Sindh Univ. Res. Jour. (Sci. Ser.) Vol.44 (4) 717-722 (2012)

SINDH UNIVERSITY RESEARCH JOURNAL (SCIENCE SERIES)

Multi-input and Multi-output Fuzzy Logic Controller for a Submarine

D. M. PATHAN, M. MEMON, A. F. ABBASSI, H. U. ABBASI*

Department of Mechanical Engineering, Mehran University of Engineering and Technology, Jamshoro, Sindh,

Received 12th April 2012 and Revised 17th September 2012

Abstract: This paper explores the potential of rule based fuzzy logic technique for a Multi-Input and Multi-Output (MIMO) control system of a submarine. A tenth order dynamic model of a submarine has been considered for heading and diving maneuvers. The parameters of model are considered to vary with depth and wind generated waves. Mamani type inference system along with triangular membership function is used for development of controller. For defuzzification cetroid method is used. Total 98 rules are developed. To demonstrate the robustness of Fuzzy controller, the performance of controller is tested in different operating conditions: in ideal conditions and in presence of waves. Simulations results show that in both cases, the heading error comes to zero, which indicates that the actual heading converges to the desired heading in finite time.

Keywords: Fuzzy Logic, Multi-Input And Multi-Output, Heading Control, Diving Control, Wind Generated Waves

1. INTRODUCTION

It has been great challenge to design a controller for dynamical systems. As the degree of freedom of a system increases the complexity of the system also increases. Submarine is one of the under-water vehicles having six degree of freedom of motion. The dynamics of submarine is not only nonlinear but also coupled with hydrodynamics. The motion of submarine is highly influenced by external environmental disturbances like waves, sea currents and wind. If these effects are considered the dynamics of submarine becomes more complex. Traditional autopilots require exact knowledge of the system. Owing to nonlinear dynamics coupled with hydrodymics and possessing higher degree of freedom, it is hard enough to obtain exact model of submarine. Therefore many assumptions are made to design conventional linear and nonlinear autopilots for a submarine. Fuzzy logic is one of the behavioral based control technique which do not rely on model. The literature review presents the work of different authors on fuzzy logic for underwater vehicles. DeBitetto (1995) developed fuzzy logic controller for under unmanned water vehicle for depth motion. Guo *et al.*, (2003) demonstrated the feasibility of fuzzy logic technique along with sliding mode theory for line of sight guidance of a testbed autonomous underwater vehicle "AUV-HM1". (Akkizidis *et al.*, 2003) used fuzzy logic in combination of PD control technique for an underwater vehicle "GARBI" for steering and depth motions. (Kim and Shin 2007) used Sugeno type fuzzy inference system in combination with sliding mode theory for depth control for underwater vehicle. (Kumar *et al.*, 2008) developed fuzzy logic direction controller for an unmanned autonomous underwater vehicle.

The literature review reveals that the work of some researcher (DeBitetto, 1995; Kim and Shin, 2007; Kumar *et al.*, 2008) is based on single manipulated variable. The work of these researchers is based on Single Input and Single Output (SISO) control system. While other researchers (Guo *et al.*, 2003; Akkizidis *et al.*, 2003; Kim and Shin 2007) developed hybrid type fuzzy control system, where the fuzzy logic is used in combination of other techniques. However in this work we developed a Multi-Input and Multi-Output (MIMO) control system by using fuzzy logic technique only.

2. MATERIAL AND METHODS

Mathematical Model Of A Submarine

To describe complete motion of a submarine six independent co-ordinates are required, which represent the position and orientation of submarine. Therefore the motion of a submarine is considered as six degree of freedom (DOF) motion:

These coordinates are:

surge (u): linear velocity along x-axis
sway (v): linear velocity along y-axis
heave (w) linear velocity along z-axis

Integration of (u, v, w) corresponds to linear positions (x, y, z) along X, Y and Z axes.

roll (p): angular velocity about x-axis
pitch (q): angular velocity about y-axis
yaw (r): angular velocity about z-axis

Integration of (p, q, r) corresponds to angular positions (ϕ, θ, ψ) about X, Y and Z axes.

By considering the kinematics, rigid body dynamics and hydrodynamics, the model of submarine is represented by a set of equations, known as standard equations of motion. The state space form of these equations is given by Eq. 1 (Fossen,1994; Gertler and Hagan, 1967).

++Corresponding author, D. M. PATHAN email durmohd66@yahoo.com +92-3012117998
*Department of Energy and Environment, Quaid-e-Awam University of Engineering, Science and Technology, Nawbshah , Sindh, Pakistan

$$\dot{x} = Ax + Bu \quad (1)$$

where

$x=[u\ v\ w\ p\ q\ r\ \phi\ \theta\ \psi\ z]$

$u = [\delta b\ \delta r\ \delta s]$

x is state vector, u is input vector, A is system matrix and B is input matrix, δb is bow_plane defection, δr is rudder deflection and δs is stern_plane deflection.

3. Control Objective

This paper proposes a fuzzy logic control system for heading and diving motions of a submarine. Heading motion refers to regulate the psi ψ (angle about z-axis) in response to rudder deflection δr. On other hand the diving motion pertains to the regulation of the depth z (distance along z-axis) in response to stern-plane deflections δs.

The controller is designed in such a way that it provides satisfactory performance for any reference heading ranging from $\pm 3^o$ to $\pm 45^o$ and for any reference depth ranging from ± 5 m to ± 200 m. The reference model of system is obtained by second order differential equation.

The performance criteria for presumed for controller is that the errors should not exceed $\pm 3^o$ for heading and ± 3 m for diving respectively. The controller should be capable to perform optimally in ideal conditions but it has also capability to reject the effects of randomly varying waves.

4. Controller Design

Designing a fuzzy logic controller means selection of specific structure and parameters of controller in such a manner that the actual states of submarine tracks the desired states as minimize the difference (i.e error) between them. The structural design determines the selection of input/output of controller, selection of Fuzzy Inference System, selection of membership function and method of defuzzification.

The parametric design depends on selection for ranges of universal sets for input and output variables, selection of number of rules, selection number of membership functions.

5. STRUCTURAL DESIGN OF CONTROLLER

The idea behind developing the FL controller is to map the input states for a particular output. For this purpose Mamdani type Fuzzy Inference System (FIS) is used.

5.1 Inputs and outputs

The heading motion of submarine is achieved by the deflection of rudder δr. In this motion the submarine is confined to maneuver in earth fixed X_E-Y_E plane. Similarly the diving motion of the submarine is achieved by stern-plane deflection δs. In this motion the submarine is confined to maneuver in earth fixed X_E-Z_E plane. The states which significantly change during these motions are ψ, r, v, θ, q, w and z. The performance of the controller is based on minimization of errors. Therefore the input for controller is the set of errors, given as x_{error}= [ψ_{error}, r_{error}, θ_{error} q_{error}] and output/target for controller is the set of control components, given as u = [δr δs].

5.2 Membership function

A membership function demonstrates extent of membership of a particular value in a fuzzy set. For this purpose a triangular membership function given by Eq (2) is used. This equation smoothly maps the any input to a value in between 0 to 1.

$$\mu(x_{error},a,b,c) = \begin{cases} 0 & x_{error} < a, x_{error} > c \\ \dfrac{x_{error}-a}{b-a} & a \le x_{error} \ge b \\ 1 & x_{error} = b \\ \dfrac{c-x_{error}}{c-b} & b \le x \ge c \end{cases} \quad (2)$$

where μ is membership value, while a, b and c are the parameters of function. a and b describe the limits of function and b is core having membership of one.

6. PARAMETRIC DESIGN OF CONTROLLER

The important phase of designing a FL controller is selection of optimal parameters. The parametric development of fuzzy controller depends on the knowledge of human expertise in that field.

6.1 Universal sets for input and output variables.

Starting from performance criteria selected in section 3, the ranges for input and output variables are tuned as:

ψ_{error}, :	from -2.0° to 2.0°
r_{error} :	from -1.5° to 1.5°
θ_{error} :	from -2.0° to 2.0°
$q_{error:}$	from -1.2° to 1.2°
δr :	from -35° to 35°
δs :	from -25° to 25°

The negative to positive signs of ranges show that submarine can attain clockwise or anticlockwise direction.

6.2 Fuzzification of variables

Fuzzification is a process of converting the mathematical variables into linguistic variables. Accordingly the universal sets of each variable ψ_{error}, r_{error}, θ_{error}, q_{error}, δr and δs is divided into seven sub-sets labeled as Big negative (BN), Medium negative (MN), Small negative (SN), Zero (ZE), Small positive (SP), Medium positive (MP) and Big positive (BP). Each subset is defined in such a manner that their values overlap with neignbouring subset as given in **(Table 1)**.

Table 1 Fuzzy sub-set of submarine heading and diving controller variables

Heading fuzzy variables	ψ_{error}			r_{error}			Δr		
	a	***b***	***c***	***a***	***b***	***c***	***A***	***B***	***c***
BN	-2.66	-2.000	-1.333	-2.000	-1.500	-1.000	-46.69	-35.00	-23.32
MN	-2.000	-1.333	-0.666	-1.500	-1.000	-0.500	-35.00	-23.32	-11.67
SN	-1.333	-0.666	0.00	-1.000	-0.500	0.0000	-23.32	-11.67	0.000
ZE	-0.666	0.000	0.666	-0.500	0.000	0.5000	-11.67	0.000	11.67
SP	0 .00	0.666	1.333	0.0000	0.5000	1.0000	0.000	11.67	23.32
MP	0.666	1.333	2.000	0.5000	1.0000	1.5000	11.67	23.32	35.00
BP	1.333	2.000	2.66	1.0000	1.5000	2.0000	23.32	35.00	46.69
Diving fuzzy variables	θ_{error}			q_{error}			Δs		
	a	***b***	***c***	***a***	***b***	***c***	***A***	***B***	***c***
BN	-2.66	-2.000	-1.333	-1.608	-1.200	-0.800	-33.35	-25.00	-16.66
MN	-2.000	-1.333	-0.666	-1.200	-0.800	-0.400	-25.00	-16.66	-0.833
SN	-1.333	-0.666	0.00	-0.800	-0.400	0.000	-16.66	-0.833	0.000
ZE	-0.666	0.00	0.666	-0.400	0.000	0.40	-0.833	0.000	0.8335
SP	0 .00	0.666	1.333	0.0000	0.40	0.8000	0.000	0.833	16.660
MP	0.666	1.333	2.000	0.4000	0.8000	1.2000	0.833	16.660	25.00
BP	1.333	2.000	2.66	0.8000	1.2000	1.6080	16.66	25.00	33.35

6.3 Rules and processing of rules

The rules are collection of IF THEN statements, which are processed by Fuzzy Inference System. If a system is simple, having single input and single output, the statement may be very simple. The rules can be read as:

Rule 1: IF *r_error* is *big negative* AND *ψ_ error* is *big negative* THEN *δr* is *big negative*

Rule 2: IF *r_error* is *medium negative* AND *ψ_ error* is *big negative* THEN *δr* is *big negative*

Rule 3: IF *r_error* is *small negative* AND *ψ_ error* is *big negative* THEN *δr* is *medium negative*

Rule 4: IF *r_error* is *zero* AND *ψ_ error* is *big negative* THEN *δr* is *medium negative*

Rule 5: IF *r_error* is *small positive* AND *ψ_ error* is *big negative* THEN *δr* is *small negative*

Rule 6: IF *r_error* is *medium positive* AND *ψ_ error* is *big negative* THEN *δr* is *small negative*.

and so on A

The outputs of all active rules are combined to form the resultant fuzzy set, which is converted into single crisp output by defuzzification process. For this work centriod method is used for defuzzification. finally a control system with four inputs, two outputs and 98 rules provides the good result.

7. CONTROL SYSTEM

A control system based on a closed loop system is developed. This system consists of desired state model, desired state signals, actual state signal, error signals, fuzzy logic controller and submarine model as shown in Figure 1. By providing the command inputs ($\psi_{command,}$ $z_{command}$) , the desired states ψ_d,_r_d, θ_d and q_d are obtained from second orde system. The desired states are compared with actual states ψ_{act},_r_{act}, θ_{act} and q_{act} of submarine coming from the feedback path. The comparison element generates the errors ψ_{error}, r_{error}, θ_{error}, q_{error}. These errors are fed to fuzzy controller. On basis of errors the controller decides for deflection of control component (δr and δs) to achieve the desired direction ψ and desired depth *z*.

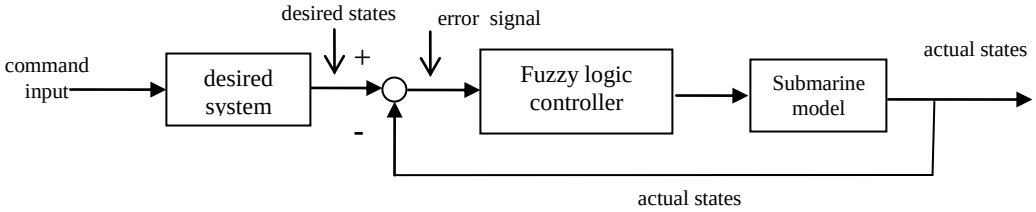

Figure 1: control system model

By using above control system first the simulations are carried out under ideal conditions by using Eq (1). In second phase the simulations are carried out by incorporating the effects of wind generated waves in the model of submarine.

8. WIND GENERATED WAVES

Blowing of wind develops ripples on the surface of ocean, these ripples ultimately generate waves that results in oscillations of surface of the water in a spectrum of frequencies that develops forces and moments on the ocean surface.

8.1 Forces and moments induced by waves

When the submarine experiences the forces and moments created by waves, these occur in the X_B - Y_B plane. This means that the force along the z-axis and moment about x-axis and y-axis will be zero. The resulting *X*, *Y* forces will act along the 'x' and 'y' axis and *N* moment about z-axis and are denoted as X_{wave}, Y_{wave} and N_{wave} .

By integrating the forces and moments developed by waves in a submarine model Eq. 1, the model becomes as:

$$\dot{x} = Ax + Bu + f \qquad (3)$$

$$f = [\dot{u}_{wave}\ \dot{v}_{wave}\ 0\ 0\ 0\ \ \dot{r}_{wave}\ 0\ 0\ 0]$$

where

$\dot{u}_{wave}$ = κcos(β). s(t)

$\dot{v}_{wave}$ = - κ sin(β). s(t)

$$\dot{r}_{wave} = \kappa \frac{(L^2 - B^2)}{24D} \sin(\beta).\ s^2(t)$$

where $\dot{u}_{wave}$ is the acceleration of the waves along body fixed x-axis, $\dot{v}_{wave}$ is the acceleration of the waves along body fixed y-axis $\dot{r}_{wave}$ is the moment of the waves about body fixed z-axis, κ is constant that depends upon dimensions (Length L, breadth B and depth D) of submarine and β angle of wave encounter. In this paper it is taken as 45° and s(t) is the slope at which the wave strike the submarine.

The wave slope s(t) depends upon various factors like wave elevation, wave numbers, amplitude of wave and wave spectral density functions (Fossen, 1994). For this paper Pierson-Moskowitz (PM) Spectrum density function has been chosen.

9. SIMULATION RESULTS

By using the closed loop control system, various simulations are carried out which are presented in the following section.

9.1 Controller under ideal conditions

The performance of the controller for ideal conditions is represented by Figures 2 and 3. In these figures the first graph of first row represents diving behavior and second graph of first row represent the heading behavior. In both graphs the actual behavior is shown by solid lines where the desired states are represented by dashed lines because of minute difference between desired and actual states, both lines coincides each other and are visible as single line. The second row graphs show depth and heading errors. The third row graphs depict the stern plane deflection and rudder deflection.

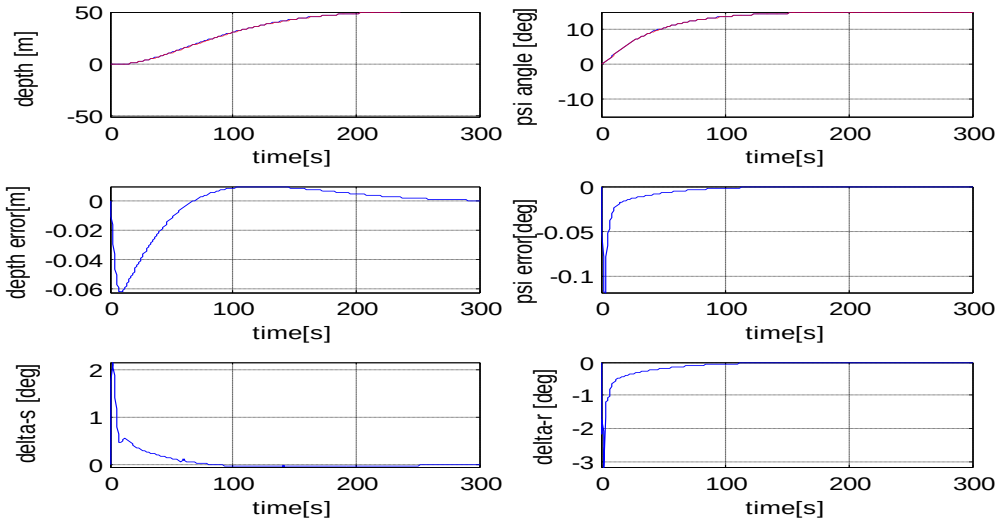

Fig. 2: Simulation results for 15° command heading angle and 50 m command depth

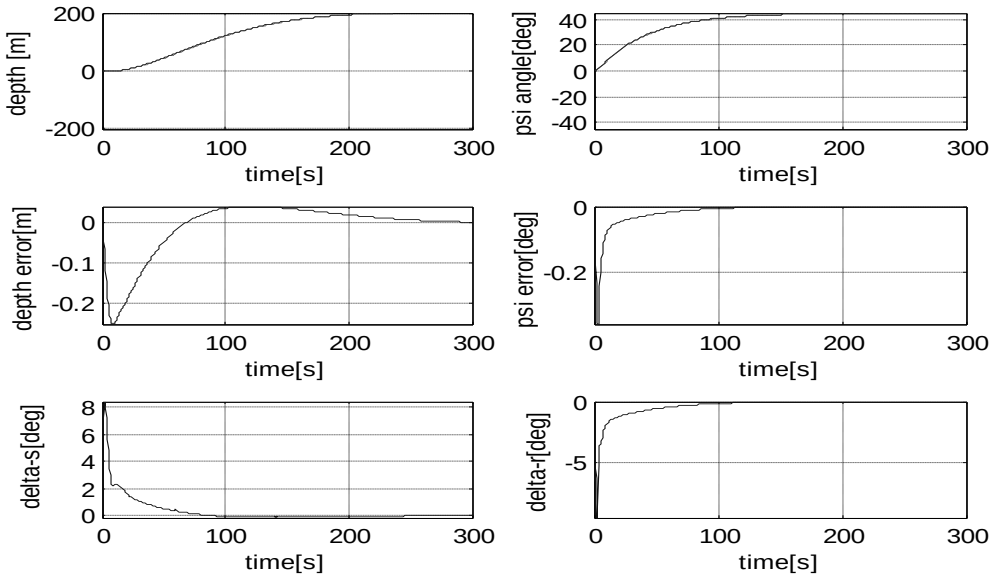

Fig. 3: Simulation results for 45º command heading angle and 200 m command depth

9.2 Controller in presence of waves

By taking the model of submarine represented by Eq.3, simulations are carried out. The simulations are assumed to be carried out at surface of sea (i.e taking depth as zero) to observe maximum influence of waves. The results obtained are given in Figure 4 . In this figure the first row graphs represent desired and actual heading and diving, the second row graphs show the errors of direction and depth. The third row graphs exhibit the performance of control components, stern-plane deflection and rudder deflection. The last three graphs show the components of randomly varying wave forces along x and y axes and about z axis.

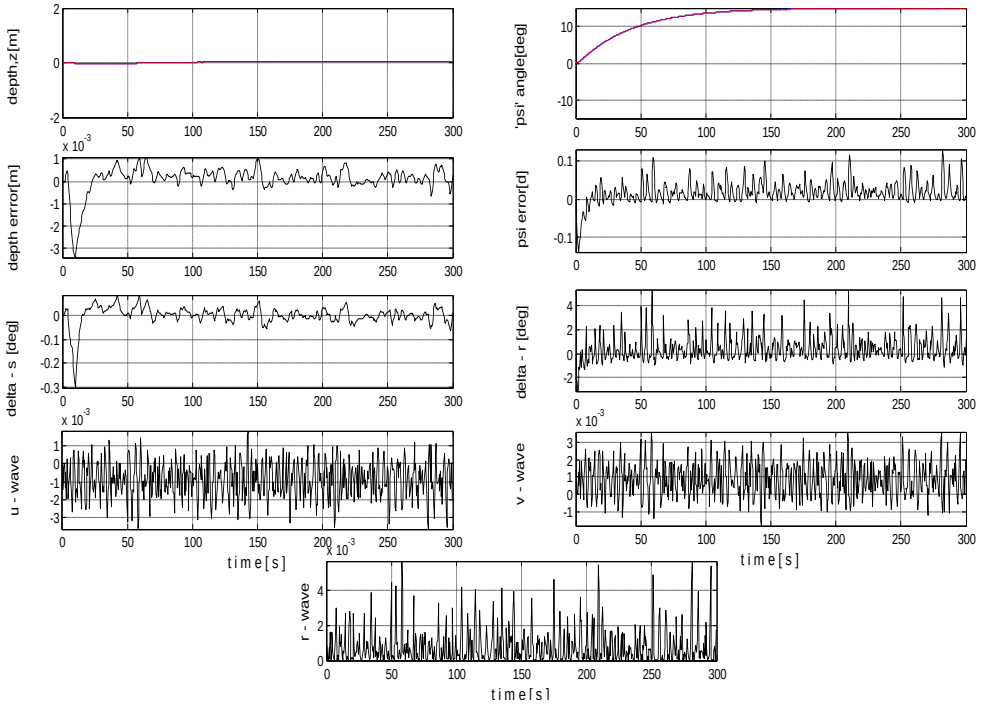

Fig. 4: Simulation results of FL controller at 15º command heading angle and 0m command depth

10. RESULTS AND DISCUSSIONS

Graphical results show the performance of controller for different operating conditions. In ideal conditions figure 2 shows that for 15° command heading angle the heading error is -0.15^o and the rudder angle is $-3^o$and for 50 m command depth the error is -0.06 m, the stern plane deflection is 2.1^o. Figure 3 represents that for 45° command heading angle the heading error is -0.4^o and the rudder angle is -10° and for 100m command depth the error is -0.25^o, the stern plane deflection is -8.5^o.

In presence of waves figure 4 shows that for 15° command heading angle the actual states oscillates about the desired state, however these oscillation are minutes resulting the the maximum heading error is -0.15^o and similarly to overcome the error the rudder angle also exhibits oscillations from -3.0^o to $+6.0^o$. To observe the effects of waves the simulations are carried out at surface of sea (by keeping depth = 0), but due to strong influence of waves some oscillations are also observed in z-axis direction and a minute depth error is observed.

From given results it is observed that in ideal conditions the control component rudder smoothly tracks to steady state condition but in presence of waves the control component tracks to steady state but it exhibits some oscillations, this is because of influence of randomly varying waves.

11. CONCLUSION

In this paper Fuzzy Logic control system is applied for heading and diving motions of a submarine. The development of controller is based on model of submarine without incorporating the external environmental disturbances, but the performance controller proved to be satisfactory not only in ideal conditions but in presence of randomly varying waves. This proves that once the development of controller is completed, the configuration controller remains fixed and resulting control systems have capability to cope with unpredictable characteristics of system.

12. ACKNOWLEDGEMENTS

This work is a part of PhD research work. The first author is thankful to Higher Education Commission of Pakistan for funding for accomplishing this work. Authors are also thankful to Department of Electronic & telecommunication MUET Jamshoro for providing basic facilities for research. The authors also pay homage for Mehran University of Engineering and Technology, Jamshoro, for providing the facilities to carry out the research work.

REFERENCES:

Akkizidis, I.S, G.N. Roberts P. Ridoa and J. Batlle (2003) "Designing of Fuzzy like PD controller for an underwater robot", Control Engineering Practice Vol. **(11):** 471-480.

DeBitetto P.A., (1995) "Fuzzy logic for depth control of unmanned undersea vehicles", IEEE Journal of Oceanic Engineering, Vol. **(20)**: No.3, 233-241.

Fossen, T. I., (1994) "Guidance and Control of Ocean Vehicles," John Wiley and Sons, New York.

Gertler, M., and G.R.Hagan (1967) "Standard Equation of motion for submarine simulation", Research and Development Report 2510, Naval Ship Research and Development Centre, Washington DC, June 1967.

Guo, J., F.C. Chiu, and C.C. Haung (2003) "Design of a sliding mode fuzzy controller for the guidance and control of an autonomous underwater vehicle", Ocean Engineering, Vol. **(30)**: 2137-2155.

Kim H-S., and Y.K. Shin (2007) "Expanded adaptive Fuzzy Sliding Mode Controller using expert knowledge and Fuzzy Basis Function Expansion for UFV depth control", Ocean Engineering Vol. **(34):**1080-1088.

Kumar, G.V.N., R.K.P. Gopala, P.V.S. Sobhan and D. Chowary, D. Deepak, (2008) "Robustness of Fuzzy Logic based Controller for Unmanned Autonomous Underwater Vehicle", IEEE Region 10 Colloquium and the third International Conference on Industrial and Information Systems, .1-6, Kharagpur, India.

McGookin, E. W., and D.J. Murray-Smith (2006) "Comment on "Nonlinear Optimal Tracking Control with Application to Super-tankers for Autopilot Design" by T. Çimen and S.P. Banks", *Automatica*, Vol. **(42)**: 2223 – 2225.