Fuzzy Control of Motion of Underwater Robotic Vehicle

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Abstract: - The paper addresses nonlinear control of an underwater robot. A way-point line of sight scheme is incorporated to following a desired path. Command signals are generated by an autopilot consisting of three fuzzy controllers. A methods of thrust distribution among propellers in the robot's propulsion system is also proposed. Optimisation of thrust allocation is directed towards minimisation of energy expenditures necessary to obtain required control. Some computer simulations are provided to demonstrate effectiveness, correctness and robustness of the approach.

Key-Words: - Underwater robot, Fuzzy control, Propulsion system, Thrust allocation

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 dangers of the undersea environment and reduction of costs of exploration of deep seas. Currently, it is common to use the URVs to accomplish such missions as the inspections of coastal and off-shore structures, cable maintenances, as well as hydrographical and biological surveys. In a military field they are employed in such tasks as a surveillance, an intelligence gathering, a torpedo recovery and mine counter measures.

The URV is considered as a floating platform carrying tools required for performing various functions. These include manipulator arms with interchangeable end-effectors, cameras, scanners, sonars, etc. An automatic control of the such object is a difficult problem caused by its nonlinear dynamics [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 these difficulties, the control system should be flexible.

Basic modules of the control system are depicted in Fig. 1. The autopilot computes command signals $\boldsymbol{\tau}_d$ by comparing a desired robot's position and an orientation with their current estimates. Corresponding values of propellers thrust $\mathbf{f}$ are calculated in a thrust distribution module and transmitted as control inputs to a propulsion system.

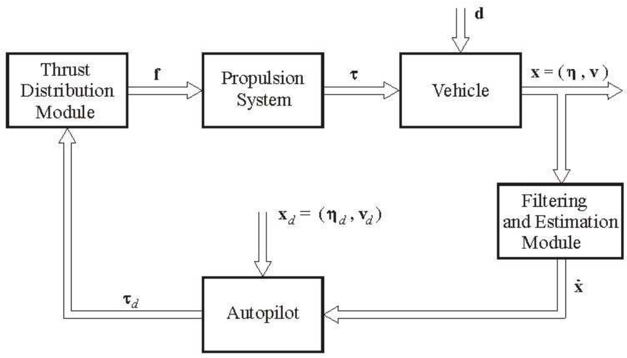


Fig.1. The main parts of the control system.

An objective of the paper is to present an usage of the fuzzy technique to driving the robot along a desired path in a plane motion. The work consists of the following sections. It starts with a brief description of dynamical and kinematical equations of motion. Then a fuzzy control law and a power distribution algorithm are presented. Next some results of a simulation study are provided. Conclusions are given in the last section.

2 Equations of motion

The following vectors describe motion of marine vessels of six degrees of freedom (DOF) [1, 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:

- $\boldsymbol{\eta}$ – position and orientation vector in an inertial system;
- x, y, z – coordinates of position;
- ϕ, θ, ψ – coordinates of orientation (Euler angles);
- $\mathbf{v}$ – linear and angular velocity vector with coordinates in a body-fixed system;
- 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 forces and moments acting on it robot in the body-fixed system;
- X, Y, Z – forces along longitudinal, transversal and vertical axes;
- K, M, N – moments about longitudinal, transversal and vertical axes.

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

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

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 forces and moments;
- $\mathbf{J}(\boldsymbol{\eta})$ – velocity transformation matrix between body fixed system and inertial one.

3 Path following and course keeping control

It is convenient to define three coordinate systems when analysing the underwater robot's motion in a horizontal plane (see Fig. 1) [4, 6]:

1. the global coordinate system $O_0X_0Y_0$ (called also the earth-fixed system);
2. the local coordinate system OXY (fixed to a body of the robot);
3. the reference coordinate system $P_iX_iY_i$ (system is not fixed).

The main task of the control system is to minimize a distance of an attitude of the robot's centre of gravity d to the desired path under assumptions:

1. the robot can move with varying linear velocities u, v and angular velocity r;
2. its positions x, y and heading ψ are measurable;
3. the command signal $\boldsymbol{\tau}$ consists of three components: τ_X and τ_Y - forces respectively in x- and y-axis, τ_N - moment around z-axis;
4. travel time is not fixed, it means the navigation between two points is not constrained by time.

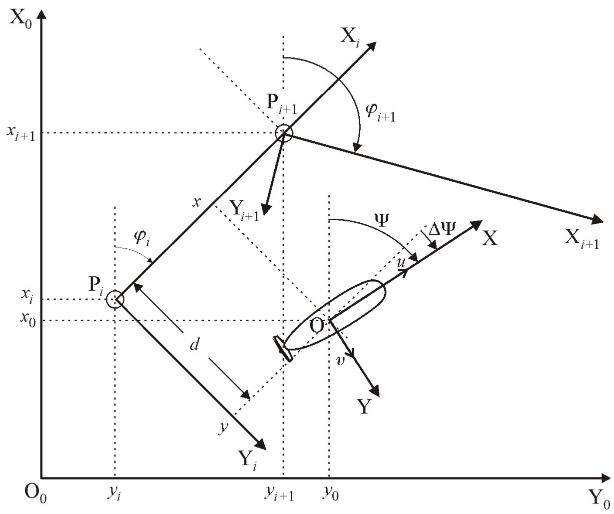


Fig.2. Coordinate systems used to description of motion in the horizontal plane: $O_0X_0Y_0$ – earth-fixed system, OXY – body-fixed system, $P_iX_iY_i$ – reference system.

The autopilot has to provide both path following and course keeping capabilities. Hence, it should minimize mean squares of deviations d from the desired track and $\Delta\psi$ from the desired course:

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

where:

$d(t) = -\sin(\Delta\psi)(x_0(t) - x_i) + \cos(\Delta\psi)(y_0(t) - y_i);$;

$\Delta\psi(t) = \psi(t) - \varphi_i$;

$\psi(t)$ - robot's heading angle;

φ_i – angle of rotation of reference coordinate system with respect to global one:

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

λ – constant coefficient.

Each time a robot's location $(x_0(t), y_0(t))$ at the time *t* satisfies:

$$[x_{i+1} - x_0(t)]^2 + [y_{i+1} - y_0(t)]^2 \leq \rho_0^2 \qquad (4)$$

where ρ_0 is a circle of acceptance, the reference coordinate system $P_iX_iY_i$ changed into $P_{i+1}X_{i+1}Y_{i+1}$, the angle of rotation ϕ_{i+1} calculated and its position updated corresponding to the new reference coordinate system.

4 Fuzzy control law

Adopted from [3, 10] the fuzzy proportional derivative controller working in a configuration presented in Fig. 3 has been designed for control of the robot in the horizontal motion.

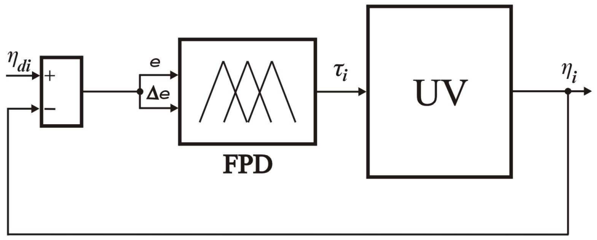


Fig.3. A structure of the fuzzy controller.

Membership functions of fuzzy sets of input variables: an error signal $e = \eta_{di} - \eta_i$ and a derived change in error $\Delta e = \eta_i - \eta_{i-1}$ as well as an output one τ_i (command signals) are shown respectively in Fig. 4. (The following notation is applied: N – negative, Z – zero, P – positive, S – small, M – medium and B – big). Values of unknown parameters: x_e, $x_{\Delta e}$, x_S and x_M used in computer simulations are given in Table 1. Evaluation of them can be done by means of numerous optimisation techniques, classical or modern ones like e.g. Genetic Algorithms [6, 9].

Table 2 shows rules, taken from the Mac Vicar-Whelan's standard base of rules, chosen as the control rules [3, 8, 10].

Table 1. Parameters of membership function.

	Controller		
	position in x-axis	position in y-axis	course
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

Table 2. The base of rules.

		Error signal *e*				
		NB	NM	Z	PM	PB
Derived change in error Δe	N	NB	NM	NS	Z	PS
	Z	NM	NS	Z	PS	PM
	B	NS	Z	PS	PM	PB
		Command signal τ_i				

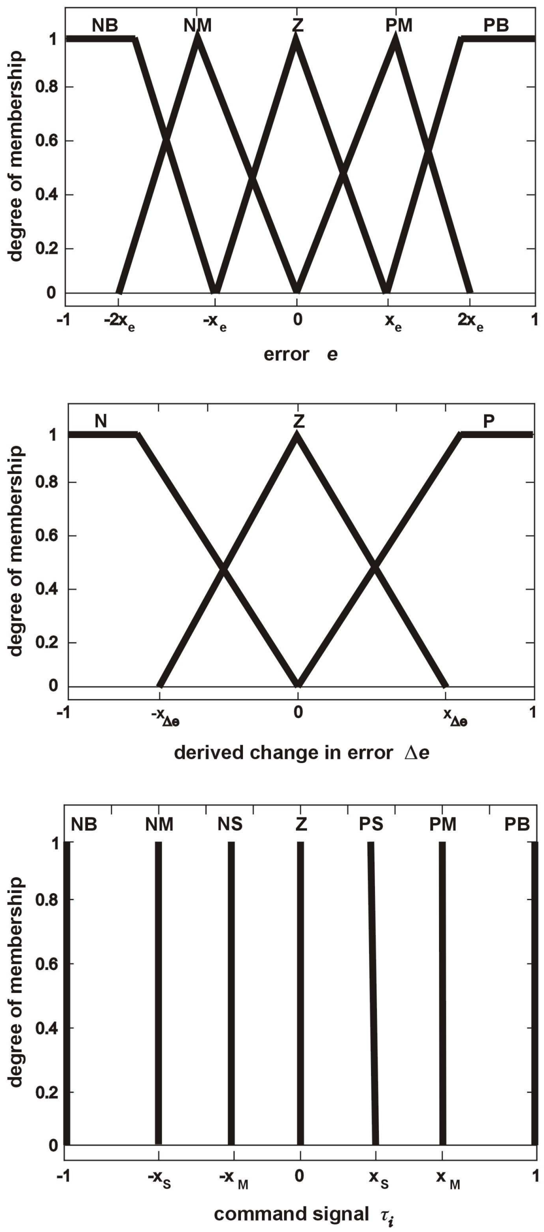


Fig.4. Membership functions for fuzzy sets: error e, derived change in error Δe and command signal τ_i.

5 Procedure of power distribution

Basic motion of the URVs is movement in a horizontal plane with some variation due to diving. They operate in crab-wise manner in four DOF with small roll and pitch angles that can be neglected during normal operations. Therefore, it is on purpose to regard three-dimensional motion of the robot as superposition of two displacements: motion in the horizontal plane and motion in the vertical plane. It allows to divide a its power transmission system into two independent subsystems, i.e. the subsystem realizing vertical motion and the subsystem responsible for horizontal motion. A general structure of the propulsion system shows Fig. 5.

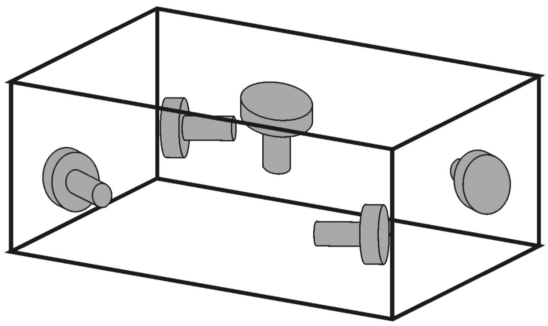


Fig.5. A structure of power transmission system with five propellers

The second subsystem consists of four propellers mounted askew in relation to main axes of symmetry and assures surge, sway and yaw motion. Demanded inputs, i.e. forces along roll and lateral axes and moment around vertical axis, are linear combination of thrusts of propellers produced by the all subsystem. Hence, from an operating point of view, the control system should have a procedure of power distribution among the propellers.

Relationship between the vector of forces and moments $\boldsymbol{\tau}$ acting on the vehicle and the thrust vector of propellers $\mathbf{f}$ is a complicated nonlinear function depending on density of water, a tunnel length and a cross-sectional area, a propeller diameter and its revolutions and the robot's velocity [5].

In many practical applications it is approximated by so called simplified model, i.e. the system being linear in its input [4]:

$$\boldsymbol{\tau} = \mathbf{T}\mathbf{f} \tag{5}$$

where:

$\boldsymbol{\tau} = [\tau_X, \tau_Y, \tau_N]^T$

$\mathbf{T}$ – propellers configuration matrix,

$\mathbf{f} = [f_1, f_2, ..., f_n]^T$ – thrust vector.

The solution proposed below is restricted to the URV having the configuration of the propellers exactly as shown in Fig. 6, where the propulsion system consists of four identical propellers located symmetrically around the centre of gravity.

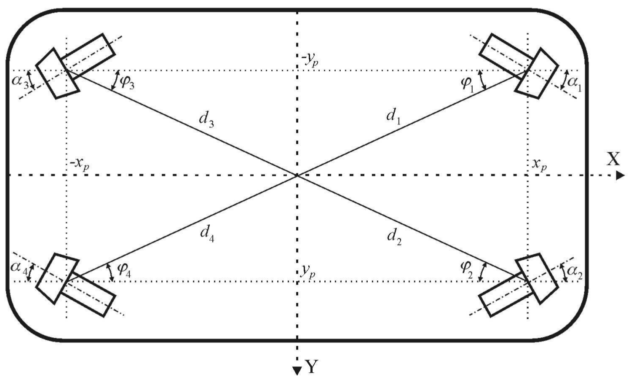


Fig.6. Layout of propellers responsible for horizontal motion

In this kind of situation $d_j = d_k = d$, $\alpha_j \bmod \frac{\Pi}{2} = \alpha_k \bmod \frac{\Pi}{2} = \alpha$, $\varphi_j \bmod \frac{\Pi}{2} = \varphi_k \bmod \frac{\Pi}{2} = \varphi$ for $j,k = \overline{1,4}$ and the configuration matrix $\mathbf{T}$ can be written in the form:

$$\mathbf{T} = \begin{bmatrix} \cos\alpha & \cos\alpha & -\cos\alpha & -\cos\alpha \\ \sin\alpha & -\sin\alpha & \sin\alpha & -\sin\alpha \\ d\sin(\alpha-\varphi) & -d\sin(\alpha-\varphi) & -d\sin(\alpha-\varphi) & d\sin(\alpha-\varphi) \end{bmatrix}$$

The matrix $\mathbf{T}$ has the following properties:

a) is a row-orthogonal matrix,

b) $|q_{ij}| = |q_{ik}|$ for $i = \overline{1,3}$ and $j,k = \overline{1,4}$,

c) can be written as a product of two matrices: a diagonal matrix $\mathbf{Q}$ and a row-orthogonal matrix $\mathbf{W_f}$ having values ± 1:

$$\mathbf{T} = \mathbf{Q}\mathbf{W_f} = \begin{bmatrix} q_{11} & 0 & 0 \\ 0 & q_{21} & 0 \\ 0 & 0 & q_{31} \end{bmatrix} \begin{bmatrix} 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \tag{6}$$

It allows to use the following simple form to calculate the desired thrust vector [7]:

$$\mathbf{f} = \frac{1}{4}\mathbf{W}\mathbf{S} \tag{7}$$

where:

$$\mathbf{S} = \begin{bmatrix} 0 \\ \mathbf{Q}^{-1}\boldsymbol{\tau} \end{bmatrix} = \begin{bmatrix} 0 \\ \frac{\tau_X}{q_{11}} \\ \frac{\tau_Y}{q_{22}} \\ \frac{\tau_N}{q_{33}} \end{bmatrix}, \quad \mathbf{W} = \begin{bmatrix} \mathbf{w}_0 \\ \mathbf{W_f} \end{bmatrix}, \quad \mathbf{w}_0 = [1 \quad 1 \quad 1 \quad 1].$$

6 Simulation results

The proposed method of control and power distribution was applied to motion control of the URV called “Ukwiał”. The vehicle, used on board of Polish minesweepers, is the open frame robot controllable in four DOF and has the power transmission system consisting of six propellers. A displacement in the horizontal plane is realized by four propellers assuring speed up to ±1.2 m/s and ±0.6 m/s consequently along longitude and transversal directions.

Its propellers configuration matrix has the following form:

$$\mathbf{T} = \begin{bmatrix} 0.875 & 0.875 & -0.875 & -0.875 \\ 0.485 & -0.485 & 0.485 & -0.485 \\ 0.332 & -0.332 & -0.332 & 0.332 \end{bmatrix}$$

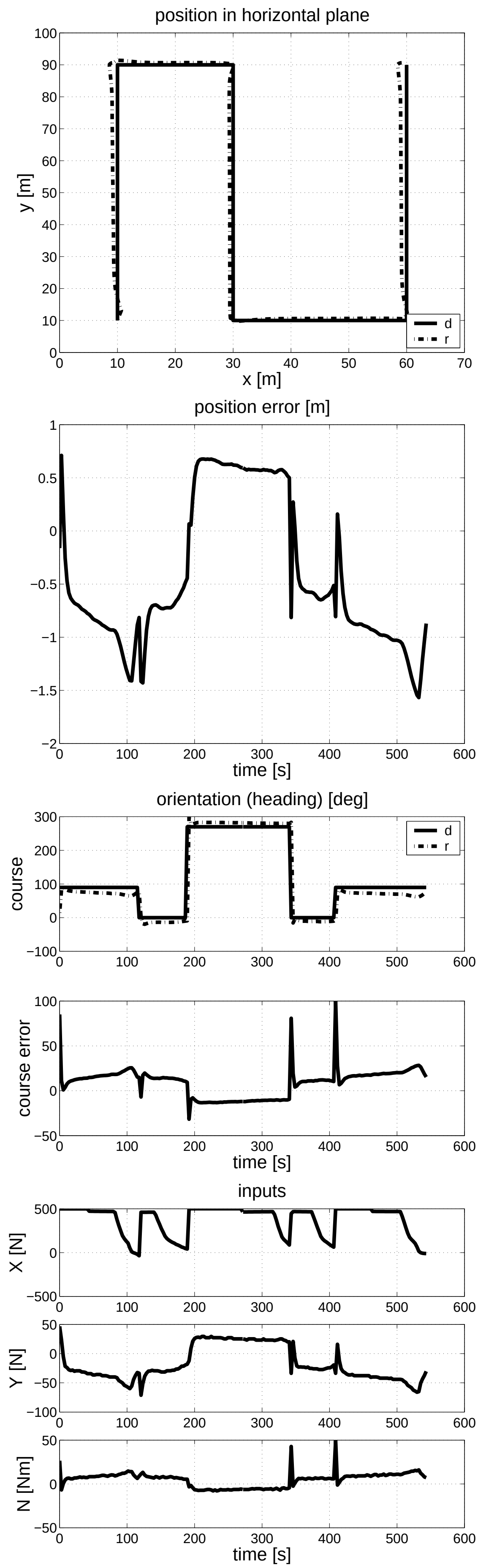
A simulation study has been performed for the model of dynamics written in the Appendix A. Simulation experiments were made for path following control under interaction of sea current disturbances (speed 0.3 m/s, direction 135^0). The robot was assumed to follow the path beginning from the position and orientation (10 m, 10 m, 0^0), passing target waypoints (10 m, 90 m, 90^0), (30 m, 90 m, 0^0), (30 m, 10 m, 270^0), (60 m, 10 m, 0^0) and ending at (60 m, 90 m, 90^0). The autopilot calculated command signals, the power distribution module processed them and gave required hydrodynamic thrusts.

The desired and real paths, position and course errors, commands and the thrust of propellers are shown in Fig. 7. It can be noticed that a level of the errors is quite small.

7 Conclusions

The paper presents a method of control of the underwater robotic vehicle. In the described solution using of the fuzzy controllers for the path following control was proposed. Dynamics of the propulsion system was regarded by using of both the affine model of the propeller and the propellers configuration matrix to determine of thrust allocation. It makes the algorithms simple and useful for practical usage.

The nonlinear mathematical model of the real underwater robot was applied for computer simulations. The obtained results show the presented control system enhanced god path following control in the horizontal plane.



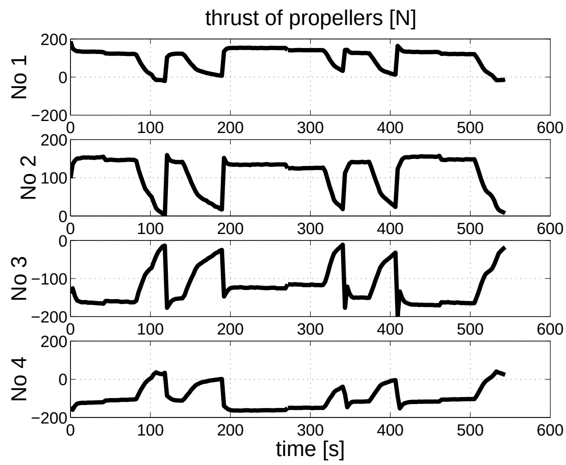


Fig.7. The vehicle's position and orientation /d – desired, r – real/, deviation from position and orientation, command inputs and thrusts of propellers.

A main advantage of the approach is its flexibility with regard to the construction of the robot's power transmission system and the number of thrusters.

Further works are needed to identify the best fuzzy structure of the autopilot and test a quality of this approach during sea trials.

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Appendix A

The URV model

The following parameters of dynamics of the underwater robot were used in the computer simulations:

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

$$\mathbf{D}(\mathbf{v}) = diag\{10.0 \quad 0.0 \quad 0.0 \quad 0.2 \quad 1.9 \quad 1.6\} + diag\begin{Bmatrix} 227.2|u| & 405.4|v| & 478.0|w| & & & \\ & & & 3.2|p| & 14.0|q| & 12.9|r| \end{Bmatrix};$$

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

where:

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

$$\mathbf{C}_{12} = \begin{bmatrix} 0 & 26.0w & -28.0v \\ -26.0w & 0 & 18.5u \\ 2.0v & -18.5u & 0 \end{bmatrix},$$

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

$$\mathbf{C}_{22} = \begin{bmatrix} 0 & 5.9r & -6.8q \\ -5.9r & 0 & 1.3p \\ 6.8q & -1.3p & 0 \end{bmatrix};$$

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