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# NONLINEAR CONTROL OF UNDERWATER ROBOTIC VEHICLE IN PLANE MOTION

## ABSTRACT

A control system supporting motion of an underwater robotic vehicle along a reference trajectory in the horizontal plane is presented in the paper. A waypoint line-of-sight scheme and nonlinear PD control law are applied to calculate command signals. Parameters of the proposed control law are tuned using genetic algorithms. The validity and advantages of the approach are illustrated through numerical simulation results.

Key words:
underwater robot, autopilot, nonlinear control, genetic algorithms.

## INTRODUCTION

Underwater robotics has known an increasing interest in the last years. Nowadays, it is common to use underwater robotic vehicles (URVs) both in routine tasks where machine mobility can effectively replace direct human presence and everywhere where people cannot go, or where the hazards of human presence are great. Typical applications including both commercial and military activities as well as scientific researches are: inspection of coastal and off-shore structures, cable maintenance, hydrographical and biological surveys, dumps or toxic waste location, marine archeology, ships rescue, intelligence gathering, torpedo recovery and mine hunting and many others.

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The URV is connected to a mother ship by an umbilical cable which all communication is wired through. It is equipped with propulsion systems and controlled by an operator. Therefore, in order to simplify the operator's work and improve an operational performance, the contemporary URV is often equipped with a control system making possible to execute some manoeuvres and operations without constant human being interventions

An automatic control of the underwater robot is a difficult problem caused by its nonlinear dynamics. Moreover, the dynamics can change according to the alteration of configuration to be suited to the mission. The implemented control systems are based on both classical and modern techniques [1–4, 9, 10]. But practical experiences show that one of the most important task in designing of control system is to apply fast and simply algorithm of control [1]. Therefore the objective of the paper is to present a usage of nonlinear PD algorithm to driving of the robot along the desired trajectory in horizontal motion.

The paper consists of four sections. After the introduction, a brief descriptions of dynamical equations of motion of the URV and the control law are presented. The next section presents results of simulation study. Concluding remarks are given in the last section.

## NONLINEAR PD CONTROL LAW

Motion of the URV in six degrees of freedom (DOF) is expressed by the following vectors [1, 2]:

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

where:

- $\boldsymbol{\eta}$ — the position and orientation vector with coordinates in the inertial frame;
- $x, y, z$ — coordinates of position;
- $\phi, \theta, \psi$ — coordinates of orientation (Euler angles);
- $\mathbf{v}$ — linear and angular velocity vector with coordinates in the body-fixed frame;
- $u, v, w$ — linear velocities along longitudinal, transversal and vertical axes;
- $p, q, r$ — angular velocities about longitudinal, transversal and vertical axes;
- $\boldsymbol{\tau}$ — vector of generalized forces in the body-fixed frame;

$X, Y, Z$ — forces along longitudinal, transversal and vertical axes;
$K, M, N$ — moments about longitudinal, transversal and vertical axes.

Nonlinear dynamical equations of motion can be expressed as [1, 2]:

$$\mathbf{M}\dot{\mathbf{v}} + \mathbf{C}(\mathbf{v})\mathbf{v} + \mathbf{D}(\mathbf{v})\mathbf{v} + \mathbf{g}(\boldsymbol{\eta}) = \boldsymbol{\tau}, \tag{2}$$

where:
$\mathbf{M}$ — inertia matrix (including added mass);
$\mathbf{C}(\mathbf{v})$ — matrix of Coriolis and centripetal terms (including added mass);
$\mathbf{D}(\mathbf{v})$ — hydrodynamic damping and lift matrix;
$\mathbf{g}(\boldsymbol{\eta})$ — vector of gravitational/buoyancy forces and moments.

Under assumptions that:
- vectors $\boldsymbol{\eta}$ and $\mathbf{v}$ are measured;
- robot's position and orientation in the earth-fixed frame is defined by the reference trajectory $\boldsymbol{\eta}_d = [x_d, y_d, z_d, \phi_d, \theta_d, \psi_d]^T$;
- mathematical model of the robot dynamics is represented by (2).

The PD control law takes the form [5, 8]:

$$\boldsymbol{\tau} = -\mathbf{K}_P\tilde{\boldsymbol{\eta}} - \mathbf{K}_D\mathbf{v}, \tag{3}$$

where:
$\tilde{\boldsymbol{\eta}} = \boldsymbol{\eta} - \boldsymbol{\eta}_d$ — control error;
$\mathbf{K}_P, \mathbf{K}_D$ — diagonal matrices of gain coefficients.

As shown in [2, 5] the control law (3) allows us obtain the control error equal to zero only in case of lack of gravitational forces in the equation (2). It means that unless $\mathbf{g}(\boldsymbol{\eta})$ is equal zero then the proposed law does not guarantee asymptotic stability. Therefore, in practical implementations a steady state displacement can be observed. In order to eliminate it, the control law (3) should be modified as follows [8]:

$$\boldsymbol{\tau} = -\mathbf{K}_P\tilde{\boldsymbol{\eta}} - \mathbf{K}_D\mathbf{v} + \mathbf{g}(\boldsymbol{\eta}). \tag{4}$$

Such nonlinear control law compensates influence of gravitational forces and improve a quality of control.

## SIMULATION STUDY

For the conventional underwater robot pitch and roll motion are left uncontrolled, since the metacentric height is sufficient large to provide static stability. Therefore, the robot operates in a crab-wise manner in four DOF and its basic displacement is motion in horizontal plane with some variation due to diving.

A structure of the proposed automatic control system is presented in figure 1. A main task of the system is to minimize distance of attitude of the robot's centre of gravity to the desired trajectory. Its main part is an autopilot computing commands taking into account both desired vehicle's positions and orientations and their current estimates.

In this paper the motion only in horizontal plane is examined so the regarded autopilot is responsible only for three motions: two linear (surge *u*, sway *v*) and a rotational (yaw *r*). Hence, the command vector $\boldsymbol{\tau}$ consists of three components: $\tau_X = X$, $\tau_Y = Y$, $\tau_N = N$ and has a form $\boldsymbol{\tau} = [\tau_X, \tau_Y, \tau_N]^T = [X, Y, N]^T$. Therefore, in the equation (3) the matrices $\mathbf{K}_P$ and $\mathbf{K}_D$ are reduced to the following forms: $\mathbf{K}_P = diag\{k_{P1}, k_{P2}, k_{P3}\}$ and $\mathbf{K}_D = diag\{k_{D1}, k_{D2}, k_{D3}\}$ as well as the vectors $\boldsymbol{\eta}$ and $\mathbf{v}$ to forms $\boldsymbol{\eta} = [\eta_1, \eta_2, \eta_3,]^T = [x, y, \psi]^T$ and $\mathbf{v} = [v_1, v_2, v_3,]^T = [u, v, r]^T$.

To validate the performance of the proposed nonlinear PD control law, some numerical experiments were done. The URV used in these experiments was an open-frame submersible controllable in four DOF, being: 1.5 m long, 0.7 m wide and 0.8 m high, and having a propulsion system consisting of six tunnel thrusters (see fig. 2).

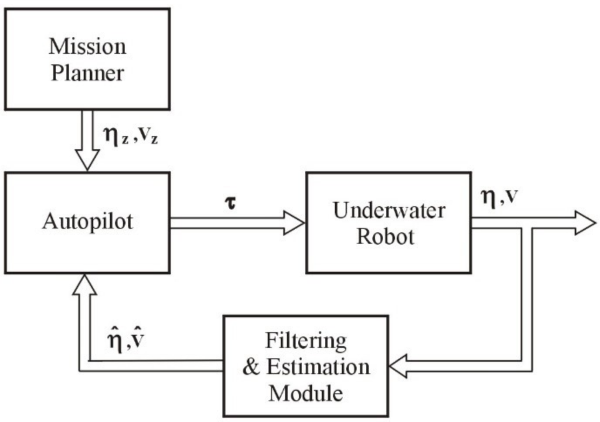


Fig. 1. A block diagram of the automatic control system [own work]

The investigations were conducted under following conditions:

- the full nonlinear mathematical model of the URV is applied (see the appendix A);
- the robot moves with varying linear velocities *u*, *v* and the angular velocity *r*;
- its velocities *u*, *v*, *r* and coordinates of position *x*, *y* and heading $\psi$ are measurable;
- a desired trajectory is given by means of set of way-points with coordinates $\{(x_{di}, y_{di}, \psi_{di})\}$.

The genetic algorithms (GAs) were applied to find a proper values of matrices of gain coefficients (3). The GAs are adaptive heuristic search algorithm based on the Darwin's principle of reproduction and survival of the fittest [3, 6]. In general this technique manipulates sets of individuals (solutions) by using genetic operators (selection, reproduction, crossover and mutation) in order to propose better ones. The individuals in a population are represented by chromosomes.

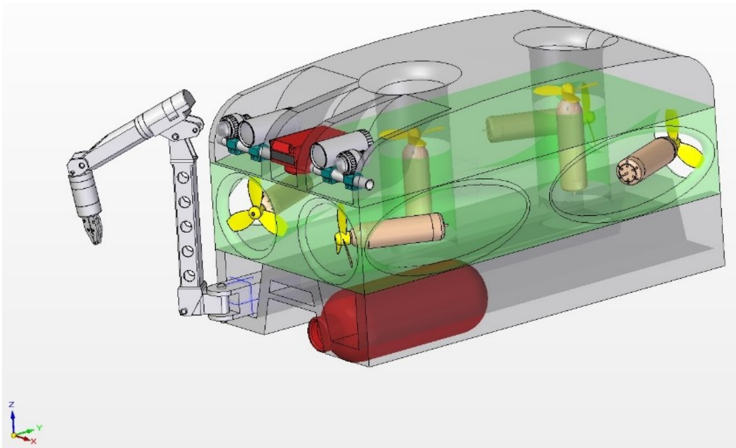

Fig. 2. Virtual view of the URV [own work]

The chromosomes, used in calculations, consisted of six parameters corresponded to unknown values of the diagonals of the matrices $\mathbf{K}_P$ and $\mathbf{K}_D$. Their searched values were restricted as follows: $0 < k_{P1} \leq 500$, $0 < k_{P2} \leq 200$, $0 < k_{P3} \leq 100$, $0 < k_{D1} \leq 200$, $0 < k_{D2} \leq 100$, $0 < k_{D3} \leq 50$ and calculated for the following configuration of the GAs: population — 25 individuals, crossing probability — 0.8, mutation probability — 0.01, number of generation — 100. The process of optimizing was realised for the objective function in the form of a sum of squared errors of control taking into account manoeuvre of the robot transition from way-point (0, 0, 0) to (50, 50, 45). Obtained results are presented in the Appendix A.

Due to assumption that all segments of the reference trajectory had to be the smooth and bounded curves they were generated using speed profile [8]. Such approach allowed to keep constant speed along certain part of the trajectory. Hence, for a period of time $t \in \langle t_b, t_f \rangle$, given $\boldsymbol{\eta}_d = [\eta_{d1}, \eta_{d2}, \eta_{d3}]^T = [x_d, y_d, \psi_d]^T$, and initial conditions:

1. $\eta_{dj}(t_b) = \eta_0$, $\qquad \dot{\eta}_{dj}(t_b) = \dot{\eta}_0$,
2. $\eta_{dj}(t_f) = \eta_1$, $\qquad \dot{\eta}_{dj}(t_f) = \dot{\eta}_1$,
3. $\max \dot{\eta}_{dj}(t) = \dot{\eta}_{\max}$, $\qquad j = \{1, 2, 3\}$,

the $i^{\text{th}}$ segment of the trajectory was modelled according to the following equation [7]:

$$\eta_{dj}(t) = a_0 + a_1(t - t_b) + a_2(t - t_b)^2 + a_3(t - t_b)^3, \tag{5}$$

where:

$a_0 = \eta_0$;

$a_1 = \dot{\eta}_0$;

$$a_2 = \frac{3(\eta_1 - \eta_0) - (2\dot{\eta}_0 + \dot{\eta}_1)t_k}{t_k^2};$$

$$a_3 = \frac{2(\eta_0 - \eta_1) + (\dot{\eta}_0 + \dot{\eta}_1)t_k}{t_k^3};$$

$t_k = t_f - t_b$.

The simulations were carried out in the MATLAB/Simulink environment for the following assumptions:

- the robot had to follow the desired trajectory beginning from (0 m, 0 m), passing target way-points: (50 m, 0 m), (80 m, 30 m), (80 m, 80 m), (30 m, 80 m), (0 m, 50 m) and ending in (0 m, 0 m);
- the components of the command vector $\boldsymbol{\tau}$ were bounded: $|\tau_X| \le 700\ \text{N}$, $|\tau_Y| \le 100\ \text{N}$ and $|\tau_N| \le 50\ \text{Nm}$;
- the robot moved under interaction of environmental disturbances i.e. a sea current (a fixed direction and slowly varying velocity);
- the turning point was reached when the robot was inside a meter circle of acceptance.

Results of track-keeping and the courses of command signals are presented in figure 3. They show that the proposed autopilot enhanced good tracking control of the desired trajectory in the plane motion. The main advantage of the approach is using the simple nonlinear law to design the autopilot and its high performance for relative large environmental disturbances.

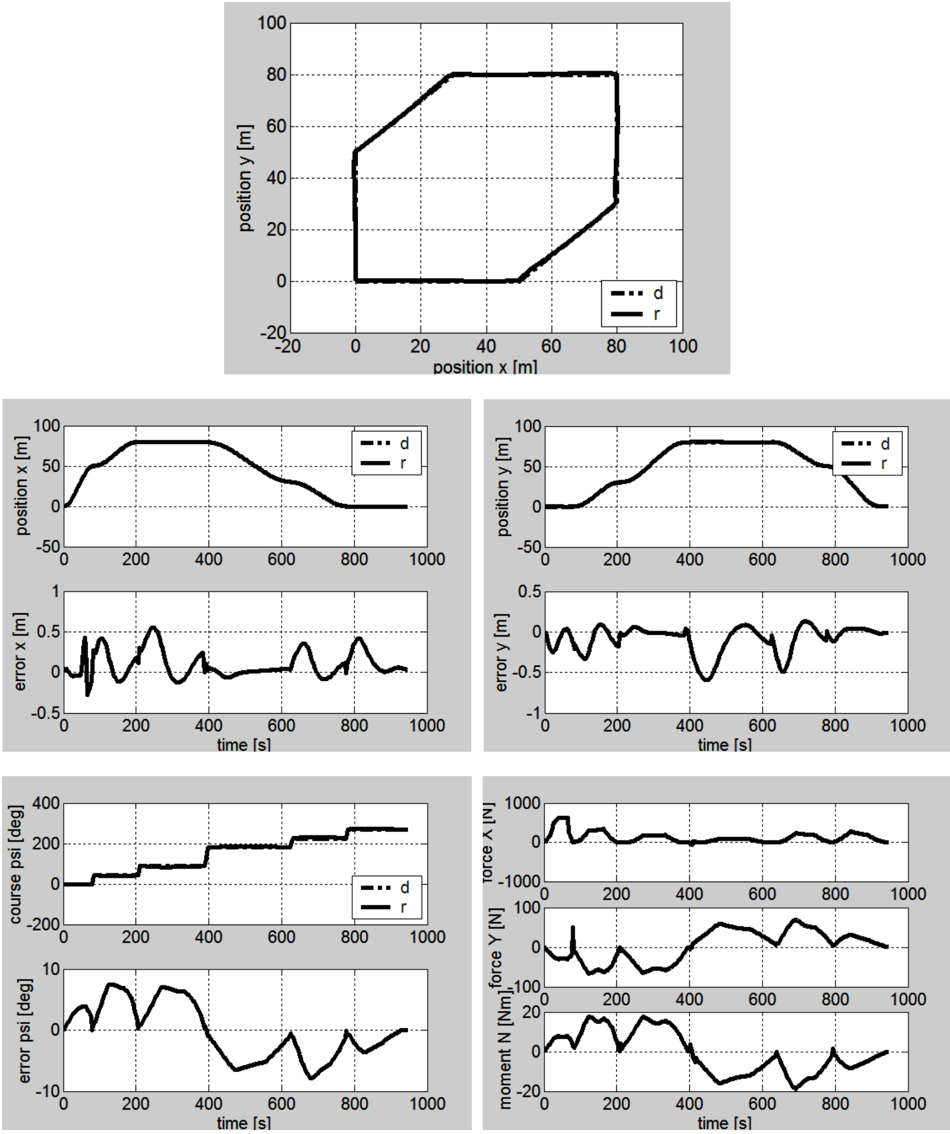


Fig. 3. Track-keeping control under interaction of sea current disturbances (average velocity 0.3 m/s and direction $135^0$): desired (d) and real (r) trajectories (upper plot), *x*-, *y*-position and error of position (middle plots), course and its error and commands (low plots) [own work]

## CONCLUSIONS

In this paper the nonlinear PD autopilot for underwater robotic vehicle has been described. The simulation study, performed on the mathematical model of the real underwater robot, indicates that the proposed control scheme assures the automation of the elementary robot's behavior and can be used to support a human operator making the URV a more efficient tool for exploring a subsea space.

Disturbances from the sea current were added to verify the performance, correctness and robustness of the approach.

An important advantage of the proposed solution is its flexibility with regard to the robot's dynamics. Further works are needed to identify a best structure of the autopilot in a three dimensional space and test a robustness of the proposed approach in the real world.

## APPENDIX A

The following model of the URV dynamics was used in the simulation study:

$$\mathbf{M} = diag\{99.0, \quad 108.5, \quad 126.5, \quad 8.2 \quad 32.9, \quad 29.1\};$$

$$\mathbf{D}(\mathbf{v}) = diag\{10.0, \quad 0.0, \quad 0.0, \quad 0.223 \quad 1.918, \quad 1.603\} + diag\begin{Bmatrix} 227.18|u|, & 405.41|v|, & 478.03|w| & \\ & 3.212|p|, & 14.002|q|, & 12.937|r| \end{Bmatrix};$$

$$\mathbf{C}(\mathbf{v}) = \begin{bmatrix} 0 & 0 & 0 & 0 & 26.0w & -28.0v \\ 0 & 0 & 0 & -26.0w & 0 & 18.5u \\ 0 & 0 & 0 & 28.0v & -18.5u & 0 \\ 0 & 26.0w & -28.0v & 0 & 5.9r & -6.8q \\ -26.0w & 0 & 18.5u & -5.9r & 0 & 1.3p \\ 28.0v & -18.5u & 0 & 6.8q & -1.3p & 0 \end{bmatrix};$$

$$\mathbf{g}(\boldsymbol{\eta}) = \begin{bmatrix} -17.0\sin(\theta) \\ 17.0\cos(\theta)\sin(\phi) \\ 17.0\cos(\theta)\cos(\phi) \\ -279.2\cos(\theta)\sin(\phi) \\ -279.2(\sin(\theta)+\cos(\theta)\cos(\phi)) \\ 0 \end{bmatrix}.$$

The matrices $\mathbf{K}_P$ and $\mathbf{K}_D$ corresponding to the control law (3) were as follows: $\mathbf{K}_P = diag\{350, 127, 35\}$ and $\mathbf{K}_D = diag\{115, 43, 12\}$.

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# NIELINIOWE STEROWANIE RUCHEM PŁASKIM ROBOTA PODWODNEGO

## STRESZCZENIE


W artykule przedstawiono koncepcję system automatycznego sterowania ruchem płaskim robota podwodnego wzdłuż trajektorii odniesienia. Układem odpowiedzialnym za wyznaczanie sygnałów sterujących jest autopilot, w którym zaimplementowano nieliniowy regulator PD. Parametry regulatora dostrojono z wykorzystaniem algorytmów genetycznych. Zamieszczono wyniki badań symulacyjnych ruchu robota w płaszczyźnie poziomej z wykorzystaniem zaproponowanego algorytmu sterowania.



Słowa kluczowe:
robot podwodny, autopilot, układ nieliniowy, algorytmy genetyczne.