Kinematical control of motion of underwater vehicle in horizontal plane

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ABSTRACT

In the paper presented is a method of designing a fuzzy-logic-based autopilot for control of horizontal motion of an unmanned underwater vehicle. The control system's synthesis was performed under the assumption that the vehicle can move with variable linear and angular velocities and the quantities possible to be measured are : position and orientation of the vehicle in the inertial reference system. The task of the autopilot was to minimize the mean squares of deviations from the motion trajectory given in the form of a broken line defined by the coordinates of successive turning points. To generate control signals three independent fuzzy PD controllers using the control principles based on the Mac Vicar-Whelan's standard base, were applied. For the linguistic variables of each controller appropriate fuzzy sets were selected and linear membership functions of trapezoidal and triangular form were defined. The presented results of the simulation tests performed for the remotely operated underwater vehicle „Ukwiał", with and without influence of disturbances resulting from sea current, confirm the proposed approach to be correct and effective.

Key words : Underwater vehicle, autopilot, fuzzy logic

INTRODUCTION

An increasing interest has been given to underwater robotics in the last years. Currently, it is common to use unmanned underwater vehicles (UUVs) to accomplish such missions as : inspection of coastal and off-shore structures, cable maintenance, as well as hydrographical and biological surveys. In the military field they are employed in such tasks as surveillance, intelligence gathering, torpedo recovery and mine counter measures. The main benefits of usage of the UUVs can be the possibility of removing a man from the dangers of the undersea environment, and of reduction in cost of exploration of underwater space.

There are various categories of the UUVs. The most often used are remotely operated vehicles (ROVs). The ROV is usually connected to a surface ship by a tether through which all communication is wired. The tether's drag influences motion of the vehicle and may produce significant disturbances and energy loss. The ROV is equipped with a power transmission system and controlled only by thrusters. Simultaneously the spatial station-keeping or tracking of the underwater vehicle is a difficult task for a human operator, hence a supervisory control has been developed to support its own intelligence and autonomy.

Automatic control of underwater vehicles is a complex problem due to their strongly coupled and highly nonlinear dynamic characteristics. Moreover, the dynamic characteristics can change depending on a chosen vehicle's configuration suitable to its mission. In order to cope with the difficulties the control system should be flexible. An interesting review of classical and modern techniques adopted to control the dynamic behaviour of unmanned underwater vehicles was presented in [1,3]. Nowadays fuzzy logic control systems have been successfully applied to a wide variety of mechanical systems [2,7,9]. The primary advantage of the fuzzy controllers is the possibility of easy incorporating heuristic knowledge of experts into a control strategy. In this paper a fuzzy autopilot for tracking control of the ROV is described.

TRACKING CONTROL

The general motion of a marine vehicle of 6 degrees of freedom (DOF) can be described by the following vectors [3] :

$$\begin{aligned} \eta &= [x, y, z, \phi, \theta, \psi]^T \\ \nu &= [u, v, w, p, q, r]^T \\ \tau &= [X, Y, Z, K, M, N]^T \end{aligned} \qquad (1)$$

where :

- η - the position and orientation vector in the earth--fixed frame
- ν - the linear and angular velocity vector in the body-fixed frame
- τ - the forces and moments acting on the vehicle in the body-fixed frame.

The nonlinear dynamic equations of motion can be expressed in matrix form as [3] :

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

where :

- $\mathbf{M}$ - inertia matrix (including added mass)
- $\mathbf{C}(\nu)$ - matrix of Coriolis and centripetal terms (including added mass)
- $\mathbf{D}(\nu)$ - hydrodynamic damping and lift matrix
- $\mathbf{g}(\eta)$ - vector of gravitational forces and moments
- $\mathbf{J}(\eta)$ - velocity transformation matrix.

Coordinate systems and tracking control

For the conventional ROVs a basic motion is the movement in horizontal plane with some variation due to diving. They operate in crab-wise manner with 4 DOF and small roll and pitch angles which can be neglected during normal operation. Therefore, it is purposeful to regard 3-dimensional motion of the vehicle as the superposition of the motion in the horizontal plane and that in the vertical plane. Farther in the paper only the movement of the vehicle in the horizontal plane is considered.

It is convenient to define three coordinate systems when analysing route tracking systems for the marine vehicle moving in horizontal plane (Fig.1) [6] :

- ✶ the global coordinate system $O_0X_0Y_0$ (the earth-fixed frame)
- ✶ the local coordinate system OXY (fixed to the body of the vehicle)
- ✶ the reference coordinate system $P_iX_iY_i$ (not fixed).

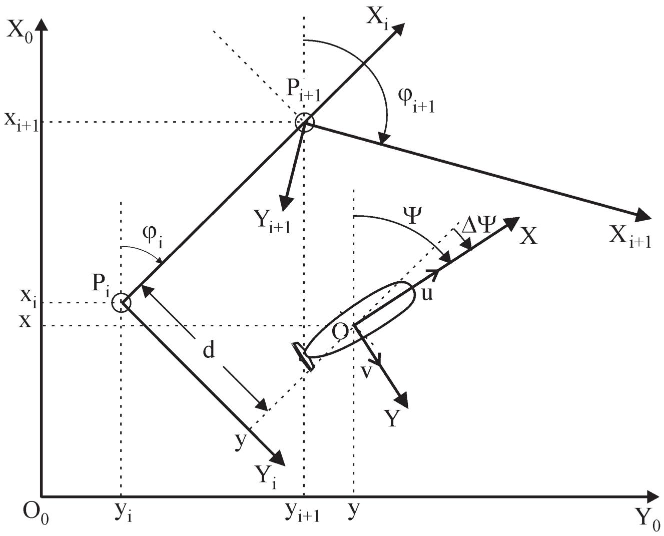

Fig. 1. *Coordinate systems used to describe tracking control of the underwater vehicle moving in the horizontal plane:* $O_0X_0Y_0$ *– global system,* OXY *– local system,* $P_iX_iY_i$ *– reference system*

The main task of the designed tracking control system is to minimize the distance of attitude of the vehicle's centre of gravity, d, to the desired trajectory under the following assumptions :

- ➲ the vehicle can move with variable linear velocities u, v, and angular velocity r
- ➲ the vehicle's position coordinates, x, y, and heading angle ψ are measurable
- ➲ the command signal τ consists of three components : *X* and *Y* - forces along X- and Y-axis, respectively, and *N* - moment around Z-axis
- ➲ a travel time is not given in advance, thus the navigation between two points is not constrained by time.

The tracking autopilot has to provide both track-keeping and course-keeping capabilities. Hence, the autopilot should minimize the mean squares of deviations "d", from a desired track, and Δψ deviations from a desired course:

$$J = \min_t \sum \left[d^2(t) + \lambda \Delta\psi^2(t) \right] \qquad (3)$$

where:

$$d(t) = -\sin(\Delta\psi)\left(x(t) - x_i\right) + \\ + \cos(\Delta\psi)\left(y(t) - y_i\right)$$

$$\varphi_i = \mathrm{arctg}\left[\frac{y_{i+1} - y_i}{x_{i+1} - x_i}\right]$$

- $\Delta\psi(t)$ - angle between the track reference line and vehicle's centreline : $\psi(t) - \varphi_i$
- $\psi(t)$ - heading angle of the vehicle
- λ - constant coefficient.

Each time the vehicle location x(t), y(t) at the instant t satisfies :

$$\left[x_{i+1} - x(t)\right]^2 + \left[y_{i+1} - y(t)\right]^2 \le \rho^2 \qquad (4)$$

where :

ρ - radius of circle of acceptance.

The next waypoint should be selected on the basis of the reference coordinate system (e.g. $P_{i+1}X_{i+1}Y_{i+1}$) and the vehicle's position should be updated in compliance with the new reference coordinate system.

Fuzzy control law

A fuzzy proportional derivative controller, adopted from [2], working in the configuration presented in Fig.2, has been designed for the tracking control.

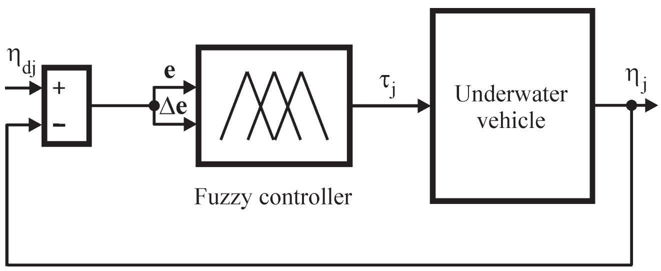

Fig. 2. *The assumed structure of the fuzzy controller*

The membership functions of fuzzy sets of the input variables : the error signal $e = \eta_{dj} - \eta_j$ and the derived change of error $\Delta e = \eta_j - \eta_{j-1}$, as well as the output variable : the command signal τ_j - for $j \in \{1, 2, 6\}$ - are shown in Fig.3.

Values of unknown parameters: x_e, $x_{\Delta e}$, x_S and x_M used in computer simulations are given in Tab.1. Evaluation of the parameters can be done by means of many optimisation techniques, classical or modern ones, e.g. Genetic Algorithms [4,5].

Tab. 1. The assumed membership function parameters

	Controller		
	position along X_0-axis	position along Y_0-axis	heading angle
x_e	0.14	0.19	0.39
$x_{\Delta e}$	0.87	0.63	0.52
x_M	0.25	0.40	0.38
x_S	0.89	0.74	0.65

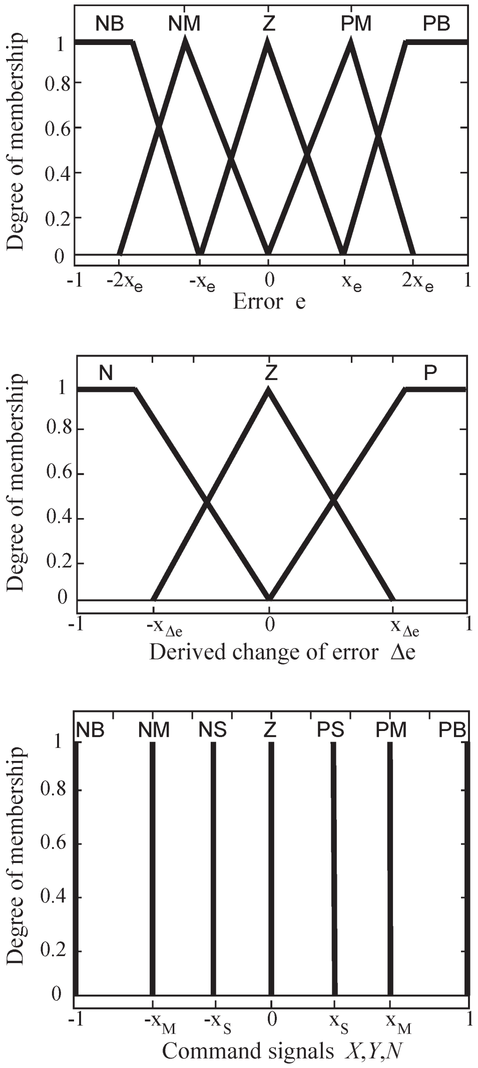

Fig. 3. *The assumed membership functions for fuzzy sets of : the error e, derived change of error Δe, and command signals X,Y,N.*
Notation *: N - negative, Z - zero, P - positive, S - small, M - medium and B - big*

The chosen control rules, taken from the Mac Vicar--Whelan's standard base of rules [8], are given in Tab.2.

Tab. 2. The assumed base of rules

		Error signal e				
		NB	NM	Z	PM	PB
Derived change of error Δe	N	NB	NM	NS	Z	PS
	Z	NM	NS	Z	PS	PM
	B	NS	Z	PS	PM	PB
		Command signals *X,Y,N*				

SIMULATIONS

A simulation study of tracking control has been performed for an underwater vehicle „Ukwiał" designed and built by Gdańsk University of Technology for the Polish Navy. The ROV is an open, 1.5 m long frame robot controllable in 4 DOF, fitted with a propulsion system consisted of 6 thrusters.

The vehicle can move in horizontal plane by using four thrusters. Every thruster can generate thrust force up to ±250 N. It assures its speed up to u = ±1.2 m/s and v = ±0.6 m/s in X and Y direction, respectively. The autopilot in question consists of 3 independent controllers producing the command signals *X*, *Y* and *N* calculated on the basis of the proposed fuzzy law (under the constraints : $|X| \le 500$ N, $|Y| \le 150$ N and $|N| \le 50$ Nm).

The structure of the proposed control system is presented in Fig.4.

Numerical simulations have been made to confirm validity of the proposed control algorithm under the following assumptions:

- the vehicle has to follow the desired route beginning from the position and orientation point : (x = 10 m, y = 10 m, ψ = 0°), passing the target waypoints : (10 m, 90 m, 90°), (30 m, 90 m, 0°), (30 m, 10 m, 270°), (60 m, 10 m, 0°) and ending at the point : (60 m, 90 m, 90°)
- the turning point is reached when the vehicle operates within the 1,5 m radius of circle of acceptance, ρ
- the initial conditions are the same.

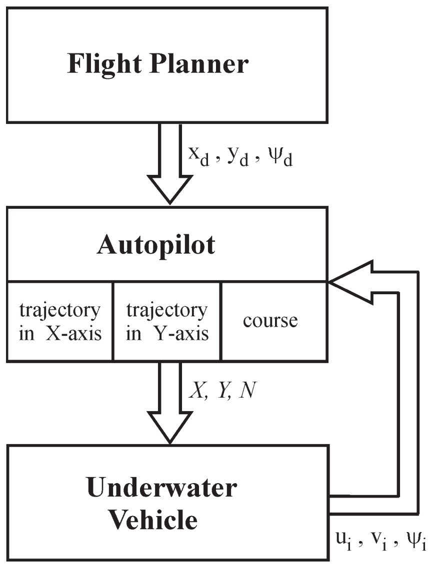

Fig. 4. *The block diagram of the track-keeping system*
Notation *: index d - desired value*

The tracking control simulation results and the courses of command signals for no added environmental disturbances are shown in Fig.5. The real route and position of the vehicle almost coincides with those desired. Also the quality of course--keeping control is satisfactory (course deviations close to zero). In Fig.6 illustrated is an influence of sea current disturbances on the vehicle's route and course. A clear difference between the desired and real tracking curves is there observed. Although the errors of position and course are much bigger than in the previous case the autopilot is able to cope with the external disturbances and to reach the turning points with the commanded orientation. It should be noted that the last simulations were performed for the sea current speed increased to 0.35 m/s.

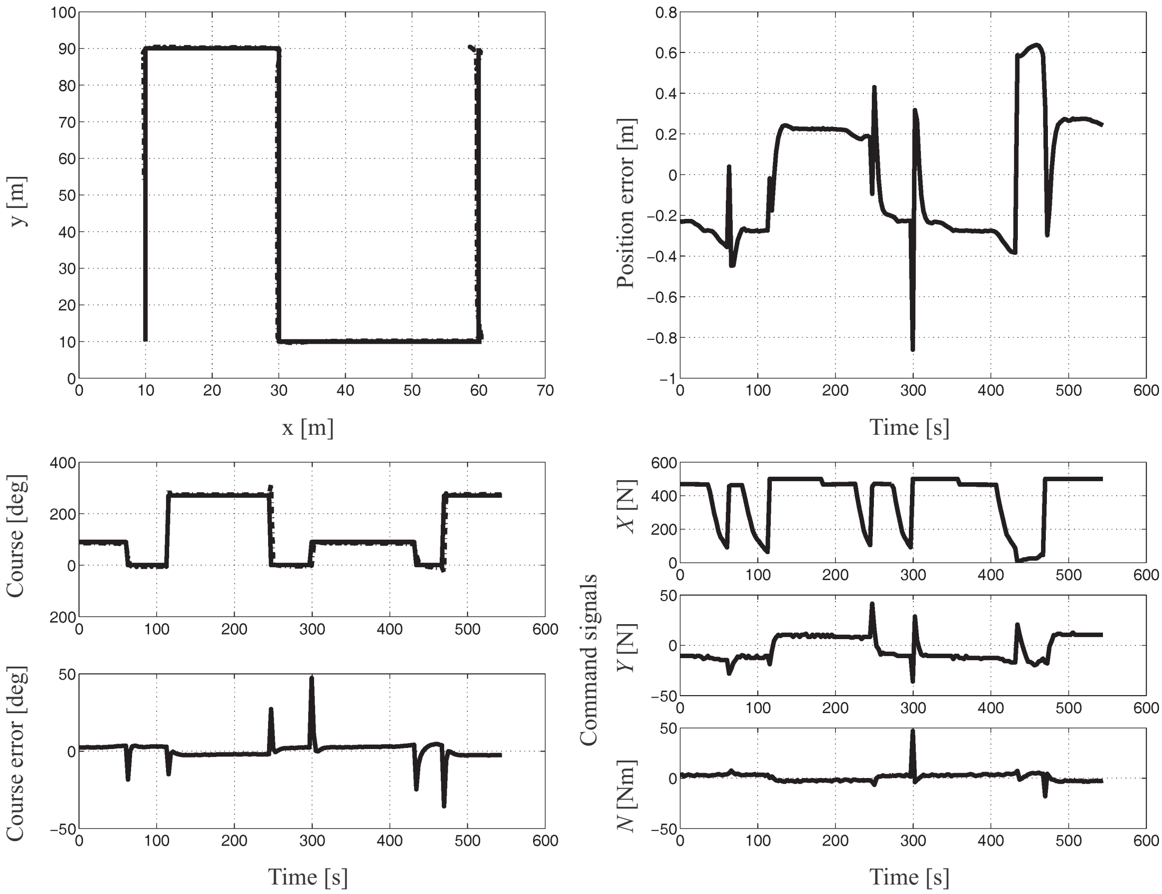

***Fig. 5.** The vehicle's tracking curve and course deviations from the desired position and course, for the command signals without interaction of environmental disturbance*
***Notation** : ——— desired –·–·– real*

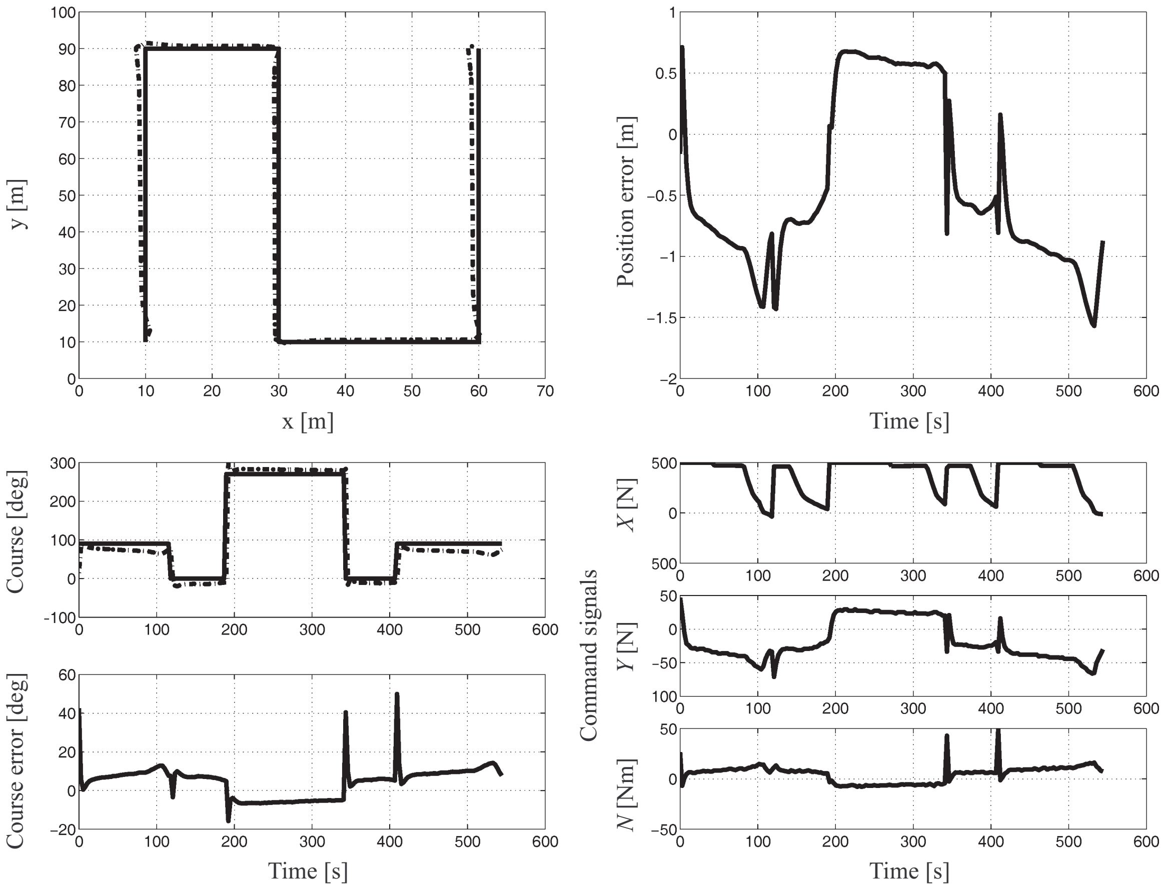

***Fig. 6.** The vehicle's tracking curve and course deviations from the desired position and course, for the command signals under influence of the sea current of 0.35 m/s speed, and 135° direction angle*
***Notation** : ——— desired –·–·– real*

This is comparable with the average speed of the vehicle. As it was expected, the guidance was very sensitive to the ratio of the vehicle speed and the current speed. It was observed that this ratio should not be smaller than 2, which is also confirmed in [6].

CONCLUSIONS

- ❖ In this paper the waypoint-tracking autopilot using fuzzy control, intended for underwater vehicles, has been described. The nonlinear model of the ROV „Ukwiał" was applied to carry out computer simulations.
- ❖ The simulation results obtained by using the control system design method based on three decoupling fuzzy controllers, showed the presented autopilot to be simple and useful for practical use.
- ❖ The main advantage of the proposed solution is its flexibility with regard to the vehicle's dynamic model, and its high performance at relatively large disturbances resulting from sea current.

NOMENCLATURE

$\mathbf{C}(\mathbf{v})$ - matrix of Coriolis and centripetal terms (including added mass)
d - distance of attitude of the vehicle's centre of gravity from the desired trajectory
DOF - degress of freedom
$\mathbf{D}(\mathbf{v})$ - hydrodynamic damping and lift matrix
e - error signal
$\mathbf{g}(\eta)$ - vector of gravitational forces and moments
J - quality index
$\mathbf{J}(\eta)$ - velocity transformation matrix
K - moment around X- axis
$\mathbf{M}$ - inertia matrix (including added mass)
M - moment around Y- axis
N - moment around Z- axis
OXY - local coordinate system (fixed to the body of the vehicle)
$O_0X_0Y_0$ - global coordinate system (the earth-fixed frame, inertial)
p - angular velocity around X- axis
$P_iX_iY_i$ - reference coordinate system (not fixed, connected with trajectory of motion)
q - angular velocity around Y- axis
r - angular velocity around Z- axis
t - time
u - linear velocity along X-axis
v - linear velocity along Y- axis
w - linear velocity along Z- axis
x - vehicle's position coordinate along X_0 - axis
x_e, $x_{\Delta e}$ - coordinates of membership functions of e and Δe, respectively, (along axis of abscissae)
x_S, x_M - coordinates of membership functions of τ_j, (along axis of abscissae)
X - force along X- axis
y - vehicle's position coordinate along Y_0 - axis
Y - force along Y- axis
z - vehicle's position coordinate along Z_0 - axis
Z - force along Z- axis

Δe - derived change of error
$\Delta\psi$ - change of heading angle (deviation from a desired course)
η - vehicle's position and orientation vector in the earth-fixed frame
θ - vehicle's pitch angle
λ - constant coefficient
ν - linear and angular velocity vector in the body-fixed frame
ρ - radius of circle of acceptance
τ - forces and moments acting on the vehicle in the body-fixed frame
φ_i - direction angle of i-th segment of trajectory
ϕ - vehicle's roll angle
ψ - vehicle's yaw (heading) angle

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FOREIGN *conference*

A Hundred-Year Jubilee

On 7 July of the year 1903 – in accordance with the record in the commemorative book – the research establishment for water engineering and shipbuilding VWS (Versuchanstalt fuer Wasserbau und Schiffbau) officially commenced its activity in Berlin.

In the course of time it could boast of outstanding - in the worldwide scale - scientific and technical achievements in the domain of inland waterways, harbour engineering and shipbuilding.

On this special occasion the German society of naval architects and marine engineers STG (Schiffbautechnische Gesellschaft) held its general assembly on 19 - 22 November 2003 just in Berlin.

Its agenda contained , apart from its organizational part dealing with STG matters, the special session devoted to the achievements of the VWS, as well as the scientific conference carried out within 5 topical sessions.

Scientific workers of the Faculty of Ocean Engineering and Ship Technology, Gdańsk University of Technology have had multi-topical contacts both with the VWS and STG. Their representative, D.Sc.Eng. Edmund Brzoska took part in these events.