RIGA TECHNICAL UNIVERSITY
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DEVELOPMENT OF CARTOGRAPHIC INFORMATION COLLECTION SYSTEM WITH REMOTELY PILOTED AERIAL VEHICLES COMPLEX FOR SAFE MARITIME VESSELS' NAVIGATION

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 defense at the open meeting of RTU Promotion Council on 1 October 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 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 has not been submitted to any other university for the promotion to a scientific degree.

Dmitrijs Goreļikovs …………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of Introduction; 4 chapters; Conclusions; Bibliography; 77 figures; 8 tables; 3 appendices; total number of pages is 183. The Bibliography contains 56 titles.

TERMINOLOGY AND ACRONYMS

CICS – cartographic information collection system
ECDIS – electronic chart display and information system
ECS – electronic chart system
ENC – electronic navigation chart
GMDSS – global maritime distress and safety system
GNSS – global navigation satellite system
GPS – global positioning system
GUI – graphical user interface
IEC – International Electrotechnical Commission
IHO – International Hydrographic Organization
IMO – International Maritime Organization
MSC – Maritime Safety Committee
NTM – notice to mariners
OPENCV – open source computer vision library
PHP – personal home page
RENC – regional ENC coordinating centers
RLS – radio location station
RNC – raster navigational chart
RNS – radio navigation system
RPV – remotely piloted aerial vehicles
SENC – system electronic navigation chart
VNC – vector navigational chart
WEND – Worldwide electronic navigational chart database

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GENERAL DESCRIPTION OF THE THESIS

Research Topicality

In recent years, sea cargo traffic is rapidly rising. According to UNCTAD (United Nations Conference on Trade and Development), the growth is almost 25 % over decade: from 8286 million tonnes in 2008 to 10282 million tonnes in 2016. As a result, there is a growing demand for fleets of shipping vessels, which entails the need to improve seagoing navigation systems – by using additional equipment, making them more efficient and safer for use on seagoing vessels.

One of navigation systems without which modern shipping is not conceivable is the electronic chart display and information System (ECDIS). The introduction of electronic chart display information systems, or ECDIS, greatly facilitates the process of using and revising of navigational charts by operator (using automatic or semi-automatic correction methods), in comparison with paper charts. However, it is very important to ensure ECDIS system itself with the latest available information and data to improve the correcting processes and make them even faster. With the development of the electronic chart system requirements for the speed of collecting information, accuracy and material expenses are also increasing.

In 2009, the International Maritime Organization (IMO) adopted mandatory requirements for installation of ECDIS for all maritime cargo vessels of over 3000 gross tonnage and for passenger ships of more than 500 gross tons. ECDIS also requires a correction of electronic navigation chart (ENC), and accuracy and timeliness of this adjustment is the responsibility of the National Hydrographic Organizations. ENC's accuracy and reliability in the defined area depend on accuracy of correction and speed of obtaining information by Hydrographic Service.

On 1 January 2010, the International Hydrographic Organization (IHO) decided to create "Universal Hydrographic Data Model", making it an active international standard. In September 2017, this ECDIS standard came into force with number S-100. Standard S-100 includes requirements to be considered when transmitting online data. This means that ECDIS system should enable maritime vessels to receive information from coastal databases in real time. Thus, time taken for correction of electronic maps on seagoing ships depends only on information provided by Hydrographic Organization.

In Latvia, the correction of information in maritime navigation charts is performed by vessel owned by the Hydrographic Organization – "Kristiāns Dals", which uses a visual method for acquisition of information. Such procedure requires a lot of time and finances. Affordable seagoing ships and trained personnel, fuel costs and repairs require a large budget. Moreover, immediate delivery of information is not ensured. The territory of the Republic of Latvia covers approximately 10 000 square kilometres, and one seagoing ship (as well as two or three seagoing ships) cannot provide visual information in such a large area in real time.

Therefore, it is necessary to develop a cartographic information collection system using remotely piloted aerial vehicle complex for maritime vessels' control (CICS), which can offer real-time information using remotely piloted aerial vehicles (RPV) in cheap and fast way, making correction of ENC more precise.

The Aim and Objectives of Research

Aim

The aim of the Thesis is to develop cartographic information collection system (CICS) with remotely piloted vehicle complex for marine cartographic information acquisition and electronic chart correction according to the requirements of marine vessels' control.

Objectives

1. To explore the existing information acquisition systems used for ECDIS charts' correction in accordance with international and national requirements. To prove weaknesses of systems used and necessity of developing a new system.
2. To develop a flight optimization model for remotely piloted aerial vehicles, used in obtaining cartographic information during flight.
3. To develop a concept for new cartographic information collection system (CICS) for acquisition, processing and correction of cartographic information; and to define necessary subsystems.
4. To develop functional requirements for RPV parameters and core systems for acquisition of marine cartographic information.
5. To develop methodology of functioning, algorithms and software realization for subsystems: CICS cartographic object identification subsystem; RPV flight route optimization subsystem; calculation of object's location subsystem; realization of object's real coordinate calculation subsystem.
6. To develop CICS with remotely piloted aerial vehicle complex for maritime vessels' control methodology, algorithm and software realization for real-time navigation of seagoing ships.

Research Methods

Methodology and research methods used in the research:

- analysis of literature sources;
- mathematical modelling;
- mathematical programming;
- graph theory;
- probability theory and mathematical statistics;
- processing of experimental testing data.

Objects of Study

- Cartographic information.
- Electronic chart display and information system (ECDIS).
- The port of Riga.
- Remotely piloted aerial vehicles.

Scientific Novelty of the Thesis

Innovative solutions developed as a result of the Doctoral Thesis as following.

- During research of functional requirements for RPV parameters and systems for obtaining marine cartographic information, two new functional systems of RPV for on-sea work were developed and patented: "Automatic alarm system for search of unmanned aircraft in case of accident" and "Emergency landing system and method for unmanned aircraft". During CICS object identification subsystem research process, a modified image identification method was created with object morphology and colour gradient algorithm for object recognition, as well as software for improving object recognition.
- RPV's flight route optimization method was developed using graph theory. Based on this method a new model of flight route optimization subsystem and algorithm for RPV were developed. Based on this algorithm, realization was created with using dynamic programming.
- Object coordinate WGS84 calculation algorithm and software realization for navigation objects' real position acquisition from raster pictures (photos) was developed. The algorithm and software are used for realization of CICS object's real coordinate calculation subsystem.

Theses to be Defended

The author of this research is defending the following.

- A model developed for optimizing RPV flight route during obtaining actual cartographic data in minimal time.
- A concept developed during research of cartographic information collection system (CICS) with remotely piloted aerial vehicle complex (RPV) for obtaining, processing and correcting cartographic information.
- Functional requirements developed for RPV parameters and for core systems for acquisition of marine cartographic information;
- Functional methodology developed for CICS cartographic object identification subsystem; RPV route optimization subsystem; subsystem of actual location of cartographic objects, subsystem for calculating coordinates of real maritime objects.

- Realizing algorithms developed for CICS cartographic object identification subsystem; RPV route optimization subsystem; actual location of cartographic objects subsystem; subsystem for calculating coordinates of real maritime objects.
- Developed cartographic information collection system (CICS) with remotely piloted aerial vehicle complex for maritime vessels' control realization and methodology.

Practical Application of the Research Results

As a result of the Doctoral Thesis, completely new cartographic information collection system (CICS) with remotely piloted aerial vehicle complex for maritime vessels' control has been developed. Based on the obtained photographs from RPV complex and information from ECS of the same area, CICS will significantly improve obtaining of maritime cartographic information from hydrographic service. Processing of cartographic information and correction data will be more precise and will be done in real time. This will ensure timely adjustment of electronic navigational charts on seagoing vessels, making sailing safer in coastal waters. The developed system works automatically, allowing RPV to be used to make cartographic information cheaper and faster comparing with present situation.

The results of the Doctoral Thesis can be used in such scientific fields as aeronautics, navigation, cartography, etc.

Approbation of the Obtained Results

The results of the work were reported in 10 international scientific conferences

1. 19th International Conference "Transport Means 2015", Lithuania, 22–23.10.2015. ("Practical Realization of Unmanned Aerial Vehicle System for Collection of Data for Maritime Navigational Charts", D. Goreļikovs).
2. RTU 55th International scientific conference, Latvia, 17.10.2014. ("Bezpilota aviācijas kompleksa kartogrāfiskās informācijas datu ieguves sistēmas izstrāde kuģu vadībai" D. Goreļikovs).
3. RTU 56th International scientific conference, Latvia, 14–16.10.2015. ("Bezpilota lidaparātu īstenošanas funkcijas kuģošanas uzraudzības un drošības misijās", D. Goreļikovs, V. Žavtkēvičs).
4. 18th International Conference "Maritime Transport and Infrastructure – 2016", Latvia, 21–22.04.2016. ("Electronic navigation: development, standardization, testing", D. Goreļikovs)
5. 19th International Conference "Maritime Transport and Infrastructure – 2017", Latvia, 20–21.04.2017. ("Development and Analysis of Evaluation Algorithm for Different Cartographic Systems (ECS, ECDIS, E-Navigation) in accordance with STCW Requirements", D. Goreļikovs).

6. 20th International Conference “Maritime Transport and Infrastructure – 2018”, Latvia, 19–20.04.2018. (“Actual development trends for electronic charts display and information system (ECDIS)”, D. Goreļikovs).
7. 22nd International Conference “Transport Means 2018”, Lithuania 03–05.10.2018. (“Applying Remotely Piloted Aircraft Systems for Correcting Electronic Chart Data and Ensuring Safe Navigation”, A. Urbahs, D. Goreļikovs).
8. 18th International Scientific Conference “Engineering for Rural Development –2019”, Latvija, 22–24.05.2019. (“Control of agricultural land flooding by using remotely piloted aircraft system”, D. Gorelikovs, M. Urbaha).
9. Urbaha M., Goreļikovs D. Optimizing the flight route of remotely piloted aircraft for updating information in electronic chart systems In: International Conference on Informatics, Control and Robotics (ICICR2019), June 16–17, 2019, Shanghai, China.
10. 3rd International Conference on Traffic Engineering 2018, Budapest, Hungary, 08–10.04.2018. (“Automatic routing for the flyby of monitoring objects by remotely piloted aircraft”, D. Goreļikovs, M. Urbaha, A. Urbahs, J. Stankunas).

The results of the work are published in 8 scientific periodicals

1. Goreļikovs D. (2017) Development and Analysis of Evaluation Algorithm for Different Cartographic Systems (ECS, ECDIS, E-Navigation) in accordance with STCW Requirements. – Maritime Transport and Infrastructure: Proceedings ofthe 19th International Conference, Latvia, Riga, 20–21 April, Latvian Maritime Academy, 2017, pp. 13–18.
2. Goreļikovs, D. (2015) Practical Realization of Unmanned Aerial Vehicle System for Collection of Data for Maritime Navigational Charts. – Transport Means: Proceedings of the 19th International Conference, Lithuania, Kaunas, 22–23 October, 2015. Kaunas: Technologija, 2015, pp. 462–465. ISSN 1822-296X. e-ISSN 2351-7034.
3. Urbahs A., Goreļikovs D. (2018) Applying Remotely Piloted Aircraft Systems for Correcting Electronic Chart Data and Ensuring Safe Navigation. In: Transport Means 2018: Proceedings of the 22nd International Scientific Conference, Lithuania, Trakai, 03–05 October, 2018. Kaunas: Kaunas University of Tehnology, Part I, pp. 430–433. ISSN 1822-296X.
4. Goreļikovs D., Urbaha M., Urbahs A., Stankunas J. (2019) Automatic routing for the flyby of monitoring objects by a remotely piloted aircraft. Procedia Computer Science, ICTE in Transportation and Logistics, Elsevier, 2019, pp.398–405. ISSN 1877-0509.
5. Gorelikovs D., Urbaha M. (2019) Control of agricultural land flooding by using remotely piloted aircraft system. Proceedings of International conference “Engineering for Rural Development 2019”, pp. 1655–1660. DOI: 10.22616/ERDev2019.18.N080.
6. Goreļikovs D., Urbaha M., Nedelko D., Stankunas J. (2019) Analysis of Systems Ensuring the Acquisition of Real-Time Cartographic Navigation Information. - Transport

and Aerospace Engineering, Vol. 7, pp. 24–31. ISSN 2255-968X, e-ISSN 2255-9876. DOI: 10.2478/tae-2019-0003 978-1-5108-7539-5.
7. Urbaha M., Goreļikovs D. Development of an image recognition subsystem for cartographic information correction based on monitored data obtained with the use of remotely piloted aircraft. Aircraft Engineering and Aerospace Technology (in press.
8. Urbaha M., Goreļikovs D. Optimizing the flight route of remotely piloted aircraft for updating information in electronic chart systems. In: International Conference on Informatics, Control and Robotics (ICICR2019), June 16–17, 2019, Shanghai, China.

Patents

1. Urbahs A., Gorelikovs D., Žavtkevičs V. Automatic alarm system for search of unmanned aircraft in case of accident. (Publication number: LV15184 (A), 20.02.2017.). Source: European Patent Office.
2. Urbahs A., Gorelikovs D., Žavtkevičs V. 3. Emergency landing system and method for unmanned aircraft (Publication number: LV15183 (A), 20.02.2017.). Source: European Patent Office.

The results of the Doctoral Thesis were used in 1 scientific project

1. Project financed by the European Regional Development Fund "LARIDAE Multipurpose Unmanned Aerial Vehicle Environmental Monitoring Project" 2014/0029/2DP/2.1.1.1/14/APIA/VIAA/088 (scientific assistant in the implementation of the project).

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 173, including 77 figures and 8 tables. The Bibliography contains 54 titles.

1. ANALYSIS OF EXISTING MARITIME CARTOGRAPHIC INFORMATION DATA PROCESSING SYSTEMS AND FORMULATION OF REQUIRED CORRECTIONS FOR ELECTRONIC CHARTS SYSTEMS

1.1. Requirements of International Maritime Organization and International Convention for the Safety of Life at Sea for Electronic Chart Display Information System (ECDIS)

Maritime navigation, as the most important element in control of seagoing ships, is regulated by documents issued by the International Maritime Organization (IMO) and by national rules defined by the Maritime Administrations. The technical means of navigation must be certified in accordance with operational standards and technical standards approved by IMO and developed by the International Electrotechnical Commission of the International Electrotechnical Commission (IEC). National Maritime Administrations must carry out control of compliance with international and national regulations, including seagoing ships' equipment set up.

International organizational and legislative support is a very important element of modern maritime system, purpose of which is clearly reflected in the title of basic act – the International Convention for the Safety of Life at Sea (SOLAS). The main objective of this document is the establishment of minimum standards that meet requirements for safety of a ship during construction and operation of seagoing ship [1].

At present, the main officially approved tool for electronic navigational cartography is the Electronic Chart Display Information System (ECDIS) [1].

ECDIS – Electronic Chart Display and Information System is a maritime navigation cartographic system that meets national requirements ("Marine Equipment Regulations" [2]; "Regulations on the Use and Maintenance of Seagoing Radio and Navigation Equipment" [3], Riga 12 January 12016); as well as international requirements (IEC-61174).

In 2009, IMO (International Maritime Organization) adopted mandatory requirements for installation of ECDIS on all cargo ships of over 3000 GT and on seagoing passenger ships larger than 500 GT. The abovementioned seagoing vessels shall be equipped with an electronic chart system in accordance with the provisions of regulation 19.2.10 of Chapter V of SOLAS Convention. Thus, further development of shipping industry is directly related to the optimization of electronic chart system [1].

ECDIS is a high-level system and must comply with all requirements from IMO, IHO (International Hydrographic Organization) and IEC (International Electrotechnical Commission) for ECDIS, as well as have a type-certificate. In accordance with the SOLAS-1974 Convention, ECDIS system has been included in seagoing vessel's navigation equipment list (Regulation 19) since 2002 and can be used for creating a vessel's voyage plan [1]. It was officially announced for the first time in IMO Resolution A.817 (19) in 1995. This resolution states that if a seagoing ship is equipped with ECDIS and has official ENC chart collections with an appropriate correction of information, then the system can be considered as legal equivalent to paper charts [4]. Consequently, it has to be clarified what is “official ENC with correction”.

1.2. Electronic Charts. Definition and Types

Electronic chart (EC) is a cartographic image that depicts a particular area of Earth on a display screen, or the amount of data that is required to create such image. ECs can be divided into official and unofficial charts. Charts issued by the Hydrographic Service of a particular country are deemed official maps. All other ECs are treated as unofficial maps.

Electronic Navigation Cards (ENC) is a database, standardized for content, structure and format for use in the Electronic Chart Display and Information System (ECDIS). The ENC contains cartographic information required for safer shipping, and the ENC can include additional information not shown on paper navigational charts (but are present in shipping publications) that is considered necessary for maritime safety [4].

Official ENCs are charts developed by the National Hydrographic Organization for use in the ECDIS system, using S-57 – basic format for electronic charts, defined by IHO, for exchange of data between hydrographic services, agencies, cartographic producers and electronic chart systems.

1.3. Requirements for Electronic Chart Corrections

Most important documents for correcting procedure in ECDIS electronic charts are IHO Standard S-57 “Data Format for the Conversion of Digital Hydrographic Data” and IHO S-52 – “Standard used by ECDIS Manufacturers to determine how ENS data is displayed on the ECDIS screen”. Requirements of these two documents are summarized in Resolution IMO A.817 (19) – “Performance Standards for the Electronic Chart Display and Information System (ECDIS)” [4].

According to the S-57 standard, all navigational information must be stored in a vector form, which ensures significant amount of memory savings in charts preservation. In addition, it describes minimum time required for restoring or restarting the chart in ECDIS. Standard S-57 describes the correction mechanism that allows the correction of individual data components [5].

The focus on practical issues regarding formal correction of ENCs is given in S-52, which contains Annex 1 “ENC Correction Instruction” [6]. The main requirements for official correction algorithm of ENS for maritime ECDIS system is set out in Resolution IMO A.817 (19). Coordination of activities of ENC distribution and adjustment information is done by special IHO Committee in accordance with the World Electronic Navigation Database (WEND) [7].

Consequently, official ENCs must be corrected. The following information describes correction principles governed by the above-mentioned documents.

The main provisions of “ENS Correction Instruction” in S-52 include a standard set of requirements for correction and distribution of correction information service. The official IHO correction must be different from local one, issued by port authority, but ECDIS system must reflect different correction methods.

The instruction sets the following service categories.

1. List Service – correction service at specified time intervals that are timely known to the sender and recipient.
2. Demand Service – any correction service determined by an individual user request, i.e. provision of correction upon request of user.
3. Emergency service – provision of any correction that is not related to the regular list and contains extraordinary information relative to ENC [8].

The main requirements of IMO A.817 (19) Resolution for ENC's correction in ECDIS are as follows.

1. The content of ENC should be adequate and comply with today's requirement level suitable for upcoming voyage, in accordance with the requirements set out in Regulation V/19 of SOLAS-74 Convention.
2. ENC and its correction must be displayed without any distortion of that information.
3. ENC data and its correction must be different from the display of other information.
4. Correction must be saved and preserved separately from ENC.
5. ECDIS must be able to accept the official data correction for ENC automatically, according to IHO standard. The procedure for uploading correction must not interfere with display of the map.
6. ECDIS must be able to accept formal correction for ENC by manually entering it using usual means. The representation of ECDIS must be distinct from ENC information and its formal correction and must not affect sharpness of display.
7. ECDIS must be able to keep correction information, including the time of acceptance by ENC.
8. ECDIS should enable seaman to display the correction and to review contents of ECDIS, specifying that it is included in ENC [4].

Consequently, as stated above, accuracy and timeliness of correction of ENC is the responsibility of the National Hydrographic Organization. Cartographic information shall correspond to the last edition of the data published by the National State Hydrographic Service and comply with IMO requirements. For example, Latvian Maritime Administration Marine Hydrographic Service is the national co-ordinator – the authorized state Authority, which is charged with collecting and receiving information about changes of navigation object positions, parameters and coordinates [9].

ECDIS is integrated into trading fleet, but at the same time, the system is still being modernized. Modernization is done to speed up the operation of system, to make information update faster, more visible and more precise. Presently the resources that are used for the improvement of ECDIS are not directly related to seagoing vessels, such as satellites, coastal segments, data transmitting lines, etc. This suggests that ECDIS covers several domains and can interact with different systems remotely [30]. Therefore, the development of system that influences acquisition and processing of information, making this method wider and easier to use, can help to improve the processing of ECDIS information.

2. DEVELOPMENT AND SIMULATION OF ALGORITHM FOR OPTIMIZATION OF FLIGHT ROUTE OF REMOTELY PILOTED AERIAL VEHICLE

One of the most important functions of operation of new cartographic information collection system (CICS) with remotely piloted aerial vehicle complex for maritime vessels' control is the determination and optimization of remotely piloted aerial vehicle's (RPV) flight route. The aim of this part of the research is to find possible improvements to check the route (created based on ECDIS data), making its implementation faster and more efficient. This opportunity can be offered by using RPV and dynamic programming methods during making choice of flight route. The route optimizing process will use positions of previously acquired maritime navigation objects from ENC, which will comprise an optimal flight route for RPV.

"Optimization" is a process that allows to choose the best option from all possible. In this process, it is usually necessary to solve the optimization problem by finding optimal values for particular parameters that determine the overall task. In this process, the solution to optimization problem is to find values whose primary function is minimum or maximum. In the case of our investigation, function values must be of minimal value for RPV to get from the initial object to end of the route in shortest possible time interval [10].

Methods for solving optimization problems:

1) Dijkstra's algorithm;
2) Floyd–Warshall algorithm;
3) Bellman–Ford algorithm;
4) Bellman function method.

The operating principles of all these algorithms are based on graph theory [11].

"Graph *G*" is a non-empty set *V* that includes elements *A*, belonging to group *V* or nodes, and group *Q* containing group's *V* different pairs of nodes.

Each pair of nodes $m = \{z, t\}$ is called arcs or edges of graph *G* and states that arc m is the path between nodes *z* and *t*. Therefore, nodes *z* and *t* are endpoints of the arc. Node *z* and arc *m* are "incidents" (have relationship), just like node *t* and arc *m*, since nodes are the extremities of edge. There are such concepts as directional (or oriented) graph and non-directional (or non-oriented) graph. Arrows represent oriented graphs. In this graphic, set *Q* consists of directional pairs $m = \langle z, t \rangle$. Node *z* is called "the start node" for arc *m*, but node *t* is "the stop node" of this arc. In the case of oriented graph $\langle z, t \rangle \neq \langle t, z \rangle$. Graph's types are shown in Fig. 2.1.

Fig. 2.1. Types of graphs.

There is a concept of a mixed graph. This graph consists of orientated and non-oriented graphs. This graph can be transformed by orienting, converting non-oriented arcs to oriented, as shown in Fig. 2.2.

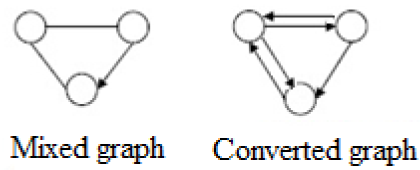


Fig. 2.2. Converting of graphs.

In graph theory there are several matrixes that determine the graphs themselves, this technique is used to achieve the goal in current research to find optimal route between navigation objects. In particular, in the task studied, all graphs are non-oriented, because the distance between any two points can be measured from both starting objects.

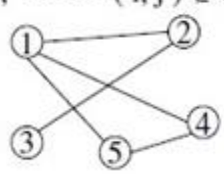
Types of matrixes:

1) **Node matrix** is square matrix ***A*** with |*Y*| × |*Y*| – matrix size (*Y* is set of nodes in graph), matrix elements are ‘1’ and ‘0’ only.

For Non-Oriented Graph

Node matrix for non-oriented graph is shown in Fig. 2.3.

$$A(i,j) = \begin{cases} 1, & \text{if arc}(i,j) \in Q \quad \text{<exist>} \\ 0, & \text{if arc}(i,j) \notin Q \quad \text{<not exist>} \end{cases}$$



A =

	1	2	3	4	5
1	0	1	0	1	1
2	1	0	1	0	0
3	0	1	0	0	0
4	1	0	0	0	1
5	1	0	0	1	0

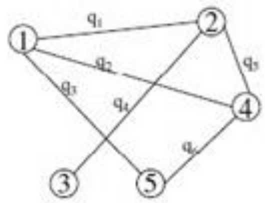
Fig. 2.3. Node matrix for non-oriented graph.

2) **Incident matrix** is rectangular matrix ***B*** with size |*Y*| × |*Q*| where rows are correspondent to nodes of the graph, and columns correspond to the graph arcs.

For Non-Oriented Graph

Incident matrix for the non-oriented graph is shown in Fig. 2.4.

$$B(i,j) = \begin{cases} 1, \text{ if node } V_i \text{ and arc } q_j \text{ are incidents} \\ 0, \text{ if node } V_i \text{ and arc } q_j \text{ are not incidents} \end{cases}$$



	q1	q2	q3	q4	q5	q6
1	1	1	1	0	0	0
2	1	0	0	1	1	0
3	0	0	0	1	0	0
4	0	1	0	0	1	1
5	0	0	1	0	0	1

Fig. 2.4. Incident matrix for non-oriented graph.

Methods for Solving Optimization Problems

For optimal route selection it is possible to use one of the following algorithms: Dijkstra's algorithm, Floyd–Warshall algorithm, Bellman–Fords algorithm or Bellman function method. Let us consider each algorithm.

Dijkstra's Algorithm

Dijkstra's algorithm calculates the shortest path from one of graph's nodes to all others in the case of positive "weights" (distances) for all graph's arcs.

The distance for node *Y* will be the distance from initial node to *Y*. Dijkstra's algorithm gives temporary initial distance consideration and will try to improve it step by step during calculations:

I. Assign the value of possible distance for each node: starting node will have zero, but for all others at this step – infinity.
II. Mark all nodes, except the starting one, as non-visited. Set the starting node as current. Create a set of non-visited nodes that contain all nodes except the starting node.
III. From the current node algorithm observe all non-visited neighbour nodes (having at least one common arc) and calculate possible distances for them. For example, if the current node V_3 has distance 2 and arc connecting it to neighbouring node V_6 have "weight" 4, then distance to V_6 (through V_3) will be 2 + 4 = 6. If this distance is less than the previously recorded distance for the calculated node (V_6), then this distance is overwritten. Although neighbour has visited, it is not currently marked as visited and remains in the non-visited set.
IV. Once all neighbours of current node are evaluated, the current node is marked as "visited" and is removed from the non-visited set. The visited node will never be tested again; its recorded distance is final and minimal.
V. The next checked node will be the node, which is indicated by least (possible) distance from the non-visited set.

VI. If the non-visited set is empty, the algorithm will stop. In another case, set the current node as a node from non-visited set with the least possible distance and return to step III.

As an example, let us check the example graph, shown in Fig. 2.5. It contains 11 nodes with V_1 as initial nodes position, marked with S (starting node).

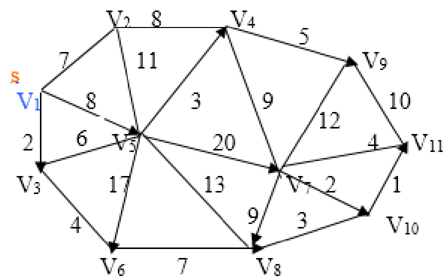


Fig. 2.5. Example graph for explanation of Dijkstra's algorithm.

All arcs of the graph have positive values as shown in Table 2.1.

Table 2.1

Arc's Values for Example Graph

$C`_{ij}$	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V_{11}
V_1		7	2		8						
V_2	7			8	11						
V_3					6	4					
V_4		8					9		5		
V_5		11	6	3		17	20	13			
V_6			4					7			
V_7				9				9	12	2	4
V_8										3	
V_9							12			10	
V_{10}								3			1
V_{11}							4		10		

To understand the nature of the method, let us look at the graph after the fourth step of algorithm. The results of calculation are shown in Fig. 2.6.

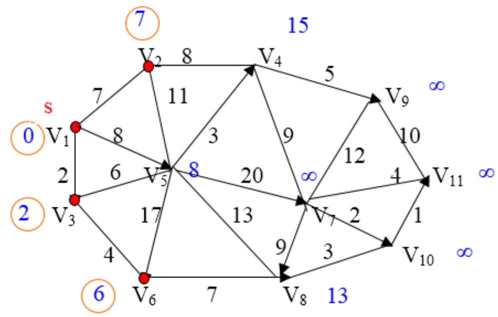


Fig. 2.6. Example graph calculations with Dijkstra's algorithm after the fourth step.

The shortest distances from the starting node are found for four nodes V_1, V_2, V_3, V_6. Their constant values are V_1 – 0, V_2 – 7, V_3 – 2, V_6 – 6, the rest of nodes are marked with infinity (as non-visited). Now let us execute the 5th repetitions of graph.

First, let us find a node with least changeable distance (blue colour) between the nodes with variable distances (not marked with red circles). This node will be current for our iteration. As it possible to check, it is node V_5, and we will find all nodes that are connected to V_5 with arcs in the graph.

In next step, the algorithm improves the value of nodes‘ variable distances.

New value V_4 will be calculated. Node V_5 is equal to 8 + distance to node V_4; 8 + 3 = 11. The resulting distance 11 is smaller than the old V_4 sign (15) and therefore the algorithm changes the sign of V_4 to 11.

V_8 and V_7 are calculated exactly like V_4 using appropriate values.

After the fifth repetition, vertex V_5 receives a constant sign and the graph will look like it is shown in Fig. 2.7.

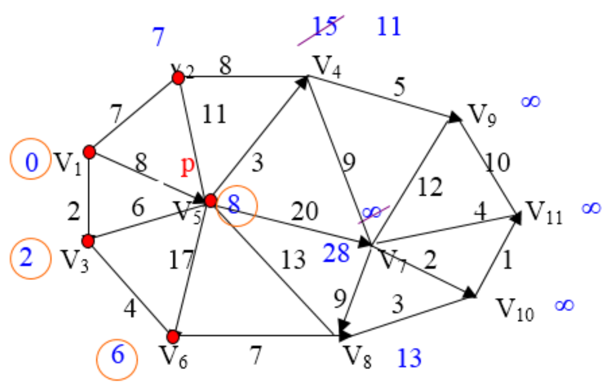


Fig. 2.7. Calculations of example graph with Dijkstra's algorithm after the fifth step.

This way, the algorithm calculates and improves values for all other nodes and finds the shortest distance [11].

Disadvantages of using Dijkstra's algorithm in present situation. In the case when the node with minimum distance $d(V)$ is searched from entire set of nodes and data array is used to save the d values, algorithm's operating time is $O(|V|^2)$. The main cycle must be executed n times, each of them uses a sequence of n operations to determine minimum value. The number of operations in each neighbourhood of visited nodes is proportional to the number of arcs $|E|$ (because each arc in these cycles is used twice and requires continuous operation). Thus, the algorithm total running time O will be $(|V|^2 + |E|)$, where $|V|$ is the number of nodes, and $|E|$ is the number of arcs [12].

The algorithm is well applicable in situations with a small number of nodes. If the number of nodes (maritime objects in case of our research) is increased, use of this algorithm will not be the optimal choice. In addition, the disadvantage of Dijkstra's algorithm in our case is that it searches for short paths from the specified node to all others, which means that the operator must determine the initial node manually.

Floyd–Warshall Algorithm

For implementing Floyd–Warshall algorithm a special matrix is used in which each node is numbered from one to the required number of nodes. Each arc of the graph has its own "weight", or distance value that must be added passing from one node to another. When applying this algorithm, such matrix will be overwritten automatically and values will be written in each cell, which will characterize the shortest distance between the two graph nodes [11].

Let us check the example graph shown in Fig. 2.8.

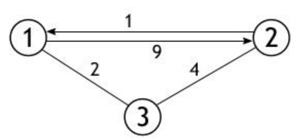


Fig. 2.8. Example graph for Floyd-Warshall algorithm's explanation.

This graph corresponds to the value matrix shown in Table 2.2.

Table 2.2

Floyd–Warshall Algorithm's Values Matrix

No/Value	**Value 1**	**Value 2**	**Value 3**
1	0	9	2
2	1	0	4
3	2	4	0

The aim of the algorithm is to overwrite this array, so that each cell has the shortest path between objects, which means the smallest possible value between objects in an array.

In Fig. 2.9, 27 steps are shown for realizing the route between objects. There are so many options because the execution time of algorithm is equal to $O(|V|^3)$. Our graph has three vertices and $3^3 = 27$. The first changes occur at algorithm's step where $k = 1$, $i = 2$, and $j = 3$. At that time, D [2][1] = 1, D [1][3] = 2, D [2][3] = 4.

D [1][3] + D [3][2] = 3 and 3 < 4, hence matrix element D [2][3] gained a new value. The algorithm will recalculate all values and will replace the matrix data with new ones.

k	i	j	aizvietojums
1	1	1	
1	1	2	
1	1	3	
1	2	1	
1	2	2	
1	2	3	3<4, D[2][3] ←3
1	3	1	
1	3	2	
1	3	3	
2	1	1	
2	1	2	
2	1	3	
2	2	1	
2	2	2	
2	2	3	
2	3	1	
2	3	2	
2	3	3	
3	1	1	
3	1	2	6<9, D[1][2] ←6
3	1	3	
3	2	1	
3	2	2	
3	2	3	
3	3	1	
3	3	2	
3	3	3	

0	9	2
1	0	4
2	4	0

0	9	2
1	0	3
2	4	0

0	6	2
1	0	4
2	4	0

Fig. 2.9. Example matrix with Floyd–Warshall algorithm's calculations.

The Floyd–Warshall algorithm's disadvantages. This algorithm finds the shortest path from one node to the rest of graph. Our task is to find the optimal way only. Excessive information on additional routes will demand additional resources. The algorithm, resulting in calculation of all nodes of graphs, will result in excessive time and resource overruns. In addition, the complexity of the algorithm is much higher than in other examples – $O(|V|^3)$ [11].

Bellman–Ford Algorithm [13]

The algorithm calculates the shortest path in upward direction. First it calculates shorter distances with maximum of one arc path. Then it calculates the shortest path with 2 arcs and so on. After repeating outer loop i times, the shortest paths will be calculated with no more than i arcs. There may be maximum number of $|V| - 1$ arcs in any path (where $|V|$ is the number of nodes in the specified graph), so outer loop runs $|V| - 1$ times. The idea is if we have calculated shortest paths with no more than i arcs, then repetition across all arcs guarantees the shortest path with most $(i + 1)$ arcs.

Let us check the example graph shown in Fig. 2.10.

A	B	C	D	E
0	∞	∞	∞	∞

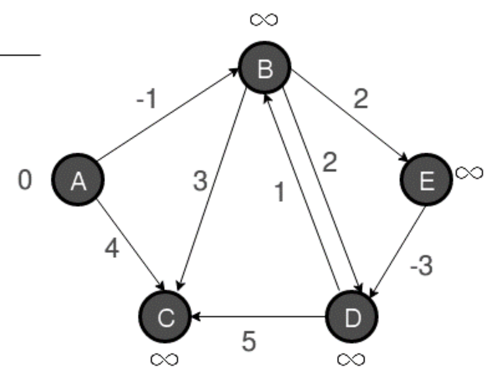


Fig. 2.10. Example of Bellman–Ford algorithm.

Let us assume that the starting node's distance is 0. The algorithm will initialize all distances as endless, except for the distance to the starting node. The total number of nodes in graph is 5, so all arcs must be processed 4 times.

The algorithm will process all arcs in the following order: (B, E), (D, B), (B, D), (A, B), (A, C), (D, C), (B, C), (E, D). During calculations, the algorithm gets the following distances when all arcs are processed for the first time. The first line displays initial distances. The second row shows distances when processing arcs (B, E), (D, B), (B, D) and (A, B). The third row shows distances when (A, C) is processed. The fourth row shows when (D, C), (B, C) and (E, D) are processed (Fig. 2.11).

The first iteration guarantees the shortest path made up of no more than one arc length. We obtain the following distances when all edges are processed secondarily (the last row shows the final values).

A	B	C	D	E
0	∞	∞	∞	∞
0	-1	∞	∞	∞
0	-1	4	∞	∞
0	-1	2	∞	∞

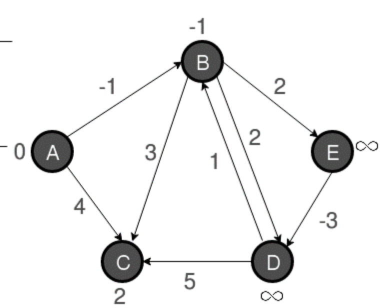


Fig. 2.11. Example of Bellman–Ford algorithm calculations after first iteration.

The second iteration guarantees the shortest path made up of no more than two arcs. The algorithm handles all arcs two more times. Distances are reduced after the second iteration, so the third and fourth iterations do not give new smaller distances (Fig. 2.12).

A	B	C	D	E
0	∞	∞	∞	∞
0	-1	∞	∞	∞
0	-1	4	∞	∞
0	-1	2	∞	∞
0	-1	2	∞	1
0	-1	2	1	1
0	-1	2	-2	1

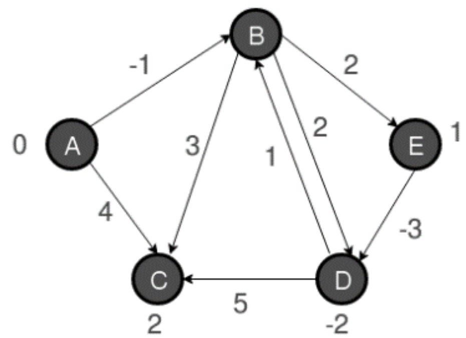


Fig. 2.12. Example of Bellman–Ford algorithm calculations after the second iteration.

The complexity of the calculation of Bellman–Ford algorithm is $O(|V||E|)$ [11]. This algorithm finds the shortest path from one node to the rest of the graph. However, our task is to find only the shortest way between two points. Excessive information on additional routes will use additional resources as compared to the next method.

Bellman Method

In cases, where only one remotely piloted vessel (RPV) is used in the cartographic data acquisition system, it is possible to explore optimization of flight path as "Classical Travel Problem". One of the most prominent problems of combinatorial optimization is to find most advantageous route going through all specified points and then returning to the starting point. This task can be solved when using dynamic programming methods, using direct or inverted Bellman function method. It enables full use of dynamic programming capabilities in both direct and iterative calculation procedures.

Given this method, we assume that the graph's nodes are cities, and distances between them correspond to the length of graphic arc between these nodes.

Let us assume that i is any of N cities ($i \in N$), and V is subset of any city except city 1 and city i. With $M(i, V)$, we denote a set of roads, where each path begins in city i, ends in city 1, and passes through cities but only through city V, entering each city from V exactly once. Assume that $B(i, V)$ denotes the shortest path for set $M(i, V)$. In this case $B(i, V)$ is Bellman function. As can be seen, $B(1, \{2, 3, ..., n\})$ is the minimal closed path that runs through all cities. If V is one set of one element, $V = \{j\}$, where $j \neq 1$ and $j \neq i$, then set $M(i, V)$ consists of one path $\mu = (i, j, 1)$.

$$B(i,\{j\}) = s_{ij} + s_{j1}. \tag{2.1}$$

where $i \in N$, $j \in \{2, 3, \dots, n\}$, $j \neq i$.

Let us assume that values of functions $B(i, V)$ for all $i \in N \setminus (1)$ and for all possible k elements

($k < n - 1$) are already calculated. Value $B(i, V')$ wherein V' is arbitrary subset of $(k + 1)$ elements of set $N \setminus \{1, i\}$, is calculated by formula

$$B(i, V') = \min_{j \in V'} (s_{ij} + B(j, V' \setminus \{j\})). \qquad (2.2)$$

Both of the above equations are dynamic programming recurrence relationship. To solve the problem of traveller sellers, they provide inverse Bellman methods of implementation [12].

Let us manually calculate the graph, with information proposed from CICS cartographic object identification subsystem in Fig. 2.13.

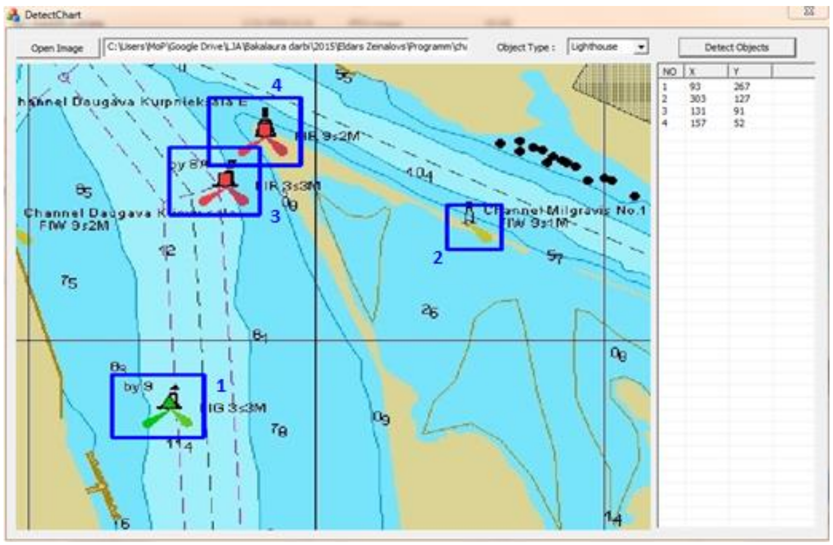


Fig. 2.13. Example of object recognition for manual calculation of Bellman function method.

We need to calculate the distance between objects (there are known pixel positions) and, as a result, we will have a distance matrix between objects:

$$\begin{bmatrix} 0 & 252 & 170 & 224 \\ 252 & 0 & 175 & 164 \\ 170 & 175 & 0 & 46 \\ 224 & 164 & 46 & 0 \end{bmatrix}$$

First, using Formula 2.1, we will calculate values $B(i, \{j\})$:

$B(2, \{3\}) = 175 + 170 = 345$;
$B(2, \{4\}) = 164 + 224 = 388$;
$B(3, \{2\}) = 175 + 252 = 427$;
$B(3, \{4\}) = 46 + 224 = 270$;
$B(4, \{2\}) = 164 + 252 = 416$;
$B(4, \{3\}) = 46 + 170 = 216$.

Next, according to Formula 2.2, we will obtain (in each of the following equations, values of parameter j are marked on left side, in which minimum in formulas is calculated on the right side of Formula 2.2):

$B(2, \{3, 4\}) = \min[s_{23} + B(3,\{4\}); s_{24} + B(4,\{3\})] = \min(175 + 270; 164 + 216) = 380;$
$B(3, \{2, 4\}) = \min[s_{32} + B(2,\{ 4\}); s_{34} + B(4,\{ 2\})] = \min(175 + 388; 46 + 416) = 462;$
$B(4, \{2, 3\}) = \min[s_{42} + B(2, \{3\}); s_{43} + B(3,\{2\})] = \min(164 + 345; 46 + 427) = 473;$
$B(1, \{2, 3, 4\}) = \min[s_{12} + B(2,\{3, 4\}); s_{13} + B(3,\{ 2, 4\}); s_{14} + B(4,\{2, 3\})] =$
$= \min(252 + 380; 170 + 462; 224 + 473) = 632.$

The completed selection allows to determine optimal routes. Because weather conditions (wind direction and velocity) were not taken into account in the proposed example, the distance matrix is symmetric, $s_{ij} = s_{ji}$ and Bellman method will offer two opposing routes with the same distance.

There are 1 → 3 → 4 → 2 → 1 and 1 → 2 → 4 → 3 → 1.

According to modelling results, Bellman method is most effective because it does not require creation of additional data structures and control of entire data flow, as is the case with Dijkstra's and Bellman–Fords algorithms. Floyd–Warshall algorithm is not used due to complexity and lengthy processing time compared to Bellman method. In addition, using Bellman method, all possible paths can be stored as data structures and can be used in future calculations in program, partly by changing initial values [33].

The inverse Bellman method can be fully implemented with dynamic programming methods, taking into account need for iteration.

3. DEVELOPMENT OF REMOTELY PILOTED AERIAL VEHICLE COMPLEX FOR CARTOGRAPHIC INFORMATION COLLECTION SYSTEM FOR MARITIME VESSELS' CONTROL

3.1. Concept for Cartographic Information Collection System (CICS) With Remotely Piloted Aerial Vehicle Complex for Maritime Vessels' Control

In order to obtain, process and correct cartographic information, and to to simplify the process, CICS has to be divided into phases [14].

Phase 1

From the proposed electronic chart (Fig. 3.1), CICS needs to create a table with key object placement for controlling other objects. In this phase, system will allow the following options: operator-specific manual selection of specific objects or automatic image recognition from chart. In this case, recognition of objects (buoys, beacons, etc.) on electronic charts, the subsystem that uses IHO standards S-52 and S-57 is used. Since these standards are mandatory, their recognition can be realized using principles of determining the colour gradient and contours of given object [15]. The recognition result is a table to be monitored with coordinates of recognized key objects (shown in Fig. 3.2). Table calibration is carried out by anchor points – on key stationary objects on the chart of the chosen area (lighthouses, coastline). The operator can enter the value of permissible coordinate changes. This parameter can be specified as global (for all objects), local (for each object type, e.g. for buoys) and individual – for each individual object. Setting the maximal allowable coordinate dispersion values for each object is optional, but allows the system to calculate more precisely the necessity for adjustments after obtaining flight results.

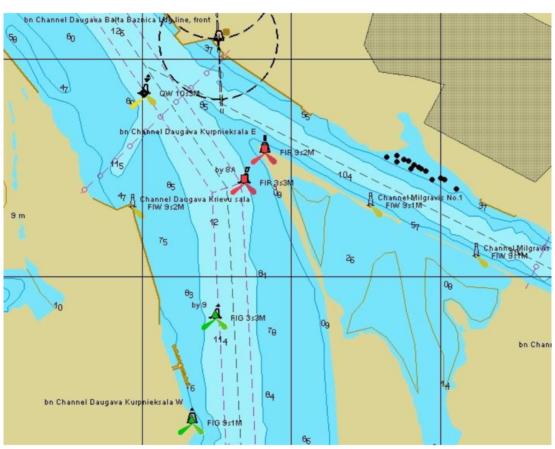


Fig. 3.1. Original electronic chart of Kurpnieku island area from "TRANSAS 4000" ECDIS.

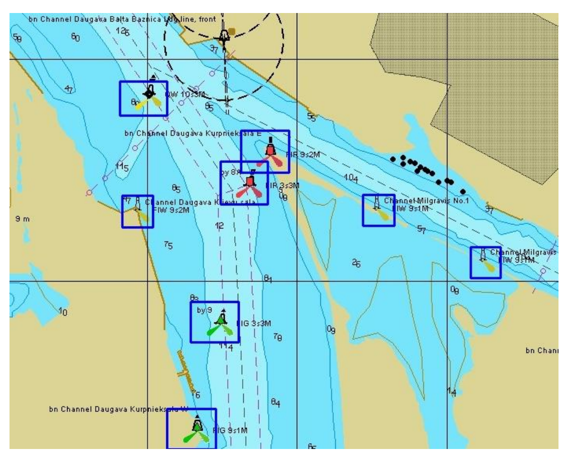


Fig. 3.2. A processed map after determining positions of the monitoring objects (blue rectangle).

Phase 2

The second phase includes a calculation of optimal flight plan for RPV and photographing area in which necessary objects are located. The process uses RPV flight route optimization subsystem with data for the objects recognized in Phase 1. The subsystem uses the dynamic programming method [16]. The result of sub-system implementation is shown in Figs. 3.3 and 3.4.

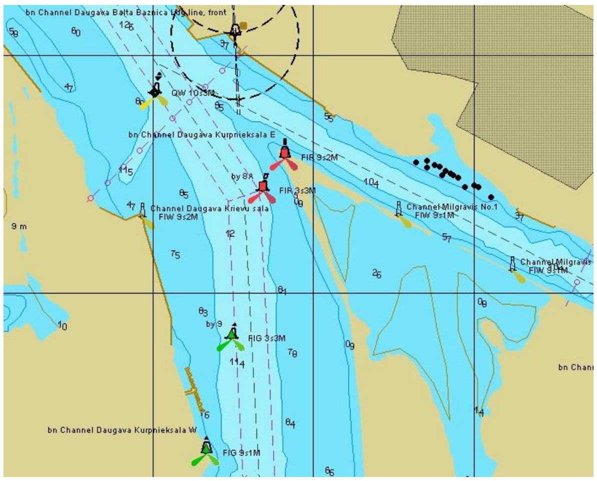


Fig. 3.3. Original electronic chart of Kurpnieku island area from ECDIS.

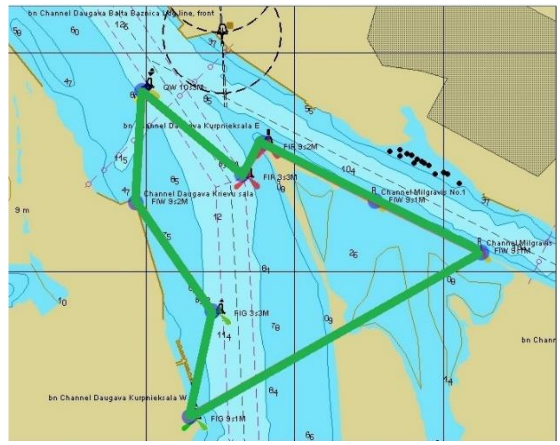


Fig. 3.4. A processed chart after completing optimal flight plan for monitoring the specified objects.

Phase 3

RPV flight and photography of objects in the chosen area. Information processing is done using shore equipment after the end of photography process. The processing of information in RPV during flight leads to significant complication of apparatus and increased requirements for equipment.

Phase 4

The resulting image is subject to graphical processing to simplify further procedures related to key object recognition: brightness, contrast, colour filtering. Then the automatic object recognition will be started on processed photos. Recognition uses the modified algorithm, which is created using programming for Phase 1, which is used in this case for photo of real object placement. Such modification predominantly uses the colour gradient principle. The result is recognition of key objects. The operator determines an anchor point (stationary points that do not change their coordinates). Anchor points are necessary for calibration of obtained key object’s location table: after the existing two or three coordinates of anchor objects, the required zoom ratio and image rotation angle are calculated in order to align the resulting image with original image on an electronic chart. An example is given in Figs. 3.5 and 3.6.

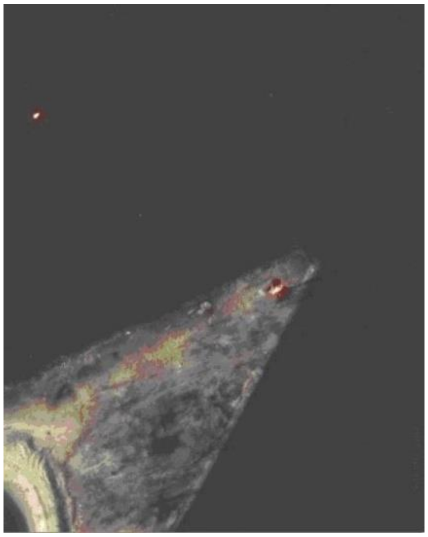


Fig. 3.5. A photograph of Kurpnieku island area from RPV after colour processing.

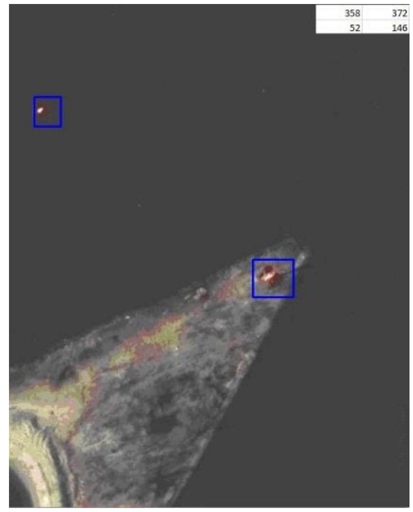


Fig. 3.6. RPV treaded photo with determined key objects' coordinates in the upper right corner.

The research describes the algorithm and operating principle of a computer program, which performs automatic image processing by making changes in the image so that it can be compared to electronic chart. To get an image that can be compared with an electronic chart and to read the coordinates of object, CICS must make scale change and turn the photo from an unknown angle to the north. The zoom ratio is calculated by the distance between two objects, which can be obtained by the distance between the same two objects in an area determined by the electronic chart. The turning angle is calculated using trigonometric formulas, Cartesian coordinate system, and polar coordinate system.

Phase 5

The pixel position of raster images is transformed into a vector format using the geostationary-coordinate algorithm. The World Geodetic System 1984 (WGS84) is mandatory for official electronic maps used by ECDIS [17]. Therefore, if there are anchor points' coordinates in WGS84 from an electronic chart, a comparison of real object coordinates in the same standard is required. It can be calculated from a photo image (which is raster image) with recognized key objects.

Phase 6

Comparison of real and sample object placement tables that are obtained from Phase 1 and Phase 5. Decisions on need for correction are made, including permissible coordinate deviations that are set by operator in Phase 1. In turn, the purpose of this phase is to create lists of objects that require adjustment and position relocation. Based on information obtained in Phase 6, a table of objects with changes in coordinates exceeding permissible deviation values, set by the operator, is created [18].

Based on this information it is possible to create a graphical layer for electronic charts with new object coordinates. This is visual layout of objects that can be mounted on the existing ECDIS's information, without changes to the chart itself. The operator can activate the use of this information for each electronic cartography system. Creating such layers allows to see real situation with the possibility to change the parameters of selected key objects without changing the information on the official electronic chart approved by the State National Hydrographic Service. In the case of permanent change in parameters (for example, change in coastline), this layer can be transmitted to the Hydrographic Service for uploading of changes in the official electronic chart. Such system will be able to simplify and speed up the mandatory procedure for obtaining information for the authorities responsible for issuing cartographic data. In addition, the response time will be decreased up to RPV flight time to key point for checking position. In view of the minimal costs of the given procedures for information collection, frequency of this procedure can be raised up to several flights a day and can be chosen by the operator [19].

3.2. Requirements for RPV Development for Remotely Piloted Aerial Vehicle Complex in CICS

Using RPV in maritime navigation cartographic sector will make it possible to receive information about changes in position of chosen navigational key objects in real time. This means that if RPV is used for obtaining information it will allow immediate processing of information, improvement of graphic image by software, recognition of cartographic objects in the chosen area from chart, determination of their actual coordinates from the processed photo images and making decision about need for correction. Taking into account nowadays computing possibilities of equipment, the whole process will take no more than a few seconds. Thus, in the case of calculating speed that is needed for making a decision on necessaries for correction, the main part will depend from the speed of initial information acquisition. However, in this case, peculiarities of the use of RPV should not be overlooked. Above all, flights will be over water surface, which means that a list of certain requirements for RPV must be complied.

The first type can be assigned to the selection of existing RPV models for creation and installation of RPV modules and their solutions from the existing offer. The second type provides development and implementation of new functionalities for RPV that are needed to resolve specific problems associated with the collection of maritime navigational information for CICS. The required RPV characteristics are as follows:

- ability to fly without interruption in large areas without refuelling;
- ability to capture objects from a height from which they are recognized;
- ability to get high-quality images;
- ability to fly in adverse weather conditions (rain, wind).

3.2.1. Determining Standard Parameters of CICS RPV

Taking into account the above-mentioned characteristics of CICS RPV for obtaining cartographic information, it is possible to formulate the list of RVP's operating conditions (LOC).

RPV should be able to operate in different conditions:

- simple and difficult weather conditions;
- above water and sea surface;
- at temperature from –40 °C to +50 °C;
- with air humidity up to 98 %;
- with wind speed up to 15 m/s from any direction.

Initial studies have shown that, in order to solve problems in these areas an average height RPV, (with medium dimensions (wing up to 5.5 m, airplane length up to 5 m, height 1.5 m), relatively small take-off weight (180–200 kg)) must be equipped with piston engine (power ~40 horsepower). Such RPV will be efficient and economically feasible to carry out the tasks listed above, including the most complex (observation of stationary objects over long periods in large areas in districts).

Therefore, justification for RPV flight technical specifications (FTS) will be made for RPV with the above-mentioned characteristics. In addition, in support of requirements for RPV motion characteristics, we assume that during optical photography, optical axes of the device are in vertical position, thus ensuring best picture quality.

Let us look at justification of claims regarding RPV flight technical specifications (FTC). FTS is a set of RPV parameters specifying its technical capabilities to fly to targets under all intended operating conditions.

From full list of FTS of RPV we will focus on characteristics that determine specific requirements of movement, taking into account the intended purpose.

They are:

- speed range;
- height range;
- practical flight range;
- practical flight duration.

Speed Range

Based on normal aerodynamic scheme analysis, an RPV equipped with piston systems has the following performance characteristics:

- wing width – up to 5.5 m;
- length of RPV – up to 5 m;
- height – up to 1.7 m;

- take-off weight – 200 kg.

Based on this, it can be concluded that maximum speed of RPV flight is 200–220 km/h.

Thus, RPV speed range is 130–220 km/h and the cruising speed is around 140 km/h in the selected tasks for selected operating conditions.

Height Range

RPV flight range must be 60–1500 m above ground, with maximum altitude of 5000 m.

Practical Flight Range

Given the fuel consumption, it can be expected that the flight distance will be about 600 km.

Practical Flight Duration

Practical flight time at a cruising speed of 140 km/h with fuel consumption 12.6 kg/h, will be about 4.5 to 5 hours.

3.2.2. Special Systems Required for CICS With RPV

In relation to non-standard requirements, it should be noted that RPV flights would usually be above surface of the water in open spaces, possibly under adverse weather conditions (high winds of ~15 m/s, rain). In addition, CICS with RPV will be used at great distance from the operator; there will be no possibility to respond promptly to emergencies. All this increases the probability of RPV being broken due to adverse events (various variants are possible: from damage to device from birds until strong wind hits). Thus, in order to avoid losing RPV, it is necessary to develop specific functionality for unforeseen emergency conditions in order to increase CICS with RPV's "viability" [20].

There are two main solutions for those cases: CICS RPV automatic landing in uncontrolled mode in the case of emergency, and automatic exposure of built-in emergency transmitters with enlarged transmitting distance thereafter. The first one allows RPV to successfully down RVP on water without special electronic devices, even in emergency mode (without power sources). The second system allows operator to find floating RPV at large distance without using sophisticated and expensive electronic satellite transmissions, which, above all, cannot be started during emergencies in case of power absence and, secondly, are expensive and unstable.

In the development process of CICS RPV, both systems that meet the above requirements were developed [21].

3.2.3. Possibilities Of Using CICS in Other Areas of Economy

The developed CICS with RPV complex can be used not only for maritime navigation. Considering rapid development of technologies in last decades, the level of practical tasks set for all agricultural directions also becomes more complicated. Specific systems, algorithms, and implementations are needed. One such tool is the geographic information systems (GIS), which contains information with geographic location, but requires an on-line correction. One of the most promising directions for use of GIS is monitoring for flooding of agricultural land. CICS can calculate the coordinates of special flood markers on an existing electronic map and draw up an optimal flight plan. After obtaining real-life photographs, CICS, taking into account the presence or absence of markers can alarm the operator [29].

4. REALIZATION AND METHODOLOGY OF CARTOGRAPHIC INFORMATION COLLECTION SYSTEM WITH REMOTELY PILOTED AERIAL VEHICLE COMPLEX FOR MARITIME VESSELS' CONTROL

4.1. Methodology and Realization of CICS Cartographic Object Identification Subsystem [22]

The CICS cartographic object identification subsystem has been realized by creating a prototype that shows operation of the subsystem and demonstrates that such subsystem can be developed using existing software solutions.

To check the prototype an area was needed, where it was possible to identify key navigation objects and compare reallocation of objects with data from ECDIS electronic chart. Thus, Kurpnieku island in the port of Riga, Riga, Latvia, was selected as a research area. In this area there were many buoys and lighthouse locations. Examples for ECDIS chart and real-life photo are shown in Figs. 4.1 and 4.2.

Fig 4.1. Part of Kurpnieku island area on ECDIS electronic chart.

Fig. 4.2. Photo of part of Kurpnieku island area taken from RPV.

For successful operating of cartographic information collection system (CICS) with remotely piloted aerial vehicle complex for maritime vessels' control, it is necessary to obtain location data of navigational objects from two sources. One data source must be electronic ECDIS chart and the other one – actual situation, filmed by RPV.

Image Identification Algorithm

There are several methods for identifying objects on image. These techniques include contour search method, colour gradient method, and templates search method. Often these methods are used together at the same time. During research, the author has chosen to use the method of determining objects according to colour gradient method and contour determination method as auxiliary algorithm.

The object detection algorithm for all images (chart or photo from RPV) is the same, therefore, as example, we will consider an electronic chart image. Once the system has received an image (see Fig 4.1), it must follow the specified principle to distinguish objects like buoys and lighthouses from the rest of image. Referring to Fig. 4.1, it becomes apparent, that buoy and beacon's red colour cannot be confused with any other object. However, there would be errors if algorithm tries to detect objects using only colour comparisons. For large areas, it will be possible to have objects of the same colour in the same chart. Thus, in addition to colour comparison, the algorithm tries to find out if the contour of the object matches the contour of buoy or lighthouse templates.

Consequently, the algorithm converts the colour image into binary image (black and white). The algorithm's realization program will process each image pixel (the smallest element of image). During processing, each pixel whose colour corresponds to the colour of buoy or lighthouse (in this case, red), the algorithm's realization program will transform into black pixel and all other pixels as white. After this processing, the image will look like shown in Fig. 4.3.

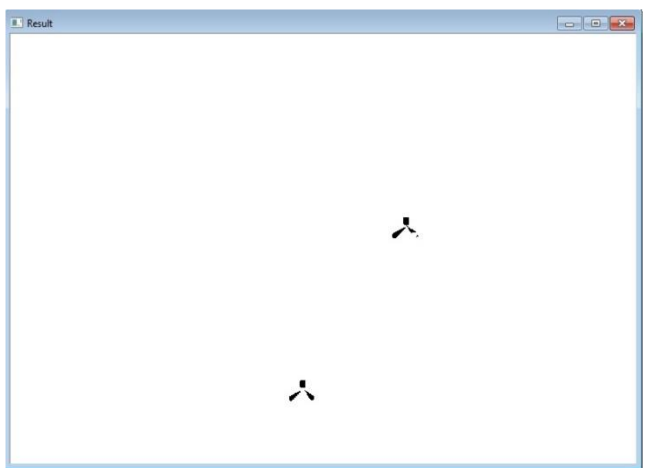


Fig. 4.3. Processed binary image from initial chart.

This binary image is identical to Fig. 4.1. Now everything has been transformed into white background and navigational objects of interest are shown in black. Looking at the picture, it can be seen that the objects of buoy and beacon are divided into several parts, i.e. their elements are separated from one another with white background. However, when determining the shape of an object, we need to get every object as a whole. In such cases, the algorithm uses a technique called morphology transformation. Morphology transformation is a set of actions that handle an image based on its form. The basic operations of morphology are **erosion** and **dilatation**. They are most commonly used to remove noise, isolate an individual element, or vice versa – to merge adjacent elements into one whole. It is the last thing we need.

The field of mathematical morphology promotes wide selection of operators for image processing based on some simple mathematical concepts from given theory. Operators are particularly useful for analysing binary images, but common uses include edge detection, noise removal, image enhancement and image segmentation.

Two of the main operations in mathematical morphology are **erosion** and **dilatation**. Both of these operators take into account two data elements: an image requiring erosion or dilation, and structuring element (also known as kernel). Two parts of input data are considered as representing coordinate sets in a way that is slightly different in the case of binary and grayscale images [15].

Erosion and dilatation actions (at least conceptually) transform the structuring element into different input image points and check the intersection between the transformed kernel coordinates and entered coordinates of the image [23], [32].

When processing the image with this technique, we will get the results shown in Fig. 4.4.

The last step in the object identification algorithm is using of contour identification method. Using this method, the algorithm's realization program is able to find out the contours of all black elements. In current realization a contour of rectangular shape was chosen. The results of this step are shown in Fig. 4.5.

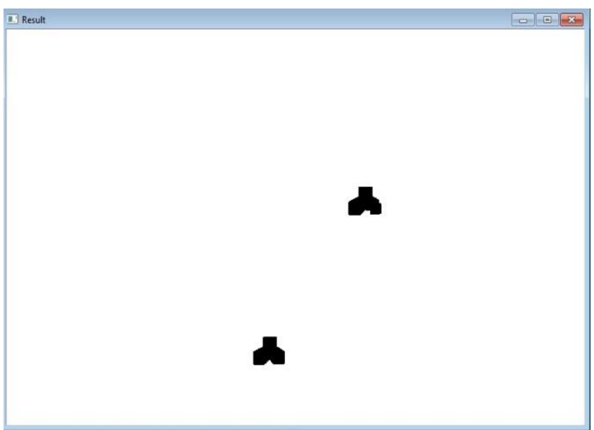


Fig. 4.4. Electronic chart image after morphology processing.

Fig. 4.5. Disclosure of contours in electronic chart image.

In the given example, there were two black elements and consequently corresponding contours for two elements were found. To exclude the possibility that in image the image identification algorithm will find other elements that are not our main goals (for example, red point will be located in the given image), contours can be used to determine the width and height parameters that filter small contours from proceeding.

Disclosure contours of objects can determine their coordinates on image (in pixels). As the last step in object detection, the algorithm will surround the coordinates of identified images with coloured rectangles (see Fig. 4.6).

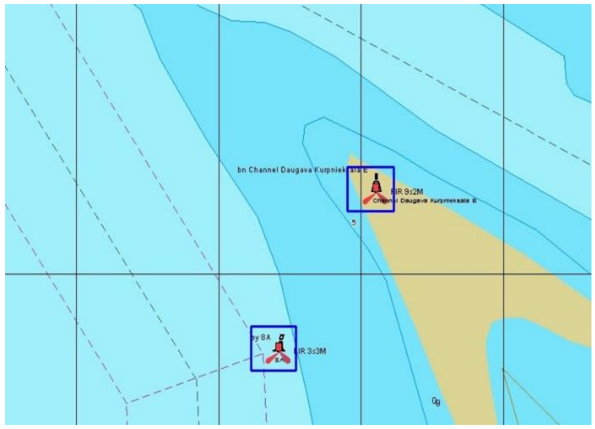


Fig. 4.6. Electronic chart image after image processing by identification algorithm's realization program.

After the objects are discovered (buoys and beacons), it is necessary to find out their coordinates on chart. Currently, the program has calculated coordinates of objects on image, measured in pixel units.

Principle of Realization of Prototype of Image Identification Algorithm's Program

The *DetectObject.exe* program has been developed to implement an image identification algorithm.

The program can work with two types of images – using ECDIS electronic chart's image and using photo image of a chosen area from RPV. To send a specific image for processing, operator has to choose "Open Image" button. Standard load window will appear where operator can select the required image (see Fig. 4.7).

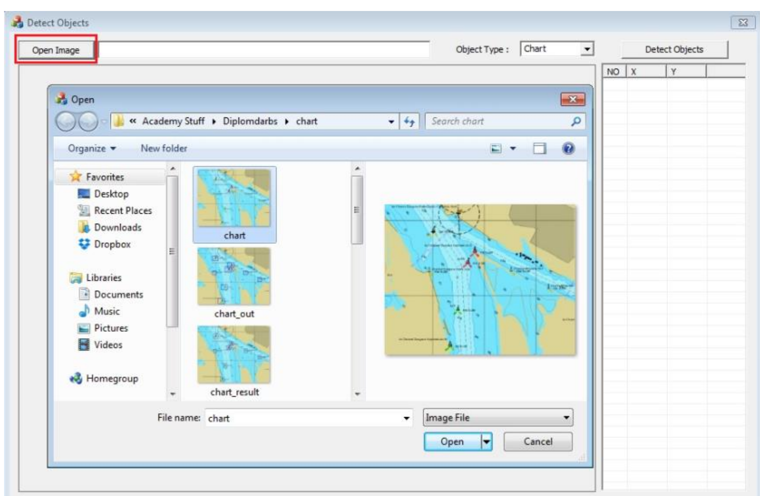


Fig. 4.7. Image selecting for processing.

Once the image is selected, it will be sent to the program for processing and displayed in the main frame. The program is ready to identify all key objects (buoys and beacons) in given area. The operator has to choose “Detect Objects” button and the program will find/disclose all objects and show them in the image for operator (see Fig. 4.8).

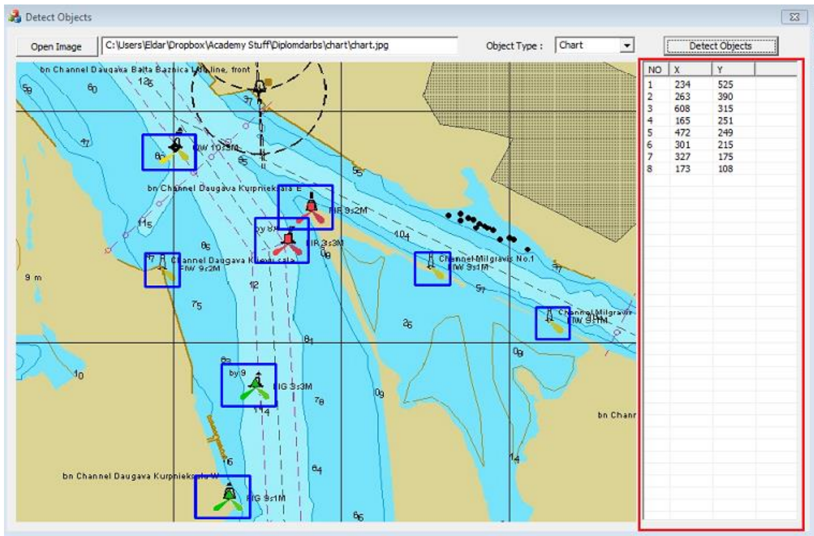


Fig. 4.8. Navigational objects in chosen area disclosed by the prototype of image identification algorithm program.

In addition to disclosure of objects, the program displays coordinates of each object in pixel units in the right corner of the program (see Fig. 4.8). Numbering of identified objects takes place from the lowest object to highest. The coordinates are shown in *x* and *y* axes. The *x*-axis reference point is considered left edge of the image. Zero reference point for *y* axis is considered as an upper edge of the image.

4.2. Practical Realization of RPV Route Optimization Subsystem Using Dynamic Programming Methods

The objective of RPV route optimization subsystem is to find possible optimal RPV route based on previously obtained information about navigational objects as points of flight, making it faster and more efficient.

Dynamic Programming

Dynamic programming is a method that allows solving complex problems by dividing them into smaller subtasks. This programming scheme allows to find successive optimal solutions for tasks that are divided into separate stages. To solve a specific task, it is divided into several subtasks, which are simplified, and each one is solved separately. Such programming method is usually applied to tasks in which the required response consists of several parts, which, when combined together, give an optimal solution to the main task. It is advisable to use this method if the same subtasks are repeated at different stages of the task. The main advantage in this case is that the system will remember the subtask solutions and in cases when such subtasks are repeated later can use previously stored information. In typical cases, dynamic programming methodology is used for tasks related to optimization, there may be many possible solutions, but it is necessary to choose the optimal one, where the parameter value is minimal or maximal [16].

Practical Implementation of RPV Route Optimization Subsystem

In order to start creating the shortest route, the route optimization subsystem lacks only the coordinates of subsystem, among which the RPV flight has to be realized.

RPV route optimization subsystem will receive object coordinates from the realizing the program of image identification subsystem named *DetectObjects.exe* mentioned above. The program is able to process images from electronic charts and RPV images and identify their location on chart in pixel form. The operating principles are described in previous section.

RPV route optimization subsystem will use the obtained object coordinates for route creating and optimization.

In the beginning the RPV route optimization subsystem neededs to get precise location and coordinates of each object using the image identification subsystem as it is shown in Fig. 4.8. Kurpnieku island area is shown with coordinates.

As you can be seen in the figure, in this area, the program has identified 8 objects that are buoys and beacons. For these objects, the practical implementation of RPV route optimization subsystem will be used for further processing. During research, the locations of objects are collected, which had been obtained with *DetectObjects.exe* (see Table 4.1).

Table 4.1

Coordinates Obtained by Realizing Image Identification Subsystem

Object No.	Coordinate *x*	Coordinate *y*
1	234	525
2	263	390
3	608	315
4	165	251
5	472	249
6	301	215
7	327	175
8	173	108

In order to achieve the aim of realizing the subsystem of RPV route optimization , special program has been written that is capable of optimizing RPV route based on predicted positions, which, as condition, have to be visited during the flight. To solve this task, programming language *GO* and programming shell *IntelliJ IDEA* were chosen. *GO* is a programming language used to create executable file types. *IntelliJ IDEA* is a specialized software that works with *GO* and other programming languages to simplify the creation of programs. In practical realization of RPV route optimization subsystem Bellman's method is used, whose optimal efficiency has been demonstrated in previous section.

Once all distances between objects and exact coordinates of each object are known, it is possible to find the shortest route between them. In the next step, the program starts to create all possible object attendance combinations or routes. For example, if we have 4 objects on the map with known coordinates and distances between them, then it works in this way. If RPV must reach the object with number 4 in minimum time and with the shortest route, then it is compulsory on the flight to visit objects with numbers 1, 2, 3, which means that the algorithm needs to solve function $f(4,\{3, 2, 1\})$ with a minimum value where 4, 3, 2, 1 are objects; and {} is the distance corresponding to each node to get to next one.

According to the nature of dynamic programming, this task can be divided into several subtasks and subfunctions, which means that function $f(4, \{3, 2, 1\})$ can be proceeded as three separate functions or flight variants: $f\,(3, \{2, 1\})$, $f(2, \{3, 1\})$, and $f(1, \{3, 2\})$. By solving them, the program finds minimum of functions $f(4, \{3, 2, 1\})$. In turn, functions $f(3, \{2, 1\})$, $f(2, \{3, 1\})$, and $f(1, \{3, 2\})$ can be subdivided into even more detailed subfunctions until it is necessary to find the distance from the starting position to each object. This distance can be calculated by the Pythagorean theorem. The possible combinations in the task with four objects are shown in Table 4.2.

Table 4.2

Possible Combinations in RPV Route Optimization Subsystem (Example)

1–2–3–4
2–1–3–4
3–1–2–4
1–3–2–4
3–2–1–4
2–3–1–4

When the program creates all possible flying combinations, it starts to analyse how long RVP would fly the distance using each combinations offered. At this stage, usual cumulative distance corresponding to each value of the route combination takes place. After the first route combination, the result of computation is recorded in program memory, so if an element with lower value appears in calculation process, the algorithm automatically replaces the previous value with a new one and compares next results with the new element from memory. In this way, the program calculates a sum of distances for all combinations and selects the shortest. This combination is also the shortest route for RPV, which minimizes the time to collect data for automatic electronic chart correction.

Principle of Realization of Programme Prototype of RPV Route Optimization Algorithm

The same way as *DetectObjects.exe* program, *Salesman.exe* can process the same image a types − electronic chart images and RPV photo images (before and after colour processing for photo). The program is able to find the required optimal route among any objects.

The graphical user interface was used for the route selection program. To find the most optimal route for RPV, it is necessary to enter the data about the controlled objects in the area of flight. To open an image with such objects, it is necessary to choose folders until the user reaches the required image and press the "*Load*" button. After selecting the image, it will be displayed in the main window.

The next step is to identify required objects and determine their coordinates. For this purpose, the *Salesman.exe* program uses data from previously mentioned *DetectObjects.exe* program. For automatically obtaining data from *DetectObjects.exe*, the operator has to choose the "*Resolve Points*" button, and *Salesman.exe* will automatically provide coordinates by making blue points on object's locations and displaying coordinates in the upper right corner. In Fig. 4.9, location of objects is shown with a green arrow and coordinates − with red.

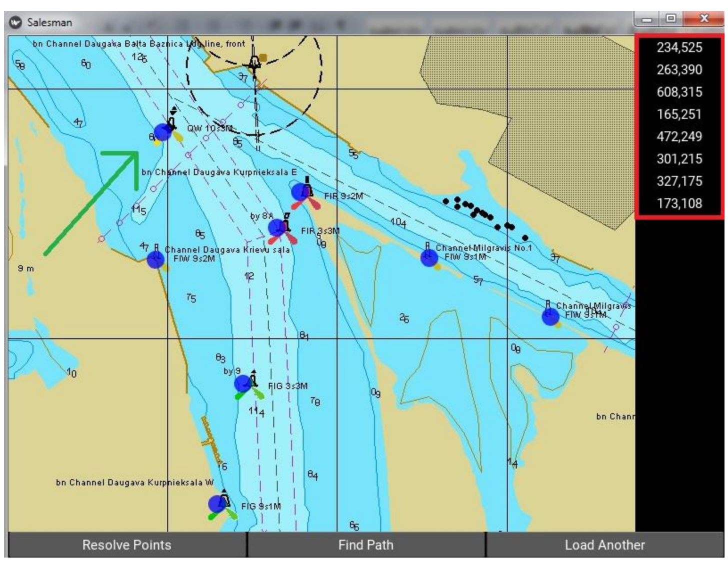


Fig. 4.9. Obtaining of an object's coordinates in RPV route optimization algorithm's program prototype.

After this program is ready to calculate the shortest route for RPV's flight, the operator needs to choose the "*Find Path*" button, and *Salesman.exe* will highlight the optimal flight route between the objects with red line located on the image (shown in Fig. 4.10).

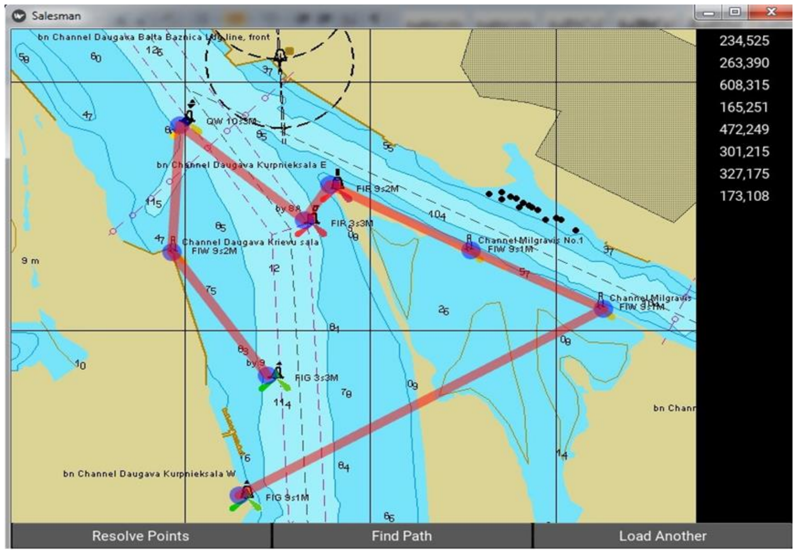


Fig. 4.10. Optimal route calculated by RPV route optimization algorithm's program prototype.

4.3. Automatic Object Recognition on Processed Photos of Real Area Using Object Identification Methodology

Using previously developed algorithms for recognizing chart objects required for image identification subsystem, cartographic information collection system (CICS) must have a possibility also to recognize images of real objects on photos taken during RPV flight. This process will use the same principles: object-detection method by colour gradient and contour determination method as an auxiliary algorithm.

The photo images received during the flight are loaded into the above-described image identification subsystem, and then buoys and lighthouses are positioned using contrast of their increased illumination and contours compared to the surrounding environment. The result of the program work is shown in Fig. 4.11.

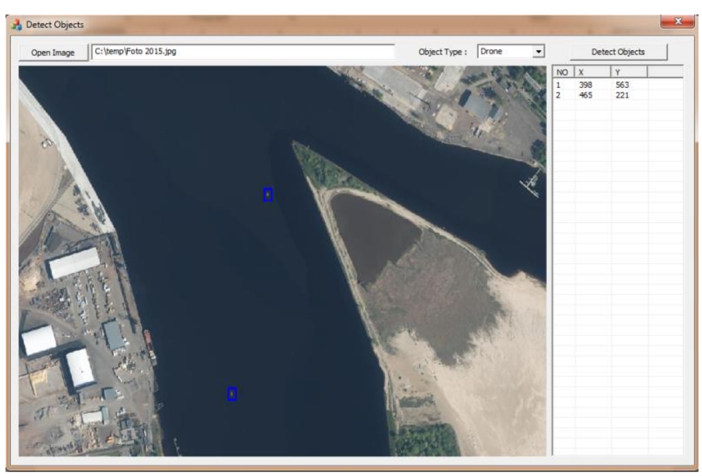


Fig. 4.11. The result of objects identification subsystem using an unprocessed photo from RPV.

As seen in the example above, the presence of large number of colours and light gradients does not always allow image identification subsystem to precisely determine the position of objects on unprocessed photographs from RPV.

Therefore, the image should be processed graphically, as mentioned in the Concept for cartographic information collection system (CICS) with remotely piloted aerial vehicle complex for maritime vessels' control (Phase 4), in order to simplify further procedures related to recognition of key objects: brightness, contrast, colour filtering. Then automatic recognition of objects on processed photos can be provided easier (Figs. 4.12 and 4.13).

In the last example (Fig. 4.13), recognition of objects from RPV photo image after processing using developed image identification subsystem's realization is fully successful.

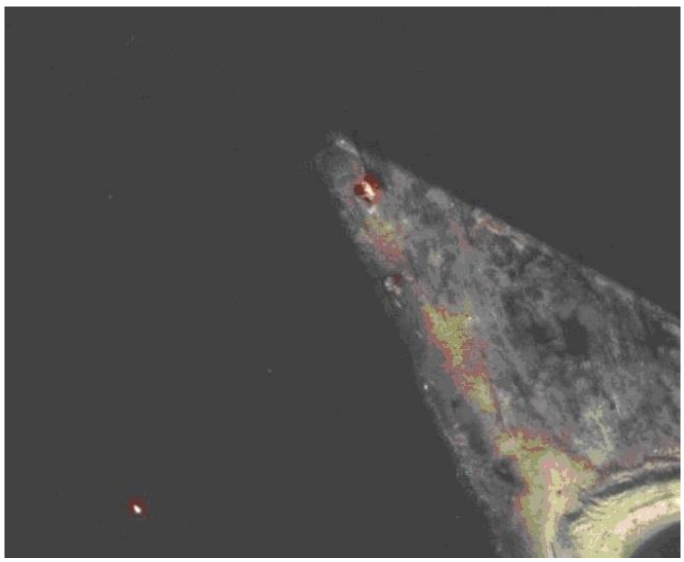


Fig. 4.12. Part of image taken from RPV after processing.

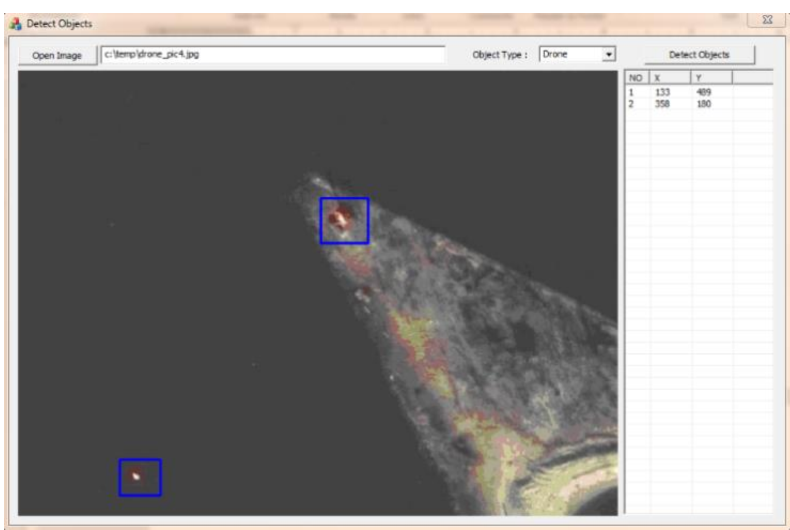


Fig. 4.13. The result of applying objects identification subsystem, used with photo taken from RPV after graphical processing.

4.4. Development of Methodology for Calculation of Actual Location of Cartographic Objects and Realization of Subsystem

As already mentioned, the best way to collect data about navigation objects in the maritime area of Latvia is to use RPV. In turn, RPV has special equipment that can capture a photo at a certain height above the surface of water. However, these photos need to be processed in such a way that the system can fully function and the photo images can be compared with objects on the electronic chart.

In order to implement this subsystem, an algorithm was developed describing the operations and their sequence to achieve functionality of CICS. Actions of the subsystem are related to the photos of actual location of cartographic objects and electronic chart representations derived from the above-mentioned subsystems. The algorithm performs operations with objects that are recognized in photographs and electronic chart, making changes and adjusting them so that the information obtained after processing can be used for determining the actual location of real object.

To develop the implementation of subsystem of actual location of cartographic, it is necessary to draw up an algorithm that shows how and in what order actions are performed to achieve the result. The algorithm is shown in Figs. 4.14 and 4.15.

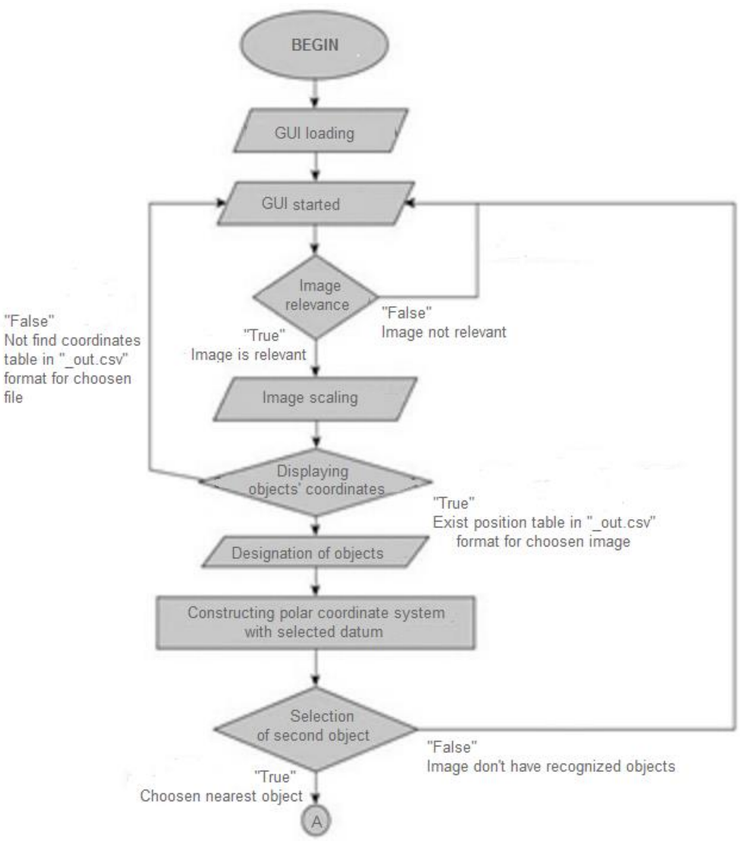


Fig. 4.15.Algorithm for calculating actual location of cartographic objects (part 1).

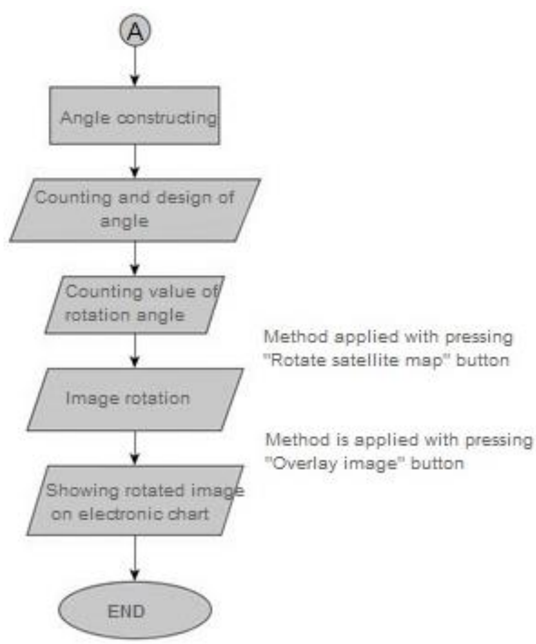


Fig. 4.16. Algorithm for calculating actual location of cartographic objects (part 2).

Adjusting the Scale of a Loaded Photo Image in Compliance With Chart Size

The chart image and photo image of real area that has been uploaded from RPV must of the size, which allows CICS to compare them for recalculating objects' positions on both images. This means that if the scale of the photo is the same as the chart scale, then it will be difficult to see the objects in RPV photo, because the ECDIS chart scale gives larger view than the photography from RPV. Remotely piloted aerial vehicle cannot take photos of such a large area because of the camera's technical limitations, therefore, the objects on the photo will be depicted in small size. The difference in visual size of different objects makes it difficult to further process the objects on the photo image, thus the scale needs to be enlarged. Consequently, dimensions of the photo will be stretched along with the coordinates, counted from the top left corner. The upper left corner is assumed to be the starting point, and any changes of the image do not change this parameter – the upper left corner of image will always coincide with upper left corner of the area of the interface with (0, 0) position. This is important because the coordinates previously calculated with the prototype of image identification algorithm's program *DetectObjects.exe* will change their value, as the coordinates are tied to pixel coordinates of the image, which have certain coordinates. To prevent this, the subsystem of actual location of cartographic objects includes a function that changes the type of coordinate data, so that before changing the scale of the image the coordinates of one point will match the same coordinates after the image is stretched, whereast the location of points in pixels can be different.

Changing the scale of RPV photos without changing coordinates makes the image clearer and more usable for future actions of CICS. Example of such procedure can be found in Fig. 4.17, where the yellow vector represents the distance from the left corner to the object. The length of vector in images varies, but coordinates of the object remain the same, and after the image is stretched (left image), all objects are depicted more clearly.

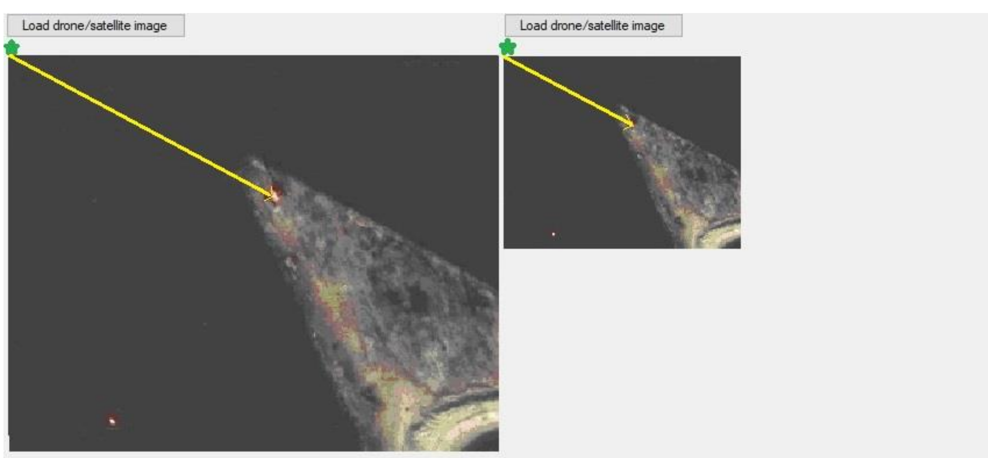


Fig. 4.17. Stretching of RPV processed photo while keeping real coordinates of objects unchanged, at the same time changing the coordinates on image in pixels.

Adjusting of the image size makes objects more visible; besides, they do not limit the ability to work with coordinates of the displayed objects.

Display of Coordinates for Recognized Objects

In addition to loading an image in the prototype of actual location of cartographic objects subsystem program, it is necessary to display the coordinates of objects that are recognized on the image. For this purpose, image was previously processed by the image identification subsystem program *DetectObjects.exe* (described in section 4.1), there objects were recognized. For automatic obtaining of results by actual location of cartographic objects subsystem, *DetectObject.exe* was modified with the possibility to create a new separate file containing the saved coordinates for recognized objects. After processing photo image with modified *DetectObjects.exe* program, no changes are made to original file, but a new one with a similar name is created in addition. This file name contains characters "*_out.csv*".

In the case when during image loading the file with coordinates is found according to the selected photo, the image will be successfully loaded in computer program interface with coordinates below the main window. In order to make it easier for the operator to use the coordinates of objects, the program will show positions in two columns – "X" and "Y", accordingly. The coordinates for each object should be displayed individually in each row, as the image must have at least 2 objects, because the algorithm for actual location of cartographic objects subsystem cannot determine the position by only one object.

As a result, the coordinates of objects in the form of a table are visualized below electronic chart and photo images.

Designation of Recognized Object on Loaded Image

Once the image is loaded, recognizable objects should be marked to know which of the objects has been recognized and to which coordinate it object has been assigned. The prototype of the actual location of cartographic objects subsystem program recognizes objects on electronic chart image as well as on the photo and marks them with crosses. This is necessary to precisely know the coordinates of objects and to exclude human factor by choosing an inaccurate centre. As a result, the program's interface will display the following images with coordinates corresponding to the objects marked with a cross. This result can be viewed in Fig. 4.18.

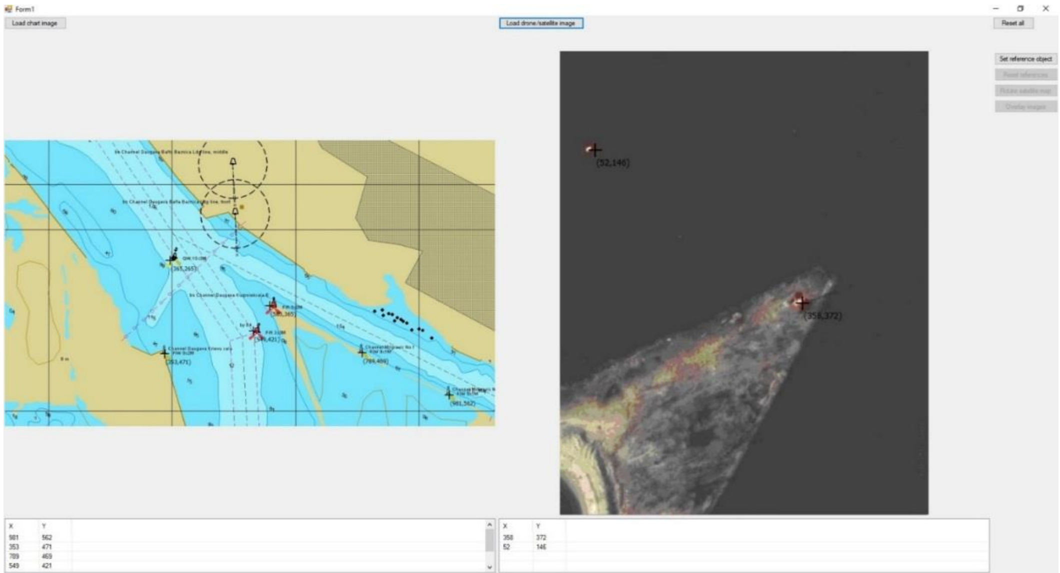


Fig. 4.18. Prototype of actual location of cartographic objects subsystem program with loaded images and a list of coordinates of crossed-out detected objects coordinates.

Determining the Angle of Photo and Aligning it to North (as ECDIS Chart)

RPV takes photos from an unknown angle to operator. It means that the region that has been photographed by RPV will not be aligned to North, and this image cannot be used without further processing, because all objects and data on electronic chart are displayed in relation to North. In order to compare actual photographed objects with chart objects, it is necessary to rotate the captured photo to the angle to align it with the electronic chart image.

Application of Polar Coordinate System for Determination of Rotation Angle

Subsystem of actual location of cartographic objects uses polar coordinate system to determine the rotation angle. Compared to Cartesian coordinate system, polar coordinate system describes the location of object with its polar coordinates: the angle (φ) and the polar radius (r), which is distance (vector module) to the starting point. The construction of polar coordinate system is based on mathematical and geometric rules. To construct a coordinate system, zero point must be recorded from the beginning. The program of actual location of cartographic objects subsystem adopts fixed object as a zero point coordinates of which are precisely known (for example, lighthouse). As another possibility, operator has an opportunity to select the zero point on the image by pressing program button "*Set reference object*". From the zero point "0", a coordinate system grid is constructed and applied (see Fig. 4.19). Coordinates x and y are calculated using mathematical formulas based on geometric rules.

$$\cos \varphi = \frac{x}{r} = \frac{x}{\sqrt{x^2+y^2}}; \tag{4.1}$$

$$\sin \varphi = \frac{y}{r} = \frac{y}{\sqrt{x^2+y^2}}. \tag{4.2}$$

As a result, a formula is obtained for calculating the angle at the zero point (stationary object) between the *x* axis and vector to the point. The operator can select zero point from which the coordinate grid is constructed. When the operator l clicks on an object, an “event” occurs, the parameter will be changed to the class assigned to this object, the colour of the cross will be changed from black to green to make it easier to navigate between objects and know which object is considered a zero point. In turn, the program uses such object as the centre of polar coordinate system and places the grid on the image.

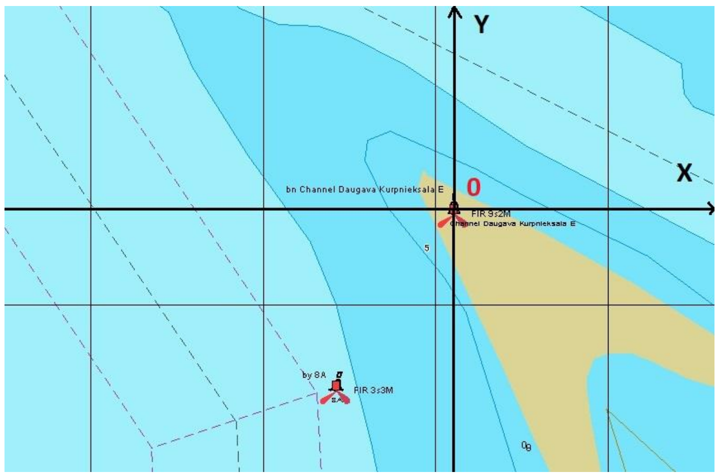


Fig. 4.19. Coordinate system grid, assuming that starting point is stationary object.

Method for Selection of Nearest Objects

The next step is to find the point to which comparable vector from RPV photo will be drawn from the zero point. In this step, it is important to choose an object that is on both pictures: on the image of the electronic chart and on the photo e.g. of beacon, lighthouse or specified coastline. For comparison it is the same area with the same objects is proposed. So same objects’ location on the electronic chart were determined at previous steps of CICS. The subsystem of actual location of cartographic objects will use polar coordinate system in realization program, because the determination of the angle with the help of this coordinate system requires only two objects. In addition, this situation often occurs in real life.

The choice of point to which the vector is drawn will be made automatically – by the principle of closest object location. Consequently, the program using the Pythagorean theorem calculates the distance of each object to the zero point. An example is shown in Fig. 4.20.

The cross programme marks the nearest object with red colour in order to make the algorithm’s work process more transparent.

Two points are enough to construct a triangle with the help of which an angle at the zero point is determined. The given angle is the direction to the second object (the closest recognized object).

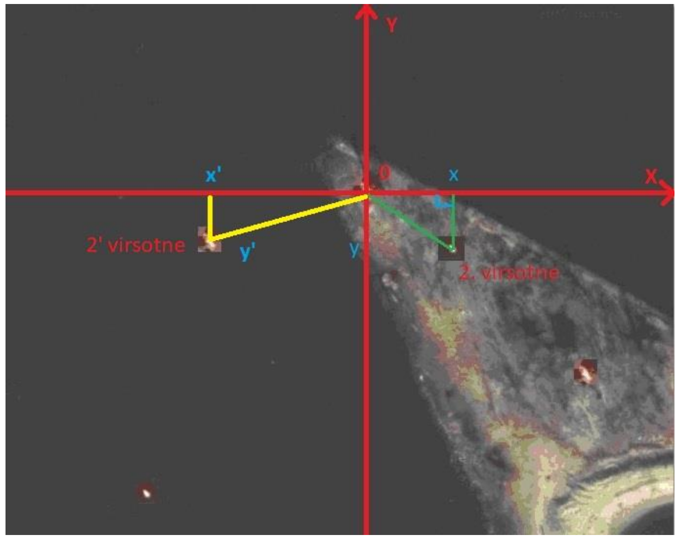


Fig. 4.20. Application of the Pythagorean theorem to determine the distance between the points.

The program of actual location of cartographic objects subsystem calculates the angle's value at the selected zero object between *x*-axis and the direction to the nearest detected object, using the method described above.

In the case of RPV taking a photo image from an angle that does not coincide with the angle of ECDIS chart, the photo must be rotated at the calculated angle. This converts the photo in such a way, that objects on the photo image are oriented towards North like on the electronic chart.

After calculating the angle of rotation Φ_{pagr}, the program displays the result visually – in a separate message window. Graphical representation for angle's value Φ_{pagr} is proposed to the operator as it is shown in Fig. 4.21.

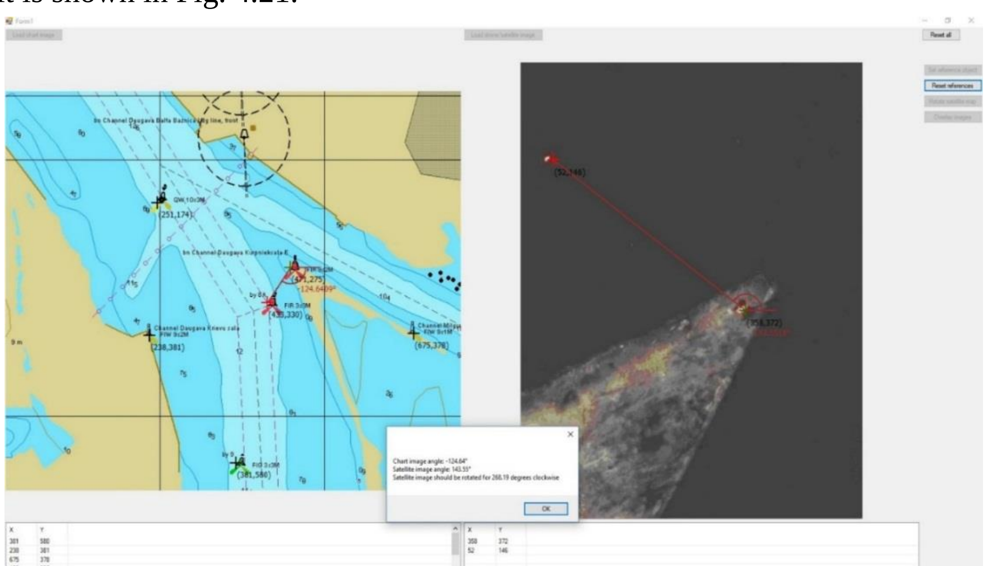


Fig. 4.21. Detection of the angle of rotation by comparing angles between zero points and nearest objects on electronic chart and RPV photo.

Rotation of Photo by the Calculated Rotation Angle

The rotation method can be described as follows.

There are two rectangular images. If the angle of the first image does not coincide with the angle of the second image, the first image will be arranged in a specific t way, described below. This nonparallel two-dimensional arrangement creates four straight-edged triangles, the vertices of which are the point of contact of the first image's perimeter with the second image's perimeter. The following schematic for two-image layout is shown in Fig. 4.22.

The angles and edges of the triangle must be determined in order to perform the rotation. Three points are needed for this purpose, which are marked red int Fig. 4.22. After rotation, the following condition must be met: two upper red points should match so that both images are positioned in parallel. Angle θ is equal to the pre-calculated angle of rotation Φ_{pagr}, or the angle indicating the value of difference between two-image parallelisms. In order to observe and fulfil the condition, distance O_h must be equal to "0". The value of h is known, since h is the width of image and will be calculated already during image uploading [24].

If the angle of RPV photo image does not coincide with the angle of ECDIS electronic chart, the photo will be rotated to calculated angle Φ_{pagr}, using the method described in the previous section. After rotating, the photo will be centred, positioning the central point of the photo where it was before, in order to prevent the photo from being positioned outside the boundaries of electronic chart area. The central point of image is calculated as an intersection of diagonals.

As a result, after pressing the "*Rotate photo map*" button, actual location of cartographic objects subsystem program rotates the photo to the calculated rotation angle, matching the RPV photo image with the electronic chart's heading. The new image will be displayed in a separate window. The result is shown in Fig. 4.23.

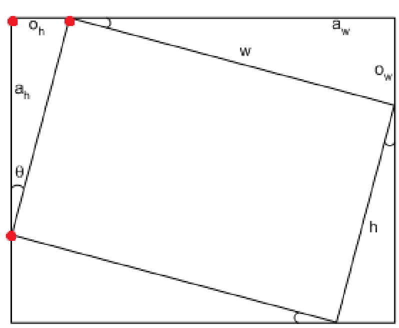


Fig. 4.22. Reciprocal placement of two images [24].

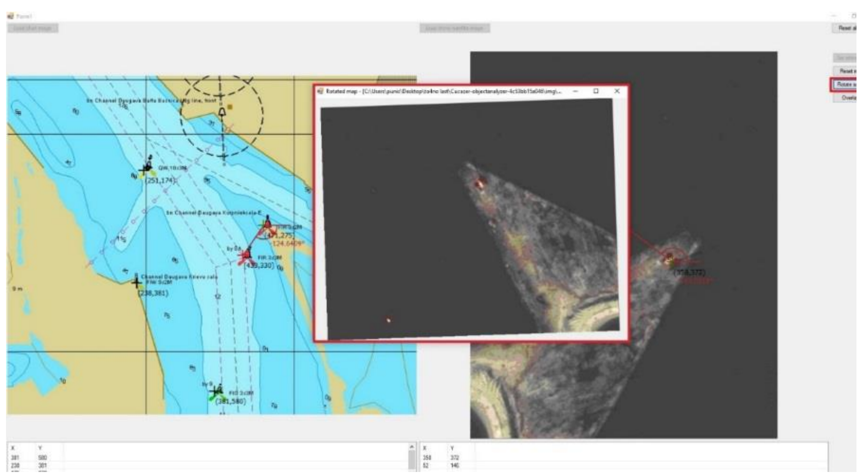


Fig. 4.23. The resulting image after rotating RPA photo by the calculated angle.

Placing of the Rotated RPV Photo on ECDIS Electronic Chart

To place the RPV photo on electronic chart, it is necessary not only to change the angle but also the scale of the photo and to find coinciding point for images.

The scale is calculated based on two objects in both images that have already been selected: zero object and the object nearest to it. Finding the distance between the two objects and describing this distance as vector length using (x, y) coordinates, for both electronic chart and RPV photo, will give two values. However, it is the same distance between the same objects. Then, by dividing the length of this vector between objects on RPV photo by the length of vectors between objects on electronic chart, the algorithm will obtain the scale coefficient. Then, using the "*TableLayoutPanel*" image stretching function, the program will change the scale of the photo in a new window, which contains both images [25].

Positioning of two similar images (after rotating and re-scaling) one above the other can be achieved by placing similar detected objects on the first image above the images on the other image. To move each single point of image to the same point on the second picture, the algorithm needs to know the direction from the coordinates of the object on the photo to to coordinates of same object on the electronic chart, as well as the distance between them. The vector can express both parameters. Since the (x, y) coordinates were known before RPV photo image rotation, it is possible to calculate the coordinates of the same object after rotation. The images are in two-dimensional format, and to find the coordinates of the object after rotation, it is possible to use a two-dimensional rotating matrix that describes the required angle value.

After this, the program of actual location of cartographic objects subsystem will place the final processed photo on a similar object (point) on the chosen electronic chart. The operator performs all these actions by clicking on button "*Overlay images*". The result is shown in Fig. 4.24.

In this figure, both objects are assigned to North, which allows the operator to work with information obtained and compare actual location of objects with the coordinates of objects indicated on ECDIS chart. The photo taken by RPV has been processed, rotated towards North, with a modified scale and placed on the electronic chart. The objects on the taken photo are exactly in the same places where they are displayed on the electronic chart. Now it is necessary to get the coordinates of objects (WGS84 format) from the raster image. To do this another subsystem was developed and realized.

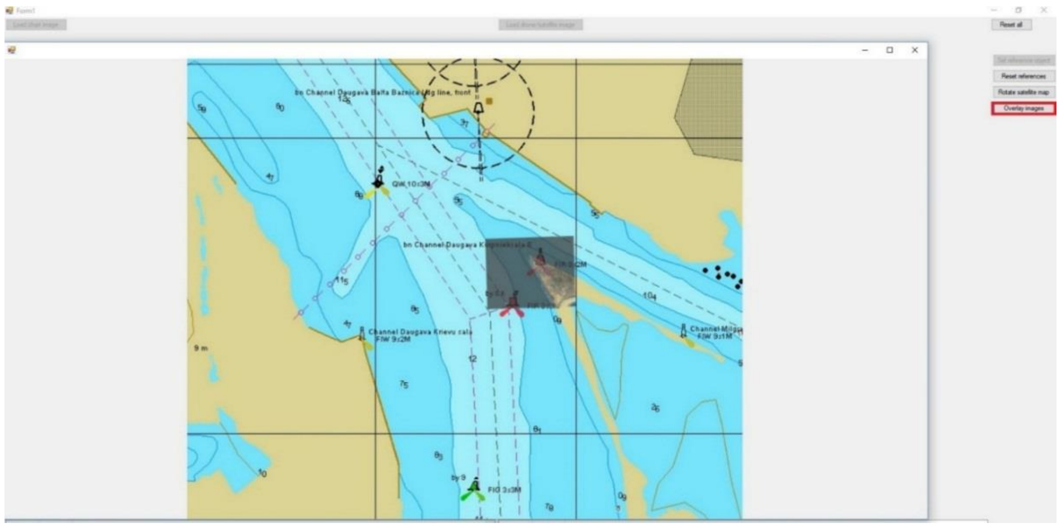


Fig. 4.24. RPV photo placed on ECDIS electronic chart as a result of using actual location of cartographic objects subsystem program.

4.5. Methodology for Real Coordinate Calculation of Objects and Realization of Subsystem

The objective of the development of subsystem of object's real coordinates (in WGS84) is to investigate and implement automatic raster chart's transformation to vector format using the geostationary-coordinate algorithm. World Geodetic System 1984 (WGS84) is mandatory for official electronic charts used by ECDIS [17]. Therefore, if there is an object for comparison with a coordinate in WGS84 from an electronic chart, second (real) object's coordinates must be present in the same standard. It is possible to calculate them from the RPV photo image (which is raster image) with recognized objects.

Development of Method for Calculating Real Coordinates of Objects

Geodesy is a science of measuring the Earth: type, form and size of the Earth. Practical task of geodesy is to make measurements in the area and use the results for various calculations to determine the distance, area, height, etc., or creating a reduced image of certain surface parts of the Earth for drawing (plans, maps and charts) [26].

Geoid – true form of the Earth, the Earth model with flat surface that coincides with the surface of world's ocean in the state of stability, it is extended through continents.

Earth ellipsoid – a spheroid, figure that simulates the shape of the Earth. It is obtained by rotating an ellipse around small axis that coincides with the Earth's axis of rotation.

Large half-axis a = 6 378 245.

Small half-axis b = 6 356 863.

Earth compression:

$$f = \frac{(a-b)}{a} = 1 : 298.3 \sim 1 : 300. \tag{4.3}$$

The ellipsoid is best suited to describe latitude and longitude coordinates in degrees. Information on height is based on geoid or reference ellipsoid. The difference between measured ortho-metered height *H* based on geoid and ellipsoid height *h* is known as geoid undulation *N*, as shown in Fig. 4.25 [27].

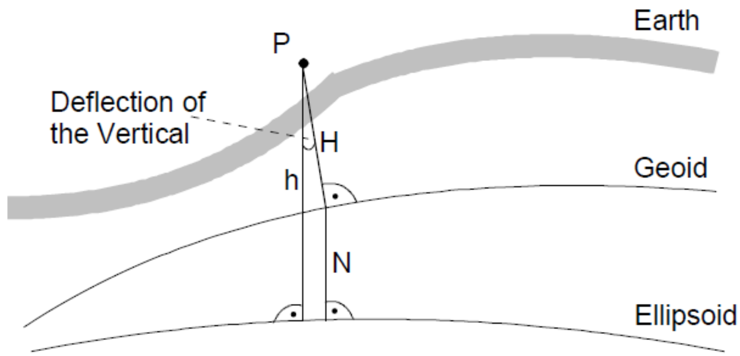


Fig. 4.25. The difference between geoid and ellipsoid.

World Geodetic System WGS84

The data and calculations provided by the Global Navigation Satellite Systems (GNSS) receiver relate mainly to the WGS-84, which is the World Geodetic System since 1984. The WGS84 coordinate system is geo-centrally positioned in relation to the Earth Centre, and is called ECEF (Earth Centred, Earth Fixed). The WGS84 coordinate system is three-dimensional Cartesian coordinate system with initial coordinate zero point in the centre of mass that is close to the total centre of Earth.

The ellipsoid positive *x*-axis is in equatorial plane (fictional plane crossed by Earth's equator) extending from the centre of mass to the point at which equator and the Greenwich meridian (or zero meridian) intersect. The *y*-axis is also located in equatorial plane and is moved 90° east of the *x*-axis. The *z*-axis is perpendicular to the *x* and *y*-axis and extends along geographic North Pole. An example is shown in Fig. 4.26.

The WGS84 ellipsoid parameters are as follows:

- large half-axis a = 6 378 137.00;
- small half-axis b = 6 356 752.32.

Earth compression

$$f = \frac{(a-b)}{a} = 1 : 298.257223563.$$

For further processing, WGS84 ellipsoid coordinates (φ, λ, *h*) are usually used instead of Cartesian coordinates (*x*, *y*, *z*), where φ is width, λ is length and *h* is the height to the ellipsoid (the length of vertical line *P* to ellipsoid). An example is shown in Fig. 4.27.

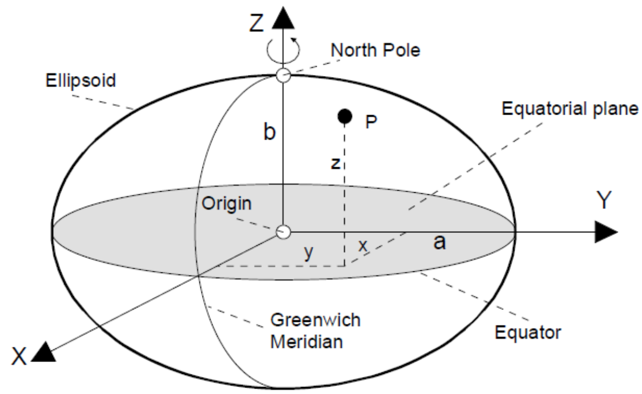


Fig. 4.26. Cartesian coordinate system.

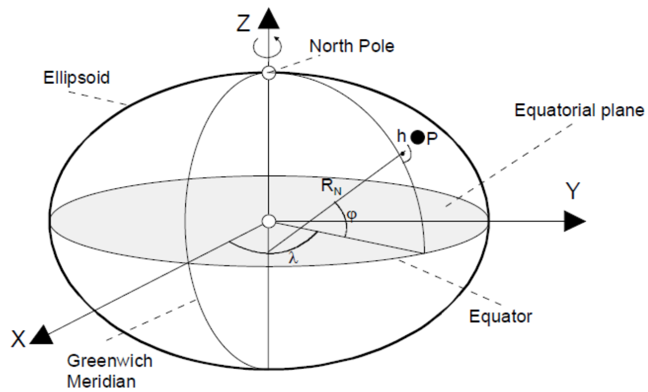


Fig. 4.27. Standard ellipsoid coordinate system.

Binding of raster chart (photo, image) to geographic position.

Geographical binding is a transformation of raster chart into a vector chart form. In raster chart form, each object's coordinates are determined by *x* and *y* coordinates in pixels and these charts can be saved in any picture format, such as JPG, BMP, GIF, or PNG. These charts can be obtained using a RPV photo for the chosen area. In the vector chart form, each object is defined by geographic coordinates *x* 'and *y*'. Raster chart can be transformed into a vector map with its geographic coordinate system using a relevant mathematical calculations.

Algorithm of Transforming a Raster Chart to Vector Chart

The transformation of raster chart into a chart with a vector coordinate system are carried out by linear transformation rules. The procedure is suitable only for small or medium areas, covering a few kilometres. The transformation of coordinates takes place from the source (pictures), i.e. *x*, *y* are converted to another (vector) system – *x*', *y*' (as shown in Fig. 4.28).

Algebraically it can be expressed as follows:

$$x' = ax + by + c;$$
$$y' = dx + ey + f. \quad (4.4)$$

It can also be expressed in the form of a matrix:

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}. \quad (4.5)$$

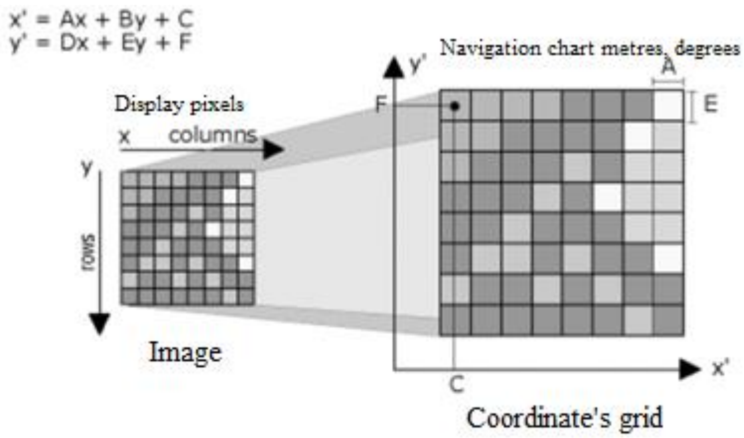


Fig. 4.28. Basis of chart conversion.

a, *b*, *c*, *d*, *e*, *f* are six transformation parameters. To calculate these parameters, six equations with six unknown variables must be solved. Calculations of formulas to determine the transformation parameters are done in three steps.

Step 1. Image calibration

Three calibration points that are located on raster image must be selected (shown in Fig. 4.29). Source coordinates in pixels (*x*, *y*) and converted coordinates in WGS84 (*x*', *y*') must be specified for each of these calibration points.

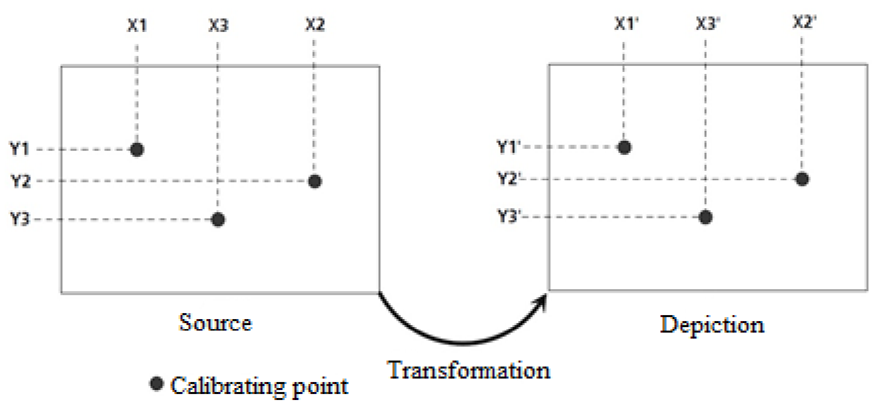


Fig. 4.29. Schematic representation of calibration points.

Step 2. Design of transformation equations

Using Formula 4.4, we obtain:

$$x'_1 = ax_1 + by_1 + c;$$
$$y'_1 = dx_1 + ey_1 + f;$$
$$x'_2 = ax_2 + by_2 + c;$$
$$y'_2 = dx_2 + ey_2 + f;$$
$$x'_3 = ax_3 + bx_3 + c;$$
$$y'_3 = dx_3 + ey_3 + f.$$

The system will look like this in a matrix form:

$$\begin{bmatrix} x'_1 \\ y'_1 \\ x'_2 \\ y'_2 \\ x'_3 \\ y'_3 \end{bmatrix} = \begin{bmatrix} x_1 & y_1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & x_1 & y_1 & 1 \\ x_2 & y_2 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & x_2 & y_2 & 1 \\ x_3 & y_3 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & x_3 & y_3 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \\ d \\ e \\ f \end{bmatrix}.$$

Step 3. Let us transform the previous matrix to see the transformation parameters:

$$\begin{bmatrix} a \\ b \\ c \\ d \\ e \\ f \end{bmatrix} = \begin{bmatrix} x_1 & y_1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & x_1 & y_1 & 1 \\ x_2 & y_2 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & x_2 & y_2 & 1 \\ x_3 & y_3 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & x_3 & y_3 & 1 \end{bmatrix}^{-1} \begin{bmatrix} x'_1 \\ y'_1 \\ x'_2 \\ y'_2 \\ x'_3 \\ y'_3 \end{bmatrix}. \qquad (4.6)$$

Realization of Subsystem Program of Objects' Real Coordinate Calculation

As a result of exploring and testing of the algorithm for transformation of raster charts (images) to vector form an objects' real coordinate calculation subsystem's algorithm for obtaining geographic coordinates of any object from raster image was developed. Calculation is possible if there are three other stationary objects with WGS84 coordinates located in a chosen area. For realization of the researched algorithm, a program was created that calculates and display the calculated coordinates of the sought-for object.

As the programming languages were chosen HTML, CSS, PHP and Java Script. In order to prove the correctness of the program's calculation, image of previously used Kurpnieku island area has been used with objects recognized by CICS in previous steps. The image is shown in Fig. 4.30.

In Fig. 4.30, it is possible to check three stationary objects in the chosen area (located on earth beacons cannot change position) that can be used as calibrating points with known WGS84 coordinates. It is possible to obtain the coordinates of these objects using the data of the official documents of the Latvian Maritime Administration Hydrographic Service [28] and ECDIS (Fig. 4.31). Information is present in Table 4.3.

Table 4.3

Coordinates of Calibrating Points

	x', degrees	*y*', degrees
Calibrating point 1	57.027133	24.082767
Calibrating point 2	57.028817	24.090167
Calibrating point 3	57.027194	24.096111

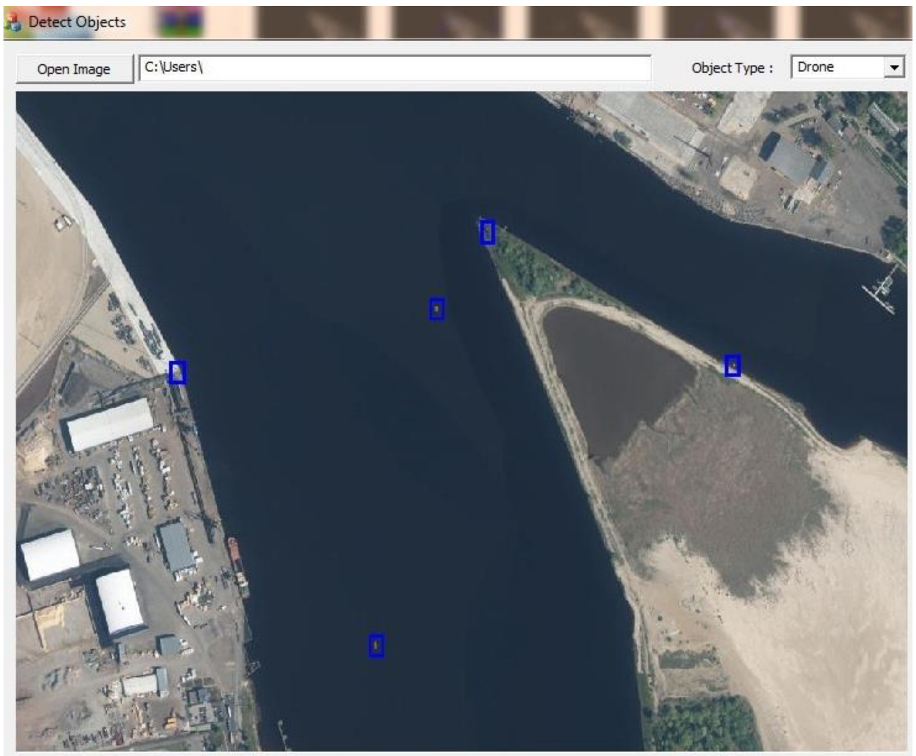


Fig. 4.30. Kurpnieku island area after processing by CICS real object identification subsystem.

Fig. 4.31. ECDIS electronic chart of Kurpnieku island area with the same object positions.

Example of the Work Process of Prototype of Object's Real Coordinate Calculation Program

The operator has to open the program in Internet site *www.bikertoyz.lv\map.php* and click "*Choose file*" for image uploading.

By clicking on four points in the picture, the operator sets first three objects as calibration points and the last one as a point to be searched. After this, a data form to be filled in appears below the image.

Calibration points are shown in Fig. 4.31, and they are:

1. Lighthouse on the Daugava Krievu island (x_1 = 57.027133, y_1 = 24.082767).
2. Lighthouse E on the Daugava Kurpnieku island (x_2 = 57.028817, y_2 = 24.090167).
3. Milgravis lighthouse No.1 (x_3 = 57.027194, y_3 = 24.096111).

And a point for calculating geographic coordinates:

Beacon from image pixel position x = 347, y = 215 (is shown in Fig. 4.32).

Geographical coordinates for calibrating the points which are known, in degrees and decimal form, must be entered in appropriate text boxes. For calculation the operator has to press the "*Submit*" button.

At result page program will show:

1) inverted matrix solution in tabular form (1);
2) data obtained for transformation parameters (2);
3) geographical coordinates for points of interest (3);
4) "*Try Again*" button, which returns the operator to the previous page with entered data if

an error is found.

Due to coordinates transformed into degree and minute form

x = 57.027908345911 = 57°01.6745' N,

and y = 24.089041762039 = 24°05.3425' E.

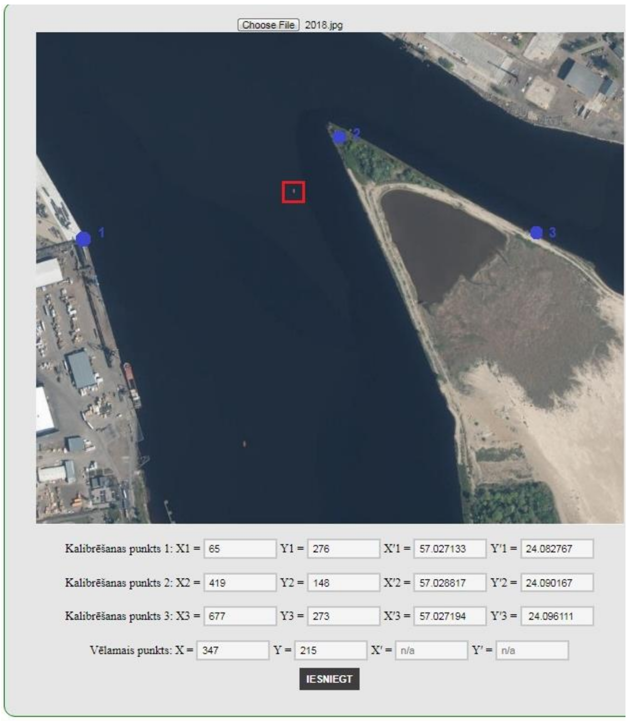


Fig 4.32. Selected points for checking the process of operation.

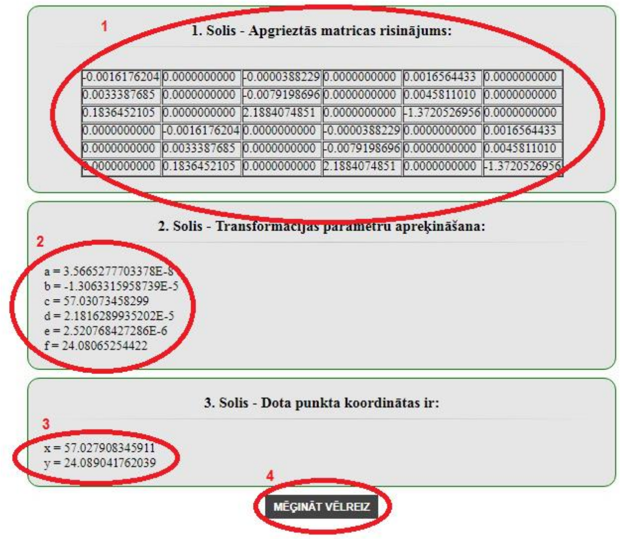


Fig. 4.33. Calculation result.

Compared to the beacon No. 12 of the left bank of Daugava the official coordinates [28] are

x_e = 57°01.673' N; and

y_e = 24°05.342' E.

The difference is:

$$\sqrt{((1.6745 - 1.673)1852.4)^2 + ((5.3425 - 5.342)1852.4)^2} = 2.92 \text{ m}$$

Possible error of inaccuracy is about 2–3 meters that could occur either due to inaccurately chosen object by the operator when clicking the mouse, or because of the limitation of decimal part of position's minutes in "Lights and signs in waters of the Republic of Latvia", where there is information about real position of beacon No. 12 on the left bank of Daugava.

Using the developed program it is possible to obtain geographic coordinates of any object on RPV photo. Implementation of object's real coordinate calculation subsystem is last subsystem that is necessary for a successful completion of development of cartographic information collection system (CICS) with remotely piloted aerial vehicle complex for maritime vessels' control due to the possibility to obtain position differences between real object's position (from ECDIS chart) and the one recognized from RPV photo real object's positions.

CONCLUSIONS

1. During current research it was proven that electronic chart correction in ECDIS is a mandatory functional requirement, taking into account official documents from IMO, IHO and IEC. As evidenced in the study, ECDIS must not be used for navigation on vessel without mandatory correction, as lack of up-to-date information may lead to distress situations [31]. The research examined existing principles for making corrections and their limitations and drawbacks, trying to get information in real-time mode. The conclusions reflect shortcomings of current situation: practical impossibility of obtaining information on observation facilities with required speed and frequency. In this context, arguments were put forward to develop a new system in this area using RPVs: possibility to receive real-time correction information, improving accuracy of coordinates for observed objects and reducing costs compared to the present methods.
2. In research process various models of creating optimal RPV route were compared by using graph theory, and an optimal model was provided. The Thesis provides the results on the development and exploration of a chosen RPV flight route optimization model and the creation of an algorithm, as well as software realization to simulate and calculate an optimal flight path trajectory to determine real coordinates of observed navigation objects, taking into account actual object coordinates on the official electronic chart.
3. The general concept and algorithm for CICS with remotely piloted aerial vehicle complex for cartographic data acquisition was developed. The CICS work process consists of several functions relating to the data obtained from or proposed to another function: calculation of RPV's optimal flight plans by using objects' coordinates existing in ECDIS; the process of photographing objects; the process of required processing of photographs; determination of real coordinates for observed objects and their comparison with reference coordinates from the electronic chart. Thus, CICS can be implemented by being divided into blocks with different functionality, which will allow using the components of CICS's subsystems not only in the field of maritime navigation, but also in agricultural areas for observation and correction of information [30]. Due to the above mentioned, the CICS algorithm was divided into phases. Each phase is designed to perform special functions and uses separate subsystems to perform these functions.
4. Functional requirements for CICS's RPV parameters and basic systems for obtaining marine cartographic information related to work under specific conditions (above the surface of water at sea) were examined and investigated. Standard characteristics such as RPV's speed and height ranges, flight distance and duration were calculated. In addition, two specific systems for RPV complex were developed. The first one is needed to provide RPV with an automatic landing in uncontrolled mode in case of emergency. The system allows successful RPV landing on water surface even in an emergency mode without using electronic control devices. The second system is designed for automatic

transmission of alarm signal in case of emergency, which also makes it possible to determine the location of RPV within tens of kilometres without using satellites or relay stations.

5. In the process of research, new object identification subsystem methodology was created and implemented, which allows to determine the coordinates of objects on electronic chart or (after additional image processing) on photographs obtained from real area with RPV. The subsystem uses consistent colour filtering as well as mathematical morphology functions. Further, methodology for the subsystem of actual location of cartographic objects was created and implemented. The subsystem is able to overlay an image from RPV photo to the electronic ECDIS chart, recalculating scale and direction. The realization of this subsystem made it possible to calculate and change the scale and angle of the photo in order to obtain an image matching to ECDIS electronic chart for the same area. Methodology for object's real coordinate calculation subsystem in WGS84 was created and subsystem realized. An algorithm and software realization were researched and proved for calculations of real object's coordinates, which allows to calculate real coordinates of a mobile object (such as buoy) from pixel photography using stationary objects (such as lighthouses or coastlines) with certain coordinates.
6. Using the above mentioned methodologies, practical experiments were carried out for separate use of each subsystem, as well as for use of cartographic information collection system (CICS) with remotely piloted aerial vehicle complex for maritime vessels' control as a whole system. The results, even in implementation with individual programs for each subsystem, allow to obtain information with minimal error for positions and in shortest possible time of reaction. Based on the obtained results during the research process, it has been proven that the development of CICS with remotely piloted aerial vehicle complex, after professional realization, will make it possible in real time to compare actual location of navigational objects with the position of these objects on ECDIS electronic chart. There is evidence in the work that at current time there are already all the necessary components for professional implementation of CICS with remotely piloted aerial vehicle complex. Algorithms, methodologies and technologies were practically developed for each subsystem; realization programs were created using different programming languages to demonstrate the feasibility of using each programming language in implementation of CICS.

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