An Alternative Approach to Design a Fuzzy Logic Controller for an Autonomous Underwater Vehicle

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Abstract—This paper presents a control scheme that provides an efficient and a simple way to design a Fuzzy Logic Controller (FLC) for the autonomous underwater vehicle (AUV). The proposed method, known as the Single Input Fuzzy Logic Controller (SIFLC), condenses the conventional two-input FLC (CFLC) to a single input single output (SISO) controller. The SIFLC significantly reduces the rules and simplifies the tuning of control parameters. Practically, it can be easily implemented by a look-up table using a low cost microprocessor due to its piecewise linear control surface. To verify the effectiveness of the designed controller, the control algorithm is simulated using the Marine Systems Simulator (MSS) on the Matlab/Simulink® platform. The result clearly indicates that both the SIFLC and CFLC give almost identical response to the same input sets. However SIFLC requires very minimum tuning effort and its execution time is in the orders of two magnitudes less than CFLC.

Keywords—Fuzzy Logic Controller, Signed Distance Method, Single Input Fuzzy Logic Control, Autonomous underwater vehicle.

I. INTRODUCTION

Autonomous Underwater vehicle (AUV) is a submarine-like robotic device powered by a propulsion system and controlled by an onboard computer. These vehicles are normally deployed for dangerous underwater tasks, for example the search and rescue operation, reconnaissance, surveillance, inspection, recovery, repair and maintenance etc. UVs are manoeuvrable in three dimensions and can be programmed to float passively or to actively loiter near a desired location or to swim at different depths. The control of the AUV is a challenging task, because of the difficult and unpredictable environmental conditions that exist below the surface of the water. During operation, the AUV undergoes complex multi-axis motion trajectories that are highly non-linear. Moreover, the subsystems in the vehicle are ill-defined and are strongly coupled [1]. Their dynamics can change considerably with the changes in surrounding conditions and external disturbances such as wind velocity, sea current etc. These hydrodynamic coefficients are normally difficult to measure or predict. However, there are various methods to model these coefficients [2]-[4] but the presences of uncertainties are still high. Another problem is of nonlinear cross-coupling effects due to lack of symmetry of axes of AUV which leads to the effects of cross-coupling during multi-axis motions when the AUV is working in ocean current. Moreover, imprecise measurements of data acquisition devices can also adversely affect the control performance.

There have been various efforts to develop the controller for the AUV which includes both the (conventional) linear and modern control schemes. The linear controller is unable to adequately control the vehicle satisfactorily due to these complexities [5]. Even for a one-axis motion, a fixed gain linear controller cannot perform consistently for a desirable speed range. The problem of motion control is more difficult to solve when the turning motion through any of the 3 body fixed axis is considered. This is due to the complex shape that usually the AUVs have, and as a result, any rotational motion around any axis causes hydrodynamic translational forces and rotating moments, which should be taken into account in the other 5 equations of motion. The consequent forces and moments are greater when the shape of the AUV is irregular and non symmetric to the x-y and z-y planes. Modern control (Intelligence Control) seems to give better performance as it is able to adopt the uncertainties of hydrodynamics more effectively and exhibit excellent immunity to disturbances. Additionally, it does not require accurate models of the vehicle and environment thus reducing the complexity of the design.

Modern control approaches include Neural Network (NN), Sliding Mode Control (SMC) and Fuzzy Logic controllers (FLC). One of the most important advantages of these controllers is their high degree of robustness and resistance to external disturbances. Furthermore, they can be configured to be self learning and adaptive. An adaptive automatic guidance system is proposed by Russel [6] to compensate the parameters changes in AUVs. Using a similar approach Yuh [7], [8] has employed an adaptive scheme to cope the parameter changes. Yoerger and Slotine [5], [9] successfully developed a sliding mode controller for the AUVs. The sliding mode approach was further explored by Healey et al. [10] and Fossen [11]. Both proposed the use of multivariable sliding mode control; the difference between the two was the selection of the sliding surface parameters. Other control schemes based on artificial intelligence include the work of Yuh [12]-[14] and Ishii in [15]. In [13] the authors attempted to apply the Neuro-Fuzzy controller called the self-adaptive neuro Fuzzy inference system (SANFIS). This is followed by a different approach using Fuzzy membership function-based Neural Networks (FMFNN). It is based on the work proposed in [16]...
and [17] for nonlinear control or nonlinear function approximation. The FMFNN combines the advantage of both FLC and NN. Some other works that apply FLC in AUV are due to DeBitetto [18] and Kato in [19].

Although modern control methods are very promising for AUV applications, they require substantial computational power because of complex decision making processes. For example FLC has to deal with fuzzification, rule base storage, inference mechanism and defuzzification operations. Larger set of rules yields more accurate control at the expense of longer computational time. Therefore it may not be practical because there are many implementation aspects that must be addressed, namely real-time response, communication bandwidth, computational capacity and onboard battery. The use of NN in AUV is also thought to be impractical due to its unpredictability, particularly when real time self-tuning is considered [20]. Despite these issues, it is known that FLC requires simpler mathematics and offers higher degree of freedom in tuning its control parameters compared to other nonlinear controllers [21].

It is envisaged that it is possible to take full advantages of FLC for AUV application if the computational time of FLC is minimized. In this paper, the Single Input Fuzzy Controller (SIFLC) is proposed. The SIFLC is a simplification of the conventional Fuzzy Controller (CFLC). It is achieved by applying the “signed distance method” [22] where the input to SIFLC is only one variable known as “distance”. This is in contrast to the CFLC which requires an error and the derivative (change) of the error as its inputs. The reduction in the number of inputs simplifies the rule table to one-dimensional, allowing it to be treated as a single input single output (SISO) controller. Comparatively, the SIFLC reduces the computational burden of the processor because it has less number of rules to compute. Moreover, the rules can be approximated as a piecewise control surface and can be constructed using a simple look-up table [23]. To verify this idea, simulation of an AUV using SIFLC is carried out. The results are compared to the CFLC applied on the same system.

II. AUV MODELLING

The notation used in this paper is in accordance to SNAME, 1950 [24]. The DSRV modeling is based on the Newton-Euler approach as suggested by Fossen, 1994 [25]. Conveniently it can be developed using two coordinate system or frames; where the first one is a global reference frame (XYZ) and the second is a body-fixed frame (X\textsubscript{B}Y\textsubscript{B}Z\textsubscript{B}). The body-fixed frame has components of motion modeled by six velocities components: [u v w p q r] that represent translation and rotation motion: [surge, sway, heave, roll, pitch, yaw]\textsuperscript{T} respectively. The velocity vector is represented as

\[
\mathbf{v} = \begin{bmatrix} u \\ v \\ w \\ p \\ q \\ r \end{bmatrix}^T
\]

(1)

Using Euler angles the position and orientation of the vehicle may be described as a vector \( \eta \) relative to the global reference frame:

\[
\eta = \begin{bmatrix} x \\ y \\ z \\ \phi \\ \theta \\ \psi \end{bmatrix}^T
\]

(2)

The mapping between the two coordinate systems is given by the Euler angle transformation:

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

(3)

Where \( J \) is the Euler angle transformation matrix which can be described by three rotations in a fixed order. The nonlinear vehicle dynamics can be expressed in a compact form as

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

(4)

where,

- \( M \) is the 6 × 6 inertia matrix including hydrodynamic added mass.
- \( C(v) \) is the Matrix of the 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 × 3 control matrix.

For a vehicle operating in the vertical plane, the following assumptions can be made: forward speed is constant, sway and yaw modes can be neglected and in steady state, \( \theta_0 = \text{constant} \) and \( q_0 = \phi_0 = 0 \). The state space model of DSRV is given by

\[
\begin{bmatrix}
\dot{\mathbf{w}} \\
\dot{\mathbf{q}} \\
\dot{\mathbf{\theta}} \\
\dot{\mathbf{\pi}}
\end{bmatrix} =
\begin{bmatrix}
-0.6529 & -2.4522 & 0.0855 & 0 & 0.4147 & 0 & 0.4147 \\
3.2219 & -3.1309 & -44.6794 & 0 & -3.6757 & 0 & 0.4147 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & -4.11 & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\mathbf{w} \\
\mathbf{q} \\
\mathbf{\theta} \\
\mathbf{\pi}
\end{bmatrix}
\]

(5)

The parameters, hydrodynamic derivatives and main dimensions are taken from [26]. The non-dimensional hydrodynamic derivatives are defined according to Prime-system I [24]. At a constant speed of \( u_0 = 4.11 \) m/s [26].

III. SIFLC DESIGN FOR DSRV

A. The Signed Distance Method

Fuzzy Logic controller (FLC) is a linguistic-based controller that tries to emulate the way human thinking in solving a particular problem by means of rule inferences. Typically, a FLC has two controlled inputs, namely error (\( \epsilon \)) and the change of error (\( \dot{\epsilon} \)). Its rule table can be created on a two-dimensional space of the phase-plane (\( \epsilon, \dot{\epsilon} \)) as shown in Table I. It is common for the rule table to have the same
output membership in a diagonal direction. Additionally, each point on the particular diagonal lines has a magnitude that is proportional to the distance from its main diagonal line \( L_Z \). This is known as the Toeplitz structure. The Toeplitz property is true for all FLC types which use the error and its derivative terms, namely \( \dot{e}, \ddot{e}, \ldots \) and \( e^{(n-1)} \) as input variables [23].

### Table I: Rule Table with Toeplitz Structure

<table>
<thead>
<tr>
<th>( e )</th>
<th>( \dot{e} )</th>
<th>PL</th>
<th>PM</th>
<th>PS</th>
<th>Z</th>
<th>NS</th>
<th>NM</th>
<th>NL</th>
</tr>
</thead>
<tbody>
<tr>
<td>NL</td>
<td>Z</td>
<td>NS</td>
<td>NM</td>
<td>NL</td>
<td>NL</td>
<td>NL</td>
<td>NL</td>
<td>NL</td>
</tr>
<tr>
<td>NM</td>
<td>PS</td>
<td>X</td>
<td>NS</td>
<td>NM</td>
<td>NL</td>
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<td>NS</td>
<td>PM</td>
<td>PS</td>
<td>X</td>
<td>NS</td>
<td>NL</td>
<td>NL</td>
<td>NL</td>
<td>NL</td>
</tr>
<tr>
<td>Z</td>
<td>PL</td>
<td>PL</td>
<td>PL</td>
<td>PL</td>
<td>PL</td>
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<td>PL</td>
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<td>PL</td>
<td>PL</td>
<td>PL</td>
<td>PL</td>
<td>PL</td>
<td>PL</td>
</tr>
</tbody>
</table>

The main diagonal line can be represented by (6)

\[
\dot{e} + \lambda e = 0
\]  

(6)

Where, variable \( \lambda \) is the slope magnitude of the main diagonal line \( L_Z \). The distance \( d \) can be written as [23].

\[
d = \frac{\dot{e} + \lambda e}{\sqrt{1 + \lambda^2}}
\]  

(7)

The overall structure of SIFLC can be depicted as a block diagram in Fig. 1 and the corresponding reduced table is shown in table II. The output equation can be written as

\[
\hat{u}(k) = \hat{u}_o(k)r
\]  

(8)

### Table II: The Reduced Rule Table Using the Signed Distance Method

<table>
<thead>
<tr>
<th>( d )</th>
<th>( L_{NL} )</th>
<th>( L_{NM} )</th>
<th>( L_{NS} )</th>
<th>( L_Z )</th>
<th>( L_{PS} )</th>
<th>( L_{PM} )</th>
<th>( L_{PL} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \hat{u}_o )</td>
<td>NL</td>
<td>NM</td>
<td>NS</td>
<td>Z</td>
<td>PS</td>
<td>PM</td>
<td>PL</td>
</tr>
</tbody>
</table>

The main advantage of SIFLC is the significant reduction of the rules that needs to be inferred. In conventional FLC, two inputs are fuzzified and depending on the level of fuzzification \( p \), the number of rules to be inferred is \( p^2 \), while the distinguishing features of SIFLC is that, it requires only \( p \) rules. The reduction in the number of rules results in faster calculation in SIFLC. Fig. 2 shows the linear PWL control surface used in the design. The equation for the mentioned PWL can be written as

\[
\hat{u}_o = \left( \frac{S_1 - S_0}{X_1 - X_0} \right) d + \left( \frac{X_1 S_0 - X_0 S_1}{X_1 - X_0} \right)
\]  

(9)

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\]  

(9)
To construct a feasible desired trajectory of states (or state vectors) for the controller to track, a first order low pass filter is included to filter the non-smooth and unfeasible signals from the reference signal.

For the fuzzy logic control, the min-max inference technique was used along with centre of gravity approach for defuzzification. Fig. 5 depicts the response of all states of diving system obtained by CFLC. All state variables successfully attained their steady state. For SIFLC, the control surface $\psi$ for all input $d$ values is formed using a look-up table. Fig. 6 shows the simulated response by employing the above model and Fig. 7 depicts the deviation between the both types of controller. It is found, as expected, that the transient and steady state response of the DSRV with the SIFLC is strongly identical to CFLC. This clearly shows that the SIFLC and CFLC are similar which validates the anticipated design.

V. COMPARISON BETWEEN SIFLC AND CFLC

A. Tuning

As can be seen from Figures 15-20, with linear control surface, SIFLC provides the exact replica of CFLC. Furthermore, for the non-linear control surface, an improved performance is observed. However, for CFLC, the optimum transient response is obtained after a lengthy complex tuning processes of fuzzification, defuzzification, and inference. In the case at hand, the evaluation has to be made for 49 rules. Unless these are properly tuned, unsatisfactory result is obtained. In contrast, the SIFLC requires only two parameters to be tuned: (1) the slope of the piecewise linear segment and (2) the break point. The design time is reduced tremendously.

B. Execution time

A significant advantage of SIFLC over CFLC is of computational time i.e. the time required to compute the control algorithm. Table III compares the (simulation) computational time between both controllers. It is seen, SIFLC is more than two orders of magnitude faster than CFLC. This observation is consistent with the fact that CFLC has number of computational stages which includes fuzzification, inference mechanism, rules computation, and defuzzification. On the other hand, the SIFLC only requires simple look-up table. Considering these facts, SIFLC can be implemented using a much slower and low cost processor.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Computation time (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIFLC</td>
<td>10</td>
</tr>
<tr>
<td>CFLC</td>
<td>1500</td>
</tr>
</tbody>
</table>

TABLE III. COMPUTATION TIME COMPARISON
VI. CONCLUSION

This paper described a control scheme that provides a simple and efficient way to design a Fuzzy Logic Controller (FLC) for the Deep Submergence Rescue Vehicle (DSRV). It is achieved by simplifying the conventional two-input FLC to a single input and approximating the control surface to a linear or piece-wise linear. The proposed method is known as the Single Input Fuzzy Logic Controller (SIFLC). It is based on the signed distance method which eventually reduces the controller as a single input single output (SISO) controller. The proposed control scheme provides a significant reduction in rules, tuning parameters and a simpler control structure as compared to conventional FLC. In addition, because it only utilizes piecewise linear control surface, it can be easily implemented by a look-up table using a low cost microprocessor. Computer simulations have validated the performance of the proposed SIFLC scheme with the results showing the exact replica of the CFLC.

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REFERENCES


