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Region Reaching Controller for Autonomous Underwater Vehicle without Velocity Measurement

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***Abstract*— This paper addresses the problem of region reaching by using the concept of potential energy of the specified region, for an Autonomous Underwater Vehicle (AUV). The six degrees of freedom AUV model has been exploited with Euler angle representation. The control law incorporates high filtered version of position error to regulate the system without velocity measurement. The proposed control law ensures stability in Lyapunov sense and simulation results shows the convergence of positional error.**

I. INTRODUCTION

Autonomous Underwater Vehicles have been an active area of research for the last few decades. Applications in Petroleum industries, subsea mapping and scientific research had been a constant source of motivation for advanced and newer design technologies. In the scope of control engineering problems, a vast amount of literature can be found which is addressing set-point control problems for robot manipulators. The global set-point control law, with a PD control and gravity compensation for robot manipulators was proposed by Arimoto [1]. The path breaking work of Arimoto, inspired to work out the set-point control problem for underwater vehicles as well [2], [3], [4], [5]. However for oceanographic survey and petroleum industries AUVs are required to have detailed mapping of the specific region and transmit the data collection dynamically. During surveys, AUVs need to encounter varying seabed altitude, under ice remote area survey and obstacle avoidance scenario. So AUVs need to maintain its path within a bounded region e.g. within a maximum and minimum depth. This specific type of control identified as region reaching based control has been introduced by Sun and Cheah [3] and later on extended by Cheah [6], [7] and Ismail and Dunnigan [8], [9], [10] for various mission requirements. This concept can be extended to obstacle avoidance for underwater vehicles where obstacle is considered as a repulsive region.

However the set point regulation or the region based control problems often encounters a drawback in terms of velocity measurement which is generally contaminated by noise. To avoid the noise problem one approach is to differentiate the position numerically. But this reconstruction of velocity is erroneous for low and high speeds. An alternative approach proposed by Ailon and Ortega [11] for robot manipulators is to design an observer to estimate the velocity from positional measurements. The same problem has been addressed by Laib [12] for robotic manipulators using high filtered version of positional error to get velocity approximate under actuator constraints. Also for multi-agent systems, Zheng ad Wang [16] have explored the advantages of using velocity estimates instead of measurements.

In this paper, we propose a new region reaching based controller for underwater vehicle without velocity measurement. The required regions are defined based upon their potential energy and we have used total work done in that region as a contributing factor in the Lyapunov function. The intersection of two region with specific radius has been considered as desired region where outer region acts as attractive region while the inner region acts as a repulsive one. The proposed control law further incorporates high filtered version of positional error to estimate the velocity. The advantage of the proposed controller is (i) the controller maintains the AUV within a specific bounded region and (ii) the controller eliminates the requirement of velocity measurement thereby reducing the cost for additional velocity sensors. Stability analysis for both with and without velocity measurement case has been carried out in the Lyapunov sense. Choice of appropriate Lyapunov function guarantees global asymptotic stability of the closed loop system. By using Lyapunov theory and the properties of rigid body we have proved that the underwater vehicle converge to the desired region. Finally simulation examples are presented to validate the proposed controller.

In section II kinematic and dynamic model of AUV in three dimension is reviewed. An introduction to region based control is given in section III whereas section IV includes region reaching control law without velocity measurement. In section V, the proposed region reaching control law is implemented on ODIN underwater vehicle and simulation results validates the effectiveness of the proposed controller. Section VI concludes the paper with final remarks.

II. MODEL DESCRIPTION

The three dimensional equations of motion for AUV have been described by Fosen in [13] using inertial reference frame $\{I\}$ and body fixed frame $\{B\}$ as shown schematically in figure 1. As rotation of earth is having little effect on low speed underwater vehicles, earth fixed frame can be considered as inertial frame. The body fixed frame has velocity components in six directions with three linear velocity *surge*, *sway*, *heave* and three rotational velocity *roll*, *pitch*, *yaw* given by the vector ν as

$$\nu = [\nu_1{}^T \ \ \nu_2{}^T]^T = [u \ v \ w \ p \ q \ r\ ]^T$$

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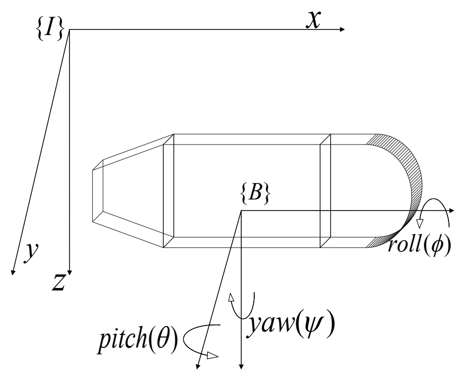

Fig. 1. Inertial $\{I\}$ and Body coordinate frame $\{B\}$

A. Kinematics

According to SNAME (1950) notation, the position and orientation of the vehicle described in earth fixed coordinate frame are expressed by $\eta = [\eta_1^T \ \eta_2^T]^T = [x \ y \ z \ \phi \ \theta \ \psi \ ]^T$. So the vehicle's flight path expressed in body fixed frame is related to position and orientation of the vehicle by a velocity transformation matrix R given by

$$\dot{\eta} = R\nu \tag{1}$$

$$\begin{bmatrix}\dot{\eta}_1 \\ \dot{\eta}_2\end{bmatrix} = \begin{bmatrix} J_1(\eta_2) & 0 \\ 0 & J_2(\eta_2)\end{bmatrix}\begin{bmatrix}\nu_1 \\ \nu_2\end{bmatrix} \tag{2}$$

B. Dynamics

The rigid body dynamics combined with added inertia (M_A), hydrodynamic damping $(D(\nu))$ and restoring forces gives six DOF dynamic equations of motion as

$$M\dot{\nu} + C(\nu)\nu + D(\nu)\nu + g(\eta) = \tau \tag{3}$$

where $M = M_{RB} + M_A$ & $C = C_{RB} + C_A$
Total hydrodynamic damping matrix can be written as sum of potential damping, linear skin friction, wave drift damping and vortex shedding.

$$D(\nu) = D_P(\nu) + D_S(\nu) + D_W(\nu) + D_M(\nu) \tag{4}$$

The detail structure of these matrices can be found in [3], [13]. The gravitational force always acts through the center of gravity of the vehicle. Similarly the buoyant force acts through the center of buoyancy . Let m be the mass of the vehicle, $\bigtriangledown$ the volume of fluid displaced by the vehicle, ρ fluid density. The buoyancy force is defined as $B = \rho g \bigtriangledown$ and weight as $W = mg$. Considering z-axis to be positive downwards the gravitational terms can be expressed as

$$g(\eta) = \begin{bmatrix} (W-B)s\theta \\ -(W-B)c\theta s\phi \\ -(W-B)c\theta c\phi \\ -(y_G W - y_B B)c\theta c\phi + (z_G W - z_B B)c\theta s\phi \\ (z_G W - z_B B)s\theta + (x_G W - x_B B)c\theta c\phi \\ -(x_G W - x_B B)c\theta s\phi - (y_G W - y_B B)s\theta \end{bmatrix} \tag{5}$$

The dynamic equations expressed in equation (3) has following properties for a rigid body moving through an ideal fluid

Property 1: The inertia matrix (M) is symmetric and positive definite.
Property 2: The inertia matrix and Coriolis matrix follows that $\dot{M} - 2C(\nu)$ is skew-symmetric matrix.
Property 3: The hydrodynamic damping matrix $D(\nu)$ is real, non-symmetrical and strictly positive definite.

III. REGION REACHING CONTROL & PROBLEM FORMULATION

Many robotic tasks are defined as to regulate the system to a desired task space set-point. But in lieu of the applications of an AUV encountered, it is more practical to regularize the AUV within a specified region with desired orientation. This type of control law is generally known as region reaching based control. The region reaching based control task reduces to set-point regulation problem when the radius of the desired region is sufficiently small. Figure 2 demonstrates the difference between a region reaching control problem and a set-point control problem. In this paper, two spherical regions are defined in terms of functions f_1 and f_2 being the locus of the point (x, y, z) with radius r_1 & r_2 respectively as shown in figure 3. The shaded region in figure 2 and 3 is the desired region for the AUV generated from intersection of f_1 & f_2. Figure 3 shows, for pipeline inspection problem, the target is to maneuver AUV within a particular region identified as shaded region.

$$f_1(\bar{\eta}) = (x-x_d)^2 + (y-y_d)^2 + (z-z_d)^2 - r_1^2 \leq 0 \tag{6}$$

$$f_2(\bar{\eta}) = (x-x_d)^2 + (y-y_d)^2 + (z-z_d)^2 - r_2^2 \geq 0 \tag{7}$$

where The desired position and orientation is given by $\eta_d^T = \begin{bmatrix} x_d & y_d & z_d & \phi_d & \theta_d & \psi_d \end{bmatrix}$ and the error in pose of the vehicle is given by $\bar{\eta} = \eta - \eta_d$.

Problem Statement: Given a desired region in (6) & (7), design a control law (τ) for the system described in (3) such that the following objectives are achieved:

1: The closed loop system in (3) must be asymptotically stable.
2: The system position converges to a particular region boundary or any specific point within the region.
3: The high filtered version of positional error eliminates the requirement for velocity measurement.

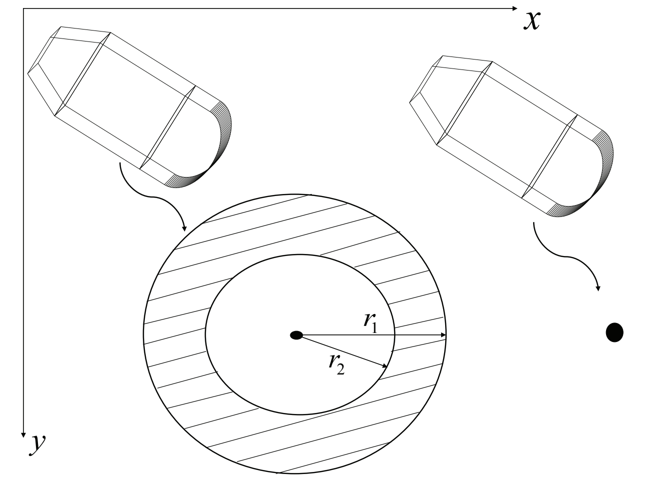

Fig. 2. AUV moving towards subregion with radius $(r_1 - r_2)$ and a fixed set-point respectively

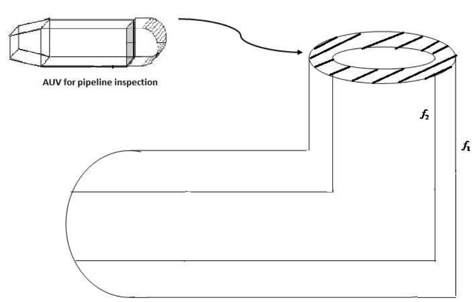

Fig. 3. Pipeline inspection scenario for an AUV

The potential energy for the outer f_1 and inner f_2 sub regions can be given as

$$P_1((\bar{\eta})) = \frac{k_1}{2}[\max(0, f_1(\bar{\eta}))]^2 = \begin{Bmatrix} 0 & f_1(\bar{\eta}) \leq 0 \\ \frac{k_1}{2} f_1^2(\bar{\eta}) & f_1(\bar{\eta}) > 0 \end{Bmatrix} \quad (8)$$

$$P_2((\bar{\eta})) = \frac{k_2}{2}[\max(0, f_2(\bar{\eta}))]^2 = \begin{Bmatrix} 0 & f_2(\bar{\eta}) \leq 0 \\ \frac{k_2}{2} f_2^2(\bar{\eta}) & f_2(\bar{\eta}) > 0 \end{Bmatrix} \quad (9)$$

By partial differentiating the potential energy of the regions, we get the net work done in the respective sub region.

$$e_1 = \frac{\partial P_1}{\partial \bar{\eta}} = \max(0, f_1)\left[\frac{\partial f_1(\bar{\eta})}{\partial \bar{\eta}}\right]^T \quad (10)$$

$$e_2 = \frac{\partial P_2}{\partial \bar{\eta}} = \max(0, f_2)\left[\frac{\partial f_2(\bar{\eta})}{\partial \bar{\eta}}\right]^T \quad (11)$$

Assuming the knowledge of the gravitational forces acting on AUV exactly, we can propose the input torque for regularizing the AUV within the sub region space as [7], [8]

$$\tau = -K_{s1}e_1 - K_{s2}e_2 + g(\eta) \quad (12)$$

where $K_{s1} = diag\{R^T k_1, 0_{3\times 3}\}$ and $K_{s2} = diag\{R^T k_2, 0_{3\times 3}\}$. However, this control law requires the knowledge of velocity. Over a past few decades there have been a significant amount of research for terrestrial robotics to develop algorithms that will eliminate the requirement of additional infrastructure for velocity measurement and to bound positional error as well. To overcome similar problems in the context of AUV, we propose a control law without velocity measurement and this is discussed in next section.

IV. Region Reaching Control without Velocity Measurement

The following control law is proposed for an AUV to maintain its position within a specified region

$$\tau = -K_{s1}e_1 - K_{s2}e_2 - K_d[\tanh(\lambda\bar{\eta})] - K_v[\tanh(\delta\varepsilon)] + g(\eta) \quad (13)$$

where ε is the high filtered version of error $\bar{\eta} = (\eta - \eta_d)$ synthesized by

$$\dot{\varepsilon} = -\alpha K\varepsilon + K\dot{\eta} \quad (14)$$

where $\varepsilon^T = [\varepsilon_1, ...\varepsilon_n]$ with $\dot{\bar{\eta}}_d = 0$. The proposed controller structure is presented in figure 4. From figure 4 we can see that controller design is based on high filtered version of positional error and proportional gain of region based error. The feedback matrices are taken as $K = diag[k]$, $K_d = diag[k_d]$, $K_v = diag[k_v]$, $\Delta = diag[\delta]$ and $\Lambda = diag[\lambda]$ for k, k_d, k_v, Δ and Λ to be positive scalar constants.

Using control law (13), the closed loop dynamics can be obtained as

$$\begin{aligned} &\dot{\bar{\eta}} = \dot{\eta} \\ &M\dot{v} + C(v)v + D(v)v + K_{s1}e_1 + K_{s2}e_2 + \\ &K_d\tanh(\lambda\bar{\eta}) + K_v\tanh(\delta\varepsilon) = 0 \\ &\dot{\varepsilon} = -\alpha K\varepsilon + K\dot{\eta} \end{aligned} \quad (15)$$

Main results are stated in the form of a theorem to prove the asymptotic stability of the nonlinear system considered.

Theorem 1: The closed loop system defined in (15), is globally asymptotically stable for damping matrix $D(v)$ and control law in (13).

Proof: Assuming the Lyapunov function to be of the form

$$\begin{aligned} V = &\frac{1}{2}v^T M v + \sqrt{L_N\cosh(\lambda\bar{\eta})}^T K_d \Lambda^{-1} \sqrt{L_N\cosh(\lambda\bar{\eta})} \\ &+ \sqrt{L_N\cosh(\delta\varepsilon)}^T K_v K^{-1} \Delta^{-1} \sqrt{L_N\cosh(\delta\varepsilon)} + \\ &\frac{1}{2}K_{s1}\left[\frac{e_1^T e_1}{\left\|\frac{\partial f}{\partial \bar{\eta}}\right\|^2}\right] + \frac{1}{2}K_{s2}\left[\frac{e_2^T e_2}{\left\|\frac{\partial f}{\partial \bar{\eta}}\right\|^2}\right] \end{aligned} \quad (16)$$

where the last two terms can be represented as

$$\frac{1}{2}K_{s1}\left[\frac{e_1^T e_1}{\left\|\frac{\partial f_1}{\partial \bar{\eta}}\right\|^2}\right] = \frac{1}{2}K_{s1}(max(0, f_1(\bar{\eta})))^2 \quad (17)$$

for outer region f_1 and similarly for the inner sub region. The time derivative for the described Lyapunov function can

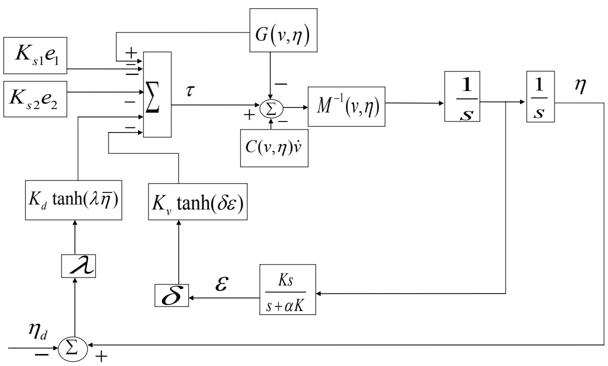

Fig. 4. Controller structure

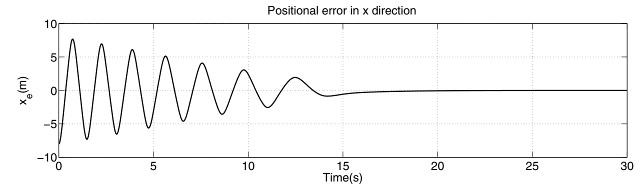

Fig. 5. Error in x-position(m)

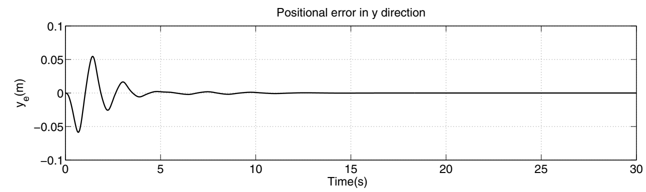

Fig. 6. Error in y-position(m)

be given as

$$\dot{V} = \dot{\nu}^T M \dot{\nu} + 2\sqrt{L_N \cos(\lambda\bar{\eta})} K_d \Lambda^{-1} \left[\frac{\tanh((\lambda\bar{\eta}))(\lambda\dot{\bar{\eta}})}{2\sqrt{L_N \cosh(\lambda\bar{\eta})}} \right]$$
$$+ 2\sqrt{L_N \cos(\delta\varepsilon)} K_v K^{-1} \Delta^{-1} \left[\frac{\tanh((\delta\varepsilon))(\delta\dot{\varepsilon})}{2\sqrt{L_N \cosh(\delta\varepsilon)}} \right]$$
$$+ K_{s1} \left[\max(0, f_1) \frac{\partial f_1}{\partial \bar{\eta}} \right] \dot{\eta} + K_{s2} \left[\max(0, f_2) \frac{\partial f_2}{\partial \bar{\eta}} \right] \dot{\eta} \tag{18}$$

Exploiting the properties of matrices defined in section II,

$$\dot{V} = -\nu^T D \nu - \alpha K_v \varepsilon \tanh(\delta\varepsilon) \tag{19}$$

As we know damping matrix $D(\nu)$ is positive definite matrix and the fact that $\varepsilon \tanh(\delta\varepsilon)$ is a positive definite function in ε, it can be concluded that $\dot{V}$ is a negative definite function. Thus the global asymptotic stability of the system is guaranteed without velocity measurement for the Lyapunov function defined in (16) with $\varepsilon \to 0$ and $\dot{\bar{\eta}} \to 0$ which leads to $\bar{\eta} \to 0$.

V. Simulation

This section illustrates the efficacy of the proposed controller in the previous section. In order to validate the control law designed in section V, ODIN underwater vehicle model [14], [15] has been used with specific mass, coriolis and damping matrix structure. The design parameters used are given as follows
$m = 125kg$, $r_G = [0,0,0.05]^T$, $\rho = 1000kg/m^3$, $\rho_v = 965kg/m^3$, $g = 9.81m/s^2$. For simulation purpose following parameters for the controllers were set at $K_d = diag[300]$, $K_v = diag[400]$, $K_{s1} = diag[18]$, $K_{s2} = diag[9.4]$, $\Lambda = I_6$, $\alpha = 0.5$, $\Delta = I_6$.

The reference set-point was given at $\eta_d = [8,0,5,0.2,0.15,0.2]^T$. The results in figure 5 - 8 shows that the control objective (i.e the regulation errors for $\bar{\eta}$ converges to zero) is achieved under the AUV model parameters chosen. The simulation work has been carried out considering radius of both region as 1 m. Figure 9 gives a 3 D view of AUV path from initial condition $[1.5,0,1,0,0,0]^T$ to target spherical region having centroid at $(8,0,5)$. Figure 10, 11, 12, 13 shows control input torques for six different velocity actuators.

VI. Conclusion

In this paper, a new region reaching based control law has been designed with and without velocity measurement for an autonomous underwater vehicle. The controller was designed such that the vehicle position converge to the centroid of the desired region. Proper controller parameters are selected for feedback to guarantee stability in the Lyapunov sense. Moreover, utilization of the filtered tracking error as a replacement for velocity measurement is novel from other region based control algorithms presented so far. However the proposed controller assumes exact knowledge of uncer-

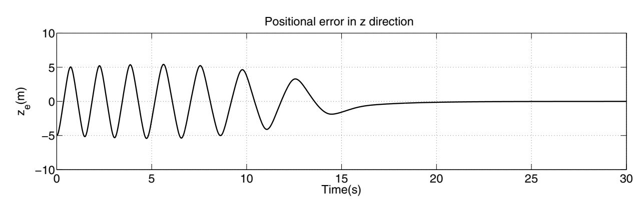

Fig. 7. Error in z-position(m)

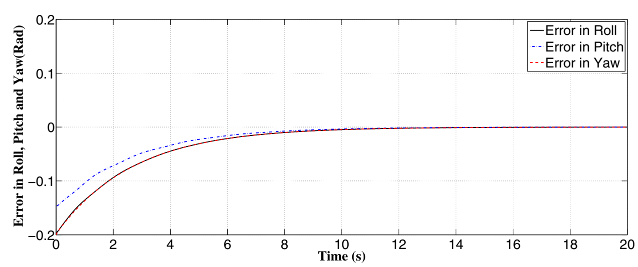

Fig. 8. Error in Roll, Pitch Yaw angle(rad)

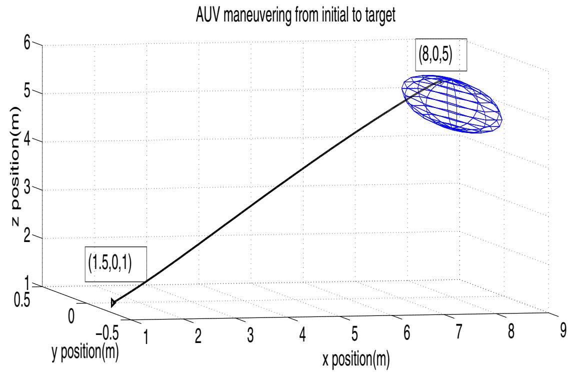

Fig. 9. Navigation of an Underwater Vehicle to a specific point within a specific region

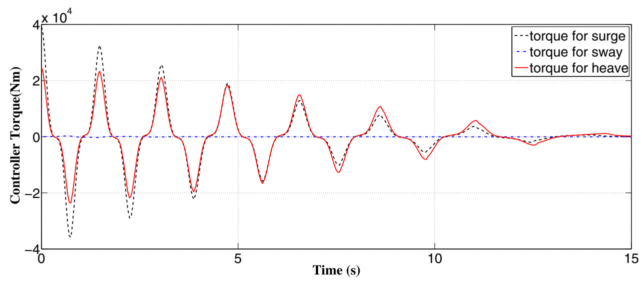

Fig. 10. Controller torque(N-m) for surge, sway and heave velocity

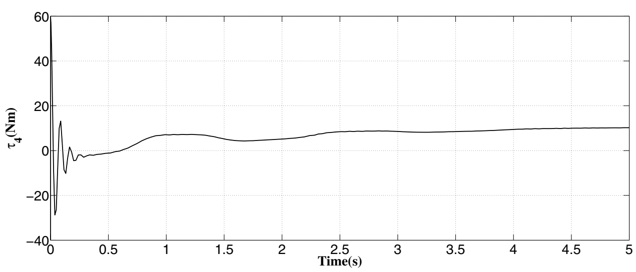

Fig. 11. Controller torque(N-m) for roll angular velocity

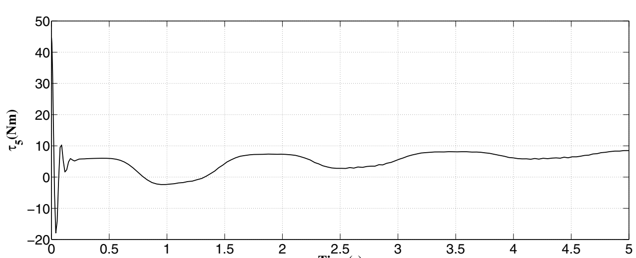

Fig. 12. Controller torque(N-m) for pitch angular velocity

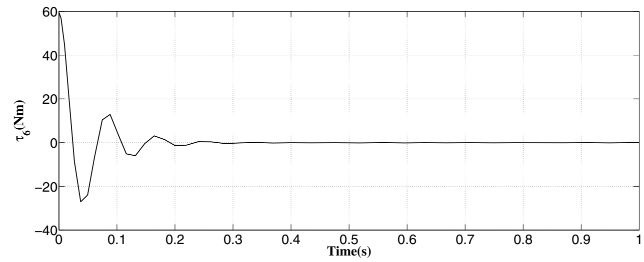

Fig. 13. Controller torque(N-m) for yaw angular velocity

tain terms which is not a realistic situation for underwater vehicles. So this work can be extended to compensation of unknown parameters.

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