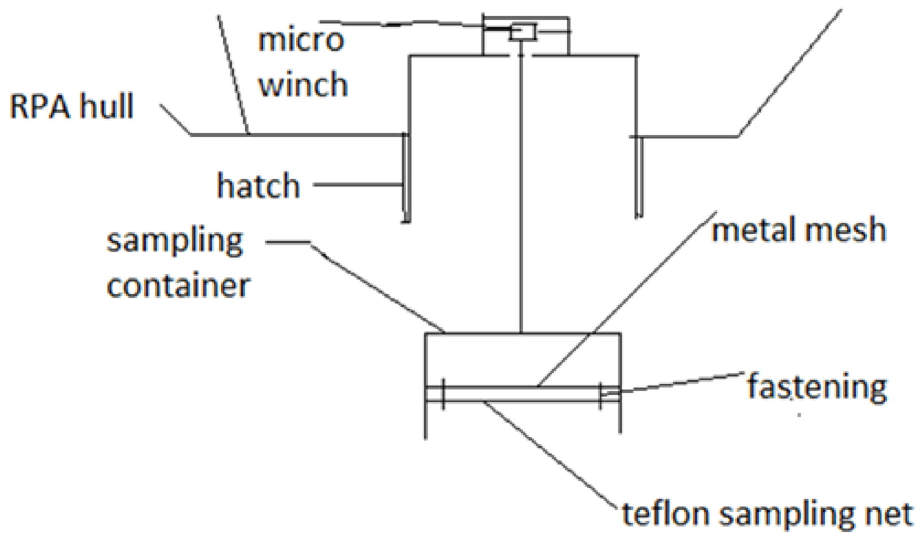

Fig. 4.2. RPA of vertical take-off and landing equipped with a special device for sample taking.

Two scenarios have been implemented for the sample taking from medium-sized oil spills. In the first scenario, the sample taking was carried out by environmentalists using a boat to navigate in the spill zone and transport by car to the laboratory. In the second scenario, RPA with a built-in sampling device took the samples of oil spill.

Using RPA, oil spill sampling program was minimized by 80 percent [19]. The RPA can be used as a platform of autonomous system for assisting in sampling oil spills.

CONCLUSIONS

1. An analysis of the main tasks and methods of monitoring the oil pollution of marine environment with remote sensing was carried out. The pollution levels and sources of the Baltic Sea area were analysed. Sea oil pollution problems and monitoring tasks were identified. An assessment of existing marine surface contamination monitoring with remote sensing systems using ships, satellites, and pilot aircraft was done. It has been found that it is necessary to develop a continuous monitoring methodology for oil pollution using RPA. To avoid false indications of contamination, it is necessary to develop sampling devices.
2. A mathematical model of optimal flight route planning for RPA for the procedure of monitoring has been developed. The following problems were defined: a set of targets with specific parameters such as target type; motion equation; positions derived from sea monitoring systems; displayed formulation (point, line, area). For optimization of the marine pollution surveillance monitoring mission carried out by the RPA, taking into account the criteria, the target matrix attendance is analysed. Targets in the dynamic environment are represented as points with key parameters, such as initial speed and course. The movement of an object, e.g. a ship, is calculated by the object's movement parameters.
3. An algorithm and software for optimizing the flight route of the RPA, performing monitoring tasks, were developed. The algorithm that implements the branch and boundary method consists of a sequence of one type of steps and finds the optimal solution in final steps. Once all the elements have been considered, the decomposition algorithm stops working and the current entry is the best solution. Otherwise, the unchecked elements choose the set that is perspective. It is subdivided. The process continues until all elements in the section are checked. This algorithm has high accuracy. An algorithm can be used with a dynamic programming algorithm. This approach allows to use strong parameters for both algorithms and excludes weak parameters. The ability to switch from one algorithm to another allows to get a solution according to the number of objects of the mission and minimize the monitoring time.
4. Methodology for continuous monitoring of marine pollution of marine waters was developed. The monitoring methodology is implemented in accordance with an algorithm that includes lifting, landing and monitoring of objects, using an automatic unmanned aerial platform. This approach allows to display information on the state of water pollution. The methodology also includes elimination of the detection error. False images that are caused by clouds, floating algae, sandy pebbles are tested using typical algorithm as potential contamination. The RPA flight task contains a proofing algorithm.
5. A mathematical model for the distribution of oil spill on the water surface was developed. The mathematical model assumes that monitoring is carried out in real time using RPA, which transfers the main parameters in real-time. It is assumed in the calculations that the outflow of oil spill on the surface of the sea takes place under the action of forces that depend

on gravity and stiff friction. The mathematical model of the process considered in the case of a symmetric axis can be imagined as a mass conservation equation. After processing the data that is received using RPA, the correction algorithm performs correction of the oil spot parameters in real-time. After the processing of the RPA data, the type of oil product, its severity, density and the volume of oil are determined.

6. An unmanned aerial platform equipped with several types of sensors (video, multispectral, thermal, and hyperspectral, etc.) and a special device for taking samples of water from the surface was developed. Taking of sea water samples is conducted from an RPA in flight mode.

   The unmanned aerial platform includes a vertical take-off and landing RPA equipped with a special sampling device made as a special container with positive buoyancy. Container construction includes metallic and special teflon small mesh. It is intended for taking water from the surface of water and included in the set for petroleum products sampling.

   The lowering of the container to the water surface and the lifting of the container into the RPA hull after sample taking, is carried out using a micro winch.

   After thesamples are taken from water and taken to the RPA hull, the container is placed in a hermetical compartment intended for the assembling of one or more containers.

   The device provides sampling of water from the surface of water, regardless of the waves and state of the sea. The use of an unmanned flying platform for organizing marine pollution monitoring in the sea will help to eliminate the disadvantages of existing remote sensing equipment, and will increase the reliability of automated monitoring systems for oil pollution detection.

7. Technology of water sampling with RPA and algorithm for implementation of this technology were developed. Sampling process and transportation are carried out in automatic mode. The RPA is sent to the sample taking zone with known GPS coordinates. After the arrival of the RPA, the electronic control module (ECM) in a certain area gives the command to open the shutters of the hermetically sealed compartment. After opening the shutters, ECM gives the command to micro winch to lower the container. When the container reaches the surface of water, the ECM stops the rotary winch coil. After the container contacts the surface of the water in a potential oil spill area, ECM gives the winch the command to lift the container with the taken sample. Upon the completion of lifting of the container, ECM gives the command to stop the winch coil and close the shutters of the compartment for sealing. After the landing of RPA at the base (for example, onshore or on ship), the container is transferred to the laboratory for the analysis of the collected samples. If necessary, water samples can be taken from different areas of water, in this case several autonomous modules with containers are located in the compartment of RPA.

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