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35. UNDERSEA DETECTION OF SEA MINES

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ABSTRACT

In this paper the authors tried to analyse the features of possible undersea threats, such as sea mines, available countermeasures and other activities. Detection, approach, inspection and destruction of an unidentified sunken object by a remotely operated underwater vehicle (ROV) is described. The authors tried to define ROV control parameters and optimisation criteria. ROV control simulation model is developed and tested with two different dynamic positioning algorithms. The paper includes results of ROV manoeuvres simulation. According to these results, the authors conclude that the use of ROVs in undersea detection and destruction of sea mines and other hazardous objects is an effective and efficient solution.

1. INTRODUCTION

Terrorist threats and ecological disasters are nowadays major concerns for virtually every country in the world. These threats are not limited to land or surface in general, but can also have dire consequences for sea depths and littoral, from ecological, as well as economic or military viewpoint. The maritime countries of the world all want to have clean and economically useful sea, and Croatia is no exception (the importance of sea and littoral to Croatia can be seen on Fig. 1). In order to provide response to such threats, a country must have some sort of rapid reaction service, which would be able to eliminate or mitigate hazards of ecological disasters, chemical or nuclear waste pollutions or sea mines.

To realise these tasks, the forces for first response at sea should be able to performthree tasks: sea routes surveillance, threat detection and threat elimination, either by eliminating or mitigating contamination, or by mine clearing.

A remotely operated underwater vehicle (ROV) is a suitable and effective solution for threat elimination. It can be used for:

a) search, identification and clearing of sea mines;
b) testing of underwater weapons (torpedoes, mines, etc.);
c) hydro-acoustical, hydro-geographical and hydrological surveys;
d) search, inspection and lifting of sunken vessels, planes and other sunken objects;
e) protection of vessels, harbours and the like against terrorist or special forces raids;
f) surveillance, inspection and repair of underwater installations;
g) laying of underwater pipelines, power and communications cables;
h) undersea exploration in archaeology, marine biology and cultural heritage protection.

In this paper the authors propose the possible use of ROVs in undersea detection and elimination of sea mines or other objects in shallow waters.

2. Characteristics of Mine Threats and Shallow Water Mine Countermeasures

Sea mines are a very effective underwater weapon. Compared to torpedoes and missiles they prove to be more cost-effective, because they are simpler, less costly to produce, more suitable for storage and handling, can be easily masked, and can be laid from any kind of vessel, either submerged or surfaced, or from low-flying aircraft. Irrespective of their size and cost, sea mines produce considerable physical and psychological effects upon aggressor, and a lot of effort is needed in order to clear and destroy them.

Three types of sea mines are used for shallow water:

1. Contact moored mines - the mine can either float or can be by means of an anchor kept at a certain position and at a certain laying depth. It is activated when a vessel hits the mine.
2. Influence moored mines - the mine is by means of an anchor kept at a certain position and at a certain laying depth, but unlike contact mines it is activated under the action of acoustic, magnetic, hydrodynamic, electric signature, or any combination of these signatures.
3. Influence ground mines - the mine is laid on the sea bottom, and is activated in a way similar to that for the influence moored mine.

The complexity of mine threat has resulted with even more complex activities of mine countermeasures. The basic shallow-waters mine countermeasure activities are given in Fig. 2.

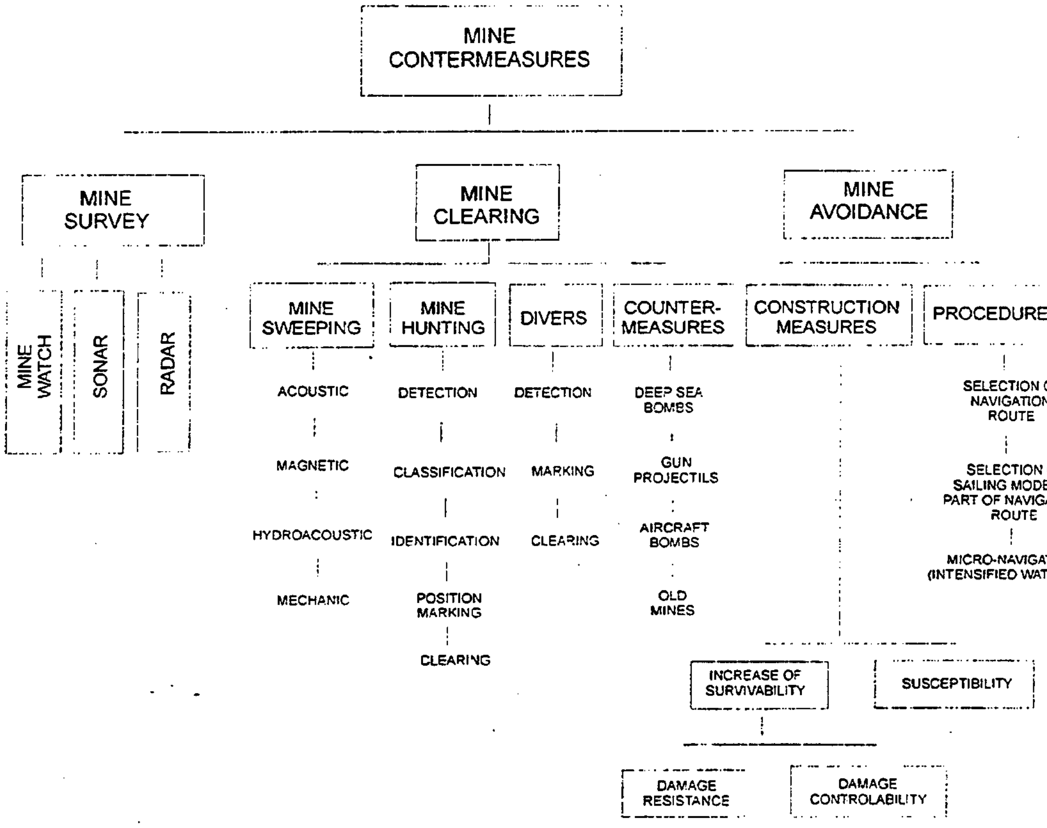


Figure 2. Mine countermeasure activities

There are two basic mine countermeasures procedures:

1. **Mine sweeping** - directed towards known mine field and known mine;
2. **Mine hunting** - directed towards unknown mine field and unknown mine. The clearing of mines by mine sweeping is done so that the mines are from a safe distance activated by means of mine sweeps.

In the case of mine hunting, the mines are cleared using the explosive brought by the ROV, or by hitting of the ROV into the mine, causing mutual destruction.

Mine hunting, thus, several steps of precisely defined order:

1. Surveillance of waterways, and correlation of previous and new bottom images;
2. Mine searching: detection, classification and identification;
3. Mine clearing or neutralization.

The critical point of mine hunting is a reliable and safe ROV which carries the explosive charge for mine clearing. The mine hunting by means of the ROV is illustrated in Figs. 3 and 4. Some commercially available ROVs are pictured in Figures 5, 6 , 7, 8 and 9.

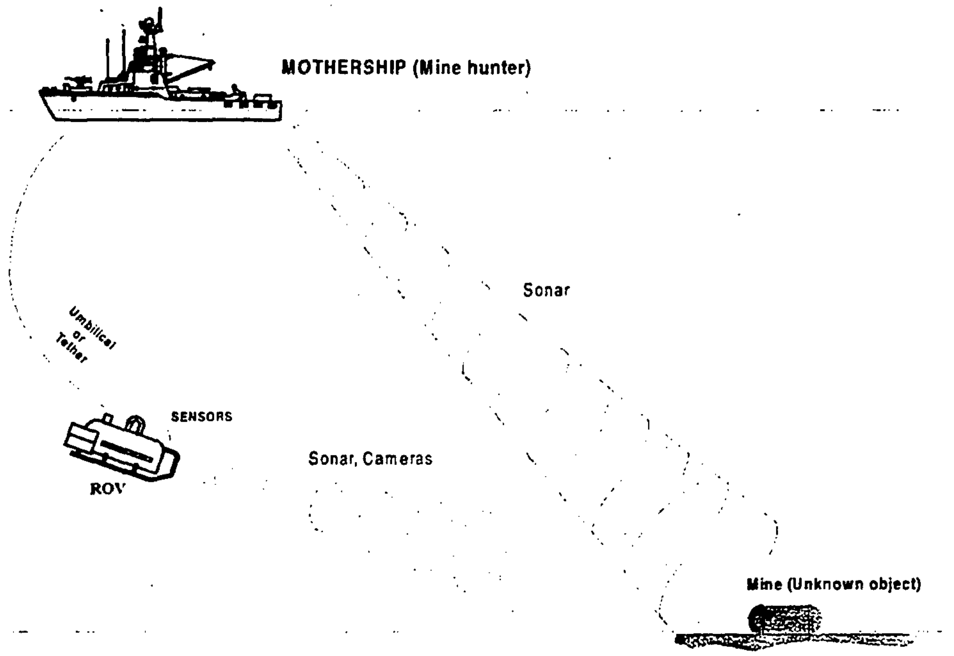


Figure 3. Mine hunting

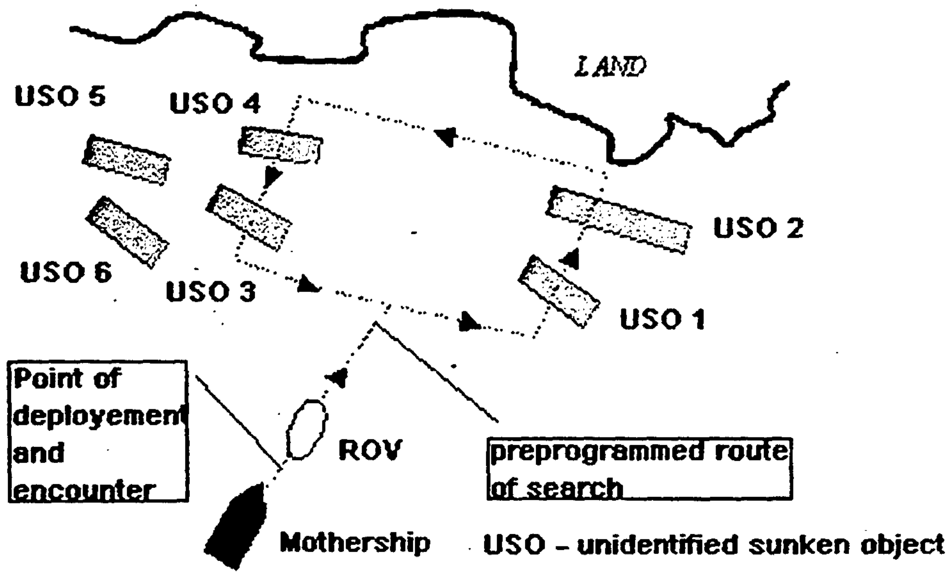


Figure 4. ROV deployment and search

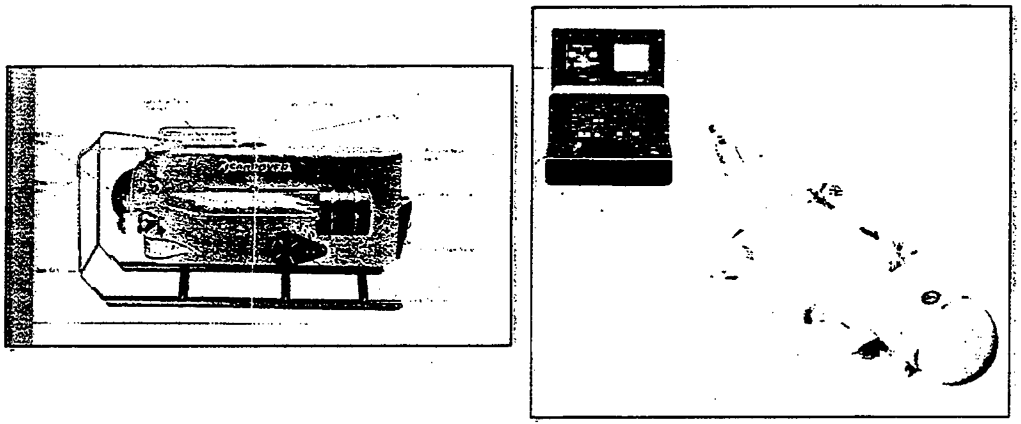


Figure 8. *Pluto* ROV

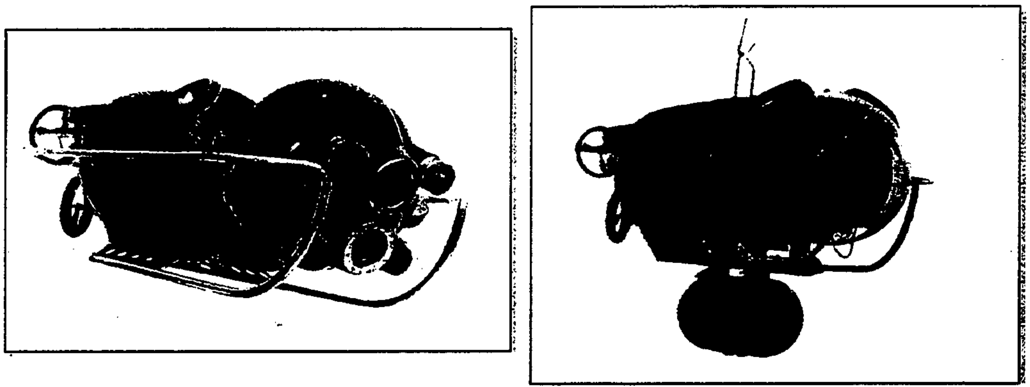


Figure 9. *Pluto* ROV in manoeuvre

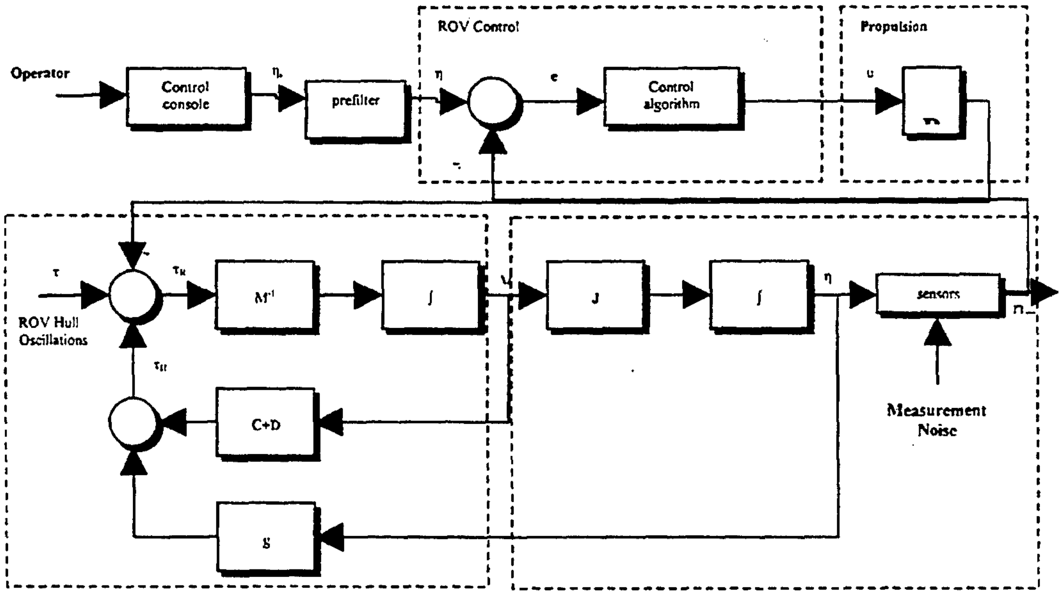


Figure 10. System Modelling

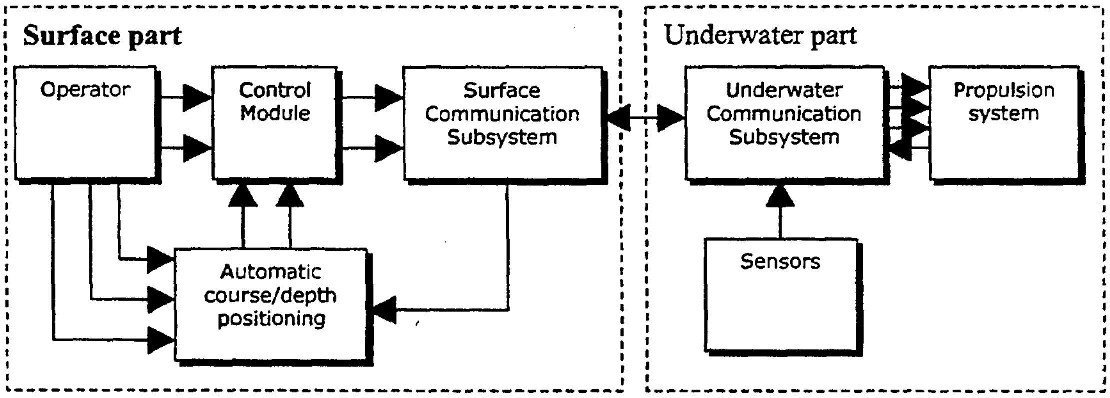


Figure 11. System Modelling - ROV Propulsion Control System

3. The Basic Mathematical Model of ROV Suitable for Dynamic Analysis

The manoeuvering of the ROV is done by the action of the forces and moments along and about x, y and z axes. The ROV propulsion system includes a number of thrusters fitted in adequate way on the hull. These thrusters are used both for propulsion and as actuators.

3.1 Mathematical model of thrusters

The mathematical model of thrusters from the control viewpoint can be generally considered as a nonlinear function

$$F = P(u_a) \qquad (1)$$

where:

u_a - armature voltage of drive, F -thrust force

Function P depends on thruster state variables, advance speed, and propeller revolutions.

For the needs of dynamic positioning system designing, the model of thrusters is often simplified and is described as a first-order transfer function with nonlinear gain.

3.2 Suitable mathematical model of ROV as a moving object

The mathematical model of the ROV kinematics and dynamics requires 6 equations, Table 1.

Table 1. - Degrees of freedom used to describe ROV dynamics and kinematics [1]

Degree of freedom	Type of motion (translation or rotation)	Forces and moments
1	SURGE	X
2	SWAY	Y
3	HEAVE	Z
4	ROLL	K
5	PITCH	M
6	YAW	N

The general form of the matrix equation for the ROV dynamics in 6 DOF according to [1, 4] is:

$$\mathbf{M}\,\dot{\nu} + \mathbf{C}(\nu)\nu + \mathbf{D}(\nu)\nu + \mathbf{g}(\eta) = \tau \qquad (2)$$

where:

- $\mathbf{M}$ -inertia matrix,
- $\mathbf{C}(\nu)$ - Coriolis and centripetal matrix
- $\mathbf{D}(\nu)$ - damping matrix
- $\mathbf{g}(\eta)$ - restoring forces
- τ - control forces

Inertia matrix $\mathbf{M}$ is given by the sum of the two matrices:

$$\mathbf{M} = \mathbf{M}_{RB} + \mathbf{M}_{A} \qquad (3)$$

where:

- $\mathbf{M}_{RB}$ -rigid-body inertia matrix;
- $\mathbf{M}_{A}$ - added inertia matrix

Coriolis and centripetal matrix $\mathbf{C}(\nu)$ is also given by as the sum of the two matrices:

$$\mathbf{C}(\nu) = \mathbf{C}_{RB}(\nu) + \mathbf{C}_{A}(\nu) \qquad (4)$$

where:

- $C_{RB}(\nu)$ - *rigid-body Coriolis and centripetal matrix;*

- $\mathbf{C}_A(\nu)$ - hydrodynamic Coriolis and centripetal matrix

Total dumping matrix $\mathbf{D}(\nu)$ is the sum of partial damping matrices:

$$\mathbf{D}(\nu)=\mathbf{D}_P(\nu)+\mathbf{D}_S(\nu)+\mathbf{D}_W(\nu)+\mathbf{D}_M(\nu) \qquad (5)$$

where:

- $\mathbf{D}_P(\nu)$ - radiation induced potential damping due to forced body oscillations;
- $\mathbf{D}_S(\nu)$ - linear skin friction due to laminar boundary layers and quadratic skin friction due to turbulent boundary layers;
- $\mathbf{D}_W(\nu)$ - wave drift damping;
- $\mathbf{D}_M(\nu)$ - damping due to vortex shedding

The transformation of the velocity vector from the coordinate frame fixed to the vehicle to the earth-fixed coordinate frame, i.e. the ROV kinematics is obtained by the Jacobi transformation:

$$\dot{\eta}=\mathbf{J}(\eta)\,\nu \qquad (6)$$

where:

η - vector of positions and Euler angles in Earth's coordinate frame
$\mathbf{J}$ - Jacobi transformation matrix

The vector of gravitation forces and moments $\mathbf{g}(\eta)$ for the selected ROV (force of buoyancy equal to weight) is defined by the expression:

$$\mathbf{g}(\eta)=\begin{bmatrix} 0 \\ 0 \\ 0 \\ -BG_y\cos\phi\cos\theta+BG_z\,G\cos\theta\sin\phi \\ BG_z\,G\sin\theta+BG_x\,G\cos\theta\cos\phi \\ -BG_x\,G\cos\theta\sin\phi-BG_y\,G\sin\theta \end{bmatrix} \qquad (7)$$

where:

$$BG=\begin{bmatrix} BG_x & BG_y & BG_z \end{bmatrix}^T=\begin{bmatrix} x_G-x_B & y_G-y_B & z_B-z_G \end{bmatrix}^T$$

- $r_G=(x_G, y_G, z_G)$ - the distance of the center of mass from the origin of the body-fixed coordinate frame;
- $r_B=(x_B, y_B, z_B)$ - the distance of the center of buoyancy from the origin of the body-fixed coordinate frame.

Sea current is a constant parameter in the field of ROV action, and is therefore described via relative velocity:

$$\nu_r=\nu-\nu_c \qquad (9)$$

where:

ν_c - sea current velocity.

The ROV equation of motion under condition that $\dot{\nu}_c\approx 0$ assumes the form:

$$\mathbf{M}\dot{\nu}+\mathbf{C}(\nu_r)\nu_r+\mathbf{D}(\nu_r)\nu_r+\mathbf{g}(\eta)=\tau \qquad (10)$$

where:

v_r - relative velocity of ROV motion.

On the basis of the presented mathematical models of subsystems, the structure of the ROV control system was defined, and is shown in Fig. 12.

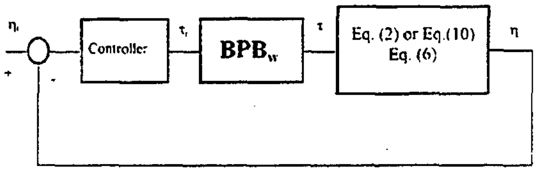


Figure 12. The structure of the ROV control

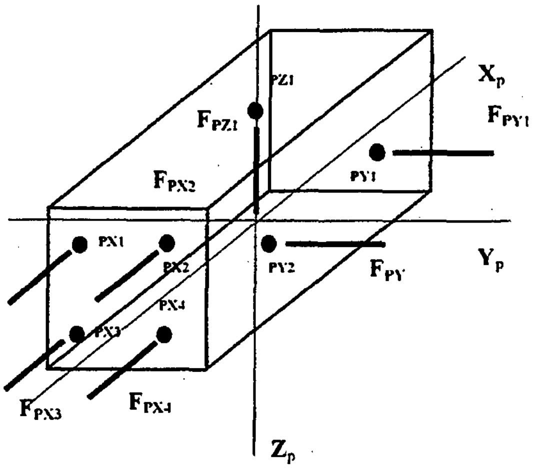
4. The Basic Simulation Model Suitable for Remote Control Algorithm Synthesis

In the considered case, it is not possible to control the ROV fitted, for example, with 7 thrusters by individual control of each thruster, in order to achieve desired manoeuvre. It is necessary to provide the coordinate control of the propulsion in a way that the operator determines intervention vector, and a special subsystem, controlled according to a pre-defined algorithm, determines the contribution of each thruster. All contributions together represent contribution matrix **B**. Matrix **B**$_W$ represents the distribution of control signals to individual thrusters, and is usually taken as pseudo-inversion of matrix **B**.

4.1 Mathematical model of contribution - contribution matrix

The configuration of the ROV thrusters is shown in Fig. 13.

Figure 13. 3-D representation of ROV thrusters configuration



Forces $F_{P...}$ represent the thrust forces of individual thrusters and the moment is defined as:

$$\bar{M} = \bar{l} \times \bar{F} \qquad (11)$$

where:

- F - force
- l - force arm

It can be seen from Fig. 4 that the contribution matrix has the following form:

$$\mathbf{B} = \begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -l_{PX1-M} & -l_{PX2-M} & l_{PX3-M} & l_{PX4-M} & 0 & 0 & 0 \\ l_{PX1-N} & -l_{PX2-N} & l_{PX3-N} & -l_{PX4-N} & l_{PY1-N} & -l_{PY2-N} & 0 \end{bmatrix} \qquad (12)$$

4.2 Optimization criteria

The possibility of multiple solutions of contribution matrix $\mathbf{B}_W$ requires defining of certain optimisation criteria on the basis of which the ROV control system chooses the most favourable solution. The easiest way is to make the inversion, i.e. pseudoinversion of contribution matrix **B,** and get the ROV intervention vector which is in accordance with the operator's intervention at the control panel. The matrix $\mathbf{B}_W$ can be, however, optimized according to some specific requirement.

The special-purpose ROV optimization criteria are the following:

1. Minimum energy criterion
2. Peak load optimization criterion
3. i^{th} thruster's load optimization criterion
4. Criterion of optimization according to the number of active thrusters.

The optimization problem to be solved by the control system involves the synthesis of the appropriate control algorithm that will during the operation of the ROV coordinate control calculate the optimum contribution of each thruster in the operating propulsion system configuration, with the aim of generating the desired intervention vector.

The intervention vector has to overcome the ROV dynamics and environmental disturbances in order to perform the task of dynamic positioning.

The most convenient method for finding out the optimum solution to this problem in real time is the least squares method.

For the purpose of the realization of the target function, i.e. dynamic positioning of the ROV at a certain subsea point with required positioning accuracy, it is necessary to realize the algorithm for the control of the subsystem "propulsion configuration-coordinate control". It is further necessary to realize the algorithm for the distribution of the contribution of individual thrusters necessary for the realization of the required intervention vector. The propulsion configuration control can be achieved using conventional and unconventional algorithms.

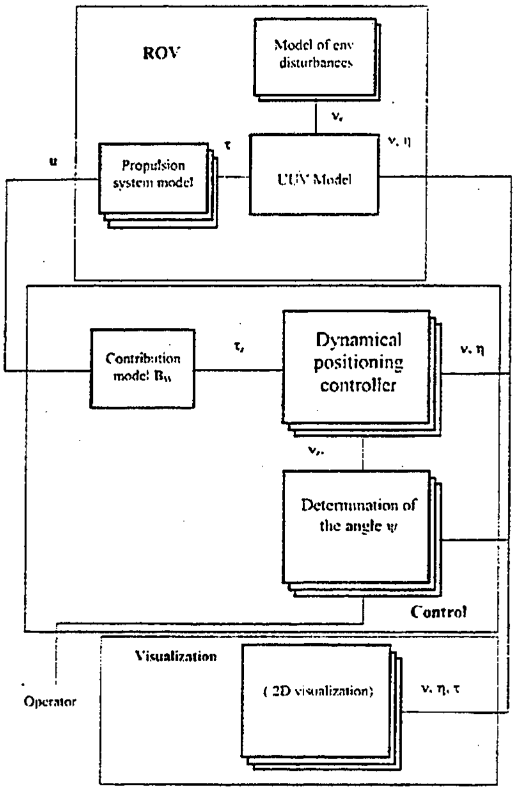
4.3 Simulation model of ROV dynamic positioning in the vicinity of unidentified object

On the basis of the structure of ROV control (Fig. 12) and dynamic positioning control algorithms, the ROV simulation model is defined (Fig. 14).

As shown in the figure, the ROV simulator includes: ROV model, disturbances model, propulsion subsystem model, contribution model, control model, planning and decision making model, and visualization model. The last four models are of modular character, which means that they can be changed in accordance with control system requirements. Also, individual modules can be, as the need requires, added or removed from the ROV simulator. The concept of the realized simulation model also allows making of extensions using additional modules, realization of particular software support, and education of operators.

On the basis of the simulation model presented in Fig. 17, the analysis of the ROV dynamic positioning in the software package MATLAB/SIMULNIK was made (Fig.18) for conventional and unconventional control of the thrusters. A fuzzy controller was, for instance, realized on the simulation model according to Fig. 24.

Figure 14. ROV simulation model during dynamic positioning



List of symbols in Fig. 14
τ - intervention vector
τ_z - given intervention vector
v_z - given velocity vector
η_z - given position vector
v - instantaneous velocity vector
η - instantaneous position vector
u - control vector
v_c - sea current velocity vector

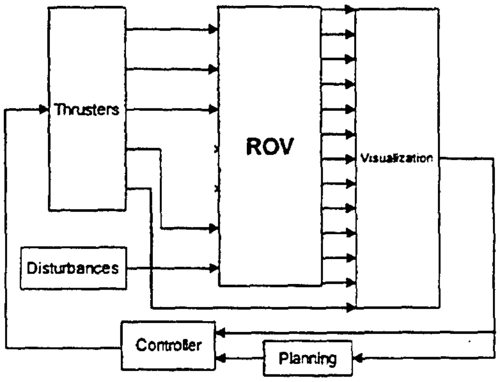


Figure 15. Simulation model in SIMULINK

4.4 Counter-mine manoeuvre scenario

The requirements on the ROV manoeuvering characteristics are determined by the combined mine searching manoeuvre. First, the mothership (mine-hunter), while sailing, searches a certain sea area for mines in the way shown in Fig.16.

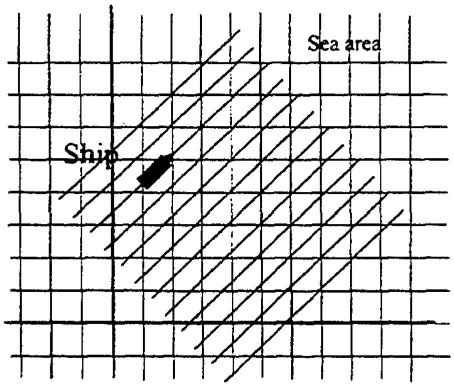


Figure 16. Searching of the sea area by a mine-hunter

In the event that ship sonars and/or other mine detection sensors detect a "dubious object" on the sea bed, that place is marked. In order to inspect the detected object, it is necessary to send a ROV to that place. The ROV manoeuvre has three phases, as illustrated in Fig. 17. These phases are the following: submerging (phase 1), approaching the detected object (phase 2), and inspecting the object (phase 3). The first part of the manoeuvre is not usually controlled automatically. After the necessary preparations, the ROV is submerged to a certain depth. Then follows the second phase during which the autopilot for course keeping switches on. When the ROV has come close to the object, the dynamic positioning system switches on (phase 2-phase 3)

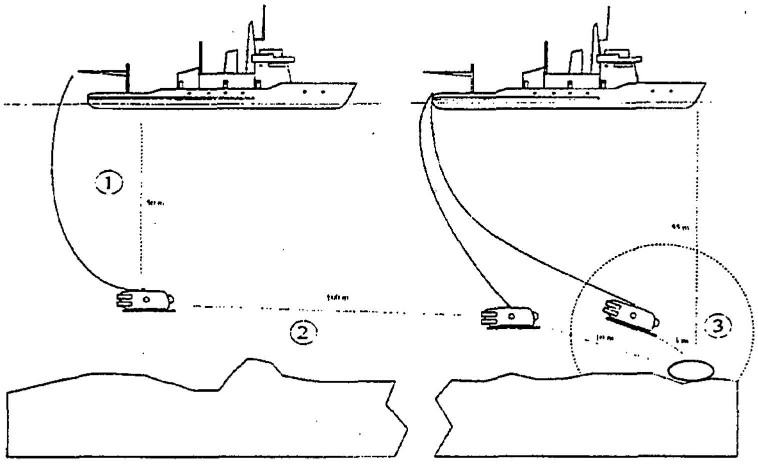


Figure 17. Mine clearing manoeuvre

The first part of the positioning manoeuvre is getting the ROV close to the object so that it can inspect it using a camera and sonars. That manoeuvre is illustrated in Fig. 18, the ROV from point A, at which the dynamic positioning system is switched on, comes to point B, where the sensor for the inspection of the object is switched on. In Figs. 19a, 19b and 19c, the results of simulation with a conventional (PID) algorithm for the control of thrusters configuration are given for the ROV having a mass of 185 kg. The results of simulation with the fuzzy control algorithm are shown in Figs. 20a, 20b and 20c, whereas the results of the simulation of ROV dynamic positioning for the manoeuvre of unknown object identification (Fig.21) are given in Figs. 22a, 22b, 22c, 23a, 23b and 23c.

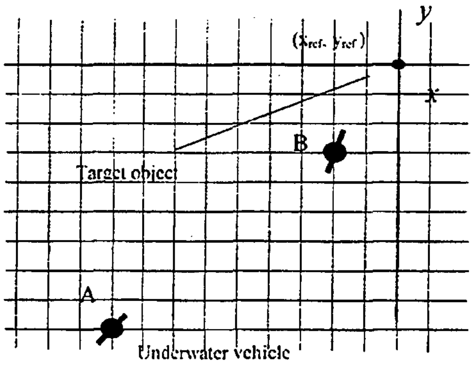


Figure 18. Approaching to the unknown object

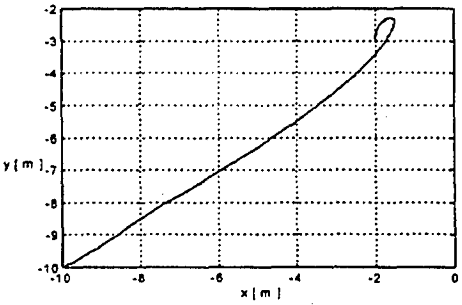


Figure 19a. Positioning in x-y plane (PID)

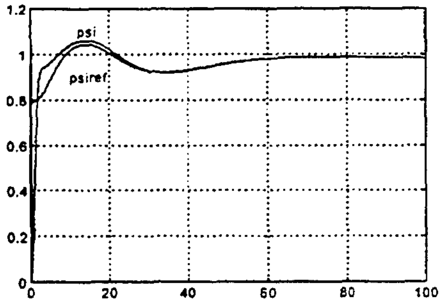


Figure 19b. Heading and reference heading(PID)

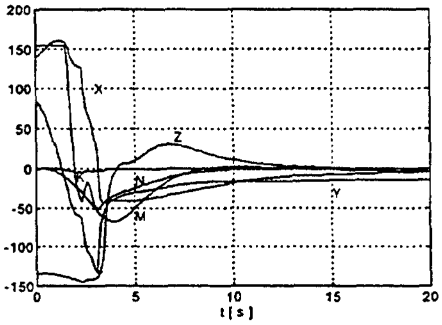


Figure 19c. Intervention vector (PID)

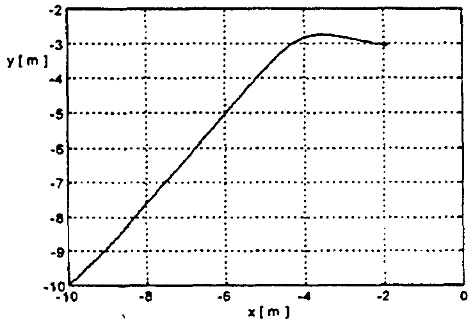


Figure 20a. Positioning in x-y plane (Fuzzy)

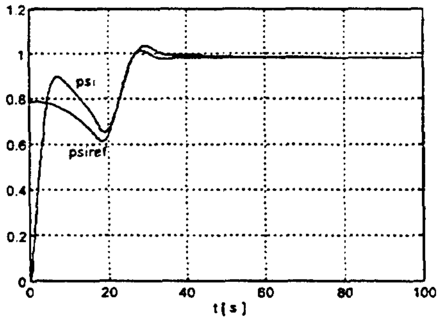


Figure 20b. Heading and reference heading(Fuzzy)

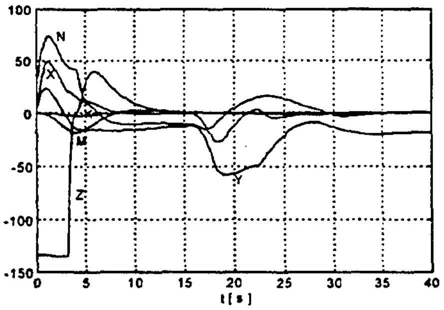


Figure 20c. Intervention vector(Fuzzy)

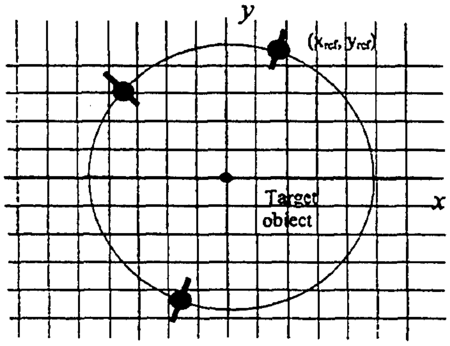


Figure 21. Unknown object inspection maneouvre

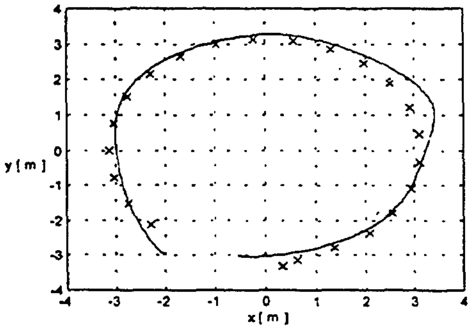


Figure 22a. Positioning in x-y plane (PID)

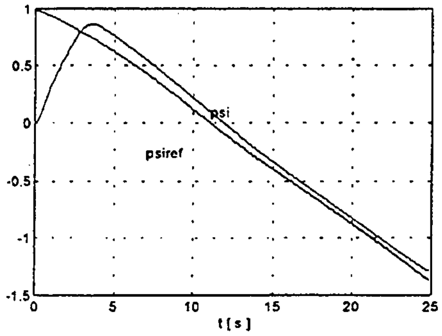


Figure 22b. Heading and reference heading(PID)

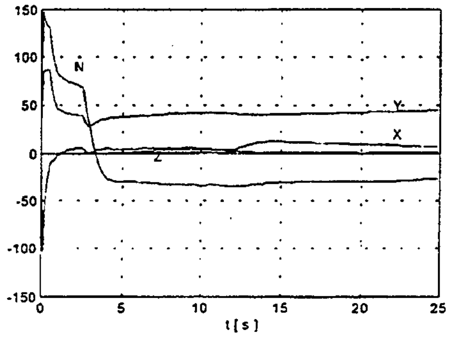


Figure 22c. Intervention vector(PID)

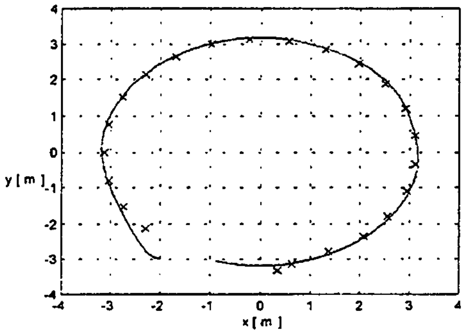


Figure 23a. Positioning in x-y plane (Fuzzy)

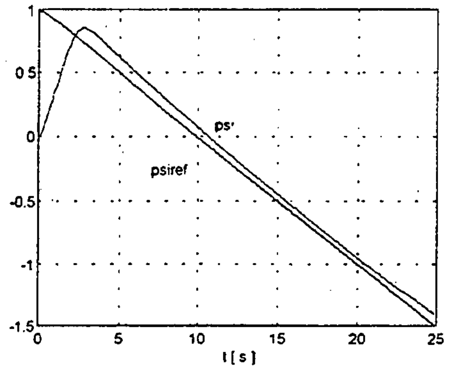


Figure 23b. Heading and reference heading (Fuzzy)

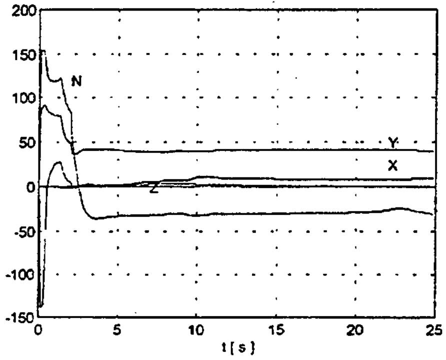


Figure 23c. Intervention vector(Fuzzy)

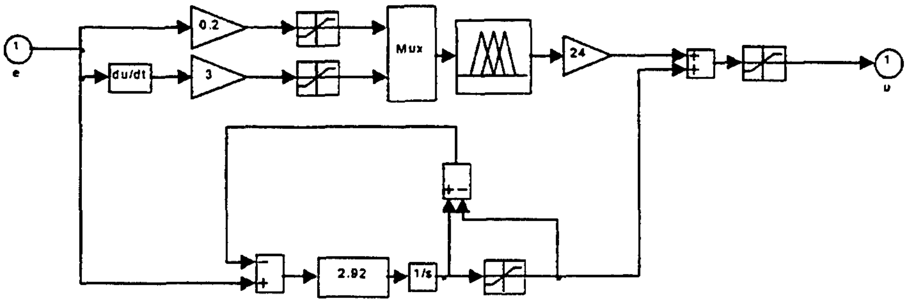


Figure 24. y-position fuzzy controller

4.5 CONCLUSION

On the basis of the presented mathematical model of ROV dynamic behaviour, and the realized simulation model and ROV dynamic behaviour simulation results for different modes of motion, it can be concluded that the application of ROV for mine detection and clearing in shallow seas proves to be a rather promising and efficient solution.

KEY WORDS

Mine threat, sea mines, mine countermeasures, remotely operated underwater vehicle, remote control, simulation model, control algorithms

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