Fuzzy Behavioral Navigation for Bottom Collision Avoidance of Autonomous Underwater Vehicles

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Abstract. This paper proposes a fuzzy behavioral navigation system with a two-layered hierarchical architecture to address the bottom collision avoidance problem of autonomous underwater vehicles (AUVs) with depth-keeping mission. In the path planning module, depth keeping and collision avoidance behaviors and a fuzzy arbiter are included. And the fuzzy logic control is used in the pitch motion control module. The main advantage of the proposed approach is its simplicity, modularity, expandability, and applicability. Simulation studies are provided on a cruising type AUV to test the performances.

Keywords: Autonomous underwater vehicle, Bottom collision avoidance, Fuzzy behavioral navigation.

1 Introduction

An autonomous underwater vehicle (AUV) is an unmanned, untethered, underwater vehicle that carries its own power source and relies on an on-board computer and build-in machine intelligence to execute a mission consisting of a series of preprogrammed instructions [1].

The AUV needs a bottom navigation ability to avoid collision with sea bottom as a basic feature for successful undersea search and survey, maritime reconnaissance, communication/ navigation aids, and tracking and trailing in uncharted shallow water [2]. However, the navigation of AUV has been a challenge to control engineers due to combined nonlinear and uncertain nature of both the vehicle itself and the environment in which it operate.

Originally advocated by Zadeh and Mamdani and Assilian, fuzzy logic control (FLC) is a convenient choice for systems that involve varying degrees of uncertainty. Now, fuzzy logic is becoming a very popular topic in control engineering. Fuzzy control is the most useful applications to a variety o consumer products and industrial systems, and attracts growing attention and interests.

The fuzzy behavioral approach has been proposed to navigate the mobile robots to avoid collision with obstacles by Wijesoma et al. [3] and Safiotti [4]. As a generalization of fuzzy logic based mobile robot path planning, Kanakakis et al. [5] presented a three-level hierarchical fuzzy controller comprising the sensor fusion module, the collision avoidance module and the motion control module to address the AUV collision avoidance problem. The rationale behind using fuzzy logic is that fuzzy logic has

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already been proven to be a very useful modeling tool when dealing with problems characterized by the presence of uncertainty.

This paper presents a fuzzy logic behavioral navigation (FLBN) method to address the bottom collision avoidance problem of a survey-class AUV equipped with downward-looking altimeter sonar. The reactive control architecture, which generates control commands based on sensor data, is adopted to handle the previously unknown environment conditions. The computer simulation results demonstrate the performances of this method.

2 AUV Modeling

The underwater vehicle is assumed to be a freely swimming rigid body in 3-dimensional space with 6 degrees of freedom. In addition to the rigid body dynamics and gravitational forces, an underwater vehicle is influenced by hydrodynamic forces like added inertia forces, hydrodynamic resistance, and buoyancy [6].

The equations of motion for a underwater vehicle is formulated as

$$\mathbf{M}\dot{\mathbf{v}} + \mathbf{C}(\mathbf{v})\mathbf{v} + \mathbf{D}(\mathbf{v})\mathbf{v} + \mathbf{g}(\boldsymbol{\eta}) = \boldsymbol{\tau} \quad (1)$$

Here $\mathbf{M}$ is the positive definite 6×6 inertia matrix containing vehicle inertia and hydrodynamic added inertia. The 6-dimensional vector $\mathbf{v} = (u\ v\ w\ p\ q\ r)^T$ is the velocity in body-fixed coordinate. Here u, v, and w are the linear velocities in the vehicle x, y, and z directions; and p, q, and r are the angular velocities about the vehicle x, y, and z-axes. $\mathbf{C}(\mathbf{v})\mathbf{v}$ is the vector of coriolis and centripetal forces. $\mathbf{D}(\mathbf{v})$ is a 6×6 matrix containing coefficients describing dissipative hydrodynamic terms. $\mathbf{g}(\boldsymbol{\eta})$ is the 6-dimensional vector of restoring forces and moments caused by gravity and buoyancy. And $\boldsymbol{\tau}$ is a 6-dimensional vector of control forces moments produced by the propeller thrusters and the control surfaces.

The Euler transformation from the body-fixed to the earth-fixed reference frame is described by the relation

$$\dot{\boldsymbol{\eta}} = \mathbf{J}(\boldsymbol{\eta})\mathbf{v} \quad (2)$$

where,

$$\boldsymbol{\eta} = \left(\boldsymbol{\eta}_1^T\ \boldsymbol{\eta}_2^T\right)^T,\ \boldsymbol{\eta}_1 = (x\ y\ z)^T,\ \boldsymbol{\eta}_2 = (\phi\ \theta\ \psi)^T \quad (3)$$

Here x and y are the horizontal position coordinates, z is the depth, and ϕ, θ and ψ are three Euler angles, namely roll, pitch, and yaw, describing the orientation of the vehicle.

3 Fuzzy Behavioral Navigation Design

The cruise mission requires the AUV to keep level flight at a constant depth under the surface. In addition, the AUV must maintain a safe distance above the bottom to avoid collision when the commanded depth is near to or greater than the water column's height, as shown in figure 1.

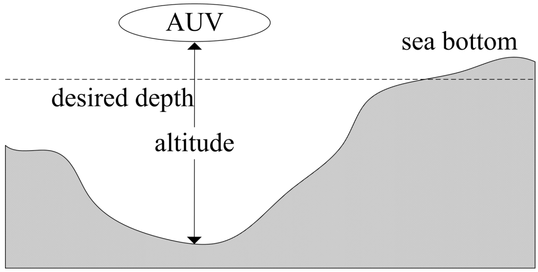

Fig. 1. Bottom collision avoidance problem of AUV

The problem of the bottom collision avoidance is to process the altimeter and depth sensor measurements, and regulate the AUV with respect to its a priori unknown environment using sensory data. When the AUV fly near the bottom, the depth keeping and collision avoidance may be conflicting objectives. Thus, the control system must satisfy multiple competing objectives. Fuzzy decision making has become a mean of collecting human knowledge and experience, and provides formalism for interpolative reasoning and the simultaneous satisfaction of multiple constraints. So a reactive fuzzy behavioral architecture is selected as a promising method to solve the problem, and it is called fuzzy logic behavioral navigation. The overall control architecture configuration is depicted in figure 2, which does clarify the modularity and generality of the control architecture, illustrating at the same time that only the pitch control may be vehicle dependent.

As shown in the figure, FLBN includes two primitive fuzzy behaviors: depth keeping and collision avoidance. Each of them receives particular sensors, and provides a desired pitch angle that best satisfies that behavior's objective. A fuzzy arbiter is used to set one of them active and pass its output. The low level pitch motion control is implemented

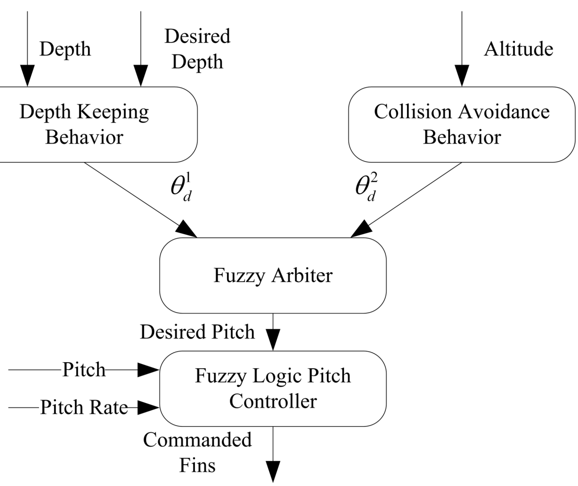

Fig. 2. Structure of the fuzzy logic behavioral navigator

with a fuzzy logic controller. Both the behaviors and the arbiter are simple fuzzy inference systems, and it is easy to design, implement and test them separately.

All the following fuzzy behaviors adopt the Mamdani fuzzy inference system using min and max for fuzzy AND and OR operators respectively, and get the final defuzzified output via calculating the centroid of area of output membership functions. We use the triangular membership functions for simple and fast calculation.

3.1 Depth Keeping Behavior

The depth keeping behavior is responsible for generating pitch command for the pitch motion controller to track the constant desired depth, as required by cruising mission. It receives data from depth pressure, and compares it with the command depth resulting in the depth error d_e.

The fuzzy behavior is implemented with seven triangular membership functions for the input fuzzy variable d_e, as shown in figure 3.

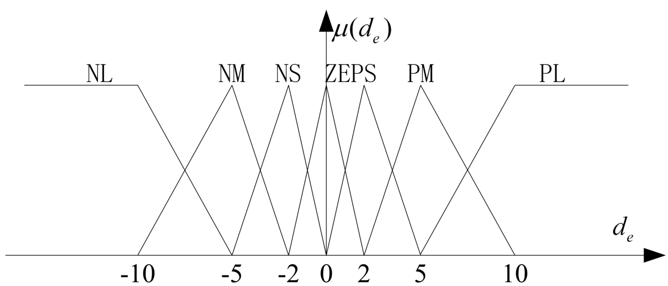

Fig. 3. Membership function of d_e (NL-Negative Large; NM-Negative Medium; NS-Negative Small; ZE-Zero;PS-Positive Small; PM-Positive Medium; PL-Positive Large)

We represent the desired pitch angle θ_d by seven linguistic variables having the shape given by Figure 4.

The fuzzy rule base consists of seven rules as follow.

- R1: IF < d_e is PL> THEN < θ_d is PL>
- R2: IF < d_e is PM> THEN < θ_d is PM>
- R3: IF < d_e is PS> THEN < θ_d is PS>
- R4: IF < d_e is ZE> THEN < θ_d is ZE>
- R5: IF < d_e is NS> THEN < θ_d is NS>
- R6: IF < d_e is NM> THEN < θ_d is NM>
- R7: IF < d_e is NL> THEN < θ_d is NL>

Clearly it is a single-input single-output fuzzy inference system. The ordered pitch angle is given by the max-min composition of the seven rules, after defuzzification using the centroid method.

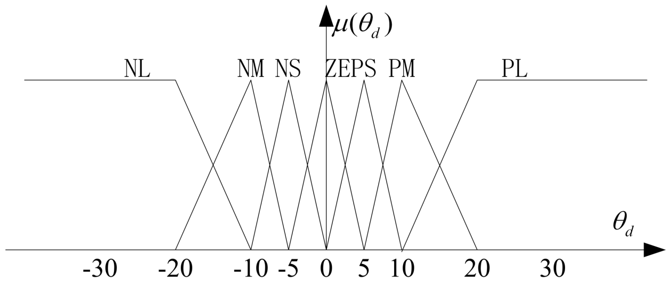

Fig. 4. Membership function of θ_d (NL-Negative Large; NM-Negative Medium; NS-Negative Small; Z-Zero; PS-Positive Small; PM-Positive Medium; PL-Positive Large)

3.2 Collision Avoidance Behavior

The collision avoidance behavior receives data from the downward looking altimeter, and the altimeter readings are mapped into the linguistic variable h with linguistic values: extremely dangerous, very dangerous, medium dangerous, little dangerous, and safe, witch provide information about potential collision with bottom. The altitude h is fed to a fuzzy inference engine that calculates the necessary upward pitch command to avoid the possible collision. The membership functions of h are shown in Figure 5.

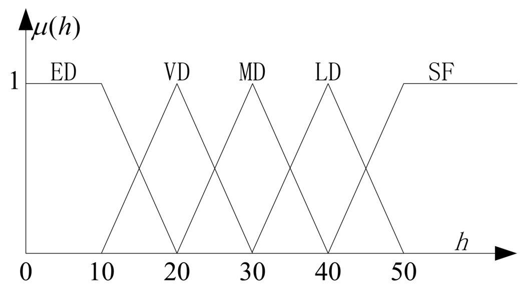

Fig. 5. Membership function of altitude h (ED-Extremely dangerous; VD-Very dangerous; MD-Medium dangerous; LD-Little dangerous; SF-Safe)

The linguistic value θ_d is define as in depth keeping behavior. The following 5 fuzzy rules are included in the collision avoidance behavior.

- R1: IF < h is ED> THEN < θ_d is PVL>.
- R2: IF < h is VD> THEN < θ_d is PL>
- R3: IF < h is MD> THEN < θ_d is PM>
- R4: IF < h is LD> THEN < θ_d is PS>
- R5: IF < h is SF> THEN < θ_d is ZE>

3.3 Fuzzy Arbitrary

The rule base of the fuzzy arbitrary module consists of following three rules to set one of the three behaviors active.

- R1: IF <altitude is ND> THEN <output is θ_d^1>.
- R2: IF <altitude is ED> OR <altitude is VD> OR <altitude is MD> OR <altitude is LD> THEN <output is θ_d^2>.

Where, θ_d^1, θ_d^2 are the output of the depth keeping and collision avoidance behaviors respectively.

In the consequence of the fuzzy arbiter, output is the numerical value, and C={ θ_d^1, θ_d^2 } is a classic discrete set. Intuitively, we use the weighted average of the three ordered pitch angles as the aggregation method, where the membership values of altitude in fuzzy sets are the weights.

The primary advantage of this approach is the interpolative nature of the fuzzy combination of behavior, ensuring smooth transitions between behaviors that prevents chattering.

4 Fuzzy Logic Pitch Control

The pitch controller is the motion control module responsible to control the vehicle's fins. It receives as inputs the calculated ordered pitch angle together with the vehicle pitch and pitch rate, and generates the elevator fins command to actuate the fins. Conventional controllers could have been used, such as sliding model control and LQR control, but fuzzy controller is used primarily because an accurate analytical model of vehicle was not available.

The fuzzy logic pitch controller has inputs with respective linguistic values $\theta_e = \theta - \theta_d$: {NL, NM, NS, Z, PS, PM, PL}; q: {N, Z, P}, with the membership functions shown in Figure 6 and Figure 7. Output is δ with linguistic values {NL, NM, NS, Z, PS, PM, PL}, and the membership functions are shown in Figure 8.

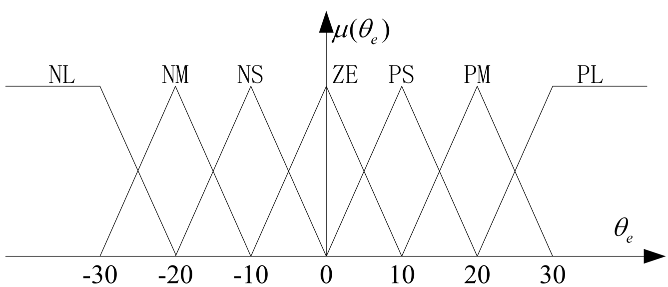

Fig. 6. Membership functions of pitch error (NL-Negative Large; NM-Negative Medium; NS-Negative Small; ZE-Zero; PS-Positive Small; PM-Positive Medium; PL-Positive Large)

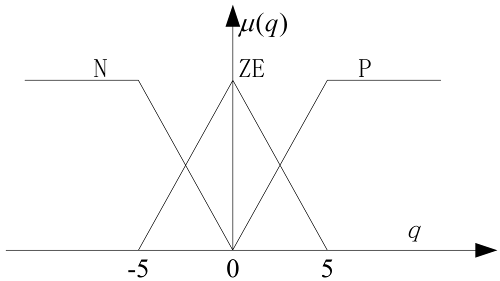

Fig. 7. Membership function of pitch rate (N-Negative; ZE-Zero; P-Positive)

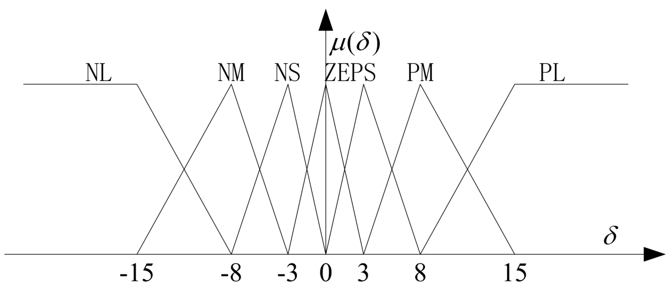

Fig. 8. Membership function of elevator fins (NL-Negative Large; NM-Negative Medium; NS-Negative Small; ZE-Zero; PS-Positive Small; PM-Positive Medium; PL-Positive Large)

The second step in designing an FLC is the fuzzy inference mechanism. Adjusted through computer simulation, the rules for the fuzzy logic pitch control are shown in Table 1.

There are many ways for performing defuzzification. The strategy we adopt here is the Mamdani fuzzy inference system again, and min and max are used for fuzzy AND and OR operators.

Table 1. Fuzzy logic rules of the fuzzy logic pitch controller

δ		θ_e						
		NL	*NM*	*NS*	*ZE*	*PS*	*PM*	*PL*
q	*N*	*NL*	*NL*	*NM*	*NS*	*PS*	*PS*	*PM*
	ZE	*NM*	*NM*	*NS*	*ZE*	*PS*	*PM*	*PM*
	P	*NM*	*NS*	*NS*	*PS*	*PM*	*PL*	*PL*

5 Simulations Results

To investigate the feasibility of the proposed fuzzy logic behavioral navigation described above, computer simulations are performed on a torpedo-like AUV. The

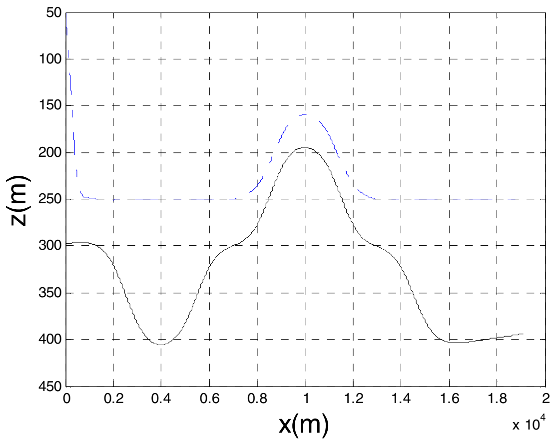

Fig. 9. Simulated AUV trajectory and the bottom profile (solid line – the bottom profile, dash line – the AUV path)

simulated AUV is commanded to keep its depth at 250 meters under the surface, starting with the depth of 50 meters. The bottom profile is simulated using a polynomial function, as shown in figure 9. The simulated AUV trajectory in vertical plane under the FLBN and fuzzy logic pitch control is plotted in figure 9.

The simulation results exhibit the satisfactory collision avoidance capability of the AUV with FLBN. As shown in the figure, when the AUV cruises high above the bottom, the fuzzy arbitrator chooses the depth keeping behavior, and once the bottom ascents above the desired depth, the arbiter switch to the collision avoidance behavior, making the AUV to climb up. Later when the sea is clear, the collision avoidance behavior becomes inhibited, and depth keeping one works again.

6 Conclusions

In this paper, a fuzzy logic behavioral navigator is developed to solve the collision avoidance problem of AUV with cruising mission. The simulations were carried out on a torpedo-like AUV to test the performances of the derived method. The results show that the vehicle has good collision avoidance capability. And the approach we propose is much simple in its design and formulation.

References

1. Valavanis, K.P., Gracanin, D., Matijasevic, M., Kolluru, R., Demetrious, G.A.: Control Architectures for Autonomous Underwater Vehicles. IEEE Control Systems Magazinem 17, 48–64 (1997)
2. Gianluca, A., Chiaverini, S., Finotello, R., Schiavon, R.: Real-Time Path Planning and Obstacle Avoidance for RAIS: An Autonomous Underwater Vehicle. IEEE Journal of Oceanic Engineering 26, 216–227 (2001)

3. Wijesoma, W.S., Khaw, P.P., Teoh, E.K.: Sensor Modeling and Fusion for Fuzzy Navigation of an AGV. International Journal of Robotics and Automation 16, 14–25 (2001)
4. Safiotti, A.: Fuzzy Logic in Autonomous Robotics: Behavior Coordination. In: The 6th IEEE International Conference on Fuzzy Systems, Barcelona, Spain, pp. 573–578 (1997)
5. Kanakakis, V., Valavanis, K.P., Tsourveloudis, N.C.: Fuzzy-Logic Based Navigation of Underwater Vehicles. Journal of Intelligent and Robotic Systems 40, 45–88 (2004)
6. Fossen Thor, I.: Marine Control Systems. Marine Cybernetics, Trondheim, Norway (2002)