Design of Sliding Mode Fuzzy Controllers for an Autonomous Underwater Vehicle without System Model

Feijun Song Samuel M. Smith
Ocean Engineering Department, Florida Atlantic University
101 North Beach Rd., Dania, FL 33004 USA
(voice) 954-924-7213, 7232, (fax) 954-924-7233
fsong@oe.fau.edu, smith@oe.fau.edu

Abstract: For 2 Dimensional systems, the time optimal control law with physically limited control command follows Pontryagin's maximum principle. The control switches its sign on both sides of a nonlinear switching curve. The key factor in robust time optimal controller design is to approximate that nonlinear curve while maintaining robustness. Time optimality and robustness are contradictory to each other. This paper describes the development of a sliding mode fuzzy pitch controller and a sliding mode fuzzy heading controller for Ocean Explorer (OEX) series Autonomous Underwater Vehicles (AUVs) developed in Florida Atlantic University. A Sliding Mode Fuzzy Controller (SMFC) inherits the robustness property of Sliding Mode Control and Interpolation property of Fuzzy Logic Control such that the nonlinear switching curve can be approximated and the robustness can be maintained. Moreover, since the physical meaning of the parameters in a SMFC is straightforward, the on-line tuning with an SMFC is much easier than with the old Fuzzy Logic Controllers used on the OEX series AUVs. The at-sea experimental results show the effectiveness of the design philosophy.

I. INTRODUCTION

Pitch and heading control are low level controls in an Autonomous Underwater Vehicle (AUV) architecture. Many control strategies have been adopted, among them are neural network control [9], sliding mode control [10][6], supervisory control [11], linear quadratic gaussian / loop transfer recovery method [12], self-tuning control [13], fuzzy logic control [8], etc. However, it is difficult to design time optimal controller for AUVs due to the fact that most optimal control design methodologies require analytical system models (equations of motion) of the AUVs, which are highly nonlinear and difficult to obtain.

Generally, for time optimal control, there exists a nonlinear switching curve where the bang-bang control should switch its sign. The curve also represents the maximal vehicle maneuvering capability in terms of time. A time optimal controller should be able to control the AUVs so that the same switching curve is always followed. A fuzzy logic controller can approximate this nonlinear switching curve since fuzzy systems are universal function approximators [7].

Sliding mode control is known for its robustness to the external disturbance and system modeling error. In order to have a controller that is not only time optimal, but also robust, a Sliding Mode Fuzzy Controller (SMFC) is presented in this paper, in which each fuzzy rule output function is exactly a sliding mode controller. The slope of the sliding mode controller in each rule is determined by the approximate slope of the nonlinear switching curve in that partition of the phase plane where the rule covers. The nonlinearity of the switching curve thus is approximated by the fuzzy rules.

The approximation property of fuzzy logic control and robustness property of sliding mode control make the Sliding Mode Fuzzy Controllers ideal for AUV time optimal and robust control. However, as in Fuzzy Logic Controller design, the parameters of an SMFC are difficult to be determined. An experimental method is proposed in this paper to determine the parametes. The method makes the design of controllers for complex highly nonlinear system possible without any analytical representations of system.

The method is based on Pontryagin's maximum principle [15]. Starting from a steady state, under maximal rudder or stern plane deflection, an AUV's open loop pitch or heading response generally is a nonlinear curve in a phase plane. This curve represents the maximal vehicle maneuvering capability in terms of time. It also represents the switching line where the bang-bang control should switch its sign. The parameters of a Sliding Mode Fuzzy Controller should be selected such that the experimental switching curve is approximated.

This paper first presents the structure of a Sliding Mode Fuzzy Controller, then describes the design of a pitch and a heading controller for OEX series AUVs. The at-sea close loop experimental data justified the methodology and is presented at the end of the paper.

II. SLIDING MODE FUZZY CONTROLLER (SMFC)

Takagi-Sugeno Type Fuzzy Logic Controller

Mainly there are two types of FLCs. One is Mamdani type [14], the other is Takagi-Sugeno (TS) type. The general form for the i th rule of a Multi-Input-Single-Output (MISO) TS type FLC is as the following [14]:

$$\text{IF } x_1 \text{ is } A_{i1} \text{ and/or } x_2 \text{ is } A_{i2} \text{ and/or } \ldots\ x_n \text{ is } A_{in}$$

$$\text{THEN } y_i = f_i(x_1, \ldots, x_n, c_{i0}, \ldots, c_{in})$$

Here

$x_1, \ldots, x_n$ are linguistic variables with respective universe of discourses. Generally they corresponds to state variables. They have fuzzy sets as their possible values.

$A_{i1},\ldots, A_{in}$ are fuzzy sets in the i th rule for the linguistic variables $x_1, \ldots\ldots, x_n$.

Y is a linguistic variable standing for the control action to the plant.

f_I is an arbitrary rule output function.

$c_{i0},\ldots, c_{in}$ are constants in the rule output function f_i.

The only different between a TS type FLC and a Mamdani type FLC is that for a TS type FLC, the rule consequents are functions of crisp inputs, whereas the rule consequents for a Mamdani type FLC are also fuzzy values.

The defuzzification of a TS type FLC is given by:

$$U = \frac{\sum_{i=1}^{n} b_i y_i}{\sum_{i=1}^{n} b_i}$$

where n is the total number of rules in the rule base. β_i is the truth value of the i th rule. y_i is the rule consequent of the i th rule.

Depending on what kind of fuzzy connection operators are used for rule antecedents. β_i can have different values. Generally, a MIN operator would be used for "and". In this case, β_i can be calculated as:

$$b_i = \mathrm{MIN}\,(m_{A_{i1}}(x_1),\ldots.,m_{A_{in}}(x_n))$$

here $m_{A_{ij}}$ is the membership function for fuzzy set A_{ij}.

To design a TS type FLC, the number of fuzzy sets for each linguistic variable, the membership function for each fuzzy set, the number of rules, the rule antecedents, and the consequent functions must be determined first. However, unlike Mamdani type FLC, the determination of parameters $c_{i0},\ldots,c_{in}$ are very difficult since most of them do not bear any physical meanings.

Sliding Mode Control

A Sliding Mode Controller is a Variable Structure Controller (VSC). Basically, a VSC includes several different continuous functions that can map plant state to a control surface, and the switching among different functions is determined by plant state that is represented by a switching function.

Without lost of generality, consider the design of a sliding mode controller for the following second order system:

$$\ddot{x} = f(x, \dot{x}, t) + bu(t)$$

here we assume $b > 0$. $u(t)$ is the input to the system. The following is a possible choice of the structure of a sliding mode controller [1] [3]:

$$u = k\,\mathrm{sgn}(s) + u_{eq} \qquad (1)$$

where u_{eq} is called equivalent control which is used when the system state is in the sliding mode [2][3]. k is a constant. k is the maximal value of the controller output. s is called switching function because the control action switches its sign on the two sides of the switching surface $s = 0$. s is defined as [1]:

$$s = e + l\dot{e}$$

where $e = x - x_d$ and x_d is the desired state. l is a constant. $\mathrm{sgn}(s)$ is a sign function, which is defined as:

$$\mathrm{sgn}(s) = \begin{cases} -1 & if \quad s < 0 \\ 1 & if \quad s > 0 \end{cases}$$

The control strategy adopted here will guarantee the system trajectories move toward and stay on the sliding surface $s = 0$ from any initial condition if the following condition meets:

$$s\dot{s} \le -h|s|$$

where h is a positive constant that guarantees the system trajectories hit the sliding surface in finite time [1].

Using a sign function often causes chattering in practice. One solution is to introduce a boundary layer around the switch surface [3]:

$$u = k\,sat(\frac{s}{f}) + u_{eq} \qquad (2)$$

where constant factor f defines the thickness of the boundary layer. $sat(\frac{s}{f})$ is a saturation function that is defined as:

$$sat(\frac{s}{f}) = \begin{cases} \frac{s}{f} & if \quad \left|\frac{s}{f}\right| \le 1 \\ \mathrm{sgn}(\frac{s}{f}) & if \quad \left|\frac{s}{f}\right| > 1 \end{cases}$$

This controller is actually a continuous approximation of the ideal relay control [2][1]. The consequence of this control scheme is that invariance of sliding mode control is lost. The system robustness is a function of the width of the boundary layer.

A variation of the above controller structures is to use a hyperbolic tangent function instead of a saturation function [4][6]:

$$u = k \tanh(\frac{s}{f}) + u_{eq} \qquad (3)$$

It is proven that if k is large enough, the sliding model controllers of (1), (2) and (3) are guaranteed to be asymptotically stable [4].

Sliding Mode Fuzzy Control (SMFC)

Pontryagin's maximum principle states that for 2 dimensional time optimal controller design, there exists a nonlinear switch curve such that the control can have maximal value on one side of the switching curve and minimal value on the other side of the curve. The nonlinear switching curve often has the form depicted in Fig. 1. It also shows there can be a switching band around the switching line to alleviate chattering.

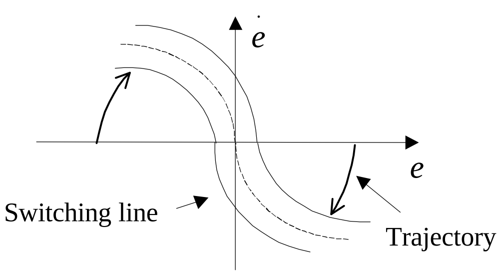

Fig. 1 A nonlinear switching curve.

There are two problems associated with nonlinear time optimal controller design. First, how to get the true switching curve. For nonlinear systems, this switching curve is very difficult to get analytically. Secondly, how to approximate the nonlinear curve.

To solve the first problem, we proposed to use system open loop experimental data. Under the maximal control command, the system output should be saturated after a period of time. The nonlinear open loop response can be used as a switching curve since it represents the system's fastest response. For example, if the maximal rudder angle is delivered to an AUV constantly, then the yaw rate of the AUV will be gradually saturated as segment AB shown in Fig. 2. The delivering of minimal rudder angle in opposite direction generates the segment CD shown in Fig. 2.

This open loop response actually represents the maximal maneuver capability of the AUV. In other words, the curve AB and CD are the quickest way the AUV can move. This curve can be used as the switching curve in time optimal controller design.

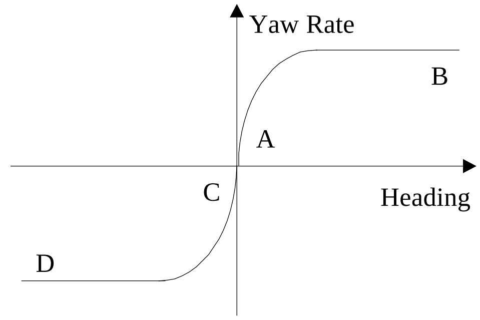

Fig. 2 Open loop step response for maximal and minimal rudder angle.

Obviously, traditional linear controller design can only linearly approximate this nonlinear curve. This paper proposes to use a Takagi-Sugeno (TS) type fuzzy logic controller to approximate this nonlinear curve. Fuzzy Logic Controller has been proven to be able to approximate any nonlinear curve with arbitrary accuracy [7].

Generally, a time optimal controller is not robust. The performance of a time optimal controller degrades severely with the external disturbance, measurement noise, or system dynamics changes. To add robustness to a time optimal controller, we propose to combine Sliding Mode Control and Fuzzy Logic Control together.

In a Takagi-Sugeno (TS) type FLC, the rule output function typically is a liner function of controller inputs. The mathematical expression of this function is similar to a switching function. This similarity indicates that the information from a sliding mode controller can be used to design a fuzzy logic controller, resulting in a Sliding Mode Fuzzy Controller (SMFC). In fact, since a fuzzy system can seamless connects different control strategies into one system, one can directly incorporate sliding mode controllers into a fuzzy logic controller [5]. Each rule in an FLC can be a sliding mode controller. The sliding mode controller in each rule can have various forms. The boundary layer and the coefficients of the sliding surface become the coefficients of the rule output function and have their physical meanings.

The i th rule for a Sliding Mode Fuzzy Controller is expressed as follows:

$$\text{IF } e \text{ is } A_i \text{ and } \dot{e} \text{ is } B_i \text{, THEN } u_i = ksat(\frac{\dot{e} + l_i e + c_i}{f_i})$$

Notice that the rule output function is not necessarily a saturation function, it could be a sign function or hyperbolic tangential function too. The fuzzification of e and $\dot{e}$ are illustrated in Fig. 3.

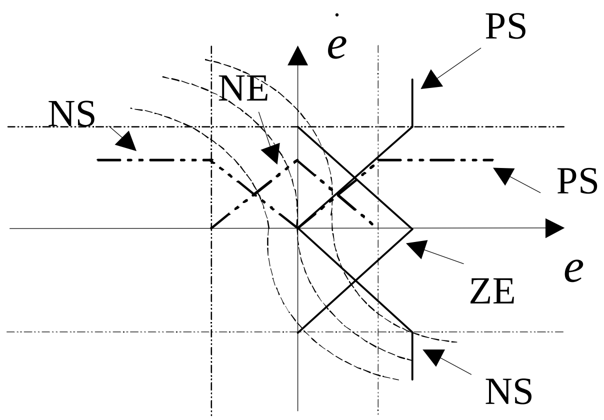

Fig. 3 Fuzzification of e and $\dot{e}$.

The constant coefficients of l_i and c_i are determined by the open loop experimental data. They are determined in such a way that the slop of the nonlinear switching curve is followed. Usually, the at-sea data has oscillation that reflects the environment disturbance and measurement noise. The magnitude of the oscillation can be use to determine the coefficient f_i.

Notice that in Fig. 1 the switching curve can be either a function of e, or a function of $\dot{e}$. Much less number of rules are needed to approximate this 1-dimensional function. This is how a Sliding Mode Fuzzy Controller reduces the rule base size. A typical rule for the simplified rule base is as the following.

$$\text{IF } e \text{ is } A_i\text{, THEN } u_i = ksat\left(\frac{\dot{e} + l_i e + c_i}{f_i}\right)$$

A Sliding Mode Fuzzy Pitch Controller and a Sliding Mode Fuzzy Heading Controller

A sliding mode fuzzy pitch controller and a sliding mode fuzzy heading controller have been designed for the OEX series AUVs that are developed in Ocean Engineering Department of Florida Atlantic University. The inputs for the heading controller are heading error and heading error rate. The output is rudder deflection. Fig. 4 shows the fuzzy sets for the heading errors. There are no fuzzy sets for heading error rate. Table I shows the rule base of the heading controller.

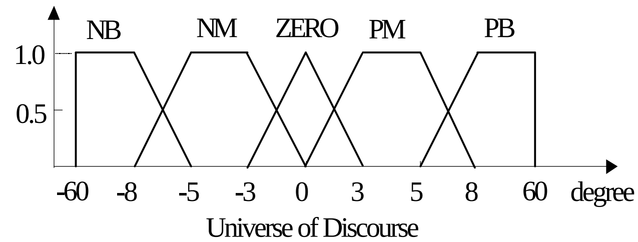

Fig. 4 Fuzzy sets for heading error.

TABLE I
RULE BASE FOR THE SLIDING MODE FUZZY HEADING CONTROLLER

5 rules for the sliding mode fuzzy heading controller, k = 20 degree			
Antecedents	Output Functions		
Heading error e	Thickness f_i	Slope l_i	Offset c_i
PB	2.5	0.01	13.5
PM	3.0	1.5	1.0
ZERO	3.0	2.0	0.0
NM	3.0	1.5	-1.0
NB	2.5	0.01	-13.5

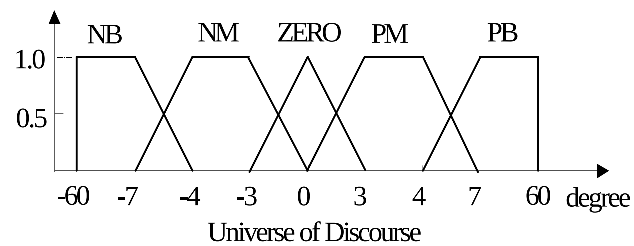

Fig. 5 Fuzzy sets for pitch error.

The inputs to the pitch controller are pitch error and pitch error rate. The output is stern plane deflection. Fig. 5 shows the fuzzy sets for the pitch errors. There are no fuzzy sets for pitch error rate. Table II shows the rule base of the pitch controller.

TABLE II
RULE BASE FOR THE SLIDING MODE FUZZY PITCH CONTROLLER

5 rules for the sliding mode fuzzy pitch controller, k = 20 degree			
Antecedents	Output Functions		
Heading error e	Thickness f_i	Slope l_i	Offset c_i
PB	1.5	0.01	13.5
PM	3.0	2.0	1.5
ZERO	3.0	3.0	0.0
NM	3.0	2.0	-1.5
NB	1.5	0.01	-13.5

III. AT-SEA EXPERIMENT RESULTS

Fig. 6 shows at-sea test data for heading control. The commanded heading first set to 20 degree and then 200 degree. The heading controller successfully controlled the vehicle to the desired heading. There is an oscillation in the heading with 2 degree in magnitude. This is normal since the sea environment is not clean.

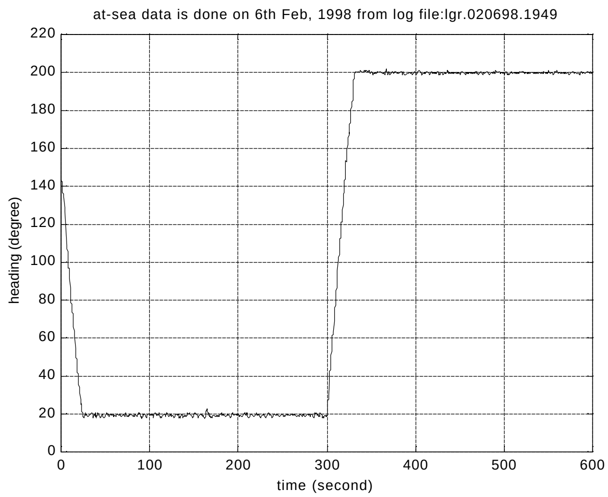

Fig. 6 At-sea experimental data for sliding mode fuzzy heading controller

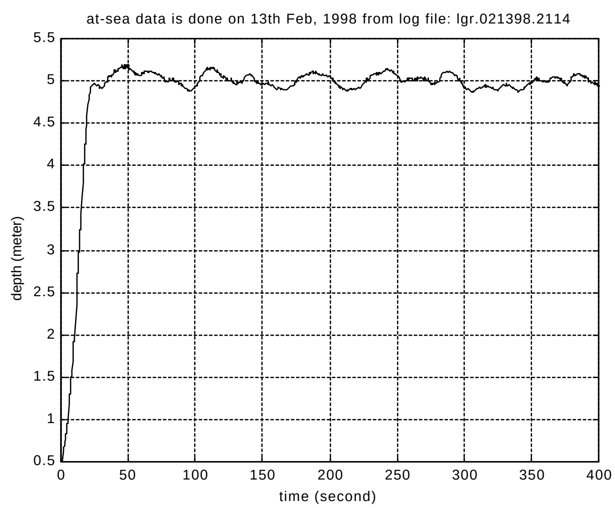

Fig. 7 At-sea depth test data for sliding mode fuzzy pitch controller

Fig. 7 shows the performance of the pitch controller. Since in the at-sea test the vehicle can not have a constant pitch with limited sea depth, the performance of the pitch controller was tested through the depth controller. In OEX series AUVs, the depth control is done through the pitch control. The control output from the depth controller is a desired pitch angle. It is the responsibility of the pitch controller to drive the vehicle to the desired pitch. The depth controller used in the test is a linear proportional-derivative controller. In Fig. 7, the depth command is set to 5 meter. The pitch controller successfully drives the vehicle to 5 meter depth.

IV. CONCLUSION

The structure of Sliding Mode Fuzzy Control is presented in this paper. A Sliding Mode Fuzzy Controller inherits the interpolation property of fuzzy logic control and robustness property of sliding mode control therefore makes it ideal for time optimal robust control. The at-sea experimental data shows that Sliding Mode Fuzzy Control can be successfully applied to Autonomous Underwater Vehicles, therefore, makes it another alternative for the robust time optimal control problem. Moreover, since the physically meaning of the rule output function parameters for a Sliding Mode Fuzzy Controller is straightforward, the on-line tuning is made easy. This is exactly why Sliding Mode Fuzzy Control is adopted in AUVs development at Florida Atlantic University.

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