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CONTROL AND INFORMATICS

# Optimization of autonomous underwater vehicle mission planning process

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**Abstract.** This article presents the information concerning aspects of the autonomous underwater vehicle (AUV) mission planning process, emphasizing maritime security monitoring and surveillance, and using side-looking sonars as a primary data source. The paper describes characteristic mission plan phases and gives suggestions for the operators, mainly concerning the safety and effectiveness of the AUV mission. The article describes the coverage path planning algorithm, which could be used to create an effective AUV mission plan, considering AUV manoeuvrability, sonar characteristics, and environmental factors. The results of the algorithms have been verified during the real mission of the AUV vehicle.

**Key words:** sea bottom research; autonomous underwater systems; AUV trajectory.

## 1. INTRODUCTION

Autonomous intelligent robotic systems are becoming increasingly important in various applications. Many of these application contexts are in physical situations out of human reach, so a robot, or a team of robots, must be capable of operating for long periods without human intervention. This requires a strategic planning capability and an ability to interpret and adapt to unexpected events [1, 2]. In the underwater environment, it is hard to communicate because of low bandwidth undersea channels. Thus, path planning for an autonomous underwater vehicle is challenging. The path planning algorithms for a single AUV are summarized in Fig. 1 [3]. This work addresses designing the optimal mission plan that an AUV, equipped with a side-looking sonar, should execute to conduct harbour and port approaches monitoring. The objective of the mission planning task is framed in terms of maximizing the success of detecting potential threats to the shipping and tracking the current state of piers, harbors, and port constructions, as well as identifying places of bottom sediments accumulation. During the I and II World Wars, thousands of mines were deployed in the area of the Baltic Sea [4, 5]. Many of them are still lying on the sea bottom, and they cause a real threat to the shipping and maritime environment. The Baltic Marine Environment Protect Commission (HELCOM) provides the information that only during the II World War around 40 000 tons of chemical ammunition and weapon were thrown into the water (Fig. 2) [6]. Considering that fact and new threats connected with terrorist activity, there is a great need to intensify the monitoring of water space. The article includes recommendations and guidance for operators, which are helpful during the preparation of autonomous underwater vehicle missions.

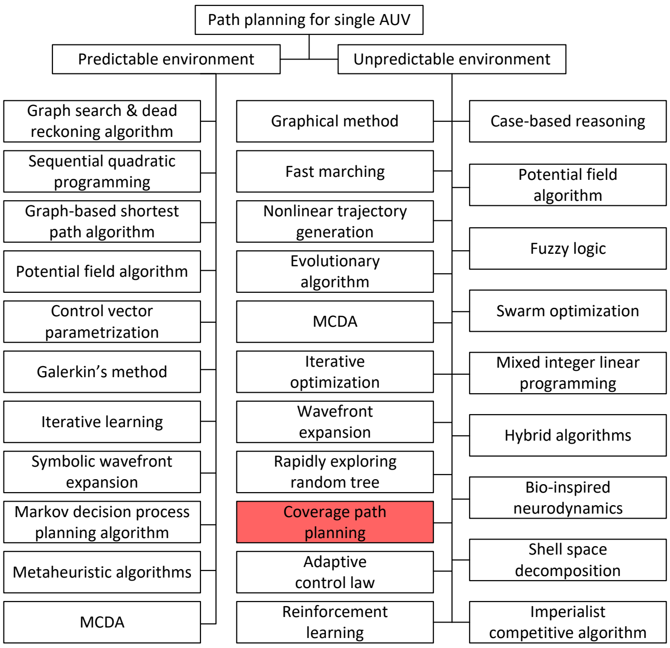

**Fig. 1.** Summary of path planning control of a single AUV [3]

The main contribution of this paper is to develop a method of conducting seabed reconnaissance for unexploded ordnance (UXO) using autonomous vehicles. Nowadays, few literature attempts exist to estimate the probability of detecting objects

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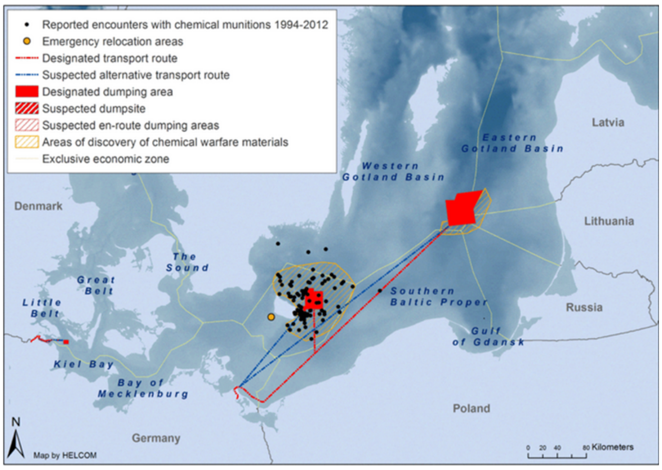


**Fig. 2.** An overview map of known and suspected dumpsites of chemical warfare materials in the Helsinki Convention Area

or the likelihood of searching a region for the detection and correct classification of UXO objects using autonomous systems, as its implementation is mainly carried out by centres and naval forces related to the military. Most of the sources are documents published by NATO. Within the framework of activities of NATO Maritime Forces, including NATO Centres of Excellence, works on the implementation of solutions related to the use of autonomous vehicles in mine countermeasures planning programmes. The fore-mentioned works are currently in the development and testing phase.

The paper is structured as follows. The first section of the paper covers the characteristics of the AUV mission plan structure and the parameters necessary to be considered during the mission planning phase. The further sections are dedicated to the coverage path planning algorithm that generates an efficient vehicle trajectory plan. The work includes results of an AUV mission using the HUGIN system in the Gulf of Gdańsk area.

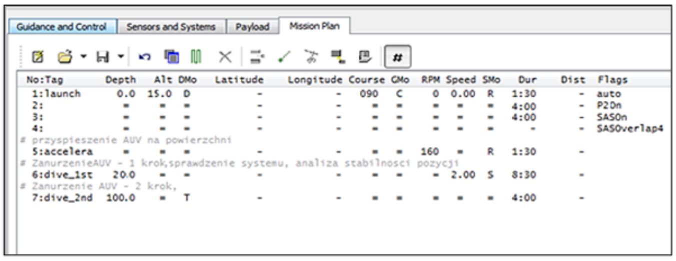
## 2. AUTONOMOUS UNDERWATER VEHICLE MISSION PLAN STRUCTURE

AUV mission planning is usually carried out with dedicated software, e.g., Hugin OS, Gavia Control Center, etc. The operator's knowledge concerning technical aspects and parameters available for used systems is a prerequisite for ensuring safety during the mission and effective sensors usage. The following pages provide information and guidelines for the operators regarding planning autonomous underwater vehicle missions. The guidelines result from experience accumulated by the operators during the use of the AUV Gavia and AUV Hugin systems.

The mission plan should consist of three basic phases (Fig. 3), i.e.:

1. Phase 1: launching and immersion of an AUV vehicle,
2. Phase 2: data collection process
3. Phase 3: ascent and recovery phase.

The first phase includes launching the vehicle, the acceleration phase that allows achieving the force necessary to submerge the vehicle, and diving. The second phase of planning is carried out by adding route points of the AUV vehicle or by planning vehicle trajectory using dedicated patterns, i.e., Lawnmower, CrossHatch, Sliding Box, RI – Pattern Anchor (Fig. 4). To carry out the mission focused on harbour facilities investigation and port monitoring, it is recommended to use the Lawnmower pattern due to the highest search efficiency within assigned time frames. The above patterns cannot be effectively used when carrying out the missions in a region described on a plan other than a rectangle. In this case, the operator must manually add each mission plan point/line. The autonomous underwater vehicle mission planning process requires setting the operating parameters of individual subsystems. Based on the solutions implemented in the AUV Hugin system, the above-mentioned parameters can be classified into the categories presented in Table 1 [10–12].



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  2:            ■     ■    ■         -           -      ■    ■     ■   ■    ■   4:00    -    P2On
  3:            ■     ■    ■         -           -      ■    ■     ■   ■    ■   4:00    -    SASOn
  4:            ■     ■    ■         -           -      ■    ■     ■   ■    ■    -      -    SASOverlap4
# przyspieszenie AUV na powierzchni
  5:accelera    ■     ■    ■         -           -      ■    ■   160   ■    R   1:30    -
# ZanurzenieAUV - 1 krok,sprawdzenie systemu, analiza stabilnosci pozycji
  6:dive_1st   20.0   ■    ■         -           -      ■    ■     ■  2.00  S   8:30    -
# Zanurzenie AUV - 2 krok,
  7:dive_2nd  100.0   ■    T         -           -      ■    ■     ■   ■    ■   4:00    -
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**Fig. 3.** The AUV HUGIN mission plan representing the parameters used during the operation

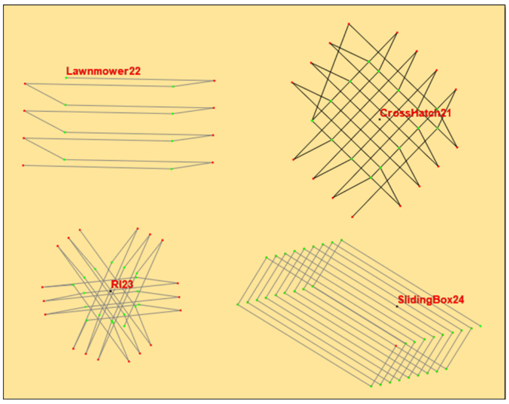


**Fig. 4.** Exemplary trajectory patterns available in Gavia Control Center software

The AUV operations focused on maritime security monitoring require collecting and displaying data with 100% area coverage. Full area coverage is crucial; for instance, during the mine countermeasure missions, confidence that all UXO objects have been found is the essential part of the whole mission [13]. Considering that fact, the operator needs to adjust the mission plan to the current environmental conditions and the sonar capabilities, mainly near and far ranges [14, 15]. One of the most effective search patterns for the AUV vehicle equipped with side-scan sonar is the 'lawnmower' pattern or paired track distribution technique (Fig. 5).

Based on the knowledge concerning the area of operation and the technical capabilities of the autonomous system, operators

**Table 1**
AUV Mission planning parameters

| No. | Parameters related to the area of operation | Parameters related to the vehicle position | Parameters related to the auv sensors |
|---|---|---|---|
| 1. | operation area limited by geographical coordinates $(\lambda_1, \Omega_1, \ldots, \lambda_n, \Omega_n)$ | vehicle altitude measured from the sea bottom | sonar (frequency, ping distance/overlap, near and far ranges, etc.) |
| 2. | depths in area | vehicle positioning accuracy (SDNE – standard deviation of navigational error) | cameras (binning, exposure level, frame rate, light beam, aperture, etc.) |
| 3. | seawater currents | vehicle depth measured from the sea surface | echo sounders (frequency, internal or external trigger, etc.) |
| 4. | water salinity | mission plan waypoints described by latitude and longitude coordinates | |
| 5. | water temperature | vehicle speed described by rpm (revolutions per minute) or speed (m/s) | |
| 6. | speed of sound in water | mission time | |
| 7. | sea state, etc. | vehicle course | |
| 8. | | vehicle manoeuvring characteristics (turn radius, acceleration, etc.) | |

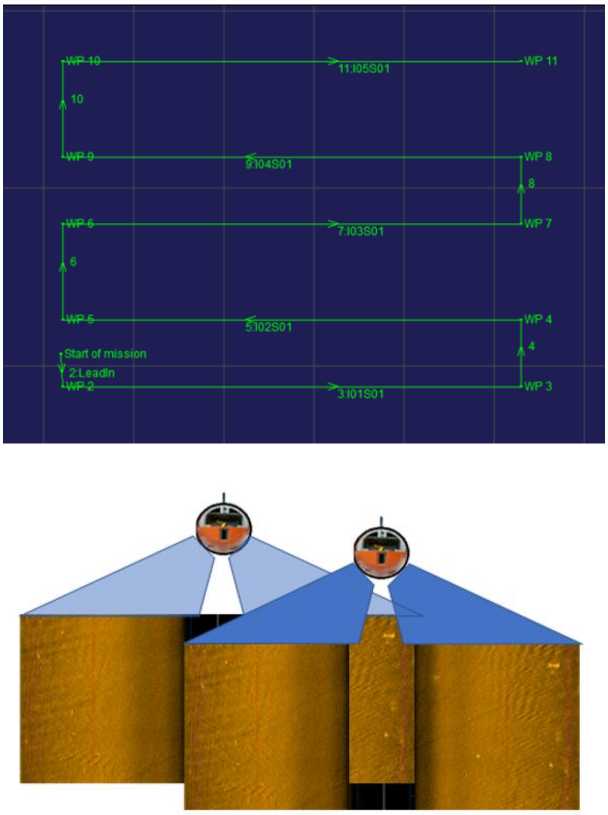


**Fig. 5.** AUV mission plan – lawnmower pattern distribution technique

must choose the optimal settings and create a mission plan that will allow finishing the task in a given time frame. Due to the number of input parameters and the need to take into account the external factors affecting the vehicle behaviour, the mission planning phase is the most essential and challenging part of the operation [16–18]. The above factors justify the need to automate the mission planning process to ensure safe, fast, and efficient data collection.

## 3. THE ALGORITHM FOR GENERATING THE MISSION PLAN OF AN AUTONOMOUS UNDERWATER VEHICLE

The algorithm for generating the vehicle route is designed to shorten the time necessary to prepare the mission plan, take into account the characteristics of the environment and the specifics of the AUV vehicle, and avoid errors generated by inexperienced operators [19]. The following pages describe the structure of the solution that allows planning the vehicle trajectory, including the parameters of the mission plan entered by the user (Fig. 6).

The optimal distribution of the search pattern and the optimal trajectory of the AUV should provide full area coverage, taking into account external factors influencing the movement of the autonomous vehicle and the characteristics of the sensors used in the data collection process. For the systems equipped with side-looking sonars, the lawnmower pattern gives a possibility to cover the nadir gap below the sonar transducer [20]. The distance between the mission plan line is determined by the sonar detection ranges, i.e., the maximum ($R_{\max}$) and the minimum ($R_{\min}$). For the vehicle equipped with synthetic aperture sonar where the detection ranges depend mainly on vehicle speed, the $R_{\max}$ and $R_{\min}$ values can be determined experimentally for the specified AUV speed [21–23]. The optimal trajectory of the autonomous vehicle can be determined by implementing the following transformations [24]:

a) entering or loading from a map based on the WGS84 projection the geographic coordinates describing the area of oper-

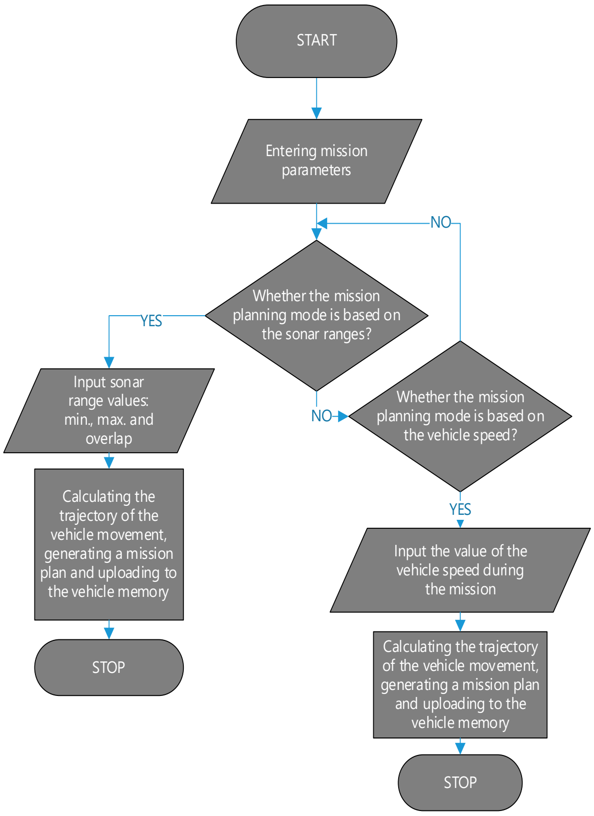


**Fig. 6.** The algorithm for generating the optimal mission plan of the AUV HUGIN system

ation in the format: $\phi = 00°00.000'$N, $\lambda = 000°00.000'$E (Fig. 7): where:

$$M_{3\times n} = \begin{bmatrix} \phi & \dots & \phi_n \\ \lambda & \dots & \lambda_n \\ h & \dots & h \end{bmatrix}, \tag{1}$$

$M_{3\times n}$ – matrix of object position (size $[3\times n]$),
$n$ – number of entered points,
$\phi$ – object longitude position,
$\lambda$ – object latitude position,
$h$ – object height;

b) conversion of the geographic coordinates to the local system relative to the central point $(\phi_o, \lambda_o, h_o)$ of the area of operation, i.e. conversion of the position of the points expressed by longitude, latitude and object height $(\phi, \lambda, h)$ to the coordinates expressed in meters $(x, y, z)$ [25, 26]:

$$x = (N+h)\cos\phi\cos\lambda, \tag{2}$$

$$y = (N+h)\cos\phi\sin\lambda, \tag{3}$$

$$z = \left[N\left(1-e^2\right)+h\right]\sin\phi, \tag{4}$$

where $N$ is the normal radius of curvature:

$$N = \frac{a}{\sqrt{1-e^2\sin^2\phi}}. \tag{5}$$

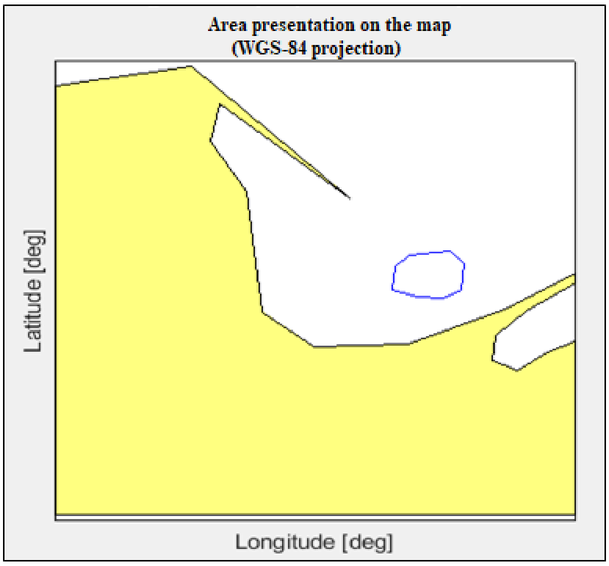


**Fig. 7.** Presentation of the area on the map in the Mercatorprojection

Since during the mission, it is recommended to maintain a constant vehicle height above the bottom (the $z$ axis coordinate does not change), the constant altitude value $Alt$ was adopted for the $z$ coordinate (Fig. 8):

$$M_{3\times n} = \begin{bmatrix} x & \dots & x_n \\ y & \dots & y_n \\ Alt & \dots & Alt \end{bmatrix}, \tag{6}$$

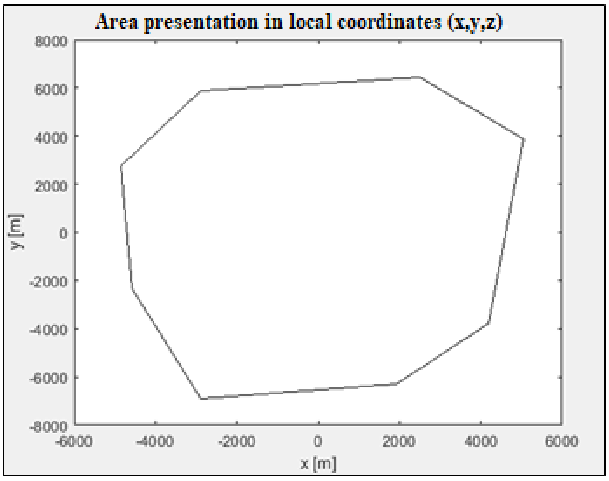


**Fig. 8.** Area presentation in local coordinates

c) rotation of the area in the $z$ axis by the angle value determined in the mission plan by the operator, equal to the general course of movement of the vehicle during the mission;

d) designation of the vertex with the maximum value $y_{(\max)}$, as the reference point from which parallel lines are determined. These lines are the basis for generating the vehicle trajectory. The rotation as a result of multiplication by the rotation matrix allows simplification of the calculation (the slope of the function is equal to 0):

$$M_{\text{rot}} = \text{rot}\, z^T \cdot M_{3\times n} = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}^T \cdot \begin{bmatrix} x_1 & \dots & x_n \\ y_1 & \dots & y_n \\ Alt & \dots & Alt \end{bmatrix}; \tag{7}$$

e) determining, as a result of successive iterations, the functions $(F_{(x1)}, F_{(x2)}, \dots, F_{(xn)})$ constituting the parallel lines as the basis for generating the trajectory of the vehicle. The formulas can determine the optimal distances between the mission plan lines:

$$D_{\text{long}} = 2 \cdot R_{\max} - SDNE_{\text{AUV}} - \text{Overlap}, \tag{8}$$

$$R_{\max} = -R_{\min} - SDNE_{\text{AUV}} - \text{Overlap}, \tag{9}$$

where:
$D_{\text{long}}$ – long spacing between the mission plan lines,
$D_{\text{short}}$ – short spacing between the mission plan lines,
$R_{\min}$ – near sonar range,
$R_{\max}$ – far sonar range,
Overlap – parameter used to increase the confidence that full area coverage will be achieved during the mission,
$SDNE_{\text{AUV}}$ – standard deviation of AUV navigational error;

f) finding the points of intersection of the designated functions $F_{(x1)}, F_{(x2)}, \dots, F_{(xn)}$ with the function $F_{(ob)}$ describing the search area and taking into account the manoeuvrability of the vehicle, i.e., the circulation radius (Fig. 9):

$$F_{(x_1,\dots,x_n)} = F_{(ob)}, \tag{10}$$

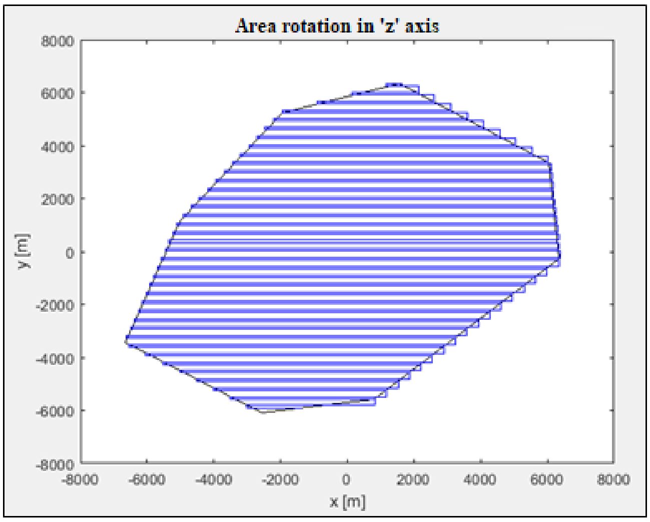


**Fig. 9.** The area rotation in $z$ axis

g) re-rotation of the area $(F_{(ob)})$ and the designated points of the mission plan $(F_{(x_1,\dots,x_n)})$ in the $z$ axis by multiplication by transposed rotation matrix and determination of the final trajectory of the AUV vehicle (Fig. 10).

$$M_{\text{rot}} = \text{rot}\, z^T \cdot M_{3\times n} = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}^T \cdot \begin{bmatrix} x_{ob1} & \dots & x_n \\ F_{(ob1)} & \dots & F_{(obn)} \\ Alt & \dots & Alt \end{bmatrix}, \tag{11}$$

$$M_{\text{rot}} = \text{rot}\, z^T \cdot M_{3\times n} = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}^T \cdot \begin{bmatrix} x_1 & \dots & x_n \\ F_{(x1)} & \dots & F_{(xn)} \\ Alt & \dots & Alt \end{bmatrix}. \tag{12}$$

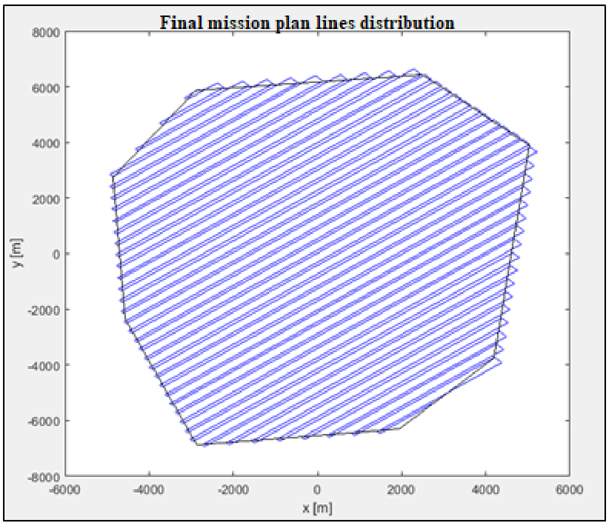


**Fig. 10.** Final mission plan lines distribution

The last element is to generate a mission plan in a format acceptable by the manufacturer's software, e.g., '*.mp', including the manoeuvring characteristics of the vehicle, parameters of the mission and the sensors used.

## 4. RESULTS

The adopted assumptions were verified through a comparative analysis of the mission plans generated using the designed algorithm with the trajectory covered during the vehicle mission in the Gulf of Gdańsk. The results of the above analysis are presented in terms of search efficiency ($F_{\text{eff}}$), sonar beam area coverage ($F_{p1}$, $F_{p2}$), mission time ($F_t$) and distance travelled by AUV. During the task execution, the efficiency of area recognition should be as high as possible and ensure full area coverage within the assigned time frame.

$$F_{\text{eff}} = \frac{S \cdot V}{s}, \tag{13}$$

where:

$F_{\text{eff}}$ – search efficiency expressed in nautical mile square per hour $\left[\frac{\text{Nm}^2}{\text{h}}\right]$,

$S$ – search area expressed in nautical mile square [Nm$^2$],
$s$ – distance travelled by AUV in nautical mile [Nm],
$V$ – AUV speed expressed in knots [kt].

As can be seen in equation (13), the objective function depends on the speed of the vehicle due to the fact that it is the speed of movement of the sonar carrier that determines the range of sonar technologies based on synthetic aperture sonar (SAS) technology. The designed algorithm determines the efficiency of the search for the range of acceptable solutions, i.e., vehicle operating speeds. Therefore, within the solution of the optimization task, the objective function is determined for speed values from 1.5 m/s to 3 m/s with a step change of 0.1 m/s, which in turn determines the total number of sixteen iterations for a single task of basin reconnaissance. Then, the algorithm examining the values of the obtained objective function in the range of acceptable solutions looks for the maximum value of the search efficiency $F_{\mathrm{eff}}$. The previously described calculations solve the algorithm problem of getting stuck at the local maximum, as all possible discretized solutions for a given interval are examined. In the range of acceptable speeds, the efficiency is highest for 1.5 m/s due to the SAS sonar technology used and its specificity.

$$F_t = t_p + t_w + t_o + \frac{s}{V}, \tag{14}$$

where:
$F_t$ – total mission time including launching and recovering AUV [s],
$s$ – distance travelled by AUV [m],
$V$ – AUV speed [m/s],
$t_p$ – time required for AUV mission planning [s],
$t_w$ – time required for taking the position and launching the vehicle in area (for trained crew $t_w = 1020$ s) [s],
$t_o$ – time required for recovering the vehicle after the mission (for trained crew $t_o = 1320$ s) [s].

$$F_{p1} = 2 \cdot \left(R_{\max(r)} - R_{\max(p)}\right) + \mathrm{Overlap}_{(p)}, \tag{15}$$

$$F_{p2} = R_{\max(r)} - R_{\max(p)} + \mathrm{Overlap}_{(p)}, \tag{16}$$

where:
$F_{p1}$ – value of sonar beam overlap between the far mission plan lines (lawnmower pattern),
$F_{p2}$ – value of sonar beam overlap between the near mission plan lines (lawnmower pattern),
$R_{\max(p)}$ – sonar far range used for planning,
$R_{\max(r)}$ – the smallest sonar far range value measured during the post mission analysis process,
$\mathrm{Overlap}_{(p)}$ – overlap between sonar beams used for planning expressed in meters [m].

For the purpose of the AUV mission planning specified parameters have been entered:

a) coordinates describing the area of operation (Fig. 11):
  - point 1 – $\phi_1 = 54°37.000'$N, $\lambda_1 = 018°38.000'$E;
  - point 2 – $\phi_2 = 54°37.000'$N, $\lambda_2 = 018°40.000'$E;
  - point 3 – $\phi_3 = 54°36.000$'N, $\lambda_3 = 018°41.619'$E;
  - point 4 – $\phi_4 = 54°36.000$'N, $\lambda_4 = 018°38.000'$E;

b) AUV speed: 2.0 [m/s];
c) AUV altitude: 20 [m];
d) course: 90–270 [°];
e) water depth: 45 [m];
f) sound velocity profile: 1480 [m/s];
g) ping distance (SAS system): 28.

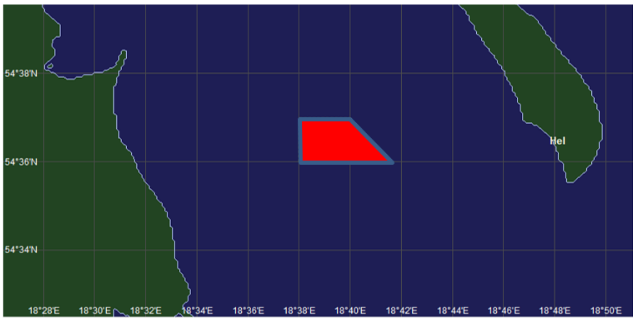
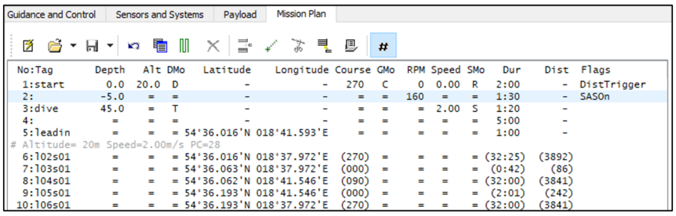


**Fig. 11.** The area of operation

Calculated theoretical range for listed parameters was equal to 180.3 [m]. The mission plan based on entered parameters was generated and saved into the AUV memory (Fig. 12).



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  2:            -5.0     =  =           -             -      =  =   160     =  =   1:30       -  SASOn
  3:dive        45.0     =  T           -             -      =  =     =  2.00  S   1:20       -
  4:               =     =  =           -             -      =  =     =     =  =   5:00       -
  5:leadin         =     =  = 54°36.016'N 018°41.593'E      =  =     =     =  =   1:00       -
# Altitude= 20m Speed=2.00m/s PC=28
  6:l02s01         =     =  = 54°36.016'N 018°37.972'E  (270)  =     =     =  = (32:25)  (3892)
  7:l03s01         =     =  = 54°36.063'N 018°37.972'E  (000)  =     =     =  =  (0:42)    (86)
  8:l04s01         =     =  = 54°36.062'N 018°41.546'E  (090)  =     =     =  = (32:00)  (3841)
  9:l05s01         =     =  = 54°36.193'N 018°41.546'E  (000)  =     =     =  =  (2:01)   (242)
 10:l06s01         =     =  = 54°36.193'N 018°37.972'E  (270)  =     =     =  = (32:00)  (3841)
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**Fig. 12.** The mission plan format (*.mp)

The mission was conducted after accomplishing the technical preparation of the system specified by the procedures. A confirmation of assumed methodology was full area coverage achieved (Fig. 13).

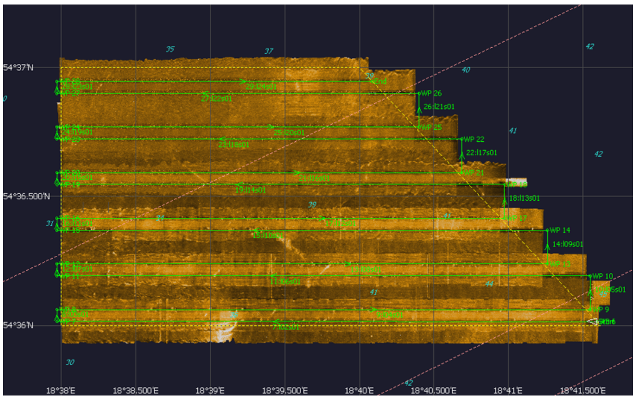

**Fig. 13.** Sonar coverage achieved during the mission

Table 2 compares planning assumptions implemented in the mission plan with the real trajectory of the HUGIN vehicle.

**Table 2**

Comparison of planning assumptions with real AUV trajectory

| No. | Verified parameters | Planned values | Values achieved as a result of AUV mission |
|---|---|---|---|
| 1. | Effectiveness of the AUV sensor ($F_{\mathrm{eff}}$) | 0.294 Nm$^2$/h | 0.312 Nm$^2$/h |
| 2. | Distance travelled during the mission ($s$) | 40.06 km | 41.41 km |
| 3. | Mission time | 5 hrs 47 min 00 sec | 5 hrs 52 min 45 sec |
| 4. | Position uncertainty during the mission | $> 10$ m | $> 35$ m |
| 5. | Value of overlap (for long spacing between mission plan line) ($F_{p1}$) | 10 m | 18 m |
| 6. | Value of overlap (for short spacing between mission plan line) ($F_{p2}$) | 10 m | 8 m |
| 7. | Re-searched area | 1.636 Nm$^2$ | 1.808 Nm$^2$ |
| 8. | Total mission time ($F_t$) including planning phase, | (mission planning time with designed algorithm $t_p = 10$ min) 6 hrs 43 min 45 sec | |
| | launching of AUV and recovering from the water. | (mission planning time without designed algorithm $t_p = 42$ min) 7 hrs 15 min 45 sec | |

The important role of parameters 4–7 should be emphasized. The parameters presented in Table 2 express: the uncertainty of the position determination during the vehicle mission, determined by the NAVLab program based on information from sensors and the INS device (parameter 4) and express the value of covering between the search lanes and the size of the searched area (parameters 5, 6, 7). To ensure the adequate level of uncertainty of the position determination, it is necessary to reposition the vehicle during the mission periodically. Critical from the point of view of mine reconnaissance missions is to obtain full coverage of the search area with a sonar beam; therefore, based on the results of verification missions, it was concluded that the proposed method was positively verified in real research. The discrepancies indicated by the professor between the planned parameters and the parameters obtained in the framework of the real research indicate the need for further research related to the tuning of the algorithm.

The total mission time with the designed algorithm was reduced by 7%. The mission planning phase was shortened by 76% compared to the time of mission planning carried out manually by the operator. The mission plan lines distribution provides the possibility to detect and classify [27] several objects as the UXOs (Fig. 14).

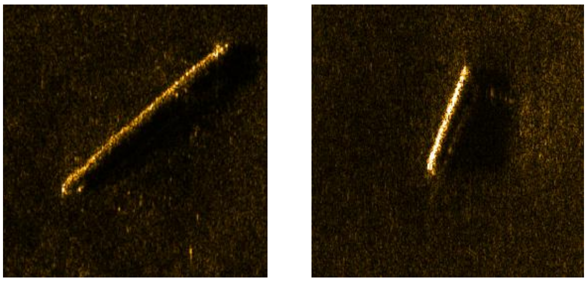

**Fig. 14.** Torpedo shape object localized in the Gulf of Gdańsk area

## 5. CONCLUSIONS

Nowadays, with very dynamic development of autonomous systems, we can discover new possibilities of detecting, classifying and identifying possible threat [28–34]. The use of autonomous vehicles for harbour and seaway traffic lines monitoring is one of the most effective solutions for maintaining security awareness. The AUV technique could also be a source of additional data valuable in many other branches. Nevertheless, technologically advanced solutions require well-trained operators with deep knowledge concerning the systems and the other aspects of efficient mission planning.

The coverage path planning algorithm described in this work provides the solution that significantly reduces the number of input parameters required to be taken into account during the AUV mission planning phase and the number of mistakes caused by the human factor. Regarding time-constrained operations, designed functionalities can significantly reduce the time required to conduct the mission effectively.

The comparison of the mission plan generated using the proposed algorithm with the AUV trajectory achieved as a result of conducted mission confirms the assumptions concerning improved effectiveness of data collection. The designed algorithm provides full area coverage using the AUV equipped with side-looking sonars and can be adapted to most autonomous underwater systems used nowadays.

The authors plan to test the developed method also on other types of objects in the future.

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