Robust Heading Stabilization and Control for a class of Autonomous Underwater Vehicles using Nonlinear State Estimators

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Abstract— **The problem addressed in this research is robust heading stabilization and control of a class of Autonomous Underwater Vehicle. Mathematical formulation of this control problem starts from the six degree of freedom model of AUV. AUV model is then decoupled in heading plane and is considered for further investigation for suitable control design. This heading plane model is then transformed into an equivalent feedback linearizable normal form based on input to output linearizable system. Robust controller that is SMC is then designed for the stabilized heading control of AUV. Furthermore, Extended High Gain Observer is used to transform the feedback control into output feedback control. Computer Simulated responses of designed robust controller and robust output feedback controller are presented to show the effectiveness of the proposed controllers in different conditions.**

Keywords— Robust Control, Sliding Mode Control, High Gain Observer, Extended High Gain Observer, Output feedback control.

I. INTRODUCTION

Underwater robots including semi-autonomous and autonomous vehicles gained attraction of researchers because of their importance in marine discoveries as well as in defense sector. Due to their versatile critical applications, they encounter different nonlinear and uncertain disturbances and perturbation in parametric coefficients exposing them to become unstable. To ensure their stability, a robust control is always needed that can cater the nonlinearities and disturbances those leads to the un-stability of the system.

Scientists and researchers are working to address this problem for the past few decades. In this view, Thor I. Fossen has carried out a comprehensive study and research work in his Handbook [7]. It provides different motions control techniques for nonlinear dynamical marine crafts with their mathematical models.

Another author in [5] comprehensively discusses modelling, control, design and simulation of Autonomous Underwater Vehicles. Researchers in [2] & [3] proposed adaptive robust controllers for AUV's with and without input nonlinearities. Whereas cost efficient steering stabilizing controller for AUV is presented in [4] in conjunction with high gain observer to propose an optimal output feedback control. In [6], [7] & [13], authors proposed Sliding Mode Control technique to eliminate the parametric perturbations effects from AUV's states. A number of researchers adopted this robust control technique in their researches addressing the problem under consideration.

Khalil & Esfandiari in [8] proposed their observer design to recover uncertain systems state feedback performance under matching conditions. Authors in [9] & [10], proposed output feedback control based on High Gain Observers. The minimum phase, feedback linearizable system is first transformed into normal form. Then feedback control applied with the full order observer. In [12], Extended High Gain Observer (EHGO) is used to estimate the states of the system. Whereas disturbance is estimated using EHGO in [11].

The prime target of this research is to design a robust stabilizing heading control for AUV. In order to assure the recovery of the systems states output feedback control using nonlinear state estimators is used in conjunction with the robust controller. To achieve these goals, a generalized 6 DOF model of underwater vehicles is considered. This model is then reduced to heading plane model after some assumptions are taken into account.

The research structure includes mathematical modeling of AUV as Section II. Section III covers designing of robust control law for heading of AUV. Extended High Gain Observer based Output feedback control is covered in Section IV incorporating robust control law. Section V includes MATLAB simulations of proposed Sliding Mode Control with and without perturbations. This section also presents simulation results of SMC based Output feedback control using EHGO. At last, the conclusion of this whole research highlighting the simulations is summarized with its possible developments and recommendations for future in Section VI.

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II. MATHEMATICAL MODELING OF AUV

Mathematical modeling of nonlinear dynamical AUV system is a complex and challenging task. In this research, already derived generalized model of AUV from [2] is considered and is represented in the below equation (1),

$$M\dot{v}_b + C(v_b)v_b + D(v_b)v_b + g(\eta_e) = \tau \qquad (1)$$

This generalized model equation of AUV has inertial terms related matrix represented as ‘M’, centripetal terms matrix denoted by ‘C’, gravitation related matrix represented as ‘g’ and damping matrix represented as ‘D’. The vector containing control forces of AUV is denoted by 'τ'.

'η_e' is a vector having quantities related to earth fixed frame of reference whereas,

'v_b' is a vector containing quantities related to body fixed frame of reference quantities.

$$\eta_e = \begin{bmatrix} x & y & z & \phi & \theta & \psi \end{bmatrix}^T \qquad (2)$$

The above described vector represents the x, y and z positions of the AUV and the orientations associated with them i.e roll, pitch and yaw respectively.

$$v_b = \begin{bmatrix} u & v & w & p & q & r \end{bmatrix}^T \qquad (3)$$

The above vector represents all of the linear and angular velocities of the AUV along x, y and z axes.
Notions used here are referenced from SNAME [14].
The vector containing control forces of AUV including diving angle 'δ_s', the rudder angle 'δ_r' and propeller revolutions ‘n’ is represented in equation (4) below,

$$\tau = \begin{bmatrix} f(\delta_s) & f(\delta_r) & f(n) \end{bmatrix} \qquad (4)$$

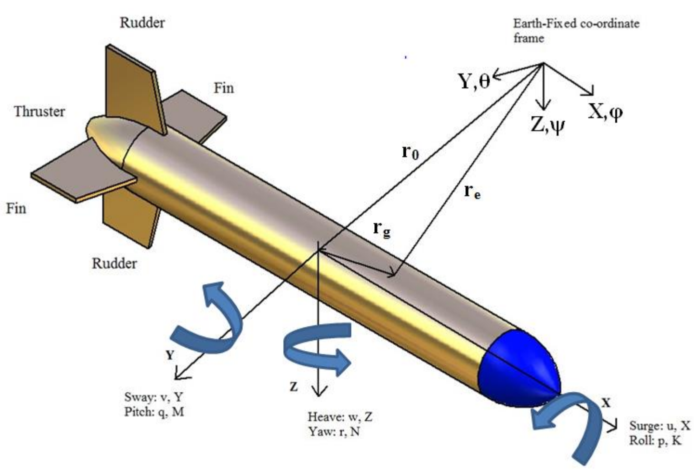

Fig. 1: Model of AUV showing earth and body fixed quantities [4]

Earth and body fixed positions and orientations with their respective linear and angular velocities are well described in Fig.1. Jacobian transformation is used to transform 'η_e' to body fixed frame of reference as shown in (5).

$$\dot{\eta}_e = J(\eta_e)v_b \qquad (5)$$

Now 6 DOF AUV model can be represented as

$$\begin{Bmatrix} M\dot{v}_b + C(v_b)v_b + D(v_b)v_b + g(\eta_e) = \tau \\ \dot{\eta}_e = J(\eta_e)v_b \end{Bmatrix} \qquad (6)$$

A generalized state space model for (6) can be represented as,

$$\dot{x} = f(x) + g(x)u \qquad (7)$$

In order to achieve heading control designing goal, coupled nonlinear dynamical model of AUV is decoupled. Heading plane decoupled model is considered with some assumptions including constant surge velocity of u=2m/s and small deflections in roll and pitch angles such that, $\phi \le 5^0$ and $\theta \le 5^0$.

Table 1: Heading Model of AUV after decoupling

Model after decoupling	Control Input	Required Elements
Heading	$\delta_r(t)$	v(t), r(t), ψ(t)

Following equations (8), (9), (10) of heading model of AUV are extracted after Jacobian transformation and decoupling of (6),

$$(\mathrm{m} - \mathrm{Y}_{\dot{v}})\,\dot{\mathrm{v}}_r = \mathrm{Y}_v v_r + (\mathrm{Y}_r - \mathrm{m}u)\mathrm{r} + \mathrm{Y}_\delta\,\delta_r \qquad (8)$$

$$(I_{zz} - N_{\dot{r}})\dot{r} = N_r r + N_v v_r + N_\delta \delta_r \qquad (9)$$

$$\dot{\psi} = r \qquad (10)$$

Heading model of AUV is represented in (11) rearranging the above equations,

$$\begin{Bmatrix} \dot{v} = \dfrac{Y_v}{m - Y_{\dot{v}}} v + \dfrac{Y_r - m\mu}{m - Y_{\dot{v}}} r + \dfrac{Y_\delta}{m - Y_{\dot{v}}} \delta_r \\ \dot{r} = \dfrac{N_v}{I_{zz} - N_{\dot{r}}} v + \dfrac{N_r}{I_{zz} - N_{\dot{r}}} r + \dfrac{N_\delta}{I_{zz} - N_{\dot{r}}} \delta_r \\ \dot{\psi} = r \end{Bmatrix} \qquad (11)$$

Representing $v_s = \begin{bmatrix} v & r \end{bmatrix}^T$ and $\eta_s = \begin{bmatrix} \psi \end{bmatrix}$, the state vector of heading model of AUV becomes $\begin{bmatrix} v_s & \eta_s \end{bmatrix}^T$.
For simplification, following change of variables are implemented in (11)

$x_1 = v =$ Linear velocity along y-axis (m/s)

$x_2 = r =$ Rate of change of heading (rad/s)

$x_3 = \psi = y =$ Heading of AUV (rad)

Now simplified heading model of AUV of (11) becomes.

$$\begin{Bmatrix} \dot{x}_1 = M_{11}x_1 + M_{12}x_2 + M_{13}\delta_r \\ \dot{x}_2 = M_{21}x_1 + M_{22}x_2 + M_{23}\delta_r \\ \dot{x}_3 = x_2 \end{Bmatrix} \qquad (12)$$

The coefficients M_{11}-M_{23} are described in the Appendix.

In order to stabilize and control the heading of AUV, steering angle 'ψ' is selected as,

$$y = x_3 \qquad (13)$$

III. ROBUST CONTROL DESIGNING

Heading control system of AUV presented in (12-13) can also be represented as,

$$\begin{aligned} \dot{x} &= M_A x + M_B \delta_r \\ y &= Cx \end{aligned} \tag{14}$$

$$M_A = \begin{bmatrix} M_{11} & M_{12} & 0 \\ M_{21} & M_{22} & 0 \\ 0 & 1 & 0 \end{bmatrix},\ M_B = \begin{bmatrix} M_{13} \\ M_{23} \\ 0 \end{bmatrix},\ C = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}^T$$

Since it is necessary to check the controllability of the system prior to design its control, controllability matrix rank is calculated using the formula

$$\hat{C}(M_A, M_B) = \begin{bmatrix} M_B & M_A M_B & \dots & M_A^{\ n-1} M_B \end{bmatrix} \tag{15}$$

After evaluation the system is found to be controllable as $rank(\hat{C}) = 3 = n$.

A. FEEDBACK LINEARIZATION OF HEADING CONTROL SYSTEM OF AUV

In this research, we are dealing with single control input that is rudder angle of the AUV expressed as $'\delta_r'$ and single control output that is steering angle of AUV expressed as $'\psi'$. This type of system can be represented as Single-Input-Single-Output (SISO) as in (16),

$$\begin{aligned} \dot{x} &= M_A x + M_B x \delta_r \\ y &= Cx \end{aligned} \tag{16}$$

In this case, the rudder angle control input $'\delta_r'$ is appearing in two states shown in (12) of heading model of AUV, it is not possible to select the control input such that it cancels the nonlinearities associated with both of the states. In order to solve this problem, the heading model of AUV of (12) is transformed to an equivalent feedback linearizable system.

$$\dot{x} = Ax + B\alpha(x) * \{u - \kappa(x)\} \tag{17}$$

here $A \in \Re^{nxn}$, $B \in \Re^{nxq}$.

The functions $\kappa : \Re^n \to \Re^q$ $and\, \alpha : \Re^n \to \Re^{qxq}$ are well defined in domain $D \subset R^n$ that contains origin. And $\alpha(x)$ is a non-singular matrix having all values of x in domain D. Let us suppose that system equations presented in (12) can be represented as system equations described in (17), then the nonlinear dynamical model for heading of AUV can be linearized using state feedback as presented in (18),

$$u = \kappa(x) + o(x)v \tag{18}$$

here, $o(x) = \alpha^{-1}(x)$

Equivalent feedback linearizable system in (17) can be represented as,

$$\dot{x} = Ax + Bv \tag{19}$$

Here 'v' will be designed such that the states of the system stabilizes.

The system represented in (14) is feedback linearized to normal form using transformation matrix. For this purpose, the relative degree $'\rho'$ of the AUV heading model required to be calculated. Output of the system, that is $'\psi'$ needs to be, differentiated a number of times until the control input $'\delta_r'$ appears. Differentiating the output,

$y = x_3,\quad \dot{y} = \dot{x}_3 = x_2,\quad \ddot{y} = \dot{x}_2 = M_{21}x_1 + M_{22}x_2 + M_{23}\delta_r$

Relative degree of the system is $\rho = 2 < n$

Since the relative degree is less than that of the system, therefore the system for heading model of AUV is input to output linearizable.

From theorem 1 of [2],

$$T(x) = \begin{vmatrix} \phi_1(x) \\ \vdots \\ \phi_{n-\rho}(x) \\ \hline h(x) \\ \vdots \\ L_f^{\rho-1} h(x) \end{vmatrix} = \begin{bmatrix} \eta \\ \hline \xi \end{bmatrix} \tag{20}$$

For the system (14),

$$T(x) = \begin{bmatrix} \eta \\ \hline \xi \end{bmatrix} = \begin{vmatrix} \phi_1(x) \\ \hline h(x) \\ L_f h(x) \end{vmatrix} \tag{21}$$

The condition described in theorem 1 of [2] should be fulfilled while choosing $\phi_1(x)$. As, $B = \begin{bmatrix} M_{13} & M_{23} & 0 \end{bmatrix}^T$ selecting

$$\phi_1(x) = \frac{x_1}{M_{13}} - \frac{x_2}{M_{23}} \tag{22}$$

and its differentiation leads to $\dot{\phi}_1(x) = \begin{vmatrix} \frac{1}{M_{13}} & -\frac{1}{M_{23}} & 0 \end{vmatrix}$

that satisfies $\dot{\phi}_k g(x) = 0$.

And

$$h(x) = x_3 \tag{22}$$

For $L_f h(x) = \dfrac{\partial h(x)}{\partial x} f(x)$

$$f(x) = \begin{vmatrix} M_{11}x_1 + M_{12}x_2 \\ M_{21}x_1 + M_{22}x_2 \\ x_2 \end{vmatrix} \tag{23}$$

$$\frac{\partial h}{\partial x} = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \tag{24}$$

$$L_f h(x) = \frac{\partial h(x)}{\partial x} . f(x) = x_2 \tag{25}$$

Resulting (21) to be,

$$T(x)=\begin{bmatrix}\eta \\ \cdots \\ \xi\end{bmatrix}=\begin{bmatrix}\frac{x_1}{M_{13}}-\frac{x_2}{M_{23}} \\ \hdashline x_3 \\ x_2\end{bmatrix} \tag{26}$$

where,

$$\eta_1=\frac{x_1}{M_{13}}-\frac{x_2}{M_{23}}$$

$$\xi_1=x_3$$

$$\xi_2=x_2$$

Writing $x_1, x_2\ and\ x_3$ in terms of $\eta_1, \xi_1\ and \xi_2$,

$$x_2=\xi_2 \tag{27}$$

$$x_3=\xi_1 \tag{28}$$

$$x_1=M_{13}\eta_1+\frac{M_{13}}{M_{23}}\xi_2 \tag{29}$$

Substituting the values of $x_1, x_2\ and\ x_3$ in (12) results in,

$$\dot{x}_3=\dot{\xi}_1=x_2=\xi_2$$

$$\dot{\xi}_1=\xi_2 \tag{30}$$

$$\dot{x}_2=\dot{\xi}_2=M_{21}(M_{13}M_{23}\eta_1+M_{13}\xi_2)+M_{22}\xi_2+M_{23}\delta_r$$

$$\dot{\xi}_2=(M_{13}M_{21}M_{23})\eta_1+(M_{13}M_{21}+M_{22})\xi_2+M_{23}\delta_r \tag{31}$$

$\eta_1=\frac{x_1}{M_{13}}-\frac{x_2}{M_{23}}$, its differentiation results in,

$\dot{\eta}_1=\frac{\dot{x}_1}{M_{13}}-\frac{\dot{x}_2}{M_{23}}$ and solving yields,

$$\dot{\eta}_1=\left(M_{11}-\frac{M_{13}M_{21}}{M_{23}}\right)\eta_1+\left(\frac{M_{11}}{M_{13}}-\frac{M_{13}M_{21}}{M_{23}^2}+\frac{M_{12}}{M_{13}}-\frac{M_{22}}{M_{23}}\right)\xi_2 \tag{32}$$

Normal form of heading model of AUV is presented in (33) combining equations (30-32),

$$\begin{Bmatrix}\dot{\eta}_1=W_1\eta_1+W_2\xi_2 \\ \dot{\xi}_1=\xi_2 \\ \dot{\xi}_2=W_3\eta_1+W_4\xi_2+W_5\delta_r\end{Bmatrix} \tag{33}$$

The coefficients M_1-M_5 are described in the Appendix.

First state equation out of three shows the internal dynamics of the system having no direct connection to the output. Internal dynamics of the systems is verified to be BIBO stable with zero dynamics condition. Now controller needs to be calculated for AUV heading models external states. In order to stabilize the AUV heading system in described in (33), δ_r must be chosen to remove all the nonlinearities in the system. To achieve this objective, a distributive controller is proposed in (34),

$$\delta_r=u+v \tag{34}$$

here $u=\frac{1}{W_5}\left[-W_3\eta_1-W_4\xi_2\right]$

B. CONTROL DESING USING SLIDING MODE CONTROLLER

Sliding Mode Control is considered as basic control approach in the development of robust control for the nonlinear dynamical system. SMC is needed to be designed for heading model of AUV to robustly stabilize the system. There are two phases in implementing the SMC. In the first phase, also called "reaching phase", systems states trajectories are brought to a sliding manifold close to origin within finite time. The second phase is called the 'sliding phase', once the state trajectories reaches the sliding manifold they should not leave it to provide semi global bounded solution.

One of the objectives of implementing SMC is that the systems states tracks the desired reference trajectories. The error state vector can be represented as,

$$\tilde{X}=X-X_D=\begin{bmatrix}x_1-x_{D1} \\ x_2-x_{D2}\end{bmatrix} \tag{35}$$

For SMC designing, a sliding surface or manifold needed to be defined, such as

$$\sigma=S^T X \tag{36}$$

The sliding surface can be represented coordinate as,

$$\sigma=\begin{bmatrix}s_1 & s_2\end{bmatrix}\begin{bmatrix}x_1-x_{D1} \\ x_2-x_{D2}\end{bmatrix} \tag{37}$$

Choosing the coefficients of surface vector 'S' such that $\lim_{t\to\infty}\dot{\sigma}\to 0$ *i.e* $\lim_{t\to\infty}\sigma\to 0$ ensuring $\lim_{t\to\infty}\tilde{X}=\lim_{t\to\infty}(X-X_D)\to 0$

Considering energy lyapunov function,

$$V(\sigma)=\frac{1}{2}\sigma^2 \tag{38}$$

Conditions need to be determined that ensures the stability of the system. Taking derivative of lyapunov function,

$$\dot{V}(\sigma)=\sigma\dot{\sigma}\le-\rho^2\left|\sigma\right|^2 \tag{39}$$

here $'\rho'$ is a design parameter and needs to be positive definite.

The condition imposed in (39) can also be expressed as,

$$\dot{\sigma}\le-\rho^2\,\mathrm{sgn}(\sigma) \tag{40}$$

Differentiating the sliding manifold defined in (37) yields

$$\dot{\sigma}=S^T\dot{\tilde{X}} \tag{41}$$

having $\dot{\tilde{X}}=AX+B\delta_r-\dot{X}_D$. Now (41) becomes,

$$\dot{\sigma}=S^T(AX+B\delta_s-\dot{X}_D)\le-\rho^2\,\mathrm{sgn}(\sigma)$$

Solving for control input $'\delta_s'$ yields,

$$\delta_r \le -(S^T B)^{-1} S^T AX + (S^T B)^{-1} S^T \dot{X}_D - (S^T B)^{-1} \rho^2 \,\mathrm{sgn}(\sigma) \quad (42)$$

The controller described in (42) is based on two types of controllers. The first controller is the stabilizing controller that is expressed as,

$$\hat{\delta}_r = -(S^T B)^{-1} S^T AX + (S^T B)^{-1} S^T \dot{X}_D \quad (43)$$

The second controller is the switching controller that is expressed as,

$$\overline{\delta}_r = (S^T B)^{-1} \rho^2 \,\mathrm{sgn}(\sigma) \quad (44)$$

Since X_D is constant in our case, the stabilizing controller of (43) becomes,

$$\hat{\delta}_s = -(S^T B)^{-1} S^T AX \quad (45)$$

Now under stabilizing control $\hat{\delta}_s = -PX$ and matrix P can be selected such that it places eigenvalues of the closed loop system to ensure the convergence of the state trajectories at the sliding surface within finite time. Now the closed loop system becomes,

$$\dot{X} = (A - BP)X \quad (46)$$

Since $\sigma = S^T \tilde{X} = 0$, so $\dot{\sigma} = S^T \dot{\tilde{X}} = 0$ and therefore, $\dot{\sigma} = S^T \dot{X} = 0$ resulting $S^T (A - BP) = 0$ or

$$(A - BP)^T S = 0 \quad (47)$$

The sliding surf face vector S coefficients is the eigenvector of $(A - BP)^T$ that is associated with null vector.

The heading model of AUV in error coordinates is now can be expressed as,

$$\dot{\tilde{X}} = (A - BP)\tilde{X} - BPX_D + (S^T B)^{-1} \rho^2 \,\mathrm{sgn}(\sigma) \quad (48)$$

Due to the discontinuous nature of $\mathrm{sgn}(\sigma)$, chattering occurs. To compensate this problem $sat(\frac{\sigma}{\lambda})$ is introduced. 'λ' is a small design parameter such that $0 < \lambda < 1$.

Now the controller becomes,

$$\delta_r = \hat{\delta}_r + \overline{\delta}_r = -P(\tilde{X} + X_D) + (S^T B)^{-1} \rho^2 sat(\frac{\sigma}{\lambda}) \quad (49)$$

The resultant closed loop system becomes,

$$\dot{\tilde{X}} = (A - BP)\tilde{X} - BPX_D + (S^T B)^{-1} \rho^2 sat(\frac{\sigma}{\lambda}) \quad (50)$$

The proposed SMC is defined in (51),

$$\delta_r = \frac{1}{M_5}\left[-M_3\eta_1 - M_4\xi_2 - \rho^2 sat\{(\alpha\xi_1 - \beta\xi_2)/\lambda\} \right] (51)$$

The values of design parameters considered are $(S^T B)^{-1} = -1$ $\rho^2 = 0.9$ $and\ \lambda = 0.5$.

IV. EXTENDED HIGH GAIN OBSERVER BASED OUTPUT FEEDBACK CONTROL

In order to recover unmeasured states of heading control system of AUV, an observer needs to be introduced with the proposed controller. Therefore observability of the system under consideration needs to be tested.

The observability matrix rank is calculated in order to evaluate the observability of the system

$$\hat{O}(W_A, C) = \left[C \quad CW_A \quad \dots \quad CW_A^{\,n-1} \right]^T \quad (52)$$

After evaluation the system is found to be observable as $rank(\hat{O}) = 3 = n$.

Due to its effectiveness in estimating systems states, EHGO has a unique position in the family of nonlinear state estimators. Therefore, the proposed SMC controller in (51) is transformed into EHGO based robust output feedback control to achieve the requirements of effective states estimation.

The basic structure of an EHGO is different from that of HGO in a sense that one extra state '$\hat{\sigma}$' is augmented in the structure of HGO. Now the EHGO set of equations for the external states of the system in (33) becomes,

$$\left\{ \begin{aligned} \dot{\hat{\xi}}_1 &= \hat{\xi}_2 + \gamma_1(y - \hat{\xi}_1) \\ \dot{\hat{\xi}}_2 &= M_3\eta_1 + M_4\hat{\xi}_2 + M_5\delta_r + \hat{\sigma} + \gamma_2(y - \hat{\xi}_1) \\ \dot{\hat{\sigma}} &= \gamma_3(y - \hat{\xi}_1) \end{aligned} \right\} \quad (53)$$

Here the gains are selected such that,

$$\begin{bmatrix} \gamma_1 \\ \gamma_2 \\ \gamma_3 \end{bmatrix} = \begin{bmatrix} 2/\gamma \\ 1/\gamma^2 \\ 1/\gamma^3 \end{bmatrix} \quad (54)$$

And 'γ' needs to be selected as small design parameter so that it can reduce error in estimated and actual states as $\gamma \to 0$.

Finally, SMC based robust output feedback controller using EHGO is proposed in (55).

$$\delta_r = \frac{1}{M_5}\left[-M_3\hat{\eta}_1 - M_4\hat{\xi}_2 - \rho^2 sat\{(\alpha\hat{\xi}_1 - \beta\hat{\xi}_2)/\lambda\} \right] \quad (55)$$

V. SIMULATIONS

For simulation purposes, the numerical values of AUV hydrodynamics coefficients, added masses and physical parameters are used of REMUS 100. Values of α and β are selected such that, $\alpha = 0.3$, $\beta = 0.5$. Initial conditions of AUV used are $\begin{bmatrix} v & r & \psi \end{bmatrix}^T = \begin{bmatrix} -0.02 & 0.09 & 0.01 \end{bmatrix}^T$. The saturation limit imposed on the controller output is 0.35 rad ($\approx 20^0$).

A. Sliding Mode Control

Systems states of heading model of AUV using Sliding Mode Controller of (51) are shown in Fig.2 and Fig.3.

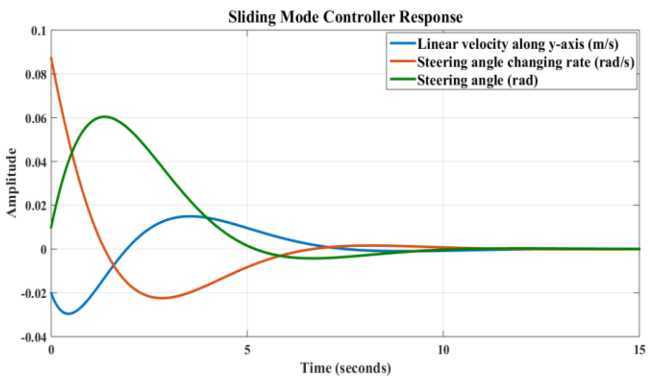

Fig. 2 States Responses using Sliding Mode Control

Systems states responses using Sliding mode control with 40% parametric perturbations of the system are shown in Fig.3.

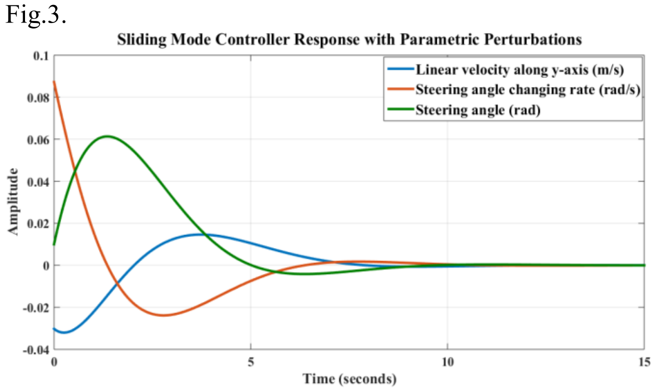

Fig. 3: States Responses using Sliding Mode Control under Perturbations

The steering angle error between the two cases (with and without perturbation) applying SMC is shown in Fig.4.

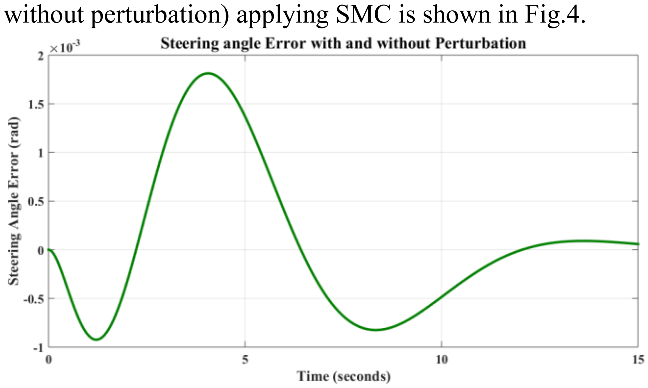

Fig. 4 Steering angle error with and without perturbation

B. Extended High Gain Observer

An EHGO based robust output feedback control proposed in (55) is used for simulation purposes. The proposed controller in Fig.5 and Fig.6 effectively estimates the steering angle and its rate.

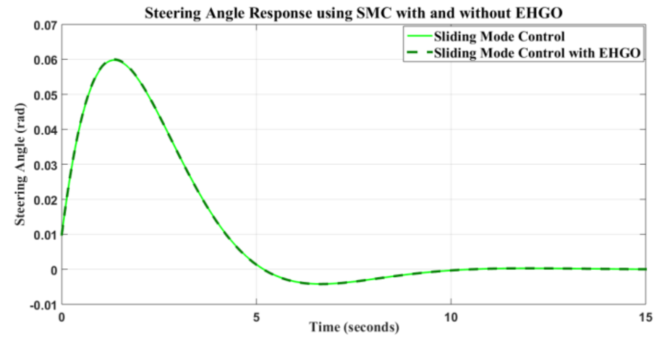

Fig. 5 Steering Angle Response using SMC with and without EHGO

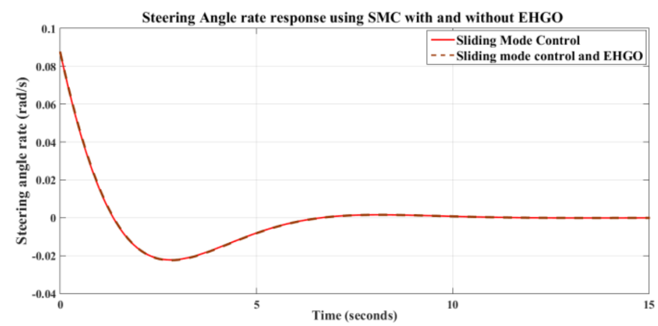

Fig. 6: Steering Angle Rate Response using SMC with and without EHGO

Both of the system states are estimated efficiently using SMC based EHGO.

VI. CONCLUSION

In this research, nonlinear dynamical model of AUV is taken as a benchmark system and is decoupled in heading plane. This system is then transformed into a feedback linearized system and a robust SMC is proposed. The effectiveness of SMC is proved in Fig.4 showing an error of only about 0.002 rad in steering angle when a parametric perturbation of 40% is introduced into the system. In Fig.5 and Fig.6 the steering angle and its rate are perfectly estimated by the EHGO showing effectiveness of the proposed controller. It is concluded that by using the SMC controller with EHGO, the system trajectories converges to the sliding surface in finite time. Also the closed loop system trajectories will stay be bounded in the bounded layer described by $\sigma \le \lambda$.

Future recommendations includes output feedback control using sliding mode observer and adaptive output feedback control of AUV using nonlinear state estimators. Higher order sliding mode output feedback control of AUV using nonlinear Extended High Gain Observer (EHGO) as state estimators.

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APPENDIX

$$M_{11} = \frac{Y_v}{m - Y_{\dot{v}}},\ M_{12} = \frac{Y_r - m\mu}{m - Y_{\dot{v}}},\ M_{13} = \frac{Y_\delta}{m - Y_{\dot{v}}}$$

$$M_{21} = \frac{N_v}{I_{zz} - N_{\dot{r}}},\ M_{22} = \frac{N_r}{I_{zz} - N_{\dot{r}}},\ M_{23} = \frac{N_\delta}{I_{zz} - N_{\dot{r}}}$$

$$W_1 = M_{11} - \frac{M_{13}M_{21}}{M_{23}},\ W_2 = \frac{M_{11}}{M_{13}} - \frac{M_{13}M_{21}}{M_{23}^2} + \frac{M_{12}}{M_{13}} - \frac{M_{22}}{M_{23}}$$

$$W_3 = M_{13}M_{21}M_{23},\ W_4 = M_{13}M_{21} + M_{22},\ W_5 = M_{23}$$