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Piece-wise Linear Fuzzy Sliding Mode Controller for Deep Submergence Rescue Vehicle (DSRV)

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Abstract

The paper aims to present the design and performance of a Single Input Fuzzy Sliding Mode Controller (SIFSMC) to control the motion of a Deep Submergence Rescue Vehicle (DSRV). The proposed controller uses the linear-single dimension rule base whereas the Conventional Fuzzy Sliding Mode Controllers (CFSMC) uses the two-dimensional rule base. Moreover, the proposed controller does not merely depend on the DSRV exact mathematical model unlike that of the linear controllers. Using SIFSMC, the number of rules governs are also greatly reduced in comparison with the CFSMC, without compromising the overall performance. The robustness, equivalency, and efficacy of the proposed idea are illustrated through the simulation results using a marine system simulator in MATLAB/Simulink® environment. The main objective of the paper is to compare CFSMC and SIFSMC for Unmanned Underwater Vehicles (UUV's). Consequently, a comparative analysis of the proposed SIFSMC is shown with the CFSMC for the same system of DSRV.

Index Terms: *Fuzzy Controller, Piece-Wise Linear Approach, Sliding Mode, Control Design, Unmanned Underwater Vehicle.*

I. INTRODUCTION

Over the years, the importance of Unmanned Underwater Vehicle (UUV), has been significantly increased in marine environmental exploration. Also, the usage and application of UUVs have increased drastically. Having said that, the dynamics of UUV'S are highly non-linear, hydro-dynamically coupled, and somehow vague [1]. Consequently, the control of such vehicles has become a very challenging task for researchers.

Several efforts have been carried out by the researchers to develop a non-linear control approach for such systems. For instance, Sliding Mode Control (SMC) [2-7], Fuzzy Logic Control (FLC) [6-15], and Artificial Neural Network (ANN) is found to be very effective in controlling these systems [16] and [17]. Furthermore, several works in the literature are reported that have employed the combination of these approaches to attain better results such as high robustness and immunity to external disturbances. An added advantage of these non-linear controllers that outperforms them from their linear counterparts is the self-learning and adaptive capability. However, due to the complexity in the dynamics of the marine vehicle, it is often difficult to obtain an exact dynamic model. Thus, the applications of model-based control schemes like SMC are found to be less interesting to the researchers as compared to the remaining two which do not require such models.

It is quite evident from the reported works that both FLC and ANN appear to be extremely promising for marine applications; however, both approaches require considerably high computational power due to intricate decision-making steps [18]. For instance, the use of ANN in ship tankers is envisaged to be unsuitable due to its impulsiveness, for real-time self-tuning [19-21]. In a similar fashion, conventional FLC involves a number of processing stages that include fuzzification, rule base, inference, and defuzzification for its proper implementation [22-25]. It should be noted that a larger set of rules brings significant improvement in the control performance; however, in that case, FLC consumes a longer computational time [26] and [27]. Additionally, several other parameters such as the system's response in real-time, bandwidth, computational capability, and the employed battery of the vehicle make the implementation aspects more difficult. Undoubtedly, employing FLC with complex computation stages might not be the correct choice under such a scenario and may lead to a significant computational burden. Similarly, nevertheless, despite these tangible issues, it is often said that, in comparison to other non-linear controllers, FLC is relatively less computationally intensive and offers a higher degree of freedom [28]. Therefore, it is believed that if a simplified FLC control structure could be achieved, it would not just improve the computational speed but will also ensure a simpler implementation strategy for fuzzy controllers [29-31]. Moreover, to achieve better performance along with robustness and simplicity in structure, a fuzzy controller is integrated with SMC.

SMC is a widely used controller and has been employed in several non-linear applications. However, a major drawback of SMC is chattering at the steady-state response of the system [32-34]. One way of reducing this chattering effect is to create a linear saturation boundary layer by embedding a sliding mode and fuzzy inference system to the main controller. The idea is to reduce the chattering by tuning the control gains continuously with the sliding surface. The employed hybrid controller is therefore termed as Conventional Fuzzy Sliding Mode Control (CFSMC).

This paper presents a simplified yet effective fuzzy sliding mode controller for a Deep Submergence Rescue Vehicle (DSRV). The key feature of the proposed scheme is a computationally effective controller with a minimum number of rules to be inferred, fuzzified and defuzzified. This reduction in computational burden and fuzzy stages is obtained by reducing a conventional two-input FLC to a single-input FLC and the proposed controller is named as Single Input Fuzzy Sliding Mode Controller (SIFSMC). Moreover, the usefulness and robustness of the proposed control strategy are demonstrated via simulation using a marine system simulator in MATLAB/Simulink® environment.

II. UUV'S KINEMATICS AND DYNAMICS

The DSRV model presented here is suggested by [35]. SNAME notations are used for the modeling of DSRV [36]. Conventionally, two reference frames are used for developing the model (i) global reference (XYZ) (ii) fixed-body frame ($X_0Y_0Z_0$). The fixed-body frame represents both translational and rotational components of motions and is modeled by six velocities components named: surge (u), sway (v), heave (w), roll (p), pitch (q), and yaw (r), respectively. These velocity factors are represented in the vector form as:

$$v = [u \quad v \quad w \quad p \quad q \quad r] \tag{1}$$

The orientation and placement of the DSRV are defined by Euler's angle, in accordance with the global frame of reference.

$$\eta = [x \quad y \quad z \quad \phi \quad \theta \quad \psi]^T \tag{2}$$

Both the coordinate systems (global and fixed body) are mapped by means of Euler's angle transformation:

$$\dot{\eta} = J(\eta)v \tag{3}$$

Where:

J is the matrix representing the Angle of 'Transformation'.

Furthermore, the non-linear dynamics of the vehicle is given by:

$$M\frac{dv}{dt} + C(v)v + D(v)v + g(\eta) = B(v)u \tag{4}$$

Where:

$M, C(v), D(v)$, and $B(v)$ are the inertial, centripetal forces, hydrodynamic damping, and the control matrix respectively.

$g(\eta)$ is a vector that contains restoring movements and forces.

The rigid-body equations of motion (w and q) are written explicitly for the horizontal and vertical axis. It is assumed that along the horizontal axis the origin is coinciding with the center of gravity, therefore, v and r are zero. While for the vertical plane, the forward speed is assumed to be constant. Thus, v and r modes are neglected. Moreover, during the steady-state, angle of roll and pitch are also assumed to be either constant or zero. The matrix form of resulting dynamics is given by:

$$\begin{bmatrix} m - Z\dot{w} & mx_G - Zq & 0 & 0 \\ mx_G - M\dot{w} & I_y - Mq & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{w} \\ \dot{q} \\ \dot{\theta} \\ \dot{z} \end{bmatrix} + \begin{bmatrix} -Zw & mu_0 - Z\dot{q} & 0 & 0 & 0 \\ Mw & mx_G u_0 - Mq & BG_z W & 0 & 0 \\ 0 & -1 & 0 & 1 & 0 \\ -1 & 0 & u_0 & 0 & 0 \end{bmatrix} \begin{bmatrix} w \\ q \\ \theta \\ z \end{bmatrix} \tag{5}$$

It is to be noted that the factor, $BG_Z W = Z_G - Z_B$ is the vertical distance between the Center of Body (CoB) and Center of Gravity (CoG).

The main dimension parameters are taken from [37] and [38]. The state-space representation of the system at a speed of 4.22 m/sec is given as:

$$\begin{bmatrix} \dot{w} \\ \dot{q} \\ \dot{\theta} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} -0.523 & -2.52 & 0.086 & 0 \\ 3.21 & -3.13 & -44.68 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & -5.11 & 0 \end{bmatrix} \begin{bmatrix} w \\ q \\ \theta \\ z \end{bmatrix} = \begin{bmatrix} 0.415 \\ -3.68 \\ 0 \\ 0 \end{bmatrix} \delta_s \tag{6}$$

III. CONVENTIONAL SLIDING MODE CONTROLLER

The proposed idea of sliding mode control is derived from the variable structure control scheme in which the control input is changed as per systems states. Consequently, it is dynamically efficient in comparison to several existing conventional control structures. In this section, the SMC method is proposed to design the trajectory tracking controller. The designing of SMC involves two steps i.e., assigning the sliding surface, and the control law in order to ensure that the system states move toward and remains on the intersection of the sliding surface [39]. The tracking error is defined as:

$$e = \eta - \dot{\eta} \tag{7}$$

The sliding surface is selected as:

$$s = \dot{e} - ce \tag{8}$$

Where:

c is the gain.

The adopted sliding law is as follows [19]:

$$\dot{s} = -\rho s - ksign(s) \tag{9}$$

Where:

ρ and k are both diagonal positive definite matrices.

IV. CONVENTIONAL FUZZY SLIDING MODE CONTROL DESIGN (CFSMC)

The Conventional Fuzzy Sliding Mode Controller (CFSMC) is known as the robust controller and for unmanned vehicles, it effectively overcomes the model uncertainties. Integrating Fuzzy control with the sliding mode is supposed to be a difficult task. In past, many researchers cascaded the SMC with fuzzy to form CFSMC [40]. Several algorithms in the literature review, are found to be integrated with robust control design i.e. SMC with the FLC. One widely used approach is the fuzzy boundary layer SMC, in which, the SIGN function is replaced by the fuzzy rule base so that the input to the system is shifted towards the sliding surface and keeps on sliding smoothly, this ultimately reduces the chattering effect. In order to design the CFSMC for the DSRV the sliding surface is of the form given below as [41]:

$$s = [e \quad \dot{e}]\begin{bmatrix} k \\ 1 \end{bmatrix} \tag{10}$$

The distance from the state trajectory error to the sliding surface s is L_{sn} and is given below as:

$$L_{sn} = \frac{(\dot{e}_Q + k\dot{e}_Q)}{\sqrt{1+k^2}} \tag{11}$$

$$L_o = \sqrt{N^2 - L_{sn}^2} \tag{12}$$

L_{sn} is the normal distance between the sliding surface s and the arbitrary point $\mathrm{Q}(\mathrm{e_Q}, \dot{\mathrm{e}}_\mathrm{Q})$ whereas, L_o is the vectorial distance from N to L_{sn} and can be found mathematically by using the eq. (15) shown graphically in Figure 1.

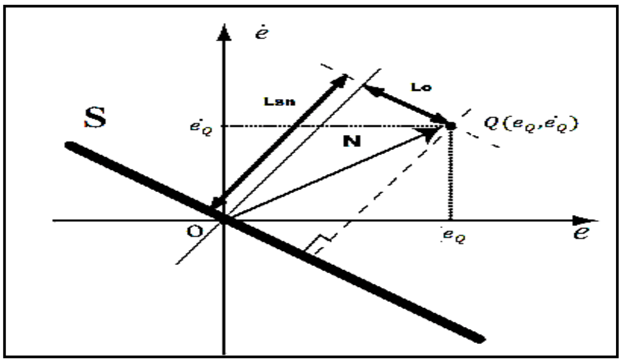

Figure 1: Graphical Representation of L_{sn} and L_o

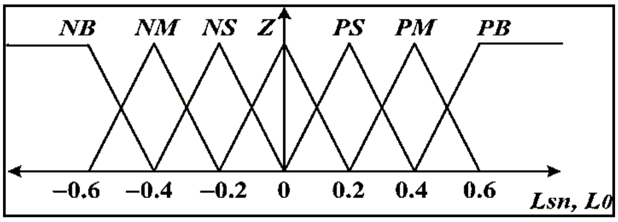

Figure 2: Input Membership Function for CFSMC

To move towards and stay on the sliding surface at an inappropriate time and with minimum chattering, one must design the fuzzy rule base by taking L_{sn} and L_o as inputs to the fuzzy controller and the output of the CFSMC serves as the control input for DSRV.

The linguistic variables used for the input L_{sn} and L_o are $NB, NM, NS, Z, PS, PM,$ and PB are of triangular memberships with except at the saturation where trapezoidal MFs are used. Whereas for the output, the membership functions used are singleton, the defuzzification method used, is the Center of Gravity method (CoG) [42]. The universe of discourse choose for all the inputs and output variables is (-1 to 1). The rule table has a Toeplitz structure [43] and [44] shown in Table 2. The inputs L_{sn}, L_o, and output d membership functions are respectively shown in Figure 2 and Figure 3. The overall principle block diagram of the FSMC when subjected to the DSRV is shown in Figure 4.

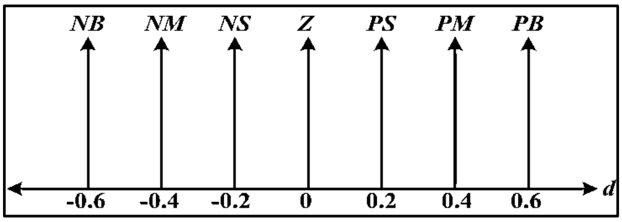

Figure 3: Output Membership Function for CFSMC

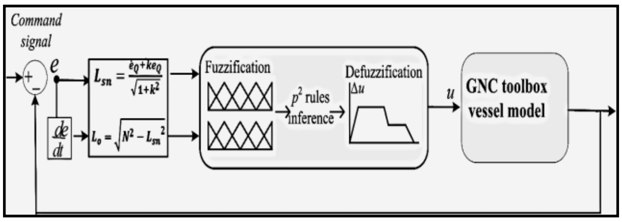

Figure 4: Overall Block Diagram for CFSMC for the DSRV

V. SINGLE INPUT FUZZY SLIDING MODE

In this proposed SIFSMC controller, by using the Signed Distance (SD) method [45] and [46] the complex structure of the 2-D rule table CFSMC is reduced into 1-D with insignificant alteration in the performance of the controller. The SIFSMC can be derived from the previously mentioned sign distance method CFSMC as the inputs to the controller L_{sn} and L_o can be reduced to single input by using the variable D assigned distance. It can be seen from Table 2 that D represents the diagonals of Table 1. So, by using the simple distance from point to line we can develop the relationship between the L_{sn}, and L_o. The equation of the main diagonal is of the form:

$$L_{sn} + \alpha L_o = 0 \tag{13}$$

In the above equation, α is the slope of the main diagonal D_Z and is equals to -1 since the diagonal is the bisector of the 2nd and 4th quadrant as shown by Table 2. Figure 5 reflects the signed distance method and its derivation. The reduced table after applying the signed distance is shown in Table 3. Now the distance between the two diagonals can find using the equation i.e., eq. (14) as shown below:

$$d = \frac{(L_{sn} + \alpha L_o)}{\sqrt{1+\alpha^2}} \tag{14}$$

Table 1: A Typical CFSMC Rules for Two Fuzzy Inputs

L_o \ L_{sn}	NB	NS	NS	Z	PS	NS	PB	
PB	Z	PS	PM	PB	PB	PB	PB	
NS	NS	Z	PS	PM	PB	PB	PB	
PS	NM	NS	Z	PS	PM	PB	PB	
Z	NB	NM	NS	Z	PS	PM	PB	
NS	NB	NB	NM	NS	Z	PS	PM	D_{PB}
NS	NB	NB	NB	NM	NS	Z	PS	D_{PM}
NB	NB	NB	NB	NB	NM	NS	Z	D_{PS}
Saturation					D_{NB}	D_{NM}	D_{NS}	D_Z

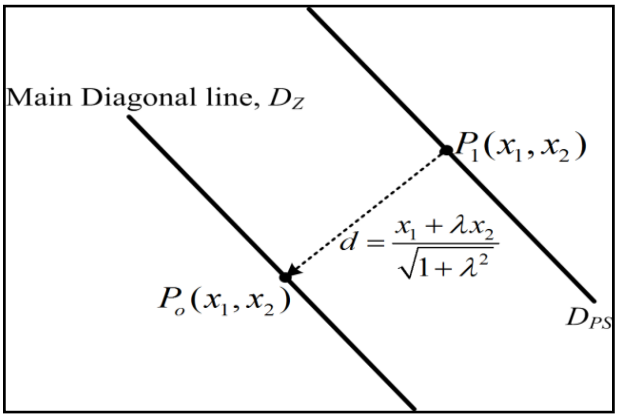

Figure 5: Simplified Approach for the Reduction of CFSMC using SD Method

Table 2 shows the relation of u as a one-dimension rule table. The diagonals $DNB, DNM, DNS, DZ, DPS, DPM, DPB$ in Table 1 now serve as the inputs for Table 2. Whereas the output is the same as was for the two-dimensional rule base. The input memberships function for the SIFSMC is shown in Figure 6, whereas the output membership function is the same as shown in Figure 3. The foremost benefit of the SIFSMC is that it can be implemented using only single input which results in the reduction of rules, so the several processes involved in the fuzzy control that include fuzzification, defuzzification, and rule inference also reduced, that ultimately reduces the computational burden for SIFSMC. The overall block diagram of the SIFSMC when subjected to the DSRV is shown in Figure 7.

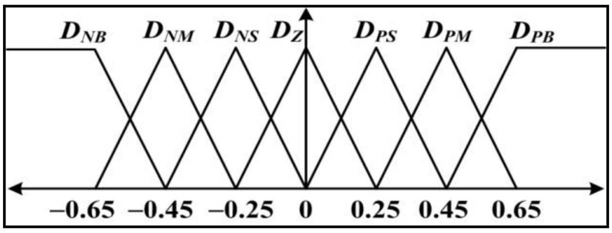

Figure 6: Input Membership Function for SIFMC

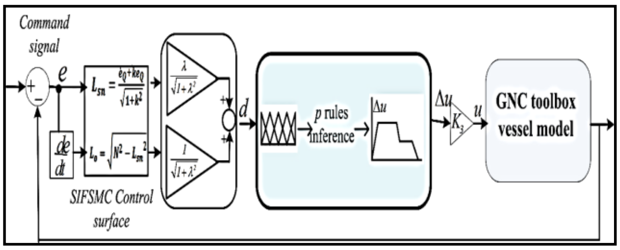

Figure 7: Overall Block Diagram for SIFSMC for the DSRV

VI. RESULTS AND DISCUSSION

To authenticate the efficiency of the proposed idea, the performance of the DSRV system is simulated on Marine Systems Simulator (MSS). The MSS is a comprehensive MATLAB/Simulink® based simulator that provides indispensable resources for the hasty implementation of marine systems while specifically focusing on control system design. The modular simulator structure and the possibility of distributed development are the main features of MSS that make it a comprehensive tool for marine simulations. The utilization of MSS for the design of marine controllers can be seen in various works, such as [47-50]. It must be noted that the objective of this paper is to show the performance equivalency of the CFSMC and SIFSMC for the DSRV system. Thus, the performance comparison with the other control scheme is not discussed here.

The FSMC and its simplification that is SIFSMC is designed as described in Section IV and V respectively. To evaluate the performance of CFSMC and SIFSMC a comparison is made with SMC. The latter is designed using the procedure outline in Section III. The simulated response of the SMC and FSMC can be shown in Figure 8; the desired depth required is $50\,m$. Both the SMC and FSMC responses successfully achieved the desired depth response with negligible overshoots, steady-state error, and a very less settling time. The superiority of FSMC can be well understood by observing the behavior of response after it got settled, SMC simulated response has visible chattering after attaining the desired steady-state whereas the FSMC response is quite smooth, which validates the effectiveness of the proposed controller.

Table 2: New Rules using SD Method

Input, d	D_{NB}	D_{NM}	D_{NS}	D_Z	D_{PS}	D_{PM}	D_{PB}
Output, Δu	NB	NM	NS	Z	PS	PM	PB

Figure 9 shows the comparative study of both the FSMC and its simplification of SIFSMC for all the four parameters of DSRV i.e., heave velocity, pitch velocity, pitch angle, and depth. As proposed, they reveal better transient and steady-state performance. The response obtained is smooth and chattering less even after the addition of environmental disturbance which validates the effectiveness of FSMC and SIFSMC that encounters the robustness of SMC and reduces the chattering phenomena that are the greatest drawback of sliding mode control. However, a distinguishing attribute of SIFSMC can be readily observed due to its identical transient and steady-state response for DSRV to that of FSMC.

Table 3 shares the initial parameters of DSRV. The results in this paper, compare the computational time of the two controllers. These computations are carried out using the standard desktop PC with Intel (R) Core (TM) i5-2400 processor @ 3.10GHz, 2 GB RAM, under Windows 7 operating system. It is seen that computational-wise, SIFSMC is found to be 2 times better than CFSMC due to the elimination of one input, the processing stress is lessened and so is the computation time of SIFSMC. This observation is attributed to the fact that various processing blocks (fuzzification, inference mechanism, rules computation, and defuzzification), are reduced. Thus, an inherent advantage of SIFSMC is that it can be implemented using a slower and low-cost µ-processor.

Table 3: Initial Parameter for DSRV

Depth	0 meters
Stern plane deflection	30^0
Cruise speed	8 knots (4.11m/sec)
Ship length	5 meters.

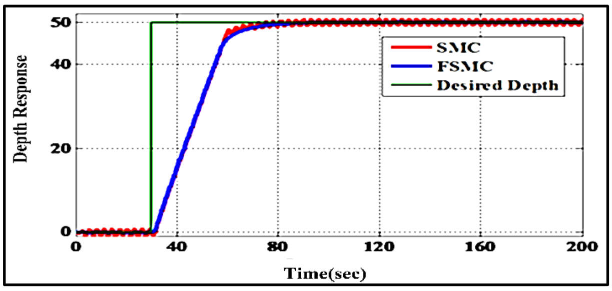

Figure 8: SMC and FSMC Controlled Response for Depth

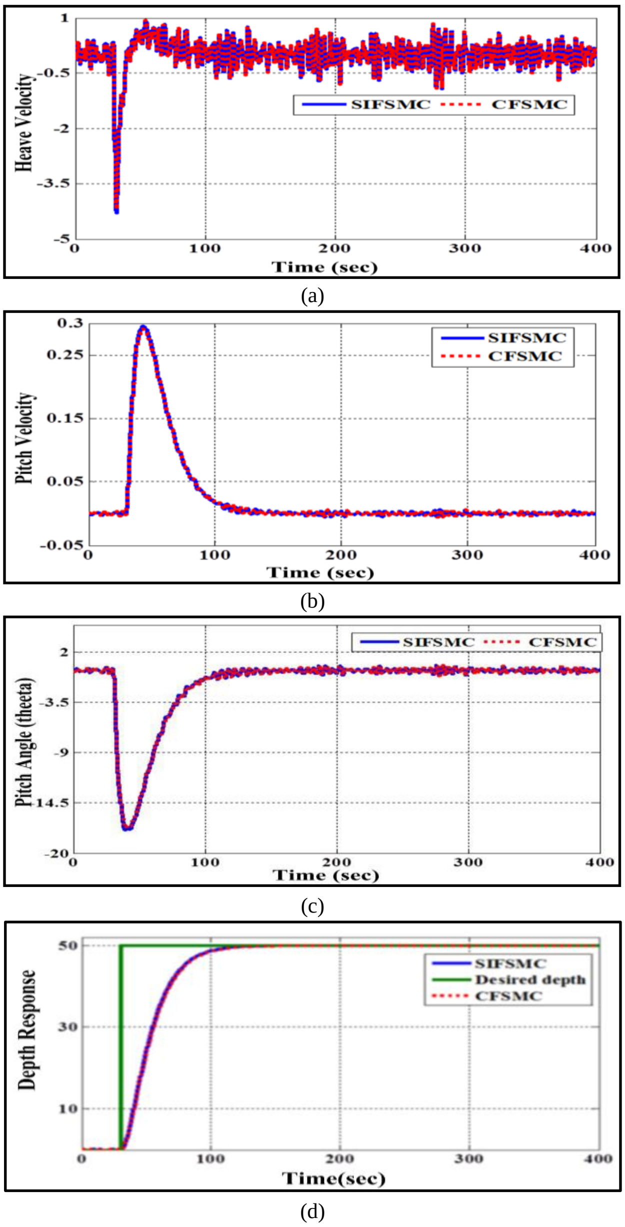

Figure 9: CFSMC and SIFSMC Controlled Response (a) Heave Velocity (b) Pitch Velocity (c) Pitch Angle (d) Depth

It should be noted that the proposed dynamic model is linearized at an equilibrium state and therefore, the research never discusses the impact of unmodelled dynamic factors. Research is still in progress for designing the intelligent observer design to address this issue.

VII. CONCLUSION

The sliding mode control technique provides better performance for trajectory tracking cases but it leads the system towards the unwanted noise of high frequency known as Zeno or chattering phenomena.

This manuscript presents the comparison between single input-based fuzzy SMC (SIFSMC) control design and conventional fuzzy SMC (CFSMC) technique for DSRV system. The simulations performed using MATLAB/Simulink demonstrate both techniques which have the same performance, but CFSMC needs some extra processing time as compared to the SIFSMC technique which can lead to expensive hardware design and implementation. The scope of this work at this moment is limited to only simulations but the researchers of this manuscript are still working to propose prototype level experiments to validate the simulation results with the hardware results.

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Authors Contribution

Conceptualization, Saba Javed and GM Abro; methodology, GM Abro; software, Saba Javed; GM Abro. validation, GM Abro; formal analysis, Saba Javed; investigation, GM Abro; resources, Saba Javed; writing—original draft preparation, Saba Javed; writing—review and editing, Saba Javed; and GM Abro visualization, Saba Javed; supervision, Saba Javed. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

There is no conflict of interest between all the authors.

Data Availability Statement

The testing data is available in this paper.

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