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UNDERWATER REMOTELY OPERATED VEHICLE DESIGNED for SEARCH in MARITIME and RIVER AREAS

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The ROV prototype is designed to carry out underwater surveillance in lakes, harbors and maritime environment, under a remote control system placed onshore or on seaborne platforms. ROV consists of a watertight streamlined body that includes the sensors, projectors and electronic microcontrollers, linked to the remote control station (laptop) via an umbilical cable that transfers data from the vehicle and commands from the operator. ROV is destined to assist divers during reconnaissance operations or to fully replace them in tough hydro-meteorological conditions.

Research and development of the prototype has been accomplished in the "Mircea cel Batran" Naval Academy under a contract awarded by the Romanian Naval Forces.

The necessity to use such means is given by the multiple benefits they provide, whereas the most important are:

- monitoring and classification of underwater objects in harbors, passes, in order to increase the safety of navigation in the present conditions of asymmetric threats facing NATO forces;
- assistance or even replacement of EOD divers in their missions of mine classification and neutralization;
- increase the safety of forces by operating at a safe distance.

The main objective for the development of a ROV prototype in the Naval Academy is to draw some conclusions about technical and tactical capabilities necessary for future acquisitions and use of ROV`s in minehunting operations. The ROV is a system with the following subsystems: the vehicle, the remote control subsystem, devices used for launching and bringing back the ROV and power supply subsystem.

In order to develop the ROV product we made the following steps:

1. Measurement of hydrostatic and hydrodynamic characteristics of the experimental model in laboratory and real environmental (Mamaia lake).
2. Evaluation and validation of CAD model developed in previous phases.
3. Experimental determination of kinematic parameters to define the dynamic properties of ROV (maneuverability, stability).
4. Evaluation of the ROV subsystems functioning (sensors and effectors) in laboratory and real environmental.
5. Establish requirements for remote control system using determined values of characteristics and dynamic properties.

The ROV movement on underwater trajectory consists in permanent changes of kinematic parameters. The possibility and the precisions of these maneuvers are given by dynamic properties of ROV. The most important are maneuverability, stability and responsiveness to remote control commands. These characteristics depends on ROV`s technical, tactical and hydrodynamic characteristics, all of them being in interdependence.

The maneuverability of ROV reflects his capacity to alter course, speed and depth. These changes in direction, speed and immersion are made both horizontally and vertically by four auxiliary engines (two vertical and two horizontal). Depending on some motion parameters, the possibilities of movement are classified as acceleration and braking, movement along inclined trajectories, curved horizontally and vertically trajectories.

The testing/evaluation and validation process of hydrodynamic characteristics for the ROV prototype is based on the water movement equations of a solid with 6 degrees of freedom (DOF).

„Mircea cel Batran" Naval Academy swimming pool used to simulate laboratory environmental for ROV

The movement equations for a solid with 6 DOF could be written as:

$$m\cdot\frac{dv_x}{dt}+(m+\lambda_{33})\cdot\omega_y v_z-(m+\lambda_{22})\cdot\omega_z v_y-\lambda_{26}\cdot({\omega_y}^2+{\omega_z}^2)=F_x$$

$$(m+\lambda_{22})\cdot\frac{dv_y}{dt}+m\cdot\omega_z v_x-(m+\lambda_{33})\cdot\omega_x v_z+\lambda_{26}\cdot(\frac{d\omega_z}{dt}-\omega_x\omega_y)=F_y$$

$$(m+\lambda_{33})\cdot\frac{dv_y}{dt}+m\cdot\omega_y v_x+(m+\lambda_{22})\cdot\omega_x v_y+\lambda_{26}\cdot(\frac{d\omega_z}{dt}-\omega_x\omega_z)=F_z$$

$$(J_x+\lambda_{44})\cdot\frac{d\omega_x}{dt}=M_x$$

$$(J_y+\lambda_{55})\cdot\frac{d\omega_y}{dt}+(J_x+\lambda_{44}-J_z-\lambda_{66})\cdot\omega_x\omega_z-\lambda_{26}(\frac{dv_z}{dt}+\omega_x v_y-\omega_y v_x)=M_y$$

$$(J_z+\lambda_{66})\cdot\frac{d\omega_z}{dt}+(J_y+\lambda_{55}-J_x-\lambda_{44})\cdot\omega_x\omega_y-\lambda_{26}(\frac{dv_y}{dt}+\omega_x v_z-\omega_z v_x)=M_z$$

If the ROV body masses and distribution of masses are statically determined, the meassurement values for kinematic and dynamic parameters will be used for forces and torques calculation.

The CAD modelation and simulation for dynamic behavior of ROV could be used for numerical calculation.

Applying these assumptions, the ROV movement equations could be written as (regarding [1, 2, 4, 5,]):

$$m\cdot\dot{v}\cdot\cos\alpha\cdot\cos\beta-m\cdot v\cdot\sin\alpha\cdot\cos\beta\cdot\dot{\alpha}-m\cdot v\cdot\cos\alpha\cdot\sin\beta-$$

$$-(m+\lambda_{33})\cdot\omega_z\cdot v\cdot\sin\alpha\cdot\cos\beta-\lambda_{26}\cdot(\omega_y^2+\omega_z^2)+(m+\lambda_{33})\cdot\omega_y\cdot v\cdot\sin\beta=F_x$$

$$-(m+\lambda_{22})\dot{v}\sin\alpha\cos\beta-(m+\lambda_{22})v\cos\alpha\cos\beta\dot{\alpha}+(m+\lambda_{22})v\sin\alpha\sin\beta\dot{\beta}+$$

$$m\omega_z v\cos\alpha\cos\beta-(m+\lambda_{33})\omega_x v\sin\dot{\beta}+\lambda_{26}(\dot{\omega}_z+\omega_x\omega_y)=F_y$$

$$(m+\lambda_{33})\dot{v}\sin\beta+(m+\lambda_{33})v\cos\beta\dot{\beta}-(m+\lambda_{22})\omega_x v\sin\alpha\cos\beta-$$

$$-m\omega_y v\cos\alpha\cos\beta-\lambda_{26}(\dot{\omega}_y-\omega_x\omega_z)=F_z$$

$$(J_x+\lambda_{44})\dot{\omega}_x=M_x$$

$$(J_y+\lambda_{55})\omega_y+(J_x+\lambda_{44}-J_z-\lambda_{66})\omega_x\omega_z-\lambda_{26}(\dot{v}\sin\beta+v\cos\beta\dot{\beta}-$$

$$\omega_x v\sin\alpha\cos\beta+\omega_y v\cos\alpha\cos\beta)=M_y$$

$$(J_z+\lambda_{66})\dot{\omega}_z+(J_y+\lambda_{55}-J_x-\lambda_{44})\omega_x\omega_y+\lambda_{26}(-\dot{v}\sin\alpha\cos\beta+$$

$$+v\cos\dot{\alpha}\alpha\cos\beta+v\sin\alpha\sin\beta\dot{\beta}-\omega_x v\sin\beta+\omega_z\cos\alpha\cos\beta)=M_z$$

This system of differential equations is complex and will be solved using some simplifying assumptions. These assumptions tell us to study the movement in two planes [2, 3, 4, 5, 6].

In this way, we will skip some factors which affect the ROV movement. Therefore, the results obtained by solving the general differential equations are different from the results obtained by solving the simplified equations. However the differences obtained are considerable especially since in the initial design phase all the ROV hydrodynamic characteristics are approximately determined. At this stage simplified equations are enough, because they allow some conclusions useful for ROV research and design.

In conclusion, the suggested method involves a simplification of ROV movement study without introducing excessive errors.

Assumptions in solving the ROV movement equations

The simplifying assumptions are the following:

- the roll angle is excluded because the mass center is situated bellow of hull;
- α and β parametres are small.

The errors are not so big, because the ROV is stabilized by the roll stabilizers. In addition, the α and β angles are small. With this assumptions, we can do the follwing approximations:

sin α = α	cos α =1	α = 3° . . . 5°
sin β = β	cos β =1	β = 3° . . . 5°

We should consider that:

$\omega_x=0$, resulting $d\omega_x/dt = 0$.

The movement equations in the vertical plane are:

$$m\cdot\dot{v}-m\cdot v\cdot\alpha\cdot\dot{\alpha}-m\cdot v\cdot\beta\cdot\dot{\beta}-(m+\lambda_{33})\cdot\omega_z\cdot v\cdot\alpha-$$

$$-\lambda_{26}\cdot(\omega_y^2+\omega_x^2)+(m+\lambda_{33})\cdot\omega_y\cdot v\cdot\beta=F_x$$

$$-(m+\lambda_{22})\dot{v}\alpha-(m+\lambda_{22})v\dot{\alpha}+(m+\lambda_{22})v\alpha\dot{\beta}\beta+$$

$$+mv\omega_z-\lambda_{26}\dot{\omega}_z=F_y$$

$$(J_z+\lambda_{66})\dot{\omega}_z+\lambda_{26}(-\dot{v}\alpha-v\dot{\alpha}+v\alpha\dot{\beta}\beta+\omega_z v)=M_z$$

The movement equations in the horizontal plane are:

$$m\dot{v} - mv\dot{\alpha}\alpha - mv\dot{\beta}\beta - (m+\lambda_{33})\omega_z v\alpha -$$
$$-\lambda_{26}(\omega_y^2 + \omega_z^2) + (m+\lambda_{33})\omega_y v\beta = F_x$$
$$(m+\lambda_{33})\cdot\dot{v}\cdot\beta + (m+\lambda_{33})\cdot v\cdot\dot{\beta}\cdot\beta - m\cdot v\cdot\omega_y - \lambda_{26}\cdot\dot{\omega}_y = F_z$$
$$(J_y+\lambda_{55})\dot{\omega}_y - \lambda_{26}(\dot{v}\beta + v\dot{\beta} + \omega_y v) = M_y$$

Considering that:

$$\begin{cases} \dot{v}_x = dv_x/dt = d^2x/dt^2 = \ddot{x} \\ \dot{v}_y = dv_y/dt = d^2y/dt^2 = \ddot{y} \\ \dot{v}_z = dv_z/dt = d^2z/dt^2 = \ddot{z} \\ \dot{\omega}_z = d\omega_z/dt = d^2\theta/dt^2 = \ddot{\theta} = \ddot{\alpha} \\ \dot{\omega}_y = d\omega_y/dt = d^2\Psi/dt^2 = \ddot{\Psi} = \ddot{\beta} \end{cases}$$

The movement equations of motion could be rewritten as:
- in the vertical plane:

$$\begin{cases} m\ddot{x} - m\dot{x}\dot{\alpha}\alpha + (m+\lambda_{22})\dot{y}\dot{\alpha}\alpha - \lambda_{26}(\dot{\alpha})^2 = F_x \\ -(m+\lambda_{22})\ddot{y}\alpha - (m+\lambda_{22})\dot{y}\dot{\alpha} + m\dot{x}\dot{\alpha} + \lambda_{26}\ddot{\alpha} = F_y \\ (J_z+\lambda_{66})\ddot{\alpha} + \lambda_{26}(-\ddot{y}\alpha + \dot{y}\dot{\alpha} + \dot{x}\dot{\alpha}) = M_x \end{cases}$$

where α, x and y are unknown (we also considered that α = 0 and Ψ = 0);
- in the horizontal plane:

$$\begin{cases} m\ddot{x} - m\dot{x}\dot{\beta}\beta + (m+\lambda_{33})\dot{z}\dot{\beta}\beta - \lambda_{26}(\dot{\beta})^2 = F_x \\ (m+\lambda_{33})\ddot{z}\beta - (m+\lambda_{33})\dot{z}\dot{\beta} - m\dot{x}\dot{\beta} - \lambda_{26}\ddot{\beta} = F_z \\ (J_v+\lambda_{55})\ddot{\beta} - \lambda_{26}(\ddot{z}\beta + \dot{z}\dot{\beta} + \dot{x}\dot{\beta}) = M_y \end{cases}$$

where β, x and z are the unknowns (we also considered that β = Ψ and α = θ = 0).

Furthermore we will calculate the right part of the movement equations in the vertical plane. Substituting the values of the masses, additional masses and moments of inertia calculated, the ROV movement equations in both planes will be:
- movement equations in the vertical plane

$$\begin{cases} \ddot{x} - \dot{x}\dot{\alpha}\alpha + 1.12\dot{y}\dot{\alpha}\alpha + 0.01(\dot{\alpha})^2 - 0.1\alpha = 0.04 \\ \ddot{y}\alpha + y\dot{\alpha} - 0.89\dot{x}\dot{\alpha} + 0.01\ddot{\alpha} + 0.02\alpha = 0.002 \\ \ddot{\alpha} - 0.04(-\ddot{y}\alpha + \dot{y}\dot{\alpha} + \dot{x}\dot{\alpha}) + 0.11\alpha = 0.008 \end{cases},$$

- movement equations in the horizontal plane:

$$\begin{cases} \ddot{x} - \dot{x}\dot{\beta}\beta + 1.12\dot{z}\dot{\beta}\beta + 0.03(\dot{\beta})^2 + 0.002\beta = 0.023 \\ \ddot{z}\beta + \dot{z}\dot{\beta} - 0.89\dot{x}\dot{\beta} + 0.01\ddot{\beta} + 0.11\dot{\beta} + 0.02\beta = -0.14 \\ \ddot{\beta} + 0.04(\ddot{z}\beta + \dot{z}\dot{\beta} + \dot{x}\dot{\beta}) + 0.45\dot{\beta} - 0.15\beta^2 + 0.21\beta = 0.02 \end{cases}.$$

Numerical integration of the movement equations is shown in the graphs below, in which are shown the time variation of the center of mass coordinates (trajectory), attack and drift angles.

The experimental results were determined in the swimming pool of „Mircea cel Batran" Naval Academy.

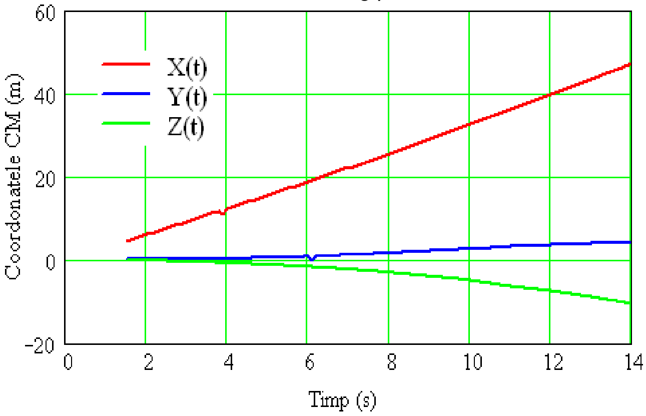


***Fig.1. The mass center coordinates, in fixed reference system*.**

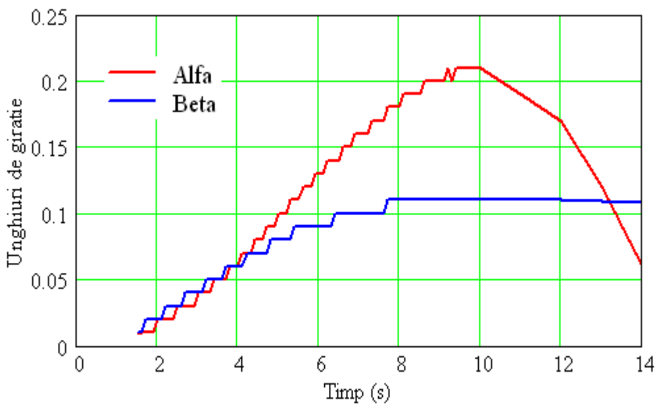
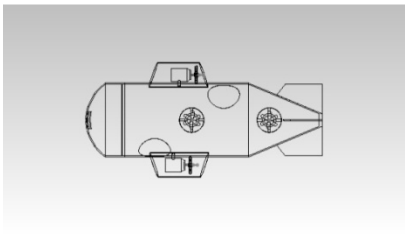


Fig. 2. The time variation of attack angle (α) and drift angle (β)

After statistical analysis of experimental results determined in the swimming pool, as shown in the two graphs, the ROV prototype is stable on the undisturbed trajectory.

VALUES DETERMINED BY AN SIMULATED EVALUATION WITH ANSYS – FLUENT

Before the experimental evaluations, the ROV prototype was modeled with SolidWorks software and the behavior of ROV in the water was simulated with CD Adapco STAR CCM software. The results of modeling / simulation were preliminary datanecessary forstatic and dynamic testing / evaluation in pool environmental and real environmental conditions.



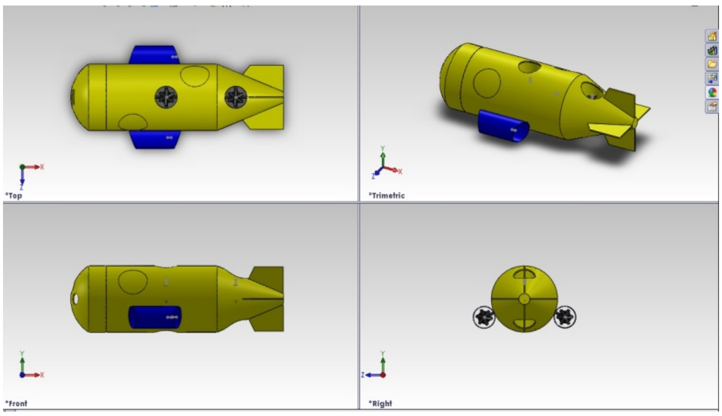


Fig. 3 Sketches and views of ROV prototype

Using CD Adapco STAR CCM software we calculated the drag force, the drag force coefficient, the Reynolds number and pressure distributions on the ROV body for different kinds of movements: ROV is moving with constant speed at the constant immersion, ROV in going to surface with constant speed and ROV in going to surface and drifting. In the following we have some results of the simulations.

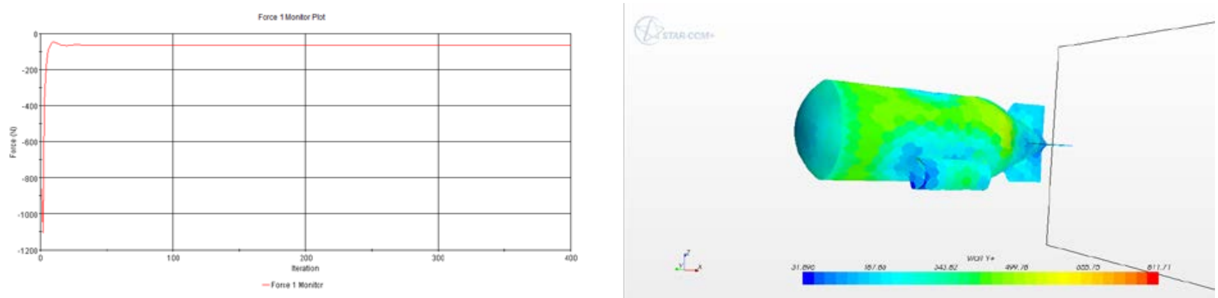


Fig. 4 The drag force and Reynolds numbers distribution for 2 m/s speed, F= - 65,94 N

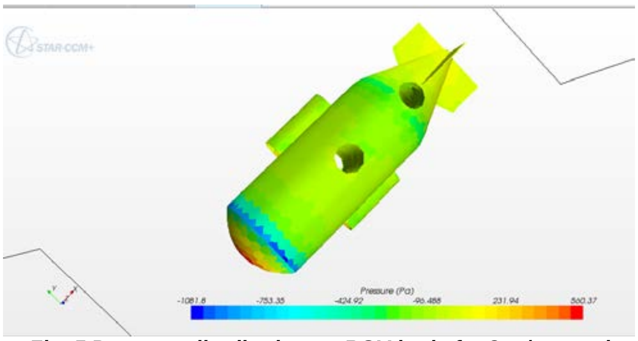


Fig. 5 Pressure distribution on ROV body for 2 m/s speed

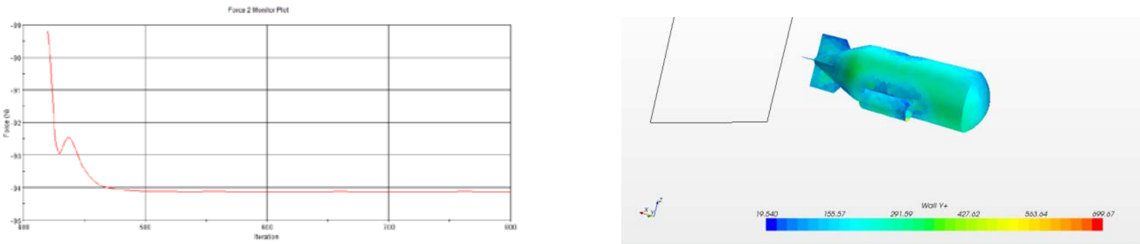


Fig. 6 The vertically component of drag force and Reynolds numbers distribution, ROV is going to surface at 30 degrees angle, 0,866 horizontal speed, 0,5 m/s ascension speed, F= - 94,128 N

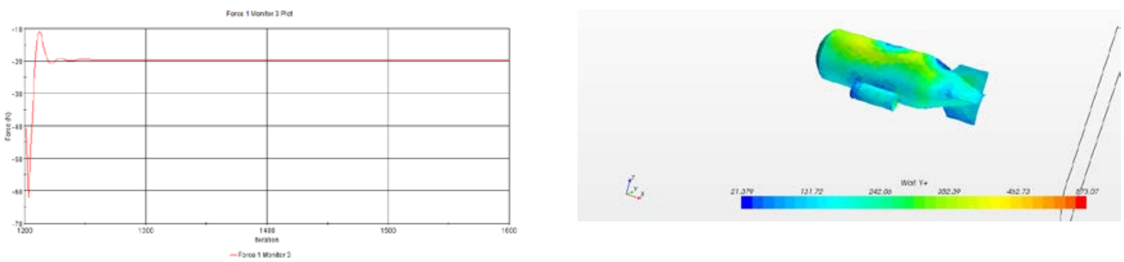


Fig. 7 The horizontal component of drag force and Reynolds numbers distribution, ROV is going to surface at 30 degrees angle and drifting to right, 0,433 lateral speed, 0,968 horizontal speed, 0,5 ascensionspeed, F= - 19,639 N

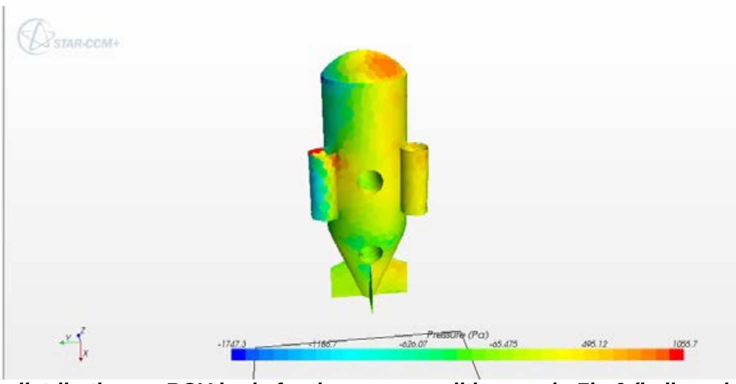


Fig. 8 Pressure distribution on ROV body for the same conditions as in Fig.6 (bellow view)

INTEGRATION OF THE ELECTRONIC DATA TRANSMISSION AND THRUSTER CONTROL SYSTEM

In order to establish the requirements for programming the remote control interface and training the ROV operator based on determined values of the dynamic characteristics and properties, we determined:

a. Physical measures for input on the “acquisition board”
b. Transfer functions for output measures
c. Procedures for visualization/analysis of data from sensors and for transmitting commands to the ROV

The transmission interface of the analogue and digital signals between the remote control post and propulsion, navigation and sensors systems of the ROV prototype must take into account the nature of these signals and of the practical command necessities for vehicle movement (transfer functions).

The remote control system-vehicle interface is made by a dataacquisition board, capable to process signals from sensors and signals for thruster control in accordance with the requirements of the laptop used by the operator.

Thereby, input signals into the data acquisition board will be the following:

- Video signal from the camera;
- Signal from the depth sensor;
- Signal from the space positioning sensor (accelerometer) ;
- Signal from the heading sensor (magnetic compass);

Effectors signals, ordered by the operator are as following:

- Thrusters control in horizontal plane;
- Thrusters control in vertical plane;
- Control for projector on/off.

Transfer functions for control signals and from sensors necessary for data interpretation and controlling the ROV on a trajectory are provided by the following requirements for the interface:

- 8 single ended input channels/ 4 differential channels;
- 14 bits resolution;
- Sampling rate of 48 kb/s;
- 2 analogue output channels;
- 8 digital TTL type input channels;
- 8 digital TTL type output channels;
- USB interface supply.

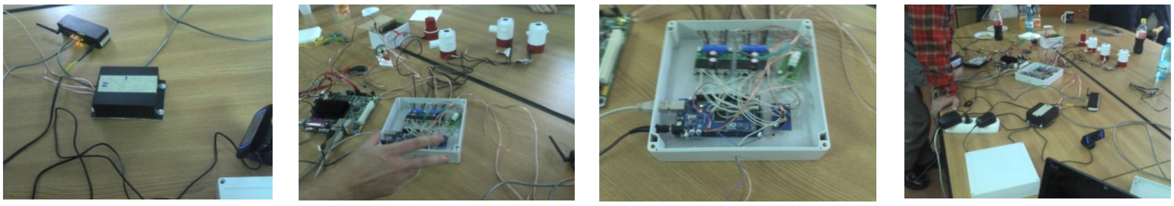


Fig. 9 The ROV electronic equipments

CONCLUSIONS

The research & development study regarding the testing/evaluation of the experimental model of the trajectory control ROV subsystem completes the development of the prototype created within the project “Underwater remotely operated vehicle designed for search in maritime and river areas”.

Information from its own sensors and controls received from an operator situated on a floatable or ground platform are transmitted through the control cable of the vehicle. ROV are generally destined for observation of the aquatic environment (maritime, fluvial or lake), search for objects in water or on the bottom and/or execution of underwater works of variable complexion.

Technical demands that the ROV should meet are:
- Design requirements
- Requirements for deployment and tests
- Technological requirements
- Requirements for incorporating within the system of which is included

Worldwide, underwater remotely operated vehicles, alongside logistic support systems are operating mainly in areas inaccessible to divers and submersibles with crew onboard. On the other hand the acquisition, maintenance and exploitation costs are far inferior compared to any other procedure for underwater works.

The ROVs have gained in the last 15 years an unprecedented development, especially due to the expansion of the economic activities that benefit from them. Main advantages in the use of ROVs are as following:

- ROVs are supplementing many of the operations that divers are executing-search, observation, monitoring, retrieval of seabed objects, works on maritime installations;
- The ROVs can reach and operate in areas inaccessible to divers or to submersibles with crew onboard (oceanic trenches, pipes, tanks of toxic liquids, etc.)
- Their use significantly reduces the costs of underwater operations by diminishing personnel, equipment and required and time for underwater work;
- The variety of operations made possible by ROVs confers them their versatile character, making them capable to complete various tasks, with a minimum use of effectors.

The specific objectives of the project have been fully reached, and the functional parameters are corresponding to all the operational requirements set in the project.

The specific objectives, fully achieved are the following:
- The integration of sensorial and command subsystems optimum from the costs/performance ratio point of view
- Designing the electronic remote control system though personal computer (laptop) of the ROV in accordance with self-imposed technical-tactical requirements;
- Programming of the acquisition board(interface)
- Assembly of the functional subsystems. Testing and static and dynamic evaluation, in laboratory conditions. Drawing of the dynamic diagrams.
- Tests in the pool in order to evaluate the dynamics on trajectory and the functioning of the sensor systems, cable control respectively.
- Training of the ROV operator.
- Exploitation of the results.