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 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 proposed idea is 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 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 has 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 the 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) are found to be very effective in controlling of 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 counterpart is the self-learning and adaptive capability. However, due to the complexity in the dynamics of marine vehicle it is often difficult to obtain 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 appears to be extremely promising for marine applications; however, both the approaches require considerably high computational power due to intricate decision making steps [18-30]. 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 number of processing stages that include fuzzification, rule base, inference and defuzzification for its proper implementation [22-25]. It should be noted that larger set of rules brings significant improvement in the control performance; however, in that case, FLC consumes longer computational time [26-27]. Additionally, several other parameters such as 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 scenario and may lead to significant computational burden. Similarly, nevertheless, despite of these tangible issues, it is often said that, in comparison to other non-linear controllers, FLC is relatively less computationally intensive and offers 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 simpler implementation strategy for fuzzy controller [29-31]. Moreover, to achieve better performance along with the robustness and simplicity in structure, 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 [30]. One way of reducing this chattering affect 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 proposed scheme is a computationally effective controller with 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 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 is 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 [23]. SNAME notations are used for the modeling of DSRV [22]. Conventionally, two reference frame are used for developing the model (i) global reference (XYZ) (ii) fixed-body frame (X₀Y₀Z₀). The fixed-body frame represents both translational and rotational component of motions and is modeled by six velocities components named as: surge (u), sway (v), heave (w), roll (p), pitch (q), and yaw (r), respectively. These velocity factors are represented in the vector form as:

\[ \mathbf{v} = [u \ v \ w \ p \ q \ r] \]  

(1)

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

\[ \eta = [x \ y \ z \ \phi \ \theta \ \psi]^T \]  

(2)

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

\[ \dot{\eta} = J(\eta) \mathbf{v} \]  

(3)

Where:

\( J \) is the matrix representing the Angle of ‘Transformation’.

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

\[ M \dot{\mathbf{v}} + C(v) \mathbf{v} + D(v) \mathbf{v} + g(\eta) = B(v) \mathbf{u} \]  

(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 \( r \) is zero. While for 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:

\[
\begin{bmatrix}
    m-Z\dot{w} & m_\alpha - Zq & 0 & 0 & 0 \\
    m_\alpha - M\dot{w} & l_y - Mq & 0 & 0 & \frac{\dot{\theta}}{\theta} \\
    0 & 0 & 1 & 0 & 0 \\
    Z_\omega & m_\omega - Z\dot{q} & 0 & 0 & 0 \\
    -Z_\omega & m_\omega u_0 - Z\dot{q} & 0 & 0 & 0 \\
    M_\omega m_\alpha u_0 - Mq & BG_\omega W & 0 & 0 & \dot{\theta} \\
    0 & -1 & u_0 & 0 & 0 \\
    -1 & 0 & u_0 & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
    \dot{w} \\
    \dot{q} \\
    \dot{\theta} \\
    \dot{w} \\
    \dot{q} \\
    \dot{\theta} \\
    \dot{w} \\
    \dot{q} \\
\end{bmatrix}
\]

(5)

It is to be noted that the factor, \( BG_\omega W = Z_\alpha - Z_\alpha \) is the vertical distance between the Center of Body (CoB) and Center of Gravity (CoG).

The main dimension parameters are taken from [29-30]. The sate space representation of the system at a speed of 4.22 m/sec is given as:

\[
\begin{bmatrix}
    \dot{w} \\
    \dot{q} \\
    \dot{\theta} \\
\end{bmatrix} =
\begin{bmatrix}
    -0.523 & -2.52 & 0.086 & 0 \\
    3.21 & -3.13 & -44.68 & 0 \\
    0 & 1 & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
    w \\
    q \\
    \theta \\
\end{bmatrix} +
\begin{bmatrix}
    0.415 \\
    -3.68 \\
    0 \\
\end{bmatrix}
\]

(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, 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 [23]. The tracking error is defined as:

\[ e = \eta - \bar{\eta} \]  

(7)

The sliding surface is selected as:

\[ s = \dot{e} - ce \]  

(8)

Where:

\( c \) is the gain.

The adopted sliding law is as follows [19]:

\[ \dot{s} = -\rho s - ksgn(s) \]  

(9)

Where:

\( \rho \) 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 the unmanned vehicles it effectively overcomes the model uncertainties. Integrating Fuzzy control with sliding mode is supposed to be a difficult task. In past many researchers cascaded the SMC with fuzzy to form CFSMC [25]. 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 keep 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 [26]:

\[
s = [e \quad \dot{e}]^T\frac{k}{1}
\]  

(10)

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

\[
L_{sn} = \frac{e_{o} + ke_{\dot{o}}}{\sqrt{1 + k^2}}
\]  

(11)

\[
L_{o} = \sqrt{N^2 - L_{sn}^2}
\]  

(12)

\( L_{sn} \) is the normal distance between the sliding surface \( s \) and the arbitrary point \( Q(e_{o}, e_{\dot{o}}) \) 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 \( L_{o} \)](image)

To move towards and stay on the sliding surface in appropriate 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.

![Figure 2: Input Membership Function for CFSMC](image)

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) [23]. The universe of discourse choose for all the inputs and output variable is \((-1 \text{ to } 1)\). The rule table has a Toeplitz structure [28-29] shown in table 2. The inputs \( L_{sn} \), \( L_{o} \) and output \( d \) membership functions are respectively shown in the figure 2 and figure 3. The overall principal block diagram of the FSMC when subjected to the DSRV is shown in figure 4.

![Figure 3: Output Membership Function for CFSMC](image)

V. SINGLE INPUT FUZZY SLIDING MODE

In this proposed SIFSMC controller, by using the Signed Distance (SD) method [30-31] 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 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 \( D \) as signed distance. It can be seen from the table 2 that \( D \) represents the diagonals of the Table 1. So, by using the simple distance from point to line we can develop the relation between the \( L_{sn} \) and \( L_{o} \). The equation of the main diagonal is of the form:

\[
L_{sn} + aL_{o} = 0
\]  

(13)

In above equation, \( a \) is the slope of the main diagonal \( D_{2} \), and is equals to \(-1\) since diagonal is the bisector of 2nd and 4th quadrant as shown by table 2. The 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:

\[
d = \frac{(L_{sn} + aL_{o})}{\sqrt{1 + a^2}}
\]  

(14)
Table 1: A Typical CFSMC Rules for Two Fuzzy Inputs

| Lsm | Lo | NB | NS | Z  | PS | NS | PB |
|-----|----|----|----|----|----|----|----|
| PB  | NS | Z  | PS | PM | PB | PB | PB |
| NS  | NM | Z  | PS | PM | PB | PB | PB |
| PS  | NB | NM | Z  | PS | PM | PB | PB |
| Z   | NB | NB | NM | Z  | PS | PM | PB |
| NS  | NB | NB | NM | NS | Z  | PS | PM |
| NS  | NB | NB | NB | NM | NS | Z  | PS |
| NB  | NB | NB | NB | NB | NM | NS | Z  |

Saturation: $D_{NB}, D_{NM}, D_{NS}, D_{DM}, D_{DS}, D_{Z}, D_{PS}, D_{PM}, D_{PB}$

Figure 6: Input Membership Function for SIFMC

VI. RESULTS AND DISCUSSION

To authenticate the efficiency of the proposed idea, the performance of DSRV system is simulated on Marine Systems Simulator (MSS). The MSS is a comprehensive MATLAB/Simulink® based simulator that provides the indispensable resources for hasty implementation of marine systems while specifically focusing on control system design. The modular simulator structure and possibility of distributed development are the main features of MSS which makes 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 [26-29]. 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 response 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 validate the effectiveness of proposed controller.

Table 2: New Rules using SD Method

| Input, $d$ | $D_{DB}$ | $D_{DM}$ | $D_{DS}$ | $D_{Z}$ | $D_{PS}$ | $D_{PM}$ | $D_{PB}$ |
|------------|----------|----------|----------|--------|----------|----------|----------|
| Output, $\Delta \mu$ | NB | NM | NS | Z | PS | PM | PB |

Figure 9 shows the comparative study of both the FSMC and its simplification 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 obtain is smooth and chattering less even after the addition of environmental disturbance which validate the effectiveness of FSMC and SIFSMC that encounters the robustness of SMC and reduces the chattering phenomena that is the greatest drawback of sliding mode control. However, a distinguish 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 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°                           |
| Cruise speed                       | 8 knots (4.11m/sec)            |
| Ship length                        | 5 meters.                      |

It should be noted that the proposed dynamic model is linearized at 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

Sliding mode control technique provide the better performance for trajectory tracking case but it leads the system towards the unwanted noise of high frequency known as zeno or chattering phenomena. This manuscript presents the comparison in between single input based fuzzy SMC (SIFSMC) control design and conventional fuzzy SMC (CFSMC) technique for DSRV system. The simulations performed using MATLAB/Simulink demonstrates both techniques which have same performance, but CFSMC needs some extra processing time as compared to 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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Author Contributions

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.

Conflicts 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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