Model Reference Adaptive Control of Underwater Robotic Vehicle in Plane Motion

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Abstract: - A paper describes a method of motion control of the underwater robotic vehicle to the problem of trajectory tracking. A multidimensional non-linear model expresses the robot's dynamics. Command signals are generated by an autopilot consisting of three independent controllers with a parameter adaptation law implemented. A quality of control is concerned without and in presence of environmental disturbances. The paper includes selected results of computer simulations to illustrate effectiveness of the proposed control system.

Key-Words: - Underwater robot, Autopilot, Non-linear control, Tracking

1 Introduction

Underwater Robotics has known an increasing interest in the last years. The main benefits of usage of Underwater Robotic Vehicles (URV) can be removing a man from the dangers of the undersea environment and reduction in cost of exploration of deep seas. Currently, it is common to use the URV to accomplish missions as the inspection of coastal and off-shore structures, cable maintenance, as well as hydrographical and biological surveys. In the military field it is employed in such tasks as surveillance, intelligence gathering, torpedo recovery and mine counter measures.

The URV is considered being a floating platform carrying tools required for performing various functions. They include manipulator arms with interchangeable end-effectors, cameras, scanners, sonars, etc. An automatic control of such objects is a difficult problem caused by their nonlinear dynamics [1, 2, 4, 5, 6]. Moreover, the dynamics can change according to the alteration of configuration to be suited to the mission. In order to cope with those difficulties, the control system should be flexible.

The conventional URV operates in crab-wise manner in 4 degrees of freedom (DOF) with small roll and pitch angles that can be neglected during normal operations. Therefore its basic motion is movement in horizontal plane with some variation due to diving.

The objective of the paper is to present a usage of the adaptive inverse dynamics algorithm to driving the robot along the desired trajectory in horizontal motion. It consists of the following four sections. Brief descriptions of dynamical and kinematical equations of motion of the floating object and the adaptive control law are presented in the next section. Section 3 provides some results of the simulation study. Conclusions are given in Section 4.

2 Nonlinear adaptive control law

The general motion of marine vessels of 6 DOF describes the following vectors [3, 4, 5]:

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

where:

- $\boldsymbol{\eta}$ – the position and orientation vector in the inertial frame;
- x, y, z – coordinates of position;
- ϕ, θ, ψ – coordinates of orientation (Euler angles);
- $\mathbf{v}$ – the 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;
$\boldsymbol{\tau}$ – a vector of forces and moments acting on the robot 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.

The nonlinear dynamical and kinematical equations of motion in body-fixed frame can be expressed as [4, 5]:

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

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

For the URVs there are parametric uncertainties in the dynamic model (2), and certain parameters are generally unknown. Hence, parameter estimation is necessary in case of model-based control. For this purpose it is assumed that the vehicle equations of motion are linear according to parameter vector **p**, that is [8]:

$$\mathbf{M}\dot{\mathbf{v}} + \mathbf{C}(\mathbf{v})\mathbf{v} + \mathbf{D}(\mathbf{v})\mathbf{v} + \mathbf{g}(\boldsymbol{\eta}) \cong \mathbf{Y}(\boldsymbol{\eta}, \mathbf{v}, \dot{\mathbf{v}})\mathbf{p} \tag{3}$$

where $\mathbf{Y}(\boldsymbol{\eta}, \mathbf{v}, \dot{\mathbf{v}})$ is a known matrix function of measured signals usually referred as the regressor matrix (dimension $n \times r$) and $\mathbf{p}$ is a vector of the uncertain or unknown parameters.

Let estimates of the matrices $\mathbf{M}$, $\mathbf{C}(\mathbf{v})$, $\mathbf{D}(\mathbf{v})$ and the vector $\mathbf{g}(\boldsymbol{\eta})$ be described $\hat{\mathbf{M}}$, $\hat{\mathbf{C}}(\mathbf{v})$, $\hat{\mathbf{D}}(\mathbf{v})$ and $\hat{\mathbf{g}}(\boldsymbol{\eta})$. If model parameters are known with some accuracy the following nonlinear control law can be applied [5, 8]:

$$\begin{aligned}\boldsymbol{\tau} &= \hat{\mathbf{M}}\dot{\mathbf{u}} + \hat{\mathbf{C}}(\mathbf{v})\mathbf{u} + \hat{\mathbf{D}}(\mathbf{v})\mathbf{u} + \hat{\mathbf{g}}(\boldsymbol{\eta}) - \mathbf{K}_D\mathbf{s} = \\ &= \mathbf{Y}(\boldsymbol{\eta}, \mathbf{v}, \mathbf{u}, \dot{\mathbf{u}})\hat{\mathbf{p}} - \mathbf{K}_D\mathbf{s}\end{aligned} \tag{4}$$

where:
$\mathbf{K}_D$ – positive definite diagonal matrix,
$\mathbf{s} = \mathbf{e}_2 + \boldsymbol{\Lambda}\mathbf{e}_1$,
$\mathbf{e}_1 = \boldsymbol{\eta} - \boldsymbol{\eta}_d$,
$\mathbf{e}_2 = \mathbf{v} - \mathbf{v}_d$.
$\mathbf{u} = \mathbf{v}_d - \boldsymbol{\Lambda}\mathbf{e}_1$,
$\boldsymbol{\Lambda}$ – positive definite weighting matrix.

Choosing the parameter update law as [4, 8]:

$$\dot{\hat{\mathbf{p}}} = -\boldsymbol{\Gamma}\mathbf{Y}^T(\boldsymbol{\eta}, \mathbf{v}, \mathbf{u}, \dot{\mathbf{u}})\mathbf{s} \tag{5}$$

where $\boldsymbol{\Gamma}$ is a positive definite symmetric matrix, guarantees stability of the control system and convergence $\mathbf{s}$ to zero.

A block diagram of the control system with parameter adaptation law is shown in Fig. 1.

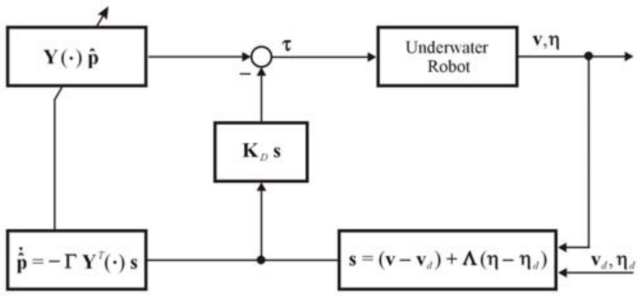


Fig. 1. Diagram showing the parameter adaptation law

3 Simulation results

A main task of the designed tracking control system is to minimize distance of attitude of the robot's centre of gravity to the desired trajectory under assumptions:

1. the robot can move with varying linear velocities *u*, *v* and an angular velocity *r*;
2. its velocities *u*, *v*, *r* and coordinates of position *x*, *y* and heading ψ are measurable;
3. a desired trajectory is given by means of set of way-points with coordinates $\{(x_{di}, y_{di})\}$;
4. a reference trajectory between two successive way-points is defined as smooth and bounded curves;
5. the command signal $\boldsymbol{\tau}$ consists of three components: $\tau_X = X$, $\tau_Y = Y$ and $\tau_N = N$ calculated using the control law (4).

A structure of the proposed control system is depicted in Fig. 2.

To validate the performance of the developed nonlinear control law, simulations results using the MATLAB/Simulink environment are presented below. The model of the vehicle is based on a real construction of an underwater robot called "Coral" designed and built for the Polish Navy. The URV is an open frame robot controllable in four degrees of freedom, being 1.5 m long and having a propulsion system consisting of six thrusters. Displacement in horizontal plane is done by means of four ones which generate force up to ±750 N assuring speed up to ±1.2 m/s and ±0.6 m/s in *x* and *y* direction, consequently. All parameters of the robot's dynamics are presented in the Appendix A.

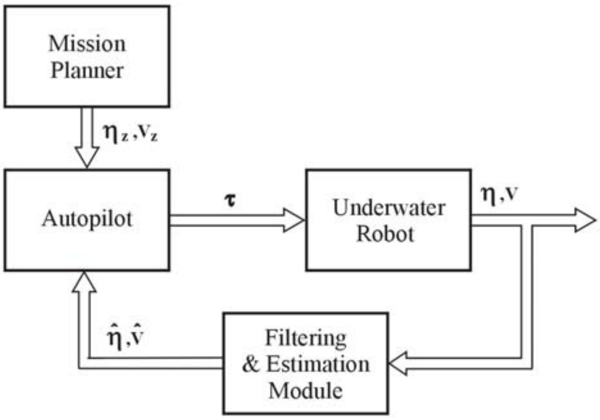


Fig. 2. The main parts of the control system

Numerical simulations have been made to confirm quality of the proposed control algorithm for the following assumptions:

1. the robot has 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);
2. the turning point is reached when the robot is inside of the 0.5 m circle of acceptance.

An algorithm of control worked out basis on simplified URV model proposed in [4, 9]:

$$\mathbf{M}_d \dot{\mathbf{v}} + \mathbf{D}_d(\mathbf{v})\mathbf{v} = \boldsymbol{\tau} \tag{6}$$

where all kinematics and dynamics cross-coupling terms are neglected. Here $\mathbf{M}_d$ and $\mathbf{D}_d$ ($\mathbf{v}$) are diagonal matrices with the diagonal elements of the inertia and damping matrices, consequently. Uncertainties in the above model are compensated in the designed control system.

The robot model for horizontal motion of 3 DOF can be written in a form:

$$\begin{aligned} m_X \dot{u} + d_X |u| u &= \tau_X \\ m_Y \dot{v} + d_Y |v| v &= \tau_Y \\ m_N \dot{r} + d_N |r| r &= \tau_N \end{aligned} \tag{7}$$

Define the parameter vector $\mathbf{p}$ in a form $\mathbf{p} = [m_X \quad d_X \quad m_Y \quad d_Y \quad m_N \quad d_N]^T$ equations (2) can be written as:

$$\mathbf{Y}(\mathbf{v}, \dot{\mathbf{v}})\mathbf{p} = \boldsymbol{\tau} \tag{8}$$

where:

$$\mathbf{Y}(\mathbf{v}, \dot{\mathbf{v}}) = \begin{bmatrix} \dot{u} & |u|u & 0 & 0 & 0 & 0 \\ 0 & 0 & \dot{v} & |v|v & 0 & 0 \\ 0 & 0 & 0 & 0 & \dot{r} & |r|r \end{bmatrix}$$

The regulation problem has been examined under interaction of external disturbances, i.e. sea currents. To simulate such influence on robot's motion the current velocity V_c was assumed to be slowly varying and having a fixed direction. For computer simulations it was calculated by using the 1st order Gauss-Markov process [5]:

$$\dot{V}_c + \mu V_c = \omega \tag{9}$$

where ω is a Gaussian white noise, $\mu \geq 0$ is a constant and $0 \leq V_c(t) \leq V_{c\max}$.

Results of track-keeping in the presence of external disturbances and the courses of command signals are presented in Fig. 3.

It can be seen that the proposed autopilot enhanced good tracking control of the desired trajectory in the spatial motion. The main advantage of the approach is using the simple nonlinear law to design controllers and its high performance for relative large sea current disturbances (comparable with resultant speed of the robot).

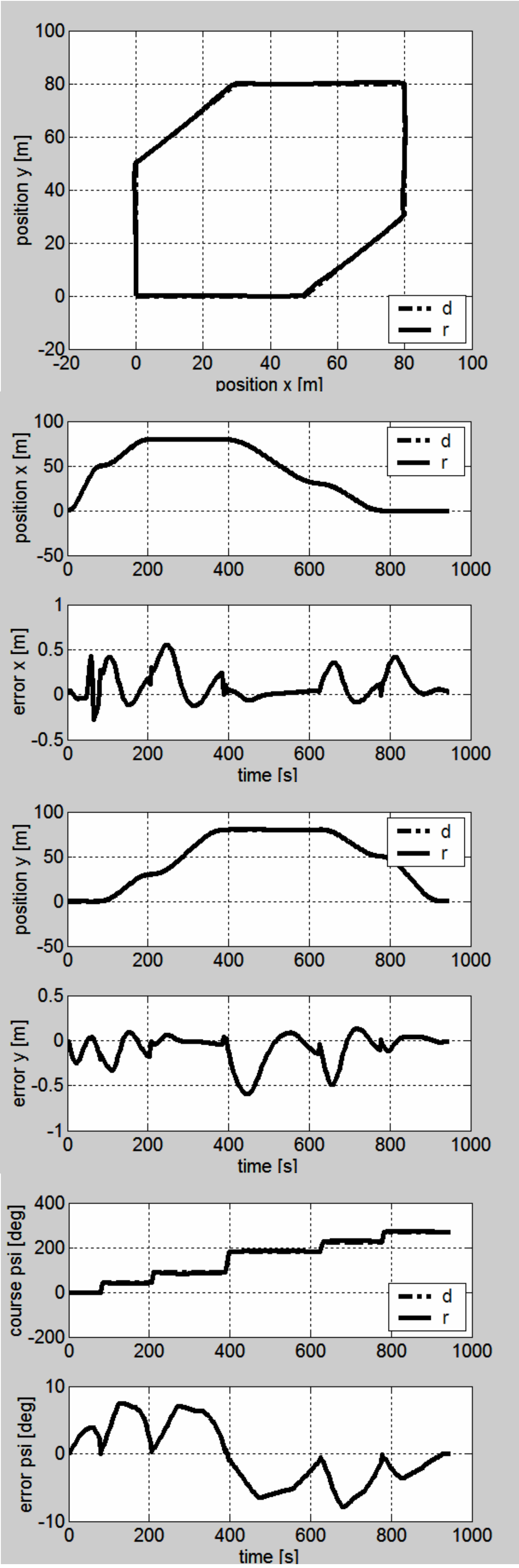
Assuming that the true values of components of the vector $\mathbf{p}$ are unknown evaluation on the level of half of nominal value has been accepted. Time histories of estimated parameters during tracking are presented in Fig. 4.

4 Conclusions

In the paper the nonlinear control system for the underwater robot has been described. The obtained results of simulation study with the autopilot consisting of three controllers with parameter adaptation law showed the presented control system to be simple and useful for the practical usage.

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

A further work is devoted to the problem of tuning of the autopilot parameters in relation to the robot's dynamics.



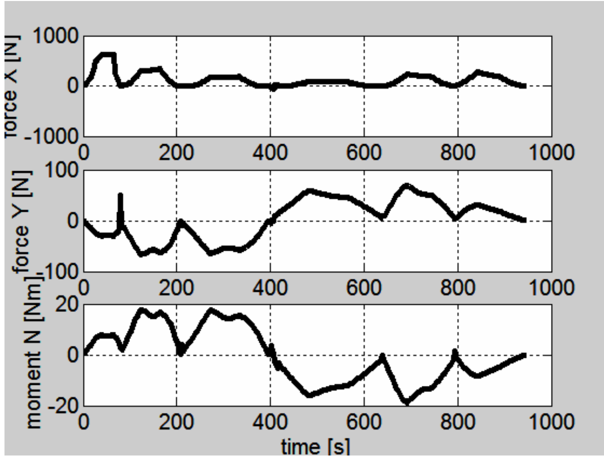
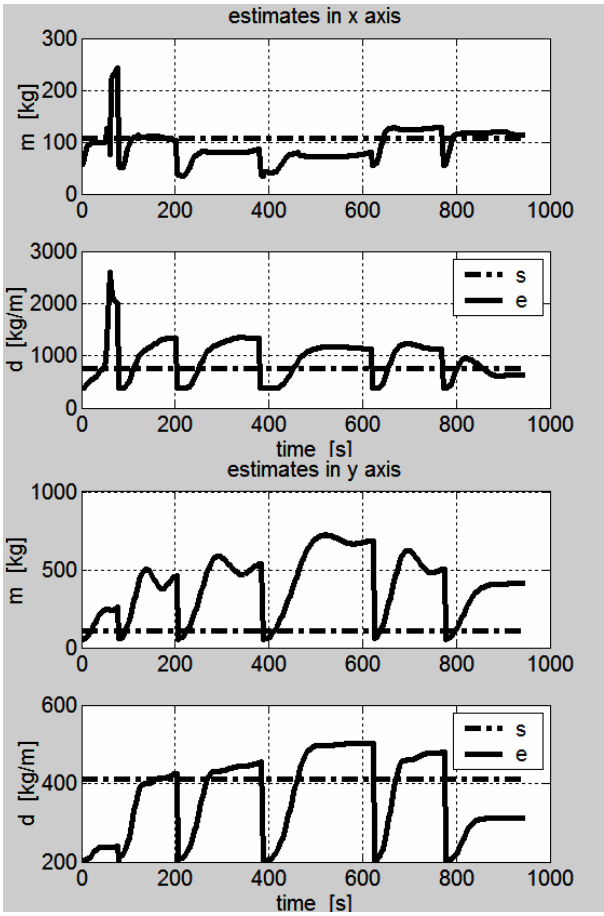


Fig. 3. Track-keeping control under interaction of sea current disturbances (average velocity 0.2 m/s and direction 135^0): desired (d) and real (r) trajectories (upper plot), *x*-, *y*-position and error of position (2^{nd} 3^{th} plots), course and its error (4^{th} plot), commands (low plot).



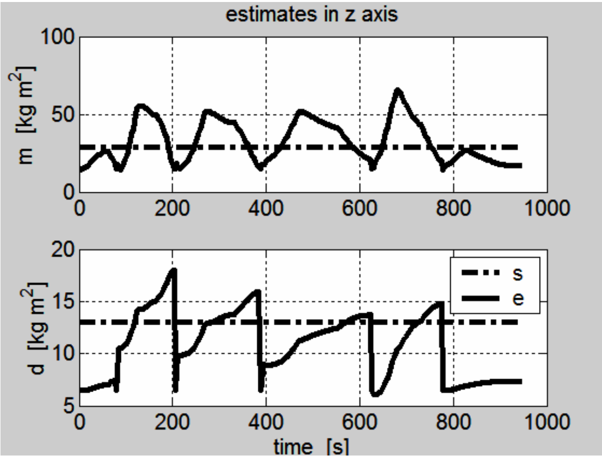


Fig. 4. Estimates of mass and damping coefficients: set value (s) and estimate (e).

References:

[1] G. Antonelli, F. Caccavale, S. Sarkar, M. West, Adaptive Control of an Autonomous Underwater Vehicle: Experimental Results on ODIN. *IEEE Transactions on Control Systems Technology*, Vol. 9, No. 5, 2001, pp. 756-765.

[2] J. Craven, R. Sutton, R. S. Burns, Control Strategies for Unmanned Underwater Vehicles. *Journal of Navigation*, No. 51, 1998, pp. 79-105.

[3] R. Bhattacharyya, *Dynamics of Marine Vehicles*, John Wiley and Sons, Chichester 1978.

[4] T .I. Fossen, *Guidance and Control of Ocean Vehicles,* John Wiley and Sons, Chichester 1994.

[5] T .I. Fossen, *Marine Control Systems,* Marine Cybernetics AS, Trondheim 2002.

[6] J. Garus, Z. Kitowski, Non-linear Control of Motion of Underwater Robotic Vehicle in Vertical Plane. In N. Mastorakis, V. Mladenov (Eds): *Recent Advances in Intelligent Systems and Signal Processing*, WSEAS Press, 2003 pp. 82-85.

[7] J. Garus, Z. Kitowski, Trajectory Tracking Control of Underwater Vehicle in Horizontal Motion. *WSEAS Transactions on Systems,* Vol. 3, No. 5, 2004, pp. 2110-2115.

[8] M.W. Spong, M. Vidyasagar, *Robot Dynamics and Control*, John Wiley and Sons, Chichester 1989.

[9] J. K. Yuh, Modelling and Control of Underwater Robotic Vehicles. *IEEE Transactions on Systems, Man and Cybernetics*, Vol. 15, No. 2, 1990, pp. 1475-1483.

Appendix A

The URV model

The following set of parameters of the underwater robotic vehicle dynamics was used in the computer simulations:

$$\mathbf{M} = \begin{bmatrix} 99 & 0 & 0 & 0 & 0 & 0 \\ 0 & 108 & 0 & 0 & 0 & 0 \\ 0 & 0 & 126 & 0 & 0 & 0 \\ 0 & 0 & 0 & 8 & 0 & 0 \\ 0 & 0 & 0 & 0 & 32 & 0 \\ 0 & 0 & 0 & 0 & 0 & 29 \end{bmatrix};$$

$$\mathbf{D}(\mathbf{v}) = \begin{bmatrix} 10 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.6 \end{bmatrix} +$$

$$+ \begin{bmatrix} 227|u| & 0 & 0 & 0 & 0 & 0 \\ 0 & 405|v| & 0 & 0 & 0 & 0 \\ 0 & 0 & 478|w| & 0 & 0 & 0 \\ 0 & 0 & 0 & 3|p| & 0 & 0 \\ 0 & 0 & 0 & 0 & 14|q| & 0 \\ 0 & 0 & 0 & 0 & 0 & 13|r| \end{bmatrix};$$

$$\mathbf{C}(\mathbf{v}) = \begin{bmatrix} \mathbf{C}_{11} & \mathbf{C}_{12} \\ \mathbf{C}_{21} & \mathbf{C}_{22} \end{bmatrix}$$

where:

$$\mathbf{C}_{11} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},$$

$$\mathbf{C}_{12} = \begin{bmatrix} 0 & 26w & -28v \\ -26w & 0 & 18u \\ 2v & -18u & 0 \end{bmatrix},$$

$$\mathbf{C}_{21} = \mathbf{C}_{12},$$

$$\mathbf{C}_{22} = \begin{bmatrix} 0 & 5r & -6q \\ -5r & 0 & p \\ 6q & -p & 0 \end{bmatrix};$$

$$\mathbf{g}(\boldsymbol{\eta}) = \begin{bmatrix} -17\sin(\theta) \\ 17\cos(\theta)\sin(\phi) \\ 17\cos(\theta)\cos(\phi) \\ -279\cos(\theta)\sin(\phi) \\ -279(\sin(\theta)+\cos(\theta)\cos(\phi)) \\ 0 \end{bmatrix}.$$

Values of the matrices corresponding to the nonlinear control law (5) were as follows:

$$\mathbf{K}_D = \begin{bmatrix} 100 & 0 & 0 & 0 & 0 & 0 \\ 0 & 20 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 10 \end{bmatrix};$$

$$\boldsymbol{\Gamma} = \begin{bmatrix} 200 & 0 & 0 & 0 & 0 & 0 \\ 0 & 50 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 100 \end{bmatrix};$$

$$\boldsymbol{\Lambda} = \begin{bmatrix} 50 & 0 & 0 & 0 & 0 & 0 \\ 0 & 10 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 20 \end{bmatrix}.$$