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Observer Based Output Feedback Tuning for Underwater Remotely Operated Vehicle Based on Linear Quadratic Performance

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Abstract: This paper describes the effectiveness of observer-based output feedback for Unmanned Underwater Vehicle (UUV) with Linear Quadratic Regulation (LQR) performance. Tuning of observer parameters is crucial for tracking purpose. Prior to tuning facility, the ranges of observer and LQR parameters are obtained via system output cum error. The validation of this technique using unmanned underwater vehicles called Remotely Operated Vehicle (ROV) modelling helps to improve steady state performance of system response. The ROV modeling is focused for depth control using ROV 1 developed by the Underwater Technology Research Group (UTeRG). The results are showing that this technique improves steady state performances in term of overshoot and settling time of the system response.

Keywords: Observer-Based Output Feedback; linear quadratic regulation; unmanned underwater vehicle; remotely operated vehicle.
PACS: 05.

INTRODUCTION

Remotely Operated underwater Vehicle (ROV) is one of unmanned underwater vehicle tether by umbilical cable at underwater platform by pilot. FIGURE 1 shows the platform of ROV developed by UTeRG team with integrated sensor to obtain the modeling using system identification technique called SMART ROV 1. Design and specification of the ROV can refer in [1][2][3][4][5].This SMART ROV 1 have four thrusters where two thrusters for depth motion whereas another two for forward or reverse motion with 45° tuning angle. The experimental set up focuses on depth control. The experimental set up will be in a controlled water environment such as a lab tank and swimming pool. For depth control, overshoot in the system response are particularly dangerous [6]. Clearly an overshoot in the ROV vertical trajectory may cause damages to both the ROV and the inspected structure such as operates in cluttered environment [6][7]. Micro-Box 2000/2000C is a solution for prototyping, testing and developing real-time system using standard PC hardware for running real-time applications as shown in FIGURE 2. Microbox 2000/2000C acts as microcontroller and also called as XPC target machine. By using system identification toolbox in MATLAB, the modeling of ROV is obtained and being use to design the best controller for depth control. This paper also describes model obtained from strip theory.

This paper is organized as follows. In section 1, the introduction of Remotely Operated underwater Vehicle attached with the pressure sensor system is mentioned. Furthermore, Section 2 presents the theoretical on the mathematical modeling while Section 3 describes the literature review of other researchers. Last but not least, Section 4 and Section 5 illustrate the field testing results and compared with other researcher's simulation results. Finally, the final remarks are elucidated in Section 6.
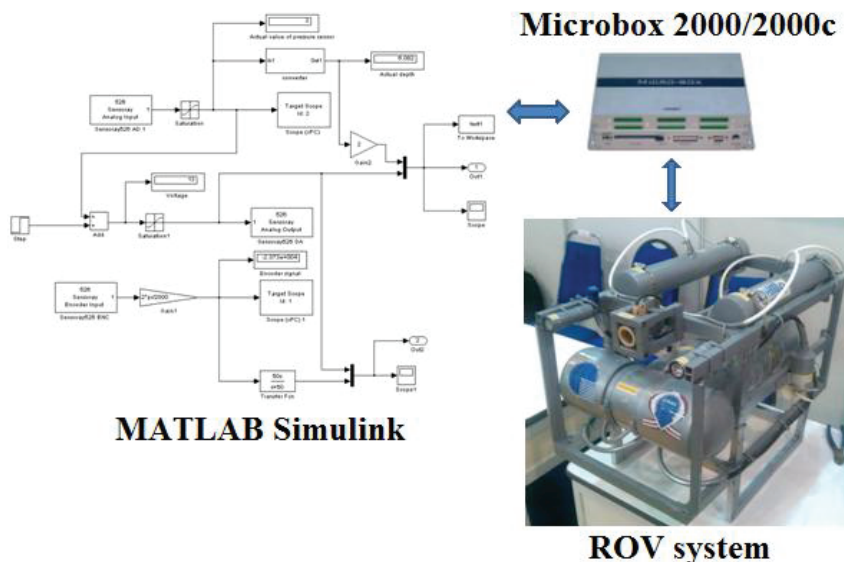
FIGURE 1. SMART ROV 1 system.

FIGURE 2. MATLAB Simulink for System Identification of ROV design.

MATHEMATICAL MODELING

When analyzing the motion of ROV in 6 Degree of Freedom (DOF) it is convenient to identify two coordinate frames that is body-fixed frame and earth-fixed frame as demonstrated [8]. Body-fixed frame is the moving coordinate frame - fixed to the centre of gravity of the ROV. Underwater vehicles motion model can be derived from dynamics equation of underwater vehicle. The dynamics of a 6-degree-of-freedom underwater vehicle can be described in the following general form as formula (1) in [8][9]:

$$m\dot{v} + C(v)v + D(v)v + g(\eta) = B(v)u \qquad (1)$$

where,

m is the 6 x 6 inertia matrix including hydrodynamic added mass.
$C(v)$ is the Matrix of Coriolis and centripetal forces.
$D(v)$ is the Hydrodynamic damping matrix.
$g(\eta)$ is the Vector of restoring forces and moments.
$B(v)$ is the 6 x 3 control matrix.

Generating mathematical model of unmanned underwater vehicle is very challenging because of the nature of underwater dynamics mainly due to the non-linear and coupled character of plant equations. The challenge is also due to the lack of precise model of underwater vehicles dynamics and parameters, as well as the appearance of environment disturbances [10]. It is possible to simplify the number of parameter making the certain

assumption related with ROV's construction. The following assertions were made for the dynamics of the ROV in order to simplify the modelling:

o The ROV travels at low speeds, that is, less than 1m/s
o Roll and pitch movement is passively controlled and therefore, considered to be negligible
o The ROV is considered to be symmetrical about its three planes
o During all manoeuvres the ROV is always maintained in a horizontal posture
o Disturbances from the water environment on the ROV such as currents and waves are negligible
o Sway, that is, movement along the vehicle's y axis, is negligible
o The ROV's degrees of freedom are decoupled

Since the ROV is considered to be fairly symmetrical and travels at low speed, the decoupling for the vehicle's degrees of freedom is valid. The decoupling means that the Coriolis and centripetal terms matrices become negligible and consequently can be eliminated from the dynamic model. The simplified dynamic model for the ROV then becomes,

$$m\dot{v} + D(v)v + g(\eta) = B(v)u \tag{2}$$

This means that only the inertial and damping parameters need to be identified for the ROV. The above assertions not only have important ramifications for the modelling of the ROV, but also for its control.

SIMPLIFYING THE DYNAMIC MODEL MATRICES

Based on the assumptions presented in the previous section, as well as measurements performed on the vehicle, the matrices of the dynamic model from [11] were simplified and adapted to the ROV. These simplified matrices are presented in this section. Note that since sway, roll and pitch are negligible, then the corresponding parameters in the following matrices have been set to zero since they are not required to be identified for controlling the ROV [12].

Mass and Inertia Matrix

With the vehicle frame positioned at the centre of gravity and since the vehicle is assumed fairly symmetrical about all axes, then M$_{RB}$ can then be simplified to a good approximation to (3) [4].

$$M_{RB} = \begin{bmatrix} m & 0 & 0 & 0 & 0 & 0 \\ 0 & m & 0 & 0 & 0 & 0 \\ 0 & 0 & m & 0 & 0 & 0 \\ 0 & 0 & 0 & I_X & 0 & 0 \\ 0 & 0 & 0 & 0 & I_Y & 0 \\ 0 & 0 & 0 & 0 & 0 & I_Z \end{bmatrix} \tag{3}$$

Since roll, pitch and sway are considered negligible, and then equation (3) can be further simplified to,

$$M_{RB} = \begin{bmatrix} m & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & m & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & I_Z \end{bmatrix} \tag{4}$$

where the mass of the "SMART ROV 1" was measured to be 18kg. It can be seen from equations (4) that the only parameter that needs identification for this matrix is the inertial moment about the z axis corresponding to yaw. Analogous to the simplification of M_{RB}, the added mass matrix, M_A, becomes,

$$M_A = \begin{bmatrix} X_{\dot{u}} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & Z_{\dot{w}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & N_{\dot{r}} \end{bmatrix} \tag{5}$$

Hydrodynamic Damping Matrix

The hydrodynamic damping matrix, D (V), simplifies to equation (6),

$$D(v) = \begin{bmatrix} X_u + X_{u|u|}\,|u| & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & Z_w + Z_{w|w|}\,|w| & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & N_r + N_{r|r|}\,|r| \end{bmatrix} \tag{6}$$

Gravitational and Buoyancy Vector

The weight of the SMART ROV was found to be 176.4N while the buoyant force was measured as 196N. Keeping in mind that roll and pitch are negligible, significantly simplifies to equation (7),

$$G = \begin{bmatrix} 0 \\ 0 \\ f_b - f_{rov} \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{7}$$

The value of -19.6N implies that the vehicle has residual buoyancy just as it was designed to have. The residual buoyancy equates to 4% of the vehicle's weight. Equation 6 shows that the gravitational and buoyant forces of the vehicle only affect the heave of the vehicle. This is expected given that the centres of gravity and buoyancy are aligned along the x and y axes, and hence, the gravitational and buoyant forces should then only affect vertical movement.

Forces and Torque Vector

By measuring the positions of the motors on the "SMART ROV 1", a layout of the thrusters depicting their respective distances to the vehicle's centre of gravity was attained. This can be seen in equation 8. The mapping matrix, L, for the SMART ROV 1 is given to a good approximation by,

$$
L = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & L3 & -L3 \\ L1 & -L1 & L4 & -L4 \\ L2 & -L2 & L5 & -L5 \end{bmatrix}
\tag{8}
$$

while the thrust vector is given by,

$$
U = \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix}
\tag{9}
$$

where T_1, T_2, T_3, T_4 represent the thrusts of the portside, starboard, bow and stern motors respectively. In equation 9, the first three rows signify whether or not a particular motor has an effect on the movement of the vehicle along the x, y and z directions. For instance, in the first row, the ones in the first two columns indicate that the horizontal motors are responsible for surge. The last three rows of the mapping matrix denote the distances from the centre of gravity to the thrusters. These values are either positive or negative corresponding to anticlockwise or clockwise moments respectively. The moments that are produced are responsible for affecting the vehicle's attitude. As can be seen in the fifth row of the mapping matrix, not only do the two vertical motors contribute to pitch, but so do the two horizontal motors. This implies that when the vehicle is surging either forwards or backwards, the horizontal motors will affect the pitch of the vehicle. However, when performing underwater manoeuvres, this effect was not observed, implying that the contribution to pitch by the horizontal motors is not significant. This is most likely attributable to the passive pitch control system. Also observed in the fifth row is the fact that each vertical motor is equidistant from the centre of gravity. Consequently, applying equal forces to these motors when diving, surfacing or hovering will maintain the vehicle in a reasonably horizontal posture.

OBSERVER BASED OUTPUT FEEDBACK BASED ON LQR PERFORMANCE

Notice that the value of *A*, *B*, *C*, and *D* matrices of our plant are known, so we can use these exact values in estimator. The input to the system, the output of the system, and the system matrices of the system are known. What we do not know, necessarily, are the initial conditions of the plant. What the estimator tries to do is to make the estimated state vector approach the actual state vector quickly, and then mirror the actual state vector. We do this using the following system for an observer. A state observer is a system that models a real system in order to provide an estimate of its internal state, given measurements of the input and output of the real system. It is typically a computer-implemented mathematical model. FIGURE 3 shows the block diagram of observer based feedback control output based on LQR using MATLAB simulink.

Parameter for N and M (observer) initially set to 1 as shown in FIGURE 3 and FIGURE 4. Value of N and M can be tune using intelligence method such as fuzzy logic controller (FLC), artificial neural network (ANN) and particle swarm optimization (PSO). MATLAB m-file used to tune the K, P, E parameter. Also in this algorithm make sure that the closed loop system is stable. If perturbation is put in system, initial condition will be set on integrator inside ROV system and then run simulation, look at the error scope to see the estimator can estimate the actual system states. Based on [13] underwater works with usage of ROV are made on the depth greater than 10 meters normally this depth (less than 10m) most underwater works is made by divers without necessity of using special equipment and this disturbance can be omitted. Based on facility and other constraints set point for depth were set to 5 meters deep. Main research and novel is to fine tuning parameter of K in LQR after tuning using MATLAB m-file and will be discussed next section.
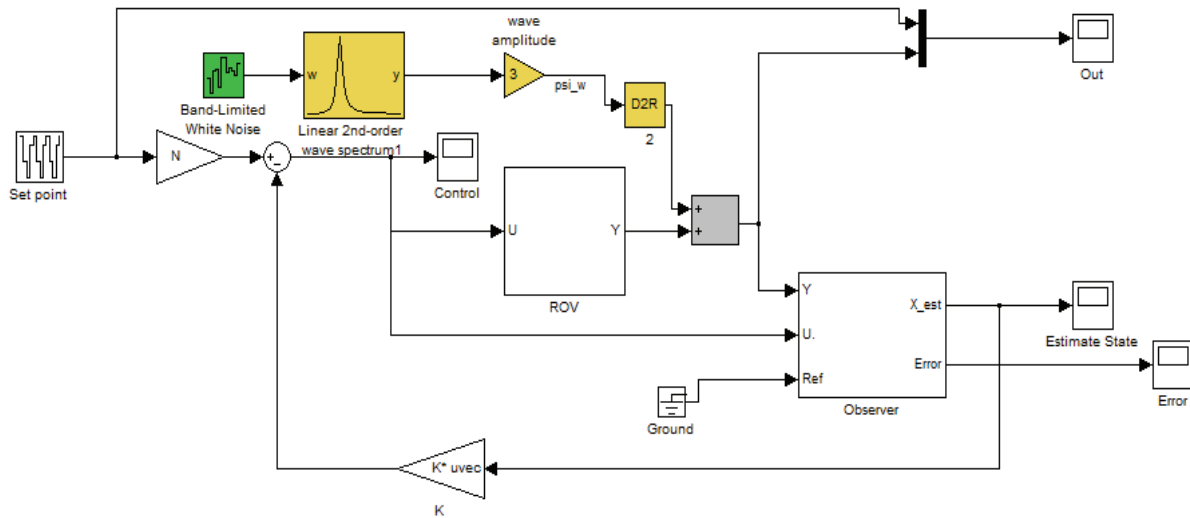
FIGURE 3. System configuration for observer based output feedback tracking control.
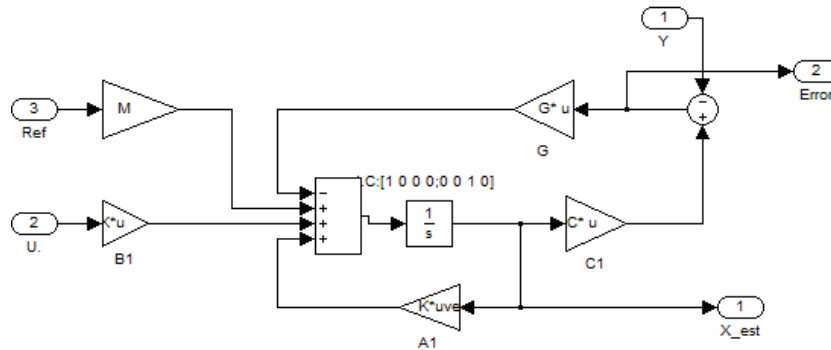

FIGURE 4. Block diagram for Observer.

RESULTS AND ANALYSIS

FIGURE 5 are shows the result observer based feedback output control based LQR. TABLE 1 and TABLE 2 are shows the performances of system response in term of steady state performances and execution time. The parameter of K, P, E will be tuning using MATLAB m-file as given in TABLE 3. FIGURE 6 shows closed up system response for observer based feedback output control based LQR. FIGURE 7 shows the estimate state. Our intention of this research to reduced error and increase steady state performances. The overshoot percentage of the system performances is below than 1.5%. So it considers being good performances and the SSE below than 1%.

TABLE (1). Steady state performances.

Item	LQR
Peak time, T_p (s)	75
Rise time, T_r (s)	70
Settling time, T_s (s)	75
Overshoot percentage (%)	0.7
Steady state error, e_{ss}	0.2

TABLE (2). Execution Time

Type of Controller	Computation Time
LQR	11.87 s

TABLE (3). Parameter of LQR

Parameter	Value			
K	0.7610	-0.6065	0.7841	1.0000
P	1.0319	-0.0906	1.4143	0.7553
	-0.0906	0.1548	0.0538	-0.1868
	1.4143	-0.0538	8.9791	0.6606
	0.7553	-0.1868	0.6606	1.8561
E				-2.5611 + 6.8916i
				-2.5611 - 6.8916i
				-0.6031 + 0.2326i
				-0.6031 - 0.2326i
G				1.0e+003 *
				6.2821
				-7.0501
				0.1209
				0.0595
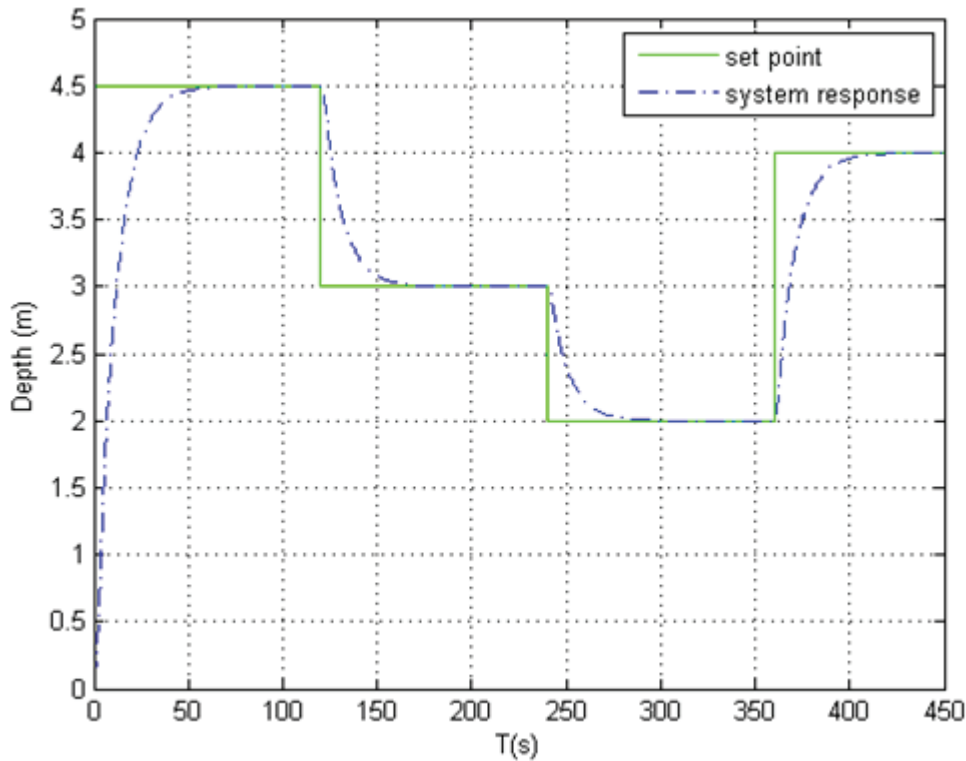
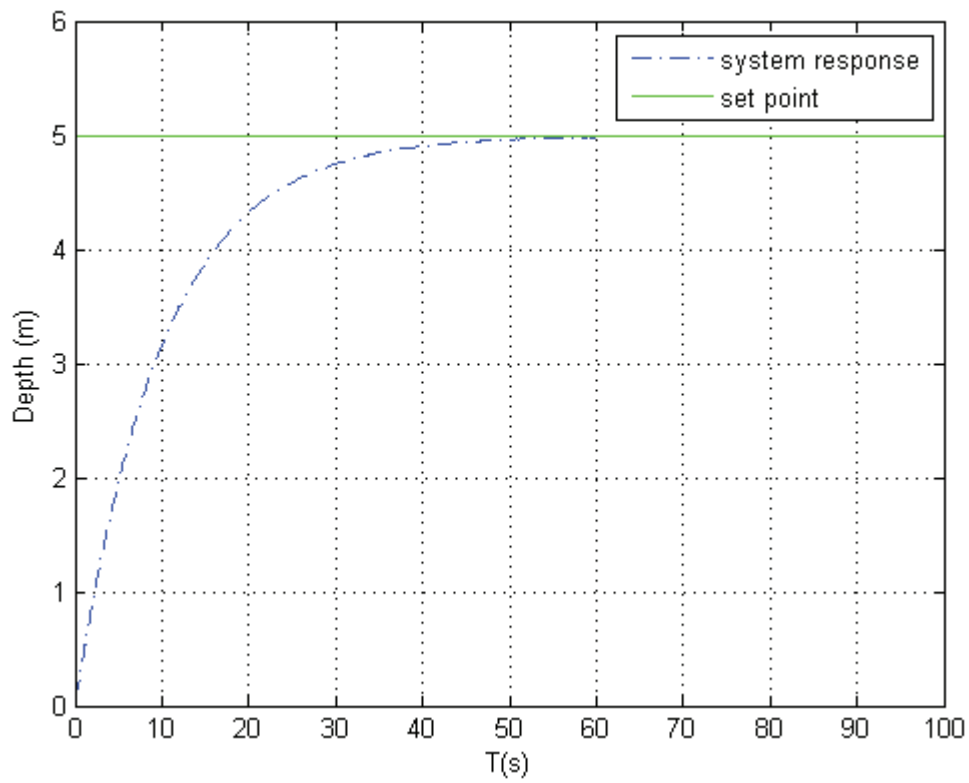**FIGURE 5.** System response for observer based feedback output control based LQR.

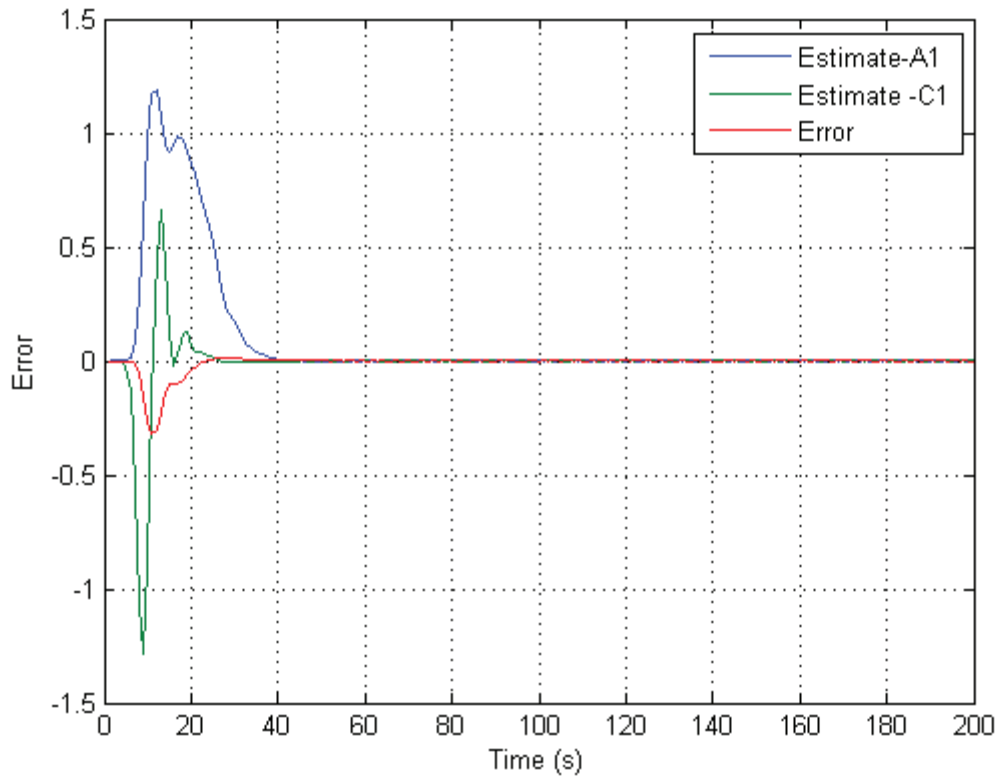**FIGURE 6.** Closed up system response.

FIGURE 7. Estimate state

CONCLUSION

The parameter of observer based output feedback based on Linear Quadratic Regulation (LQR) performance for Unmanned Underwater Vehicle (UUV) are successfully done. This technique will be improved steady state performance of system response for depth controls using SMART ROV 1 develop by UTeRG research group. The parameter LQR will be tuning based on output of system and error to get the range of parameter. The comparison between conventional controller and Observer based output feedback-LQR gives better performances compared others. The future works can be done the value of M and N can be tuned using artificial intelligence technique such as Fuzzy Logic, neural network or particle swarm so that the parameter will be better.

ACKNOWLEDGMENTS

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