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Challenges associated with the design of a small unmanned autonomous maritime vehicle

Mirosław Gerigk

Gdańsk University of Technology, Faculty of Ocean Engineering and Ship Technology
11/12 Gabriela Narutowicza St., 80-233 Gdańsk, Poland, e-mail: mger@pg.gda.pl

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Abstract

The present paper begins with a presentation of an interdisciplinary research project, the method is then introduced, followed by a brief description of the unmanned autonomous maritime vehicle. The following chapter concerns a combined model describing the motion of the vehicle, including the hydrodynamic and aerodynamic forces. The model takes into account gravity, displacement, resistance, thrust, lift, and other hydrodynamic forces. The primary task of an advanced maritime vehicle is to precisely predict its position. To do so, an integrated model for the acquisition, analysis, and processing of the signals is necessary. The processed signals should then be used for the precise steering of the vehicle. The vehicle should be equipped with a stabilization system. Information on the integrated steering, positioning, and stabilization system of the vehicle is briefly presented in the paper. Such system enables to obtain a fully autonomous vehicle. Some information on the propulsion and underwater energy supply systems is also briefly presented. In the final part of the paper, some of the issues connected with vehicle safety are introduced.

Introduction

Multi-task surface warships represent some of the most important ships and systems of the Polish navy. These vessels may constitute the surface platforms for unmanned maritime systems (UMS) and unmanned aircraft systems (UAS). The future UMS systems and their operating groups will be very often fully autonomous.

Implementation of the multi-task surface platforms and UMS systems enables the creation of very advanced solutions within the navy's operational system. The multi-task surface platforms equipped with the autonomous UMS systems may be considered as a potentially important element of deterrence for Polish and NATO armies.

The selected solutions concerning the multi-task surface platforms and unmanned UMS systems were developed at the Gdańsk University of Technology (GUT). An interdisciplinary research team, under the supervision of the author, has been organized. The team consists of specialists from GUT and other R&D institutions. Some work has been done to prepare the dedicated applications together with the industry partners.

Design, construction, and operation of the innovative multi-task surface platforms and UMS vehicles require a precise determination of dedicated applications at the concept design stage, according to the future operational tasks. Collaboration between the authorities responsible for the national safety, R&D institutions, and industry partners is necessary. A very important factor is also represented by the opinions of potential users.

It has been anticipated that the application of innovative solutions depends on the following factors: type of dedicated application; degree of innovation of proposed solution; experience and attitude of the team of specialists conducting the project; decision making process, including the risks associated with the project; financial support of project; R&D

activity and implementation (technology demonstrator, prototype, and operation).

While preparing the proposals of the multi-task platforms and UMS vehicles, special attention has been paid towards the application of innovative technologies including the combination of solutions influencing the stealth characteristics of the platforms and UMS systems.

The research

The tasks required from navy ships are leading to the use of continuously more advanced multi-task ships. Despite their size, multi-task ships are the platforms for flying drones and unmanned maritime vehicles. Unmanned maritime vehicles may be remotely operated or autonomous. The latter may be referred to as maritime or underwater drones.

In this paper, maritime and underwater drones will be called unmanned maritime objects. The reason is that unmanned water drones may not always be autonomous.

The primary task of an object should be to conduct a mission in such a way that the information it acquires is directly sent to, processed, and used by the command centre.

The main objective of the current research is to work out a functional model of an advanced object that is able to move on the water's surface with a different range of speeds. In addition, the advanced object could move above the water surface for a short period of time. The flight height should be less than 5 meters and the object should have a special power supply system, enabling it to work for time going from 30 minutes to a few hours before a new energy supply is required.

The methodology of the current research is based on a holistic approach. The implementation of this approach to the design, construction, and operation of the object is novel. The research method combines performance-oriented and risk-based approaches. The research problems in the development of an object moving in two specific operational conditions are associated with four major tasks: object definition, assessment of object performance, object steering and control, and safety assessment of the object.

The object is defined as a hybrid mono-hull, including the hull form and arrangement of internal spaces.

The problem of estimating the object's mass requires the evaluation of the weight of the following items:

- all materials of the structure, including the skin plates and main frames;
- propulsion system;
- sub-systems and equipment;
- payload.

The object performance may then be assessed. This is primarily connected with an estimation of floatability, stability, resistance, and propulsion characteristics. When the steering and control characteristics are estimated, the manoeuvrability and seakeeping ability of the object may be assessed.

The assessment of the object performance and risk assessment should be conducted for the operational conditions and sequence of events under consideration. After that, the safety assessment may be carried out.

The concept of the object has been under investigation by the author since 2010. Some parts of the latest work on the subject are associated with the research carried out by Ph.D. students since 2012. More advanced research is continued by a team of specialists and researchers from several Polish research institutions (Lamb, 2003; AUVSI/ONR, 2007; Cwojdziński & Gerigk, 2014; Gerigk, 2015).

An Unmanned Autonomous Maritime Vehicle UAMV

The primary aim of the research is to work out a functional model of the Unmanned Autonomous Maritime Vehicle (UAMV) moving in two specific operational conditions. The operational conditions are related to the tasks the UAMV is designed for.

Novel solutions have been applied to the hull form, arrangement of internal spaces, materials, and propulsion system. The final hull has a combined "planning – wing in ground" form. The basic arrangement of internal spaces has been designed according to functional requirements. The arrangement of the UAMV's internal spaces is very much affected by the sub-systems to be installed onboard. The sub-systems that have been taken into account are as follows:

- air-jet propulsion;
- water-jet propulsion;
- power supply;
- ballast;
- air supply;
- hydraulic;
- steering;
- communication and navigation;
- multi-task patrol or combat.

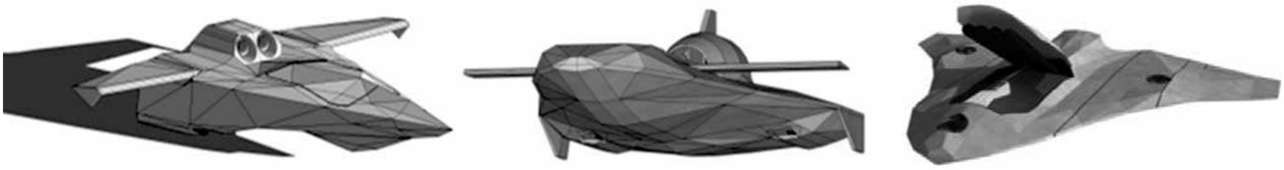

Figure. 1. Three visualizations of the Unmanned Autonomous Maritime Vehicle UAMV (Gerigk, 2011–2015)

Stealth technologies have been applied to obtain the unique characteristics of the vehicle. The major factors enabling such features are: hull form, hull skin cover, modified boundary layer, emission of noise and vibrations, hydro-acoustic space.

It has been anticipated that the UAMV may have the possibility to move on the water surface and, for a short time, above the water surface. The flight height is small and it is assumed to be lower than 5 meters. Three visualizations of the UAMV are presented in Figure 1.

The main parameters of the UAMV are as follows:

- overall length L – 5.8 meters;
- operational breadth B – 5.2 or 6.0 meters, depending on the wing system applied;
- breadth during transport B_t – 2.4 meters;
- height H – 1.1 meters;
- mass from 1.8 to 2.4 tons, depending on the mass of equipment installed onboard;
- maximum speed on the water surface v_{ws} – 15 meters per second;
- maximum speed above the water surface v_{aws} – 15 to 45 meters per second, depending on the air-jet propulsion and wing system applied.

Research method

The research method adopted for the UAMV's performance and risk assessments is a performance-oriented and risk-based method, which enables to assess the object's safety at the design stage and in operation (Gerigk, 2010). The method takes into account the influence of design and operational factors on safety, including the aspects related to safety management. The holistic approach is applied for the assessment of the object's safety. The method is based on the implementation of the system's approach to safety.

For the object performance evaluation, investigations using physical models and numerical simulation techniques may be applied. The object performance estimation enables to take into account the influence of the intermediate events, additional events (releases) and consequences on the object's behaviour. This may be done for the data sequence of events for a scenario under consideration.

The risk assessment is based on application of the matrix-type risk model, prepared in such a way that all the scenarios of events may be considered.

The criterion within the method is to achieve an adequate level of risk using the risk acceptance criteria matrix (Gerigk, 2010). Providing a sufficient level of safety based on the risk assessment is the main design, operational, or organizational objective. In particular, safety is the primary design objective. The measure of safety of the object is the risk (level of risk).

The mains steps on which the method is based are the following:

- setting the requirements, criteria, limitations, safety objectives;
- defining the object and environment;
- identifying the hazards and identifying the sequences of events (scenarios);
- assessing the object performance;
- estimating the risk according to the event tree analysis ETA and matrix type risk model (risk is estimated separately for each scenario separately);
- assessing the risk according to the risk acceptance criteria (risk matrix) and safety objectives;
- managing the risk according to the risk control options;
- selecting the design (or operational procedure) that meets the requirements, criteria, limitations, safety objectives;
- optimizing the design (or operational procedure);
- making decisions on safety.

The structure of the method for assessment of the UAMV performance and risk, which combines the design/operational procedures with those based on the risk assessment, is presented in Figure 2. A simplified practical version of the method is introduced in Figure 3 (Lamb, 2003; AUVSI/ONR, 2007; Gerigk, 2010; 2015; Cwojdziński & Gerigk, 2014).

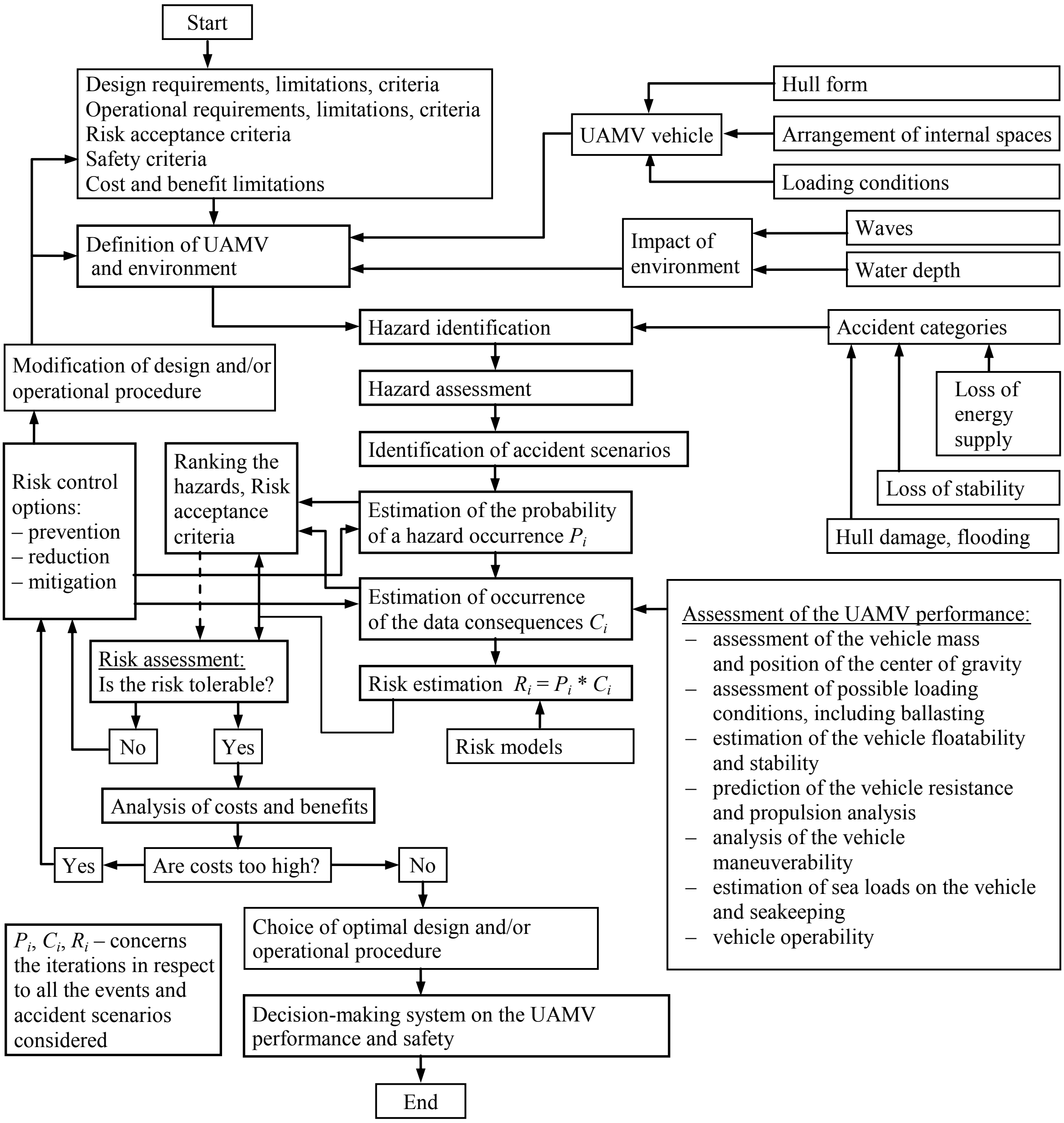

Figure 2. Structure of the method for assessment of the UAMV performance and risk assessment

Current research on UAMV. Ballasting and motion of UAMVs

Ballasting. During ballasting, the dynamic stability of the vehicle should be permanently controlled. It is very important to know the locations of the vehicle's centre of gravity and centre of buoyancy in each time step.

On the water surface, the restoring moment, M_R, (transversal or longitudinal) of the vehicle at small changes of heel is composed of the moments due to the vehicle buoyancy and weight (Dudziak, 2008; Gerigk, 2010):

$$M_R = M_B + M_W \tag{1}$$

where:

M_B – moment due to the vehicle buoyancy, $M_B = V \rho g \, GZ_{\text{quasi-static}}$;

V – immersed buoyancy of the vehicle;

ρ – density of water;

g – gravity acceleration;

$GZ_{\text{quasi-static}}$ – righting arm of buoyancy for the quasi-static condition at each buoyancy increase and time step;

M_W – moment due to the vehicle weight, $M_W = \Sigma(\rho g \Delta V_{Ti}) r_i$;

ΔV_{Ti} – volume of ballast water in the ballast tank under consideration;

r_i – heeling arm following from the ballast water in the data ballast tank.

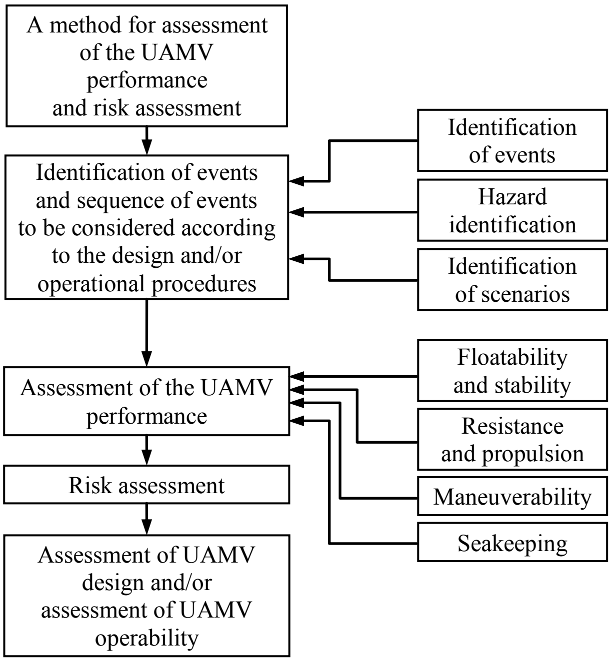

Figure 3. Simplified practical version of the method for assessment of the UAMV performance and risk assessment

Motion. The general set of equations of the UAMV moving on the water surface (for the different phases of motion) may be presented as follows (Faltinsen, 1990; 2005; Dudziak, 2008; Gerigk, 2010):

$$\sum_{j=2}^{6}(\mathbf{M_{ij}}+\mathbf{A_{ij}})\ddot{x}_j(t)+\mathbf{B_{ij}}\dot{x}_j(t)+\mathbf{C_{ij}}x_j(t)= \\ =\sum_{j=2}^{6}\mathbf{F_{ij}}(t) \tag{2}$$

where:

i – index of the data component of the vehicle motion ($i = 2,...,6$);
j – index of the data degree of freedom;
$\mathbf{M_{ij}}$ – vehicle mass matrix;
$\mathbf{A_{ij}}$ – matrix of added masses;
$\mathbf{B_{ij}}$ – matrix of dumping coefficients;
$\mathbf{C_{ij}}$ – matrix of restoring coefficients;
$\mathbf{F_{ij}}$ – matrix of external hydrodynamic and aerodynamic forces.

At the current stage of research, the following impacts have been taken into account: gravity forces, hydrodynamic restoring forces, hydrodynamic Froude-Krylov and diffraction forces, hydrodynamic slamming-based forces, hydrodynamic and aerodynamic lift forces, hydro-aerodynamic cushion forces (wing in ground forces), and thrust forces.

Current research on UAMV. A precise position stabilization system PPSS

One of the main research and design issues is to work out a precise position stabilization system (PPSS) for the UAMV. The UAMV can be immersed, afloat on the water surface, and in movement above the water surface for a short period of time. The PPSS system is independent from the main propulsion system, which is responsible for the vehicle's motion and is controlled by the navigation system. The main propulsion system and PPSS are equipped with acting electrical engines. Electric propulsion enables the vehicle to work during the submersible mode using automatic energy uploading. A fuel propulsion system is considered to be in use during the UAMV's motion above the water surface.

It should be possible to upload the batteries using the installed photovoltaic batteries. The underwater or semi-submersible mobile uploading stands enable to stay submerged without limitations.

The PPSS should be treated as a separate module because the activity of the UAMV, connected with collecting species, detecting objects, scanning the sea bottom, and measuring geometries of the surrounding environment, require high precision in maintaining the UAMV position and orientation.

The PPSS may consist of a few thrusters, located horizontally or vertically with respect to the UAMV base plane. The physical model of the PPSS consists of the geometrical position of the precise propulsion units, formal description of the sensor system, AI system for analysing the data, and system of effectors. The thrusters, located symmetrically to the vehicle's centre plane, are installed in such a way that the thrust vectors may be perpendicular to the vehicle base plane or kept horizontally if required. The vehicle motion may be controlled by acting on the rotational speed of different thrusters at the same time. For modelling purposes, given the small values of vehicle speed during precise positioning, the geometrical position of the precise propulsion units is very important, as shown in Figure 4.

The six degree-of-freedom (6 DOF) model, including the linear u, v, w (surge, sway, heave) and angular p, q, r (roll, pitch, yaw) velocities is the base for the prediction the UAMV's seakeeping capabilities. The standard model, using 6 DOF, is presented in Figure 5. The relative position to the sea bottom (or GPS coordinates) is in the form the vector of position x, y, z and Euler angles φ, θ, ψ (Faltines, 1990; 2005; Gerigk, 2010; 2015; Gerigk &

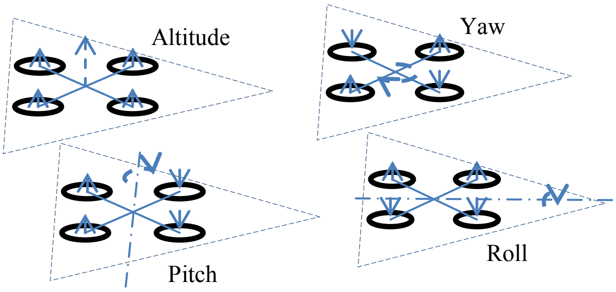

Figure. 4. Thrust vectors of the precise propulsion units during the UAMV vehicle positioning

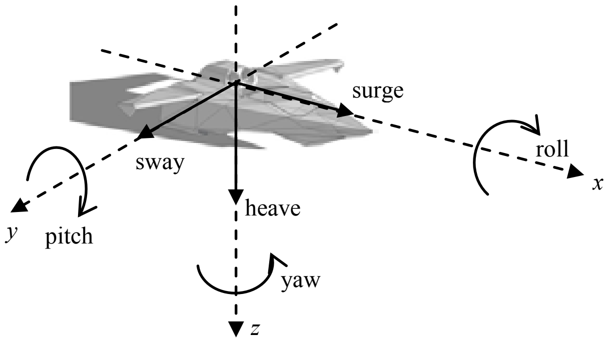

Figure. 5. Standard model using 6 DOF

Wójtowicz, 2014; Gerigk, Wójtowicz & Zawistowski, 2015).

The computational model for the vehicle motion prediction has been prepared using the Matlab environment. There are six main interrelated modules. It is possible to consider the initial and final position of the vehicle, thrust of the propeller (rotational speed) and expected impacts (current). A general view of the preliminary results of the computer simulation of the PPSS work is presented in Figure 6 (Gerigk, 2010; 2015; Gerigk & Wójtowicz, 2014; Gerigk, Wójtowicz & Zawistowski, 2015).

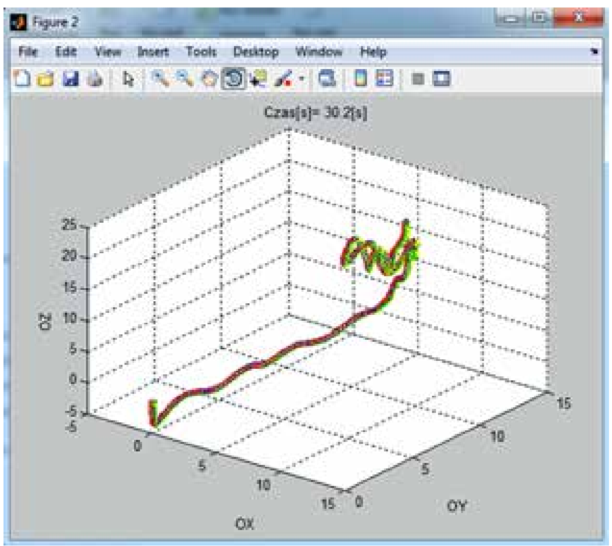

Figure. 6. The preliminary results of computer simulation of the PPSS system work

Conclusions

The preliminary results concerning the development of the UAMV concept, including the main parameters, geometry, weights estimation, vehicle performance and risk assessment have been presented in the paper.

The autonomous underwater vehicles perform the motion and manipulation tasks that require the high precision positioning. The preliminary results concerning the precise position stabilization system PPSS that ensures the stabilization of the position and the correct orientation have been obtained.

It has been assumed that the PPSS operates independently of the main drive, having separate electric executive motors. The electric drive allows working in conditions of immersion and to carry out unattended charge.

Some investigations have been done using a simulation model of the vehicle's movements during the planned mission. The simulation program allows checking the operation of algorithms of each component and vehicle movement due to interference. The designers may use the model to determine the extent of the vehicle and track energy usage during the mission.

At the current stage of research the following tasks have been performed: functionality, physical model, and computer simulation of PPSS.

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