工學碩士 學位論文

An Automatic Navigation of Ship in Dynamic Environment using Multivariable Fuzzy Control System

다변수 퍼지 제어 시스템을 이용한 동적 환경에서의 선박 자동 항해

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2000年 2月

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요약문

인공 지능 분야에서 특히 퍼지와 같은 기술은 전반적인 산업 자동화에 많이 사용되어 왔다. 퍼지 제어는 인간의 추론 과정을 모델링한 기술로서 인간에 유사한 결정 능력과 복잡하고 다양한 환경에 매우 효과적이다.

본 논문은 이러한 퍼지 제어의 장점을 연근해의 선박 자동 항해에 적용시켜 보았다. 심해에서는 공간상의 제약이 없기 때문에 선박의 자동항해는 원하는 목표지점까지 안전하게 운항할 수 있지만, 연근해안에는 심해와 달리 각종 장애물들(작고 큰 섬들과 해안, 연근해에 작업중인 선박들)이 있으며 이것들로 인한 충돌 사고가 종종 발생하고 있는 실정이다. 그러므로 연근해안에서 보다 안전하고 자율적인 항해를 위해 인공 지능 기술인 퍼지 기술을 선박에 적용시켰다. 본 논문에 사용된 퍼지 제어 시스템은 두 개의 하부 퍼지 제어시스템으로 구성되어 있으며, 3개의 입력 변수와 3개의 출력 변수를 가진 다변수 퍼지 제어시스템이다. 이러한 다변수 퍼지 시스템을 5개의 서로 다른 동적 환경을 가지는 지형에 적용시켜 보았고, 그에 따른 실험들을 수행했을 때, 만족할만한 결과를 얻을 수 있었다. 따라서, 본 논문에서 제안된 다변수 퍼지 제어시스템을 이용한 선박이 동적인 환경에서도 스스로 장애물을 인식하고 회피함으로 안전하게 연근해를 운항할 수 있음을 보였다.

Abstract

Artificial Intelligent(AI), which is called one field of science, has rapidly been developed during the last half century. It has been applied to a variety industry development. One of the new popular applications is "automatic navigation", operated without man's handling. A scope of automatic navigation was expanded into airplane, car and ship that needed speedy and correct operation[1][4][10][11].

This paper presented automatic navigation of ship using fuzzy control system in dynamic sea environment. In deep sea, because limitation of place doesn't exist, the need of automatic navigation for obstacle avoidance is a little. However in near sea, the need of automatic navigation for obstacle avoidance is big because of many obstacles (i,e., big and small island, working or moving ship, etc.). Therefore this paper used multivariable fuzzy control system for more safe and automatic navigation.

Multivariable fuzzy control system consist of two subsystems with three inputs and three outputs. Thus it is navigated at five maps. Simulation and plotting graph are found that they had satisfactory results. Therefore, ship using multivariable fuzzy control system was confirmed that it could avoid obstacle in dynamic environment and safely navigate in near sea by itself.

Chapter 1. Introduction

Automation is one of the very important part modern industry societies. The research and development for an automation of various industrial machine and automatic control of dynamic plant have been studied over the last several decades[3][4]. In particular, many research for vehicle have been progressed[10][11]. However, the works of automatic navigation of a ship for obstacle avoidance have been not enough. In the deep sea, this matter is not necessary because ship doesn't limit place. However, in near sea it is very important because it may collide with many other moving or working ships and many obstacle, such as an island or sucken lock. Because of this reason, there have unnecessary economy loss and need many people for safety in near sea. Therefore, to overcome above problems need exact system using intelligent control[2].

One of the more popular new technologies is "intelligent control", which is defined as the combination of control theory, operations research, and artificial intelligent. Among new technologies based on artificial intelligent, fuzzy logic is the popular area. Fuzzy control is one of field for global technological, economical, and manufacturing competitions[1]-[5]. In 1980's, fuzzy control is to be usefully applied the technological field that engineering design, intelligent control, signal filtering, pattern recognition, breakdown diagnosis, and the society field that decision making, the medical, action science, economy, society model, and the nature field that phenomena, geographical features, mode of life cycles, physics & chemical phenomenon[1]. Using technique such a fuzzy is efficient to automation of vehicle. Therefore this paper used control system that composed with fuzzy logic.

In chapter 2 the multivariable fuzzy equations for open-loop control system are presented, and some formal properties of the equations are discussed. The design of map and fuzzy ship for navigation are illustrated in chapter 3. Chapter 4 of this paper shown modeling of multi variable fuzzy control system and fuzzy algorithms. Simulation results and plotting graphs are illustrated in chapter 5. The concluding remarks are given in chapter 6.

Chapter 2. Multivariable Fuzzy Control System

Recent research on the application of fuzzy set theory of the design of control systems has led to interest in the theory and description of the multivariable structure of these systems. This interest has arisen mainly due to two facts. One is that real control systems are multidimensional, and the other is that the computer implementation of physical systems requires the processing of a huge database. It is often accompanied by memory overload. The analysis and design procedures for such systems are consequently very difficult.

In this chapter modeling and analysis and composition of multivariable fuzzy control system are shown. Fuzzy system by set of fuzzy equation is described at first. Series and parallel connection of multivariable fuzzy system are described secondly. Multivariable fuzzy structure of series and parallel connection are illustrated by set of fuzzy equation and block diagram and fuzzy relations and the logic operator are used in design of multivariable fuzzy systems.

2. 1 Multivariable structures of fuzzy control system

Open-loop fuzzy systems are systems in which the outputs have no effect upon the input control actions. When described by fuzzy relations, such systems are called open-loop fuzzy systems[2][3][4].

Consider now a multivariable system shown in Fig. 1.

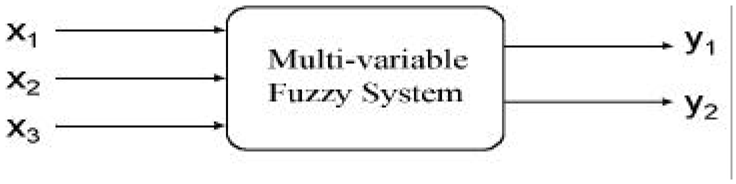


Fig. 1. Multi-input multi-output fuzzy system.

Therefore, the linguistic description of the process is given by

$$\begin{array}{l} \text{IF } X_{1(1)} \text{ AND } X_{2(1)} \text{ AND } X_{3(1)} \text{ THEN } Y_{1(1)} \text{ AND } Y_{2(1)} \\ \quad \text{ALSO} \\ \text{IF } X_{1(2)} \text{ AND } X_{2(2)} \text{ AND } X_{3(2)} \text{ THEN } Y_{1(2)} \text{ AND } Y_{2(2)} \\ \quad \text{ALSO} \\ \quad \vdots \\ \text{IF } X_{1(i)} \text{ AND } X_{k(i)} \text{ AND } X_{3(i)} \text{ THEN } Y_{1(i)} \text{ AND } Y_{j(i)} \\ \quad \vdots \\ \quad \text{ALSO} \\ \text{IF } X_{1(n)} \text{ AND } X_{2(n)} \text{ AND } X_{3(n)} \text{ THEN } Y_{1(n)} \text{ AND } Y_{2(n)} \end{array} \tag{1}$$

where **Xk(i)** is the fuzzy value of the k-input variable defined in the universe of discourse **Xk**, k=1, 2, 3; and **Yj** is the fuzzy value of the jth output variable defined in the universe of discourse **Yj** j= 1, 2. To avoid such long formulate, the following abbreviation for (1) will now be used:

$$\{(\text{IF } X_{1(i)} \text{ AND } X_{k(i)} \text{ AND } X_{3(i)} \text{ THEN } Y_{1(i)} \text{ AND } Y_{j(i)}), (\text{ALSO})\},\quad i = 1, 2, \cdots, n$$

Let the dimensions of the universe of discourses **Xk** and **Yj** be, respectively,

$$\dim[X^k] = q_k, \quad \dim[Y^j] = p_j$$

The fuzzy relation **R** of the system is expressed as follows

$$R = \bigvee_{i=1}^{n} \{X_{1(i)} X_{2(i)} X_{3(i)} Y_{1(i)} Y_{2(i)}\} \qquad (2)$$

where $\dim[R] = q_1 \times q_2 \times q_3 \times p_1 \times p_2$.

To obtain the present outputs Y_1, Y_2 given the current inputs X_1, X_2, X_3, the following compositional rule of inference[7] is used:

$$Y = X_1 \circ X_2 \circ X_3 \circ R \qquad (3)$$

The result of this composition is a compound fuzzy set **Y** in the universe $Y_1 \times Y_2$, where $\dim[Y] = p_1 \times p_2$. The individual outputs can be calculated by the projection of the compound output fuzzy set (3) on the respective universes [8]

$$Y_1 = \bigvee_{Y_2} Y, \quad Y_2 = \bigvee_{Y_1} Y \qquad (4)$$

Because of the multi-dimensionality of the relation (2) and fuzzy output (3), a straightforward analysis and synthesis of the multivariable fuzzy system is difficult to obtain. To overcome this difficulty, it is proposed, in analogy to the theory of linear systems, the following form of equations governing the three-input two-output system.

$$Y_1 = X_1 \circ R_{11} \, \Delta \, X_2 \circ R_{21} \, \Delta \, X_3 \circ R_{31}$$
$$Y_2 = X_1 \circ R_{12} \, \Delta \, X_2 \circ R_{22} \, \Delta \, X_3 \circ R_{32} \tag{5}$$

where $\mathbf{R}_{kj}$ are two-dimensional (flat) fuzzy relations, and $\mathbf{\Delta}$ denotes a certain rule of composition. As can be seen in (5), the formulas cannot be exact for all systems, no matter which composition $\mathbf{\Delta}$ is selected. Namely, **R** has $q_1 \cdot q_2 \cdot q_3 \cdot p_1 \cdot p_2$ elements which, in general, are independent, while all the $\mathbf{R}_{kj}$ contain only $(q_1 + q_2 + q_3)(p_1 + p_2)$ elements. To obtain a more tractable structure, a loss of accuracy must be accepted.

The representation (5) is obtained in the following way. Starting from (2) and (3) it is found that

$$Y = \bigvee_{X^1} X_1 \wedge \bigvee_{X^2} X_2 \wedge \bigvee_{X^3} X_3 \bigvee_{i=1}^{n} \{X_{1(i)} \wedge X_{2(i)} \wedge X_{3(i)} \wedge Y_{1(i)} \wedge Y_{2(i)}\}$$

$$= \bigvee_{i=1}^{n} \Big\{ \bigvee_{X^1} X_1 \wedge X_{1(i)} \wedge Y_{1(i)} \wedge \bigvee_{X^2} X_2 \wedge X_{2(i)} \wedge Y_{1(i)} \wedge \bigvee_{X^3} X_3 \wedge X_{3(i)} \wedge Y_{1(i)}$$

$$\wedge \bigvee_{X^1} X_1 \wedge X_{1(i)} \wedge Y_{2(i)} \wedge \bigvee_{X^2} X_2 \wedge X_{2(i)} \wedge Y_{2(i)} \wedge \bigvee_{X^3} X_3 \wedge X_{3(i)} \wedge Y_{2(i)} \Big\} \tag{6}$$

Now define the fuzzy relation R_{kj} as

$$R_{kj} = \bigvee_{i=1}^{n} \{X_{k(i)} \wedge Y_{j(i)}\}, \quad k = 1, 2, 3, \quad j = 1, 2 \tag{7}$$

By taking the projection (4), the following is obtained from (6)

$$\begin{aligned} Y_1 &= X_1 \circ R_{11} \wedge X_2 \circ R_{21} \wedge X_3 \circ R_{31} \\ Y_2 &= X_1 \circ R_{12} \wedge X_2 \circ R_{22} \wedge X_3 \circ R_{32} \end{aligned} \tag{8}$$

that is, relation (5), where **Δ** is the conjunction operator.

It should be noted now that the six-dimensional fuzzy matrix R, and two-dimensional fuzzy output Y (see (2) and (3)) are decomposed into six two-dimensional fuzzy matrices $R_{11}, \cdots, R_{32}$ and two one-dimensional fuzzy outputs Y1, Y2.

Consider now the three inputs (i,e., X_1, X_2, X_3) to be the components of an input vector. Similarily, the two outputs (i.e., Y_1, Y_2) may be regarded as the components of an output vector. Using vector-matrix notation, the input-output set of fuzzy equations in (8) can be written as

$$\begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix}' = [X_1 \ \ X_2 \ \ X_3] * \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \\ R_{31} & R_{32} \end{bmatrix} \tag{9}$$

where * is the ($\circ$, $\wedge$)-operator. In a compact form, (8) can be written as

$$Y_z = X_z * R_z \tag{10}$$

where

$$Y_z = \begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix}', \quad X_z = [X_1 \; X_2 \; X_3]$$

and

$$R_z = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \\ R_{31} & R_{32} \end{bmatrix}$$

Here **Yz** is the (p1 + p2) output vector, **Xz** is the (q1 + q2 + q3) input vector, and the compact fuzzy matrix **Rz** has (q1 + q2 + q3) rows and (p1 + p2) columns.

Equations (8)-(10) show the relationships between the three inputs and two outputs. Although the vector-matrix equation in (10) is simple, the actual relation in terms of the decomposed matrices **Rkj** are quite complex as shown by (8).

To understand better the nature of the linguistic description (1) and its mathematical counterpart (8), a multivariable block diagram form is now proposed. its mathematical equivalent in (2) that the multivariable fuzzy equations of (8) consist of a number of functional blocks linked up by the intersection operators. The multivariable structure of the fuzzy system consists, therefore, of input signals, branch points, functional blocks, inner signals, intersection blocks, and output signals as shown in Fig. 2.

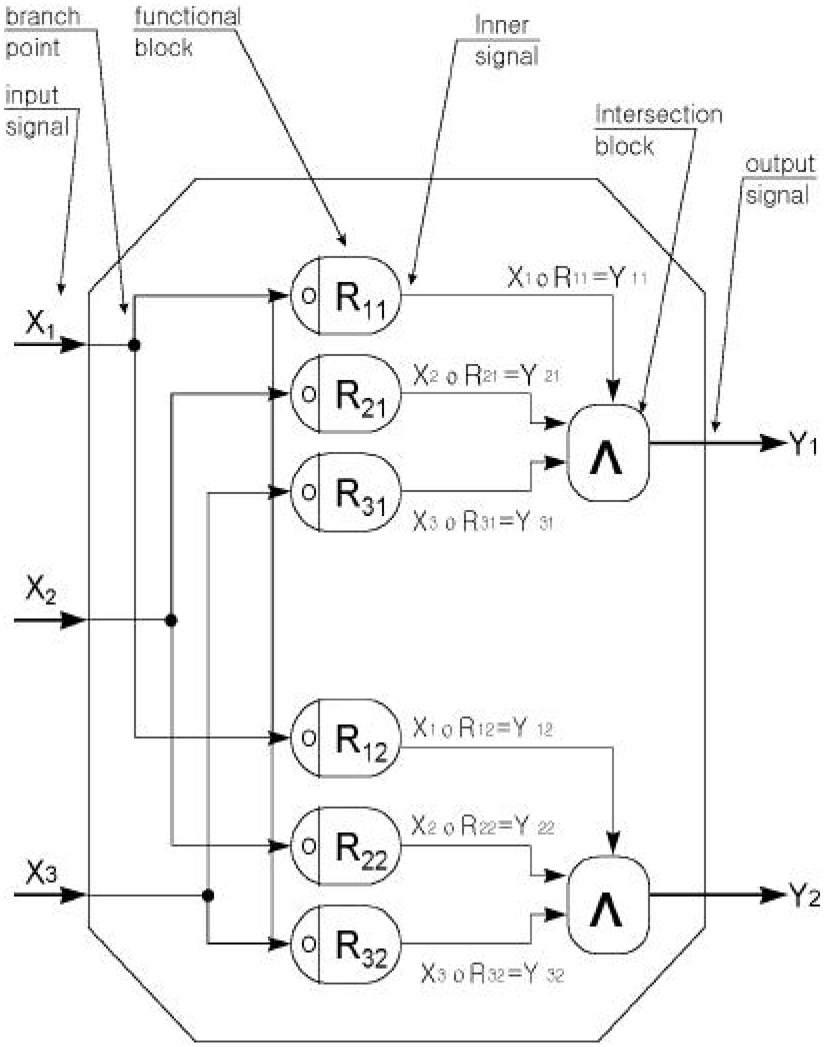


Fig. 2. Multivariable structure of fuzzy control system.

According to the multivariable structure of Fig. 2 the inner and output signals take the form

$$Y_{kj} = X_k \circ R_{kj}, \quad k = 1, 2, 3, \quad j = 1, 2 \tag{11}$$

$$Y_j = \bigwedge_{k=1}^{3} Y_{kj}, \quad j = 1, 2 \tag{12}$$

Applying the same idea to (9) and (10), a compact structure of a multivariable system as shown in Fig. 3 is obtained.

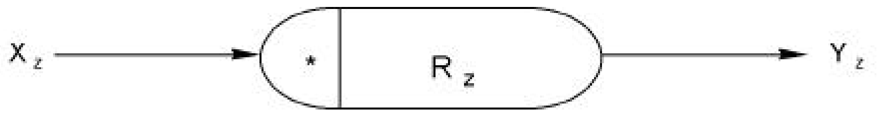


Fig. 3. Compact structure of multivariable fuzzy system

Therefore, a generalized description of the fuzzy system with M inputs and N outputs is given by

$$Y_j = \bigwedge_{k=1}^{M} X_k \circ R_{kj}, \quad j = 1, 2, \cdots, N \tag{13}$$

The multivariable structure of the system which has M inputs and N outputs contains M×N - functional blocks, M×N - inner signals **Ykj**, M-branch points, and N-intersection blocks.

The advantages of the block diagram representation of a multivariable fuzzy system lies in the fact that it allows the overall block diagram for the entire system to be easily constructed by merely connecting the blocks of the components according to the set of fuzzy equations. It is also possible to evaluate the contribution of each component to the overall performance of the system. The functional operation of the system can be visualized more readily by examining the block diagram than by examing the linguistic system itself. A block diagram contains information concerning signals flow, but it does not contain any information concerning the physical construction of the system. Therefore, many dissimilar and unrelated fuzzy systems con be represented by the same block diagram. Hence this block diagram, which is a graphical representation of the sequence of operations, can be easily converted into a computer program to compute the response sequence. By mean of this representation, it is possible to perform any analysis and synthesis on a computer. It should be noted, however, that a block diagram of a given fuzzy system is not unique. A number of different block diagrams may be drawn for the same system, depending upon the viewpoint adopted in the analysis and synthesis. To draw a block diagram for a multivariable fuzzy system, one must write first the set of fuzzy equations based on the linguistic description which describes the fuzzy behaviour of the system. Then, one must take the decomposed fuzzy matrices and represent each fuzzy equation individually in functional block form. Finally, the elements must be assembled through branch points and intersection blocks into a complete block diagram.

2.2 Interconnections of multivariable fuzzy control system

In an industrial process a complex system can be decomposed into several interconnected subsystems based on the physical structure of the process. To avoid the computational burden due to the complexity of the global model and yet retain the coupling effects, one may wish to develop a fuzzy model, which aggregates those parts of the system that are not of immediate concern, and maintain a similar structure for the subunits under consideration. Therefore, in chapter, it is explained a parallel, and a series-parallel connection of multivariable open-loop fuzzy systems will be analyzed now.

[Series Connections]

A series of connections of two multivariable systems, as shown in Fig. 4, will be described by the following linguistics description.

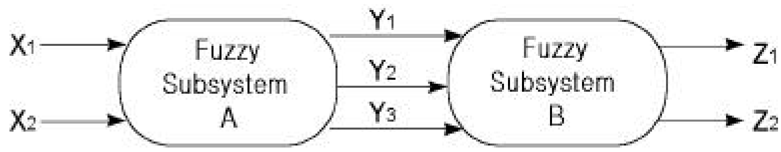


Fig. 4. Series connection of two fuzzy subsystems

Fuzzy Subsystem A:

$$\{(\text{IF } X_{1(i)} \text{ AND } X_{2(i)} \text{ THEN } Y_{1(i)} \text{ AND } Y_{2(i)} \text{ AND } Y_{3(i)}), (\text{ALSO})\}, \quad i = 1, 2, 3, \cdots, n \tag{14}$$

Fuzzy Subsystem B:

$$\{(\text{IF } Y_{1(i)} \text{ AND } Y_{2(i)} \text{ AND } Y_{3(i)} \text{ THEN } Z_{1(i)} \text{ AND } Z_{2(i)}), (\text{ALSO})\}, \quad i = 1, 2, 3, \cdots, n \tag{15}$$

Based on the previous considerations, a vector matrix notation of the subsystems in terms of the fuzzy equations has the following form:

Fuzzy Subsystem A:

$$\begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \end{bmatrix}' = [X_1 \ X_2] * \begin{bmatrix} R^A_{11} & R^A_{12} & R^A_{13} \\ R^A_{21} & R^A_{22} & R^A_{23} \end{bmatrix} \tag{16}$$

where

$$R^A_{kj} = \bigvee_{i=1}^{n} \{X_{k(i)} \wedge Y_{j(i)}\}, \quad k = 1, 2, 3$$

Fuzzy subsystem B:

$$\begin{bmatrix} Z_1 \\ Z_2 \end{bmatrix}' = [Y_1 \ Y_2 \ Y_3] * \begin{bmatrix} R^B_{11} & R^B_{12} \\ R^B_{21} & R^B_{22} \\ R^B_{31} & R^B_{32} \end{bmatrix} \tag{17}$$

where

$$R^B_{kj} = \bigvee_{i=1}^{n} \{Y_{k(i)} \wedge Z_{j(i)}\}, \quad k = 1, 2, 3, \quad j = 1, 2$$

Substituting (16) into (17), the following composite fuzzy system of two multivariable open-loop systems connected in series is obtained:

$$\begin{bmatrix} Z_1 \\ Z_2 \end{bmatrix}' = [X_1 \quad X_2] * \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} \tag{18}$$

where

$$R_{11} = R^A_{11} \circ R^B_{11} \wedge R^A_{12} \circ R^B_{21} \wedge R^A_{13} \circ R^B_{31}$$

$$R_{12} = R^A_{11} \circ R^B_{12} \wedge R^A_{12} \circ R^B_{22} \wedge R^A_{13} \circ R^B_{32}$$

$$R_{21} = R^A_{21} \circ R^B_{11} \wedge R^A_{22} \circ R^B_{21} \wedge R^A_{23} \circ R^B_{31}$$

$$R_{22} = R^A_{21} \circ R^B_{12} \wedge R^A_{22} \circ R^B_{22} \wedge R^A_{23} \circ R^B_{32}$$

Equation (18) is represented by the structure shown in Fig. 5. The reduced fuzzy model (18) contains the system's structural information. Using (16)-(18), a multivariable series-connected system with a given linguistic description can be analyzed or synthesized.

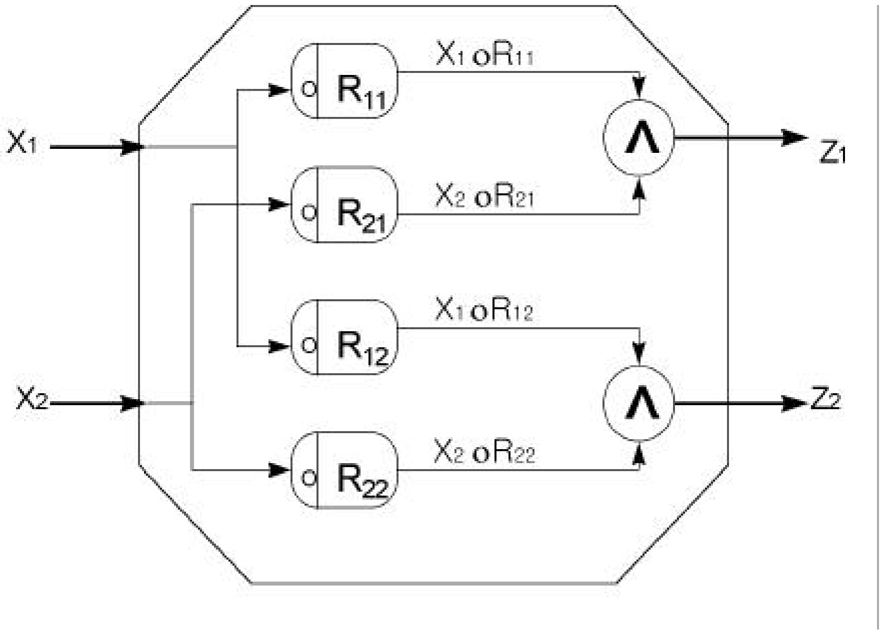


Fig. 5. Multivariable structure of series connection of two fuzzy subsystems.

[Parallel Connections]

Fig. 6 shows a parallel connection of multivariable fuzzy subsystems. Intermediate fuzzy signals Z_1, Z_3, Z_5 and Z_2, Z_4, Z_6 flow by means of junction points and the output fuzzy signals $Y1$ and $Y2$ are obtained. The junction points can realize any mathematical operation of fuzzy sets; that is, summation, subtraction, multiplication, etc. Let the three fuzzy subsystems be described by the following linguistic descriptions and their respective fuzzy equations representations.

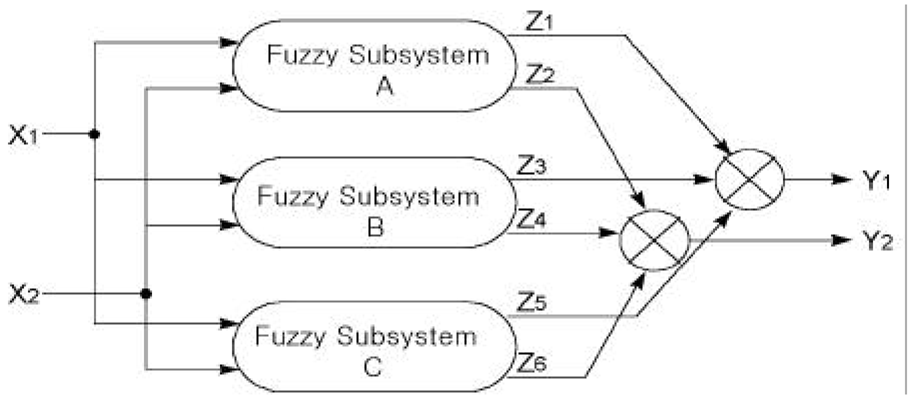


Fig. 6. Parallel connection of multivariables fuzzy subsystems.

Fuzzy Subsystem A:

$$\{(\text{IF } X_{1(i)} \text{ AND } X_{2(i)} \text{ THEN } Z_{1(i)} \text{ AND } Z_{2(i)}), (\text{ALSO})\}, \quad i = 1, 2, 3, \cdots, n. \tag{19}$$

and

$$\begin{bmatrix} Z_1 \\ Z_2 \end{bmatrix}' = [X_1 \ X_2] * \begin{bmatrix} R^A_{11} & R^A_{12} \\ R^A_{21} & R^A_{22} \end{bmatrix} \tag{20}$$

where

$$R^A_{kj} = \bigvee_{i=1}^{n} \{X_{k(i)} \wedge Z_{j(i)}\}, \quad k = 1, 2, \quad j = 1, 2$$

Fuzzy Subsystem B:

$$\{(\text{IF } X_{1(i)} \text{ AND } X_{2(i)} \text{ THEN } Z_{3(i)} \text{ AND } Z_{4(i)}), (\text{ALSO})\}, \quad i = 1, 2, 3, \cdots, n \tag{21}$$

and

$$\begin{bmatrix} Z_3 \\ Z_4 \end{bmatrix}' = [X_1 \ X_2] * \begin{bmatrix} R^B_{11} & R^B_{12} \\ R^B_{21} & R^B_{22} \end{bmatrix} \tag{22}$$

where

$$R^{B}_{kj} = \bigvee_{i=1}^{n} \{X_{k(i)} \wedge Z_{j(i)}\}, \quad k = 1, 2, \quad j = 3, 4$$

Fuzzy Subsystem C:

$$\{(\text{IF } X_{1(i)} \text{ AND } X_{2(i)} \text{ THEN } Z_{5(i)} \text{ AND } Z_{6(i)}), (\text{ALSO})\}, \quad i = 1, 2, 3, \cdots, n \tag{23}$$

and

$$\begin{bmatrix} Z_5 \\ Z_6 \end{bmatrix}' = [X_1 \;\; X_2] * \begin{bmatrix} R^{C}_{11} & R^{C}_{12} \\ R^{C}_{21} & R^{C}_{22} \end{bmatrix} \tag{24}$$

where

$$R^{C}_{kj} = \bigvee_{i=1}^{n} \{X_{k(i)} \wedge Z_{j(i)}\}, \quad k = 1, 2, \quad j = 5, 6$$

The output signals are equal to

$$\begin{aligned} Y_1 &= Z_1 \otimes Z_3 \otimes Z_5 \\ Y_2 &= Z_2 \otimes Z_4 \otimes Z_6 \end{aligned} \tag{25}$$

where $\otimes$ is an appropriate mathematical operation fuzzy sets.

To calculate the outputs, the extension principle introduced by is Zadeh is used [8]:

$$\begin{aligned} Y_1 = \sup_{\substack{z_1, z_3, z_5 \\ y = f(z_1, z_3, z_5)}} &\{X_1 \circ R^{A}_{11} \wedge X_2 \circ R^{A}_{21} \wedge X_1 \circ R^{B}_{11} \\ &\wedge X_2 \circ R^{B}_{21} \wedge X_1 \circ R^{C}_{11} \wedge X_2 \circ R^{C}_{21}\} \\ Y_2 = \sup_{\substack{z_2, z_4, z_6 \\ y = f(z_2, z_4, z_6)}} &\{X_1 \circ R^{A}_{12} \wedge X_2 \circ R^{A}_{22} \wedge X_1 \circ R^{B}_{12} \\ &\wedge X_2 \circ R^{B}_{22} \wedge X_1 \circ R^{C}_{12} \wedge X_2 \circ R^{C}_{22}\} \end{aligned} \tag{26}$$

where f is a mapping from a cartesian product of universe $Z_1 \times Z_3 \times Z_5$ to a universe $Y1$, and from $Z_2 \times Z_4 \times Z_6$ to $Y2$ such that and $y_1 = f(z_1, z_3, z_5)$, and $y_2 = f(z_2, z_4, z_6)$. The mapping f symbolizes any fuzzy mathematical operator. Using vector-matrix notation, it is found that

$$\begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix}' = \sup_{\substack{z_1, z_2, \cdots, z_6 \\ y_1 = f(z_1, z_3, z_5),\, y_2 = f(z_2, z_4, z_6)}} * \left\{ [X_1, X_2] * \begin{bmatrix} R_{11}^A & R_{11}^B & R_{11}^C & R_{12}^A & R_{12}^B & R_{12}^C \\ R_{21}^A & R_{21}^B & R_{21}^C & R_{22}^A & R_{22}^B & R_{22}^C \end{bmatrix} \right\} \tag{27}$$

Equation (27) can be rewritten in the more compact form

$$\begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix}' = \sup_{\substack{z_1, z_2, \cdots, z_6 \\ y_1 = f(z_1, z_3, z_5),\, y_2 = f(z_2, z_4, z_6)}} \left\{ [X_1, X_2] * \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} \right\} \tag{28}$$

where

$$R_{kj} = R_{kj}^A \wedge R_{kj}^B \wedge R_{kj}^{C,} \qquad k = 1, 2, \quad j = 1, 2$$

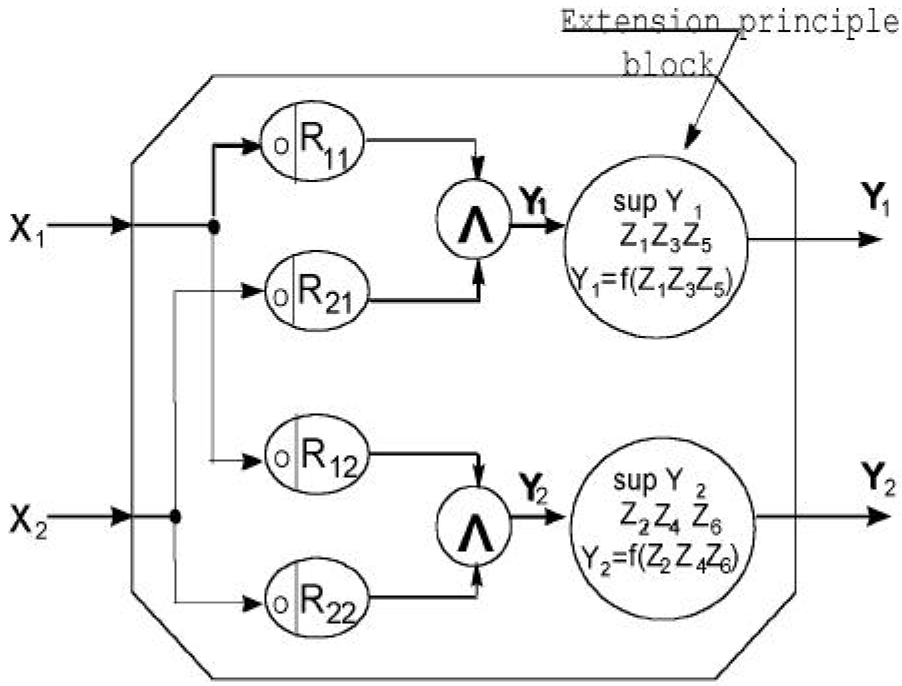


Fig.7. Multivariable structure of parallel connection of fuzzy subsystems

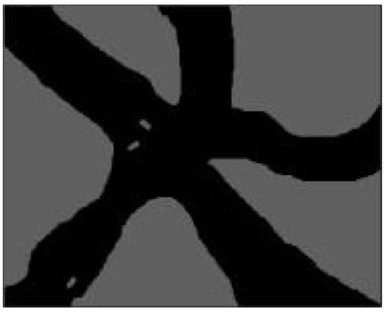
Fig. 7 is a structural representation of the reduced formula (28) of the parallel connection of multivariable fuzzy subsystems. This block diagram contains the extension principle blocks.

Chapter 3. Design of Dynamic Environment

This chapter present a need environment for simulation. (i.e., design of map and the fuzzy ship, choice of variable numbers of input and output). Section 3. 1 illustrates the designs of four maps and the fuzzy ship to navigate the proposed map and section 3, 2 explains the variable numbers of input and output that are used to analysis of maps.

3. 1 Design of map

In this paper map are designed to 640 × 480 PCX mode by NEOPAINT program which is one of many excellent graphic program. It is a convenient and simple program to draw graphic. Number of maps to simulate are four and include obstacles each other. In map static obstacles are islands and dynamic obstacles are ships which are moving or working



(a) map 1

(b) map 2

(c) map 3

(d) map 4

Fig. 8. Design of map

Map 1 in Fig. 8 is designed to know how the fuzzy ship move various courses. The first ship which is one of three ships is designed to move from down to up of map and the second ship is designed to move straightly from the middle to the right, the third ship is designed to move from the middle to the upper left.

Map 2 is designed to observe how the fuzzy ship navigates a narrow course with other ships. In the map 2, the first ship is designed to navigate a similar course with the fuzzy ship at first and the second ship is designed to work until the fuzzy ship arrives at near place and finally the third ship is designed to move together the fuzzy ship at the same time.

Map 3 is designed to know the decision ability of the fuzzy ship in several courses. The first ship is designed to obstruct the moving of the fuzzy ship at starting position and the second ship is designed to move from the lower right to the upper right at a narrow path and third ship is designed to turn around the coast line.

Map 4 is designed to know how the fuzzy ship navigate a wide space which almost never exist the interference of geographic. In this paper, this map is used twice with the different dynamic obstacles. In the first simulation each ship moves toward the center of map, but the initial places of ships are different. The first ship is designed to move to a deep sea and the second ship is designed to move from the lower right place to the upper left place and the third ship is designed to move into a port. In the second simulation, the first is designed to move together the fuzzy ship and the second is designed as the first simulation each ship and the third ship is designed to move form the deep sea to the port

The numerical value (i.e., width, length) of ship is generally made into a rate for the real geographic, but it may have a few errors. A kind of ship assumes not a boat but a vessel. Each coordinate is used to decide the next output of the fuzzy ship.

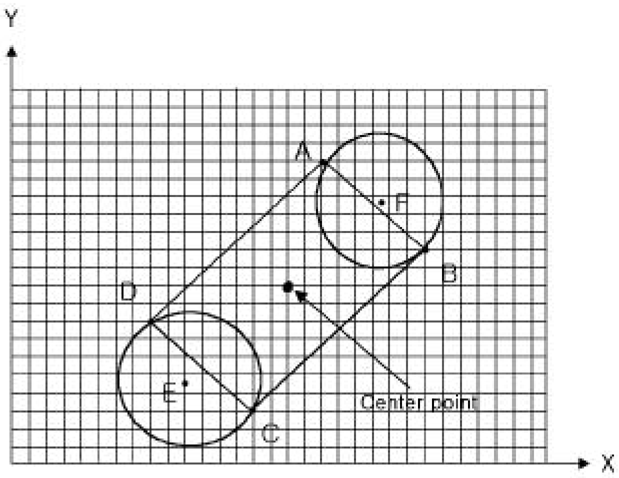


Fig. 9. Design of the fuzzy ship

Fig. 9 presents points to necessary for design of the fuzzy ship. Each point(A,B,C,D,E,F) is made by the ready-selective center point of the fuzzy ship. These points are converted by trigonometrical function. .

3. 2 Design of variable numbers of input and output

In control design of variable number of input and output is a very significant. According to their numbers, the system is complex or simple and has a good or bad efficiency[11][12]. Therefor design of variable numbers of input and output is principal. To move the fuzzy ship need variable numbers of five. Three are variable numbers of input and two are variable numbers of output parameter. The following Fig. 10 illustrates variable numbers of input and output.

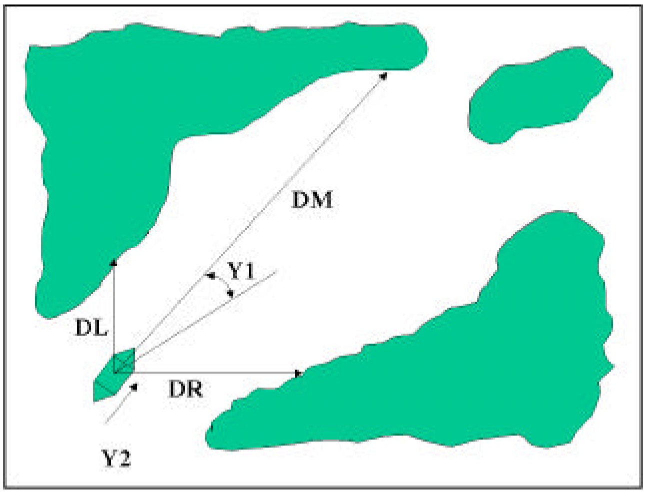


Fig. 10. Variable numbers of input and output

In Fig. 10 DL is a distance from the fuzzy ship to the left obstacle and DM is a distance from the fuzzy ship to the front obstacle and DR is a distance from the fuzzy ship to the right obstacle. Y1 is the delta angle to decide the next direction of the fuzzy ship and Y2 is the margin to move the front ship. Y2 is used to the information to decide the next coordinates of the fuzzy ship. If the fuzzy ship is to be near place of the right obstacle (i.e., island or others ships), it turn to the left at the present place and then it move with the modified direction. If the distance of the front obstacle is long, the fuzzy ship move many distances.

Chapter 4. Automatic Navigation System

Multivariable fuzzy control system presented in this paper consists of three inputs, two outputs and the structure of two subsystems. This chapter shows the structure of multivariable fuzzy system and explains input and output membership functions by fuzzy control system.

4. 1 Modeling of multivariable fuzzy system

Fig. 11 is the block diagram of multivariable fuzzy control system. This block diagram is to express the simple connection of variable numbers of inputs and outputs.

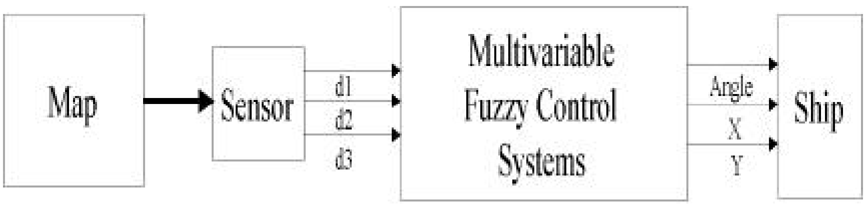


Fig. 11. Block diagram of fuzzy control systems

As shown in Fig. 10, the fuzzy ship founds distance of the left obstacle, the right obstacle and the front obstacle by three sensors.

The founded informations are transferred to input of multivariable fuzzy systems. Fig. 11 is the structure of fuzzy control system.

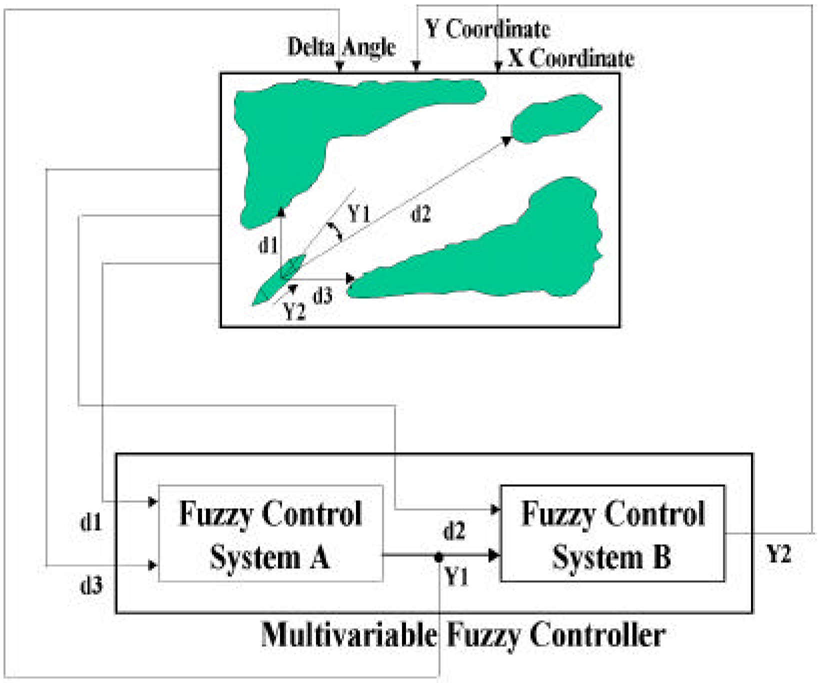


Fig. 12. Structure of fuzzy control system

In Fig. 12, DL, DM, DR is distance of each obstacle. Y1 is the delta angle of ship and Y2 is the information on x and y coordinate of the fuzzy ship. The informations collected from sensors of the fuzzy ship is used to detect the variable numbers of input and output of the fuzzy control system.

Fuzzy control system A collects a difference value of the left obstacle and the right obstacle and it is used to the variable number of input. The output of fuzzy system A modifies the angle of the fuzzy ship and it is used to one of the input variable numbers of fuzzy system B. Y1 is a half of output of the fuzzy control system A and DM which is the distance of the front obstacle of the fuzzy ship is used to the input variable number of fuzzy control system B. The output of fuzzy system B determines the next coordinate of ship.

4. 2. Fuzzy algorithm of navigation system

The need informations in navigation of ship are two that are a change of angle and distance to move the fuzzy ship. Therefore, in this paper, inputs of fuzzy control system are three and output of that is two. Fuzzy algorithms using multivariable fuzzy control system are described by the following :

[Fuzzy System A]

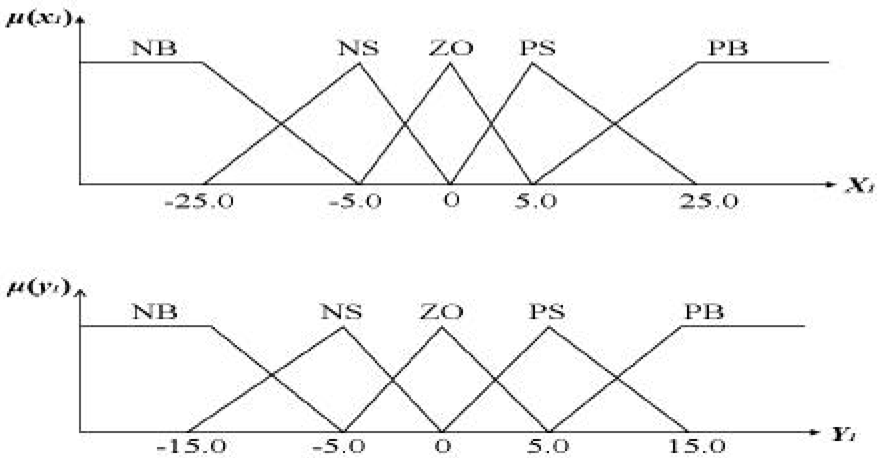


Fig. 13. Input and output membership functions of fuzzy system A

$$X1=DL-DR \tag{29}$$

Fig 13 is to present the input and output membership function of fuzzy system which is one of the subfuzzy system of multivariable fuzzy system. X1 which is the input of fuzzy system A is a difference value of DL and DR and Y1 which is the output of that is a delta angle of the fuzzy ship.

The rules are formulated by the following verbal description[15].

IF X1 = NB THEN Y1 = NB

IF X1 = NS THEN Y1 = NS

IF X1 = ZO THEN Y1 = ZO

IF X1 = PS THEN Y1 = PS

IF X1 = PB THEN Y1 = PB

where NB = negative big, NS = negative small, ZO = zero, PS = positive small, PB = positive big.

If the fuzzy ship is near by the right obstacle, it turns to the left the present place with delta angle. In reverse, if it is near by the left obstacle, it turns to the right from the present place with delta angle. If the fuzzy ship is the middle place of the right obstacle and the left obstacle, it doesn't modify the direction of fuzzy ship. Y1 is a delta angle for navigation of the fuzzy ship and it is calculated by rules.

[Fuzzy System B]

Fuzzy control system B has two inputs(Fig. 14). One is X2 that is distance in front of ship, the other is X3 that is a half of Y1 which is the output of fuzzy system A. A delta angle is already chosen as the output of fuzzy control system A.

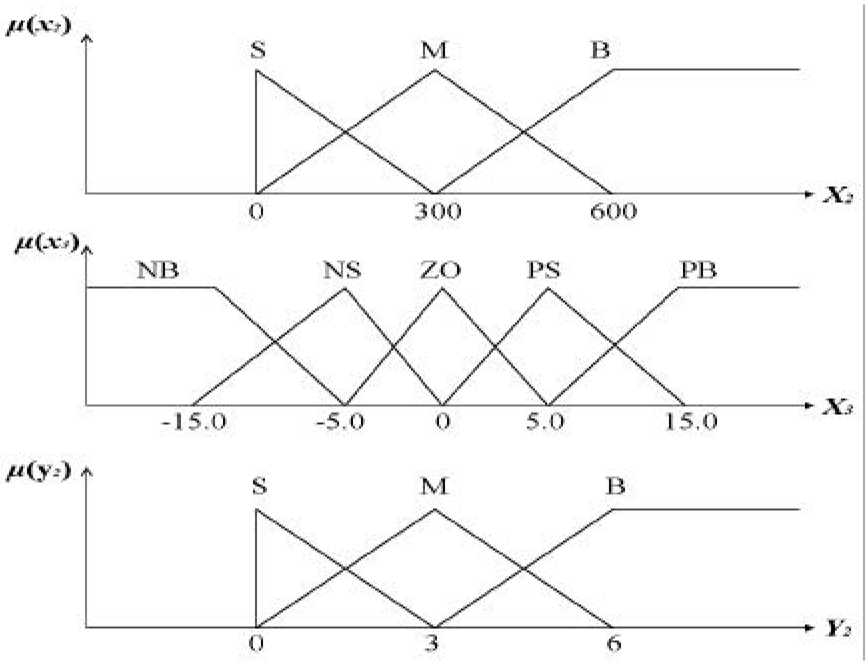


Fig. 14. Membership function of input and output of fuzzy system B

$$X2 = DM \tag{30}$$

$$X3 = \| 0.5 \times Y1 \| \tag{31}$$

Thus, the value simply relates to a quantity of distance to move the fuzzy ship. The scope of small membership function is 0 300, the scope of medium membership function is 300 600, and the scope of big is from 600 1000. Where define the maximum of x and y coordinates as each 1000. This value is changed to 640×480 mode by trigonometrical function when the fuzzy ship navigates the proposed map. Y2, which is the output of fuzzy system B is the distance to move to the next coordinate of the fuzzy ship.

X_2 \ X_3	NB	NS	ZO	PS	PB
S			S	S	S
M			M	M	
B			B	M	

Fig. 15. Rule table of fuzzy system B

Fig. 15 is the rule table of fuzzy control system B. The rules are described by the following verbal description:

X2 = S AND X3 = ZO THEN Y2 = S

X2 = S AND X3 = PS THEN Y2 = S

X2 = S AND X3 = PB THEN Y2 = S

X2 = M AND X3 = ZO THEN Y2 = M

X2 = M AND X3 = PS THEN Y2 = M

X2 = B AND X3 = PS THEN Y2 = M

X2 = B AND X3 = ZO THEN Y2 = B

where S = small, M = medium, B = big.

The whole rules are 15 but in this paper seven rules is used. To use seven rules is sufficient to control the fuzzy ship[16][17]. The membership function in X2, which is the input of fuzzy control system B use only ZO, PS, PB. Because the absolute value of Y1 transfer to the input of fuzzy control system B and NB, NS of Y1 doesn't need.

If the distance of the front obstacle of the fuzzy ship is small and the delta angle of the fuzzy ship is zero or positive small or positive big, Y2 which determined the next coordinate of the ship is small, because of the short distance of the front obstacle. If DM is the medium distance and the delta angle is zero or positive small, Y2 is medium. This is why the possible distance to move the fuzzy ship is medium. If DM is a large value and the delta angle is positive small, Y2 is to be medium. Because the ship has to rotate greatly. Therefore, when DM is big and X3 is ZO, the Y2 is big. This is to know that the ship moves to far away when the direction of the ship is right.

The form of triangle membership function is irregular. The reason is due to necessitate the delicate and clear control at the narrow place than the wide place. Then the calculated value uses to quantize output of the fuzzy system. A quantization is executed for the sake of convenience of calculation. Analog is continuous value, so difficult to calculate. Therefore it is transformed to digitalize, because digital is a dispersion value. Where use a linear quantization method[9]. Fig. 16 presents the quantization step of output membership function.

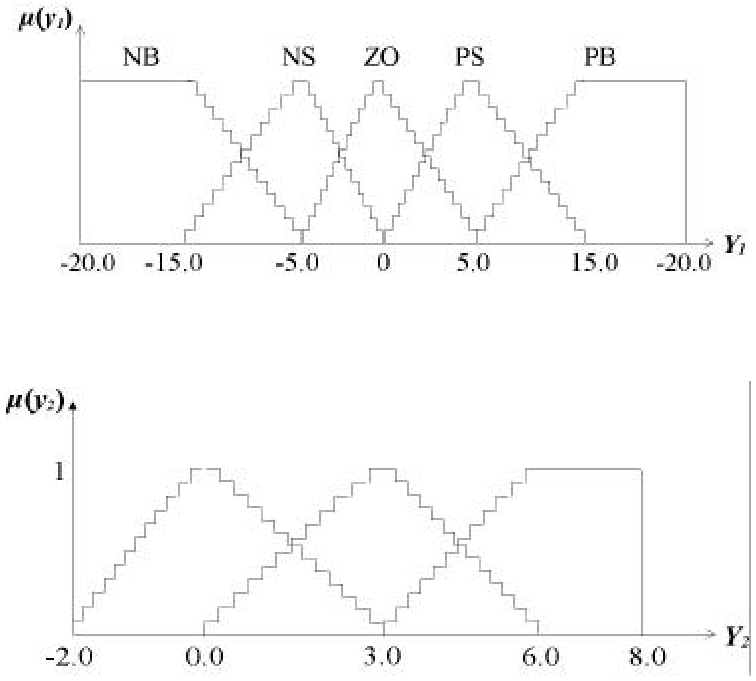


Fig. 16. Quantization of output membership function

The boundary of Y1 to decide the delta angle of the fuzzy ship is [-20, +20] and the boundary of Y2 to decide the next coordinate of that is [-2, +8]. The reason that the minimum boundary of the Y2 decides on -2 is in order to avoid that the fuzzy ship clashes into obstacle when the distance about the front obstacle of the fuzzy ship is very short. Therefore, the fuzzy ship can stop by this negative value at the same place. Here the quantization scale for the output value of fuzzy control system A is selected 0.1 and the fuzzy control system B is selected 0.05.

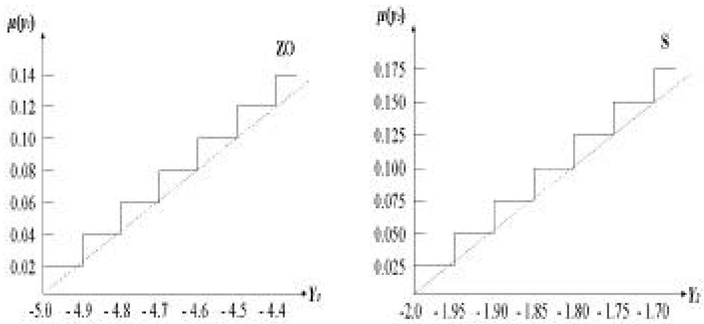


Fig. 17. Scaling of membership function

For example, the quantization scale of the ZO and S, which are in the output membership functions of fuzzy control system A and fuzzy control system B, are shown in Fig. 17.

The composition method using this paper is used mamdani's max-min implication[7].

[Max-Min composition]

$$\mu_Y(y) = \underset{(x_1, x_2)\in f^{-1}(y)}{\mathrm{Max}} \{ \mathrm{Min}[\mu_{X_1}(x_1), \mu_{X_2}(x_2)]\} \tag{32}$$

The defuzzification use the COG(Center Of Gravity) method[10].

[COG method]

$$\bar{y} = \int \frac{\sum_{i=0}^{N} \mu_Y(y) \cdot y \ dy}{\sum_{i=0}^{N} \mu_Y(y) \ dy} \tag{33}$$

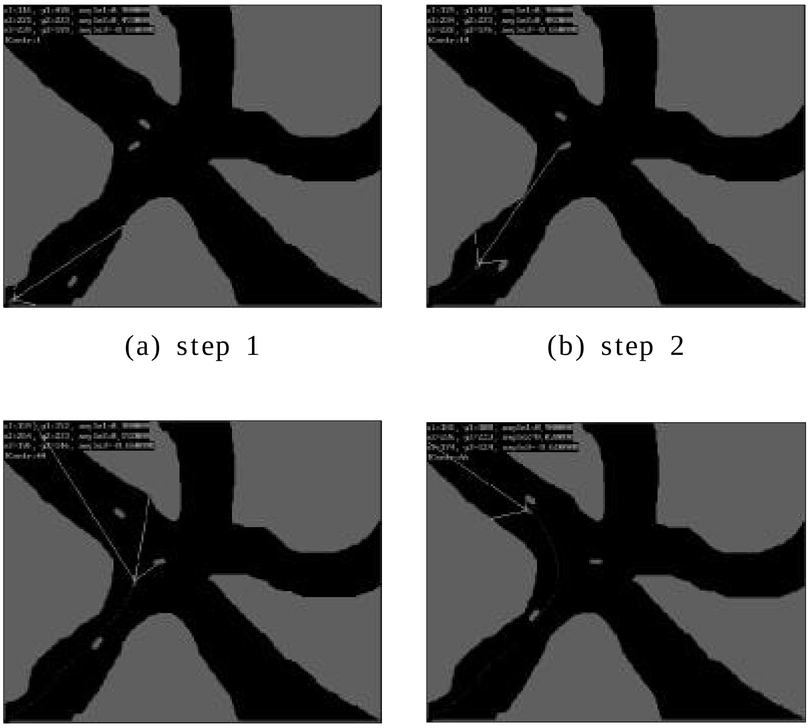
Chapter 5. Experiment Results

This chapter represents the simulation results and their plotting graphs by multivariable fuzzy control system. Section 5.1 illustrates five simulations and section 5.2 shows eight plotting graphs.

5. 1 Simulation results

The fuzzy ship using the multivariable fuzzy control systems, navigates like the following five maps, Fig. 18 to 22. Each map has the result presented by four steps. Step 1 shows the initial point of each map, step 2 shows when the fuzzy ship meets the first moving obstacle. Step 3 and 4 show when the fuzzy ship meets the second and third moving obstacles respectively.

Fig 18 illustrates the simulation results when the fuzzy ship navigates according to map 1. The purpose of this map is to know how the fuzzy ship move the simple course. As shown Fig 18, the simulation result is appeared to be successful.

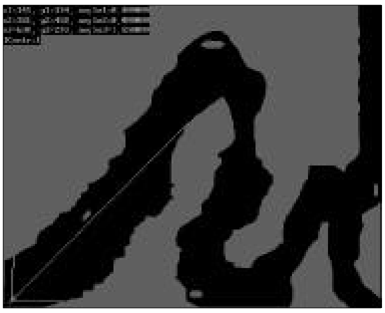


(a) step 1 (b) step 2

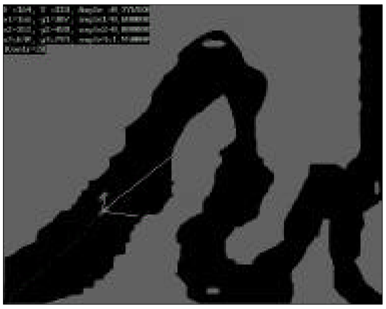
(c) step 3 (d) step 4

Fig. 18. Simulation result of map 1

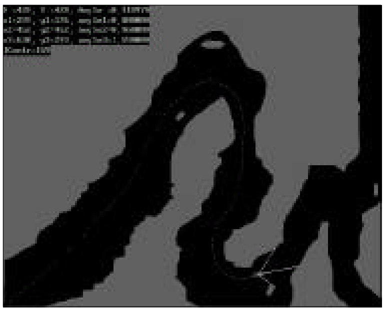
In step 1, DL is long than DR and DM shoots beam toward the right seacoast line. Therefore, the fuzzy ship moved to the left. Step 2 shows when the right sensor of the fuzzy ship meets the first obstacle. In this step, the fuzzy ship is moving to the middle of course. After that event, when it meets the new obstacle in the right side of the fuzzy ship. it immediately turns to the left. At that time, DM found other obstacle, but it isn't significant, because it is sufficient enough to avoid the obstacle. Step 3 displays when the fuzzy ship arrived at the middle of the map. Among several possible paths to move, the fuzzy ship chooses the upper left path, because the distance from the moving ship to the left obstacle is shorter to the right obstacle. In step 3, DL is longer than DR, and then the fuzzy ship moves to the left. Finally, the fuzzy ship meets with the third obstacle that is moving toward the upper left(step 4) and then it also navigates safely as the same before.



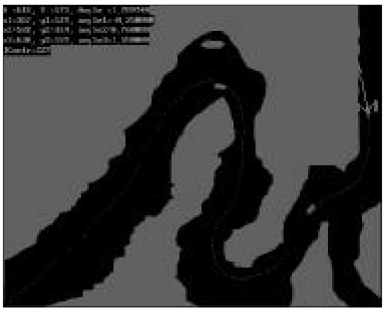
(a) step 1



(b) step 2



(c) step 3

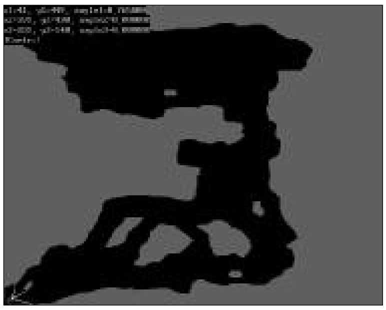


(d) step 4

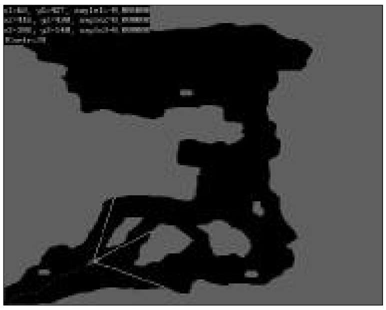
Fig. 19. Simulation result of map 2

Fig. 19 is the result when the fuzzy ship navigates map 2 and it satisfies as shown the above. Step 1 displays the starting point of the fuzzy ship and because the DL of the fuzzy ship is nearly equal to DR, the fuzzy ship moves to the middle. Step 2 shows when the fuzzy ship meets the first obstacle, which is moving the same course, and then it to avoid the obstacle move to down course. As shown step 3, the fuzzy ship meets the working ship which is the second obstacle but don't collide. Because the fuzzy ship with fuzzy control system is due to take a excellent making decision ability to avoid the obstacle[12]. Step 4 shows when the fuzzy ship meets the third obstacle, which is moving a narrow course and it navigates without collision by the obstacle. The simulation of map 2 has a good result as the map1.

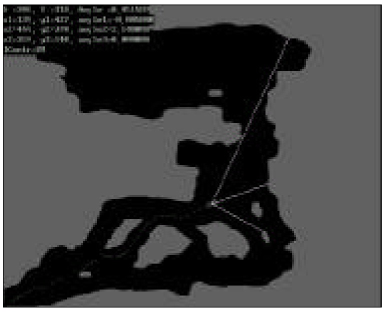
Fig. 20 is designed in order to know how the fuzzy ship move several courses. Step 1 is figure to present the initial point of the fuzzy ship and the middle sensor of that finds the first obstacle. Because DM of the fuzzy ship very short, the fuzzy ship very slowly moves to the front and the marks of that is nearby presented in step 2. At this time, the speed of fuzzy ship is slow, but when the fuzzy ship escapes from this path, it moves speedy. The speed of fuzzy ship is explained by the following plotting graph in section 5.2. Step 2 shows when the fuzzy ship arrives at various courses. As shown step 2, because DL of the fuzzy ship is shorter than DR, the fuzzy ship move to the right and then it navigates the middle course. In the result, the course is to be a optimal path which the distance short the most.



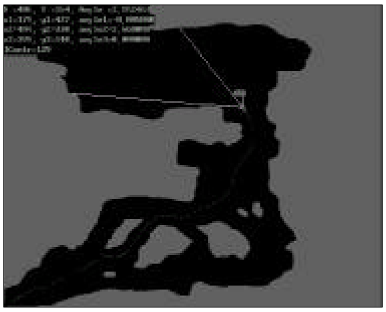
(a) step 1



(b) step 2



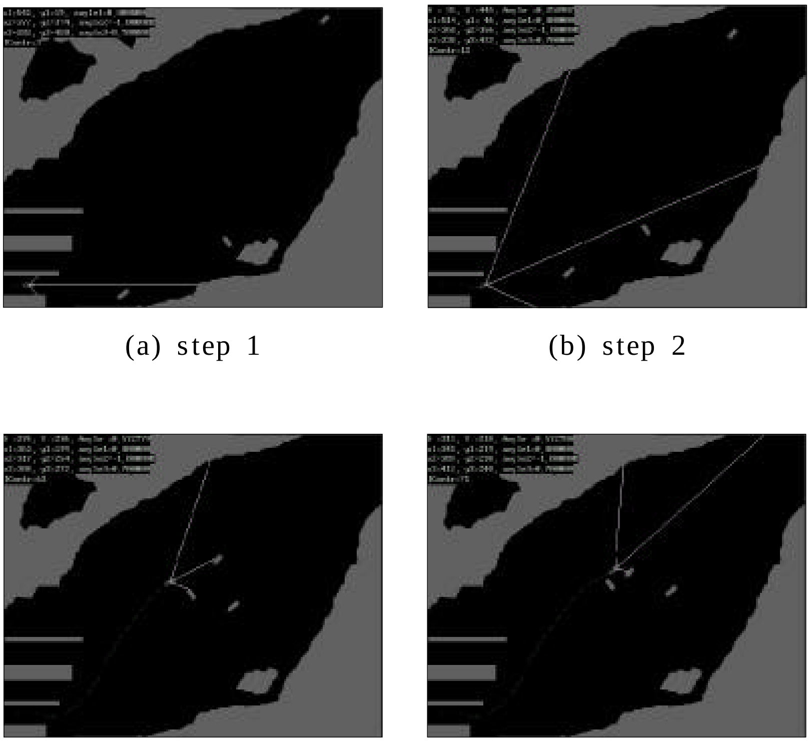
(c) step 3



(d) step 4

Fig. 20. Simulation result of map 3

Step 3 shows when the fuzzy ship is navigating the middle of course. The right beam of fuzzy ship finds the second obstacle which moves to the middle of map, but it is no matter. Because the fuzzy ship avoids the place before the obstacle arrive at there. Step 4 is a figure before the fuzzy ship nearly collides with other ship. DR of the fuzzy is very short and the mark of fuzzy ship also is very close, but the fuzzy ship perfectly avoids the obstacle which orbits the coastline. Therefore, this simulation also has the satisfied result.



(a) step 1

(b) step 2

(c) step 3

(d) step 4

Fig. 21. Simulation result of map 4

Fig. 21 shows a course of the fuzzy ship, which moves from a port to a deep sea. Step 1 is a figure before the fuzzy ship starts the navigation. Step 2 illustrates when the fuzzy ship leave a port. The fuzzy ship rapidly navigates a course because DM, which decides the next distance of the fuzzy ship are long. This mark is presented with the wide interval in step 3. Step 3 shows that ship meet with two obstacles that is moving from the lower right and the upper right at the center. The direction of fuzzy ship is modifies to avoid the obstacles, but the distance isn't big because the difference of DM and DR is similar and then the fuzzy ship avoid the obstacles in safety. The result is step 4. The fuzzy ship already avoids the ship risen from the lower right and then it navigates without collision with the third obstacle which come from a deep sea. This simulation also has a good result as the same before.

(a) step 1

(b) step 2

(c) step 3

(d) step 4

Fig. 22. Simulation result of map 5

Fig. 22 is equal to Fig. 21. Fig. 22 designed to observe how the fuzzy ship navigates map, which differs with Fig. 21 in dynamic environment. Step 1 shows the initial point of fuzzy ship and this is just the same with step 1 of Fig. 21. If the positions of dynamic obstacles set to differ, the navigation result also differ. When the fuzzy ship leave a port, DM which the left beam of fuzzy ship finds the first obstacle to be the left of fuzzy ship and then it moves to the right. Because the obstacle move to have equal speed, the fuzzy ship navigates to the right continuously (step 3). In step 4, the fuzzy ship find other ship which come into a port from a deep sea and then the direction of the fuzzy ship is modified to avoid toward up because DR is longer than DL. In above results, the fuzzy ship with fuzzy control system is found a good decision ability and a various performance.

The final navigation results are presented by the following figures. The disappeared marks in map was due to overwrite by other ships.

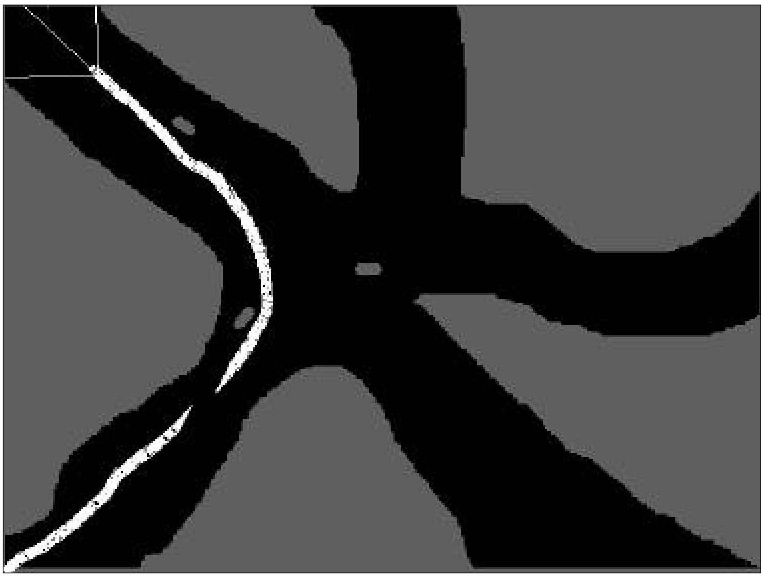


Fig. 23. Navigation result of map 1

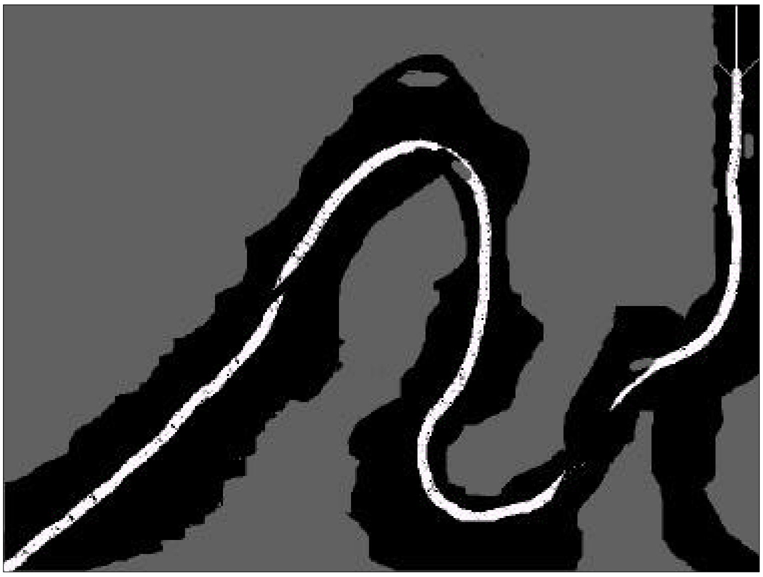


Fig. 24. Navigation result of map 2

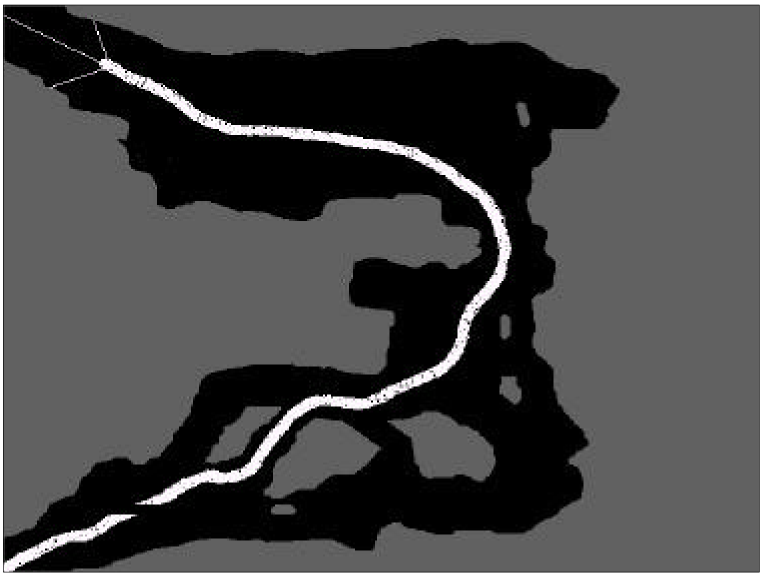


Fig. 25. Navigation result of map 3

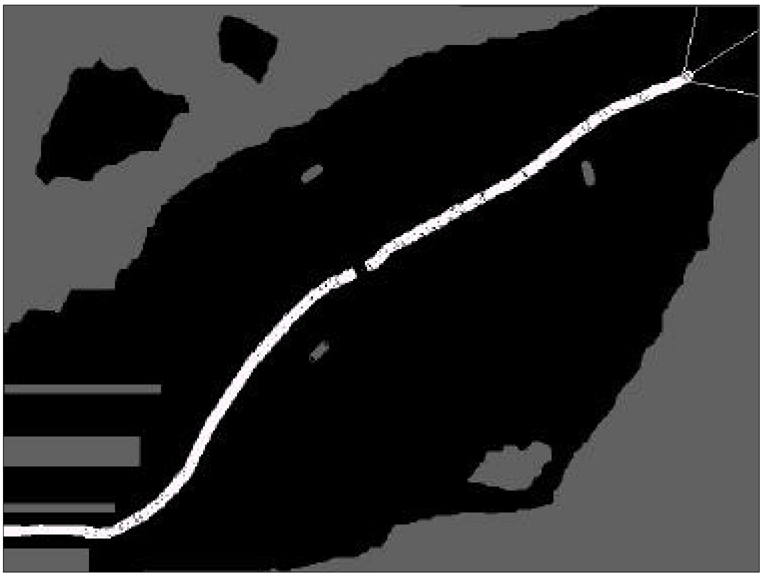


Fig. 26. Navigation result of map 4

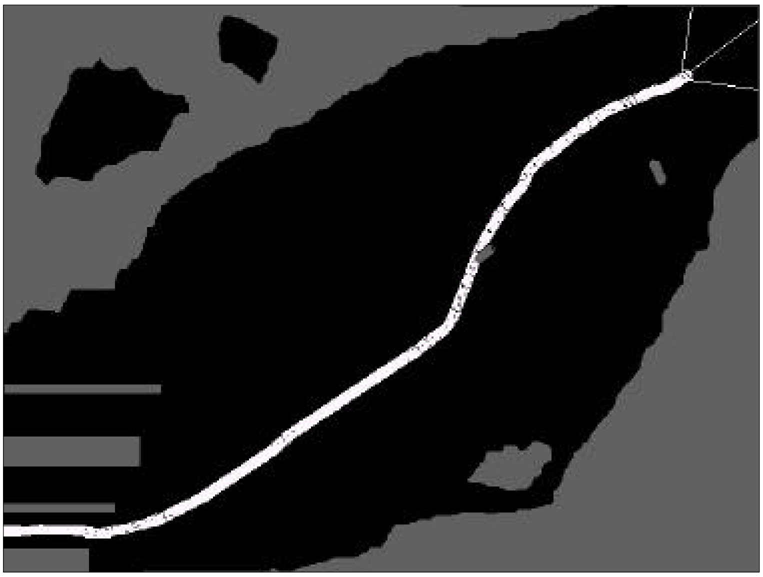
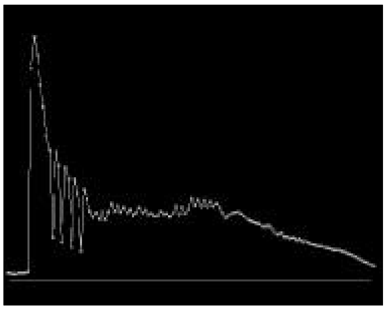


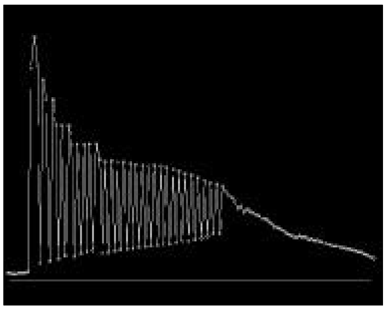
Fig. 27. Navigation result of map 5

5. 2 Plotting graphs

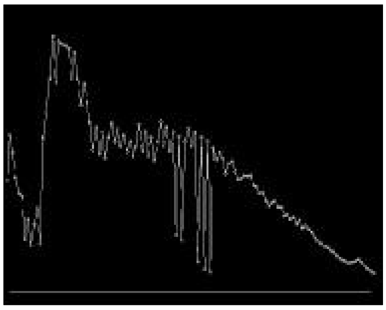
Numbers of the whole plotting graphs are 40 and each map has 8 plotting graphs, which are DL, DR, DM, DL-DR, delta angle, the speed of fuzzy ship, x and y coordinates. In this paper the whole plotting graph isn't shown because of the limitation of space. Here the plotting graphs of map 4 and map 5 are shown as an example. The following graph is the results and has each 150 step.



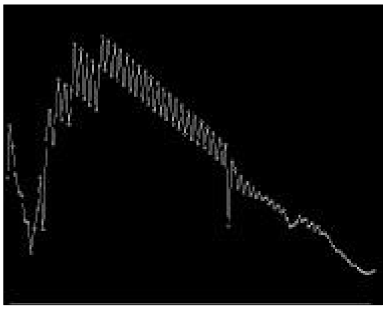
DL of map 4



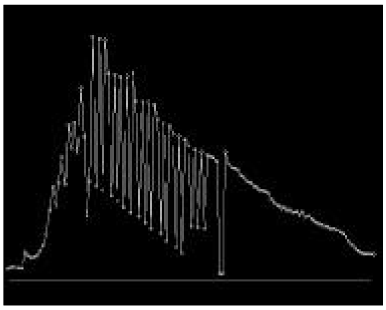
DL of map 5



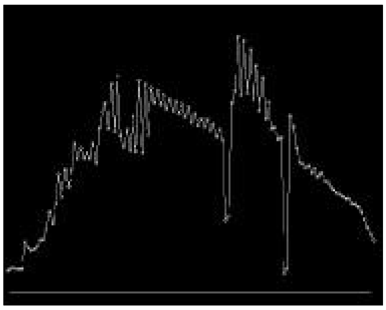
DM of map 4



DM of map 5

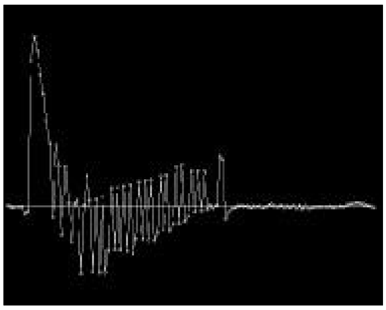


DR of map 4

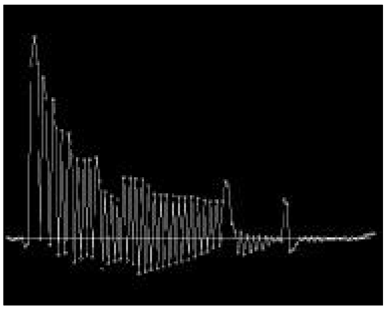


DR of map 5

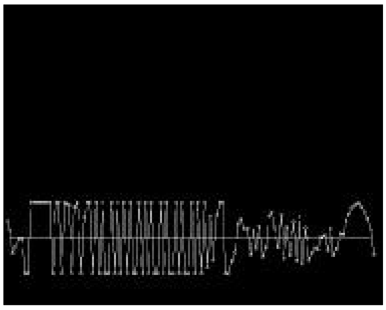
Fig. 28. Plotting graphs of map 4 and map 5



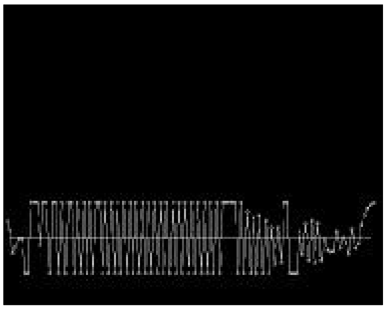
DL- DR of map 4



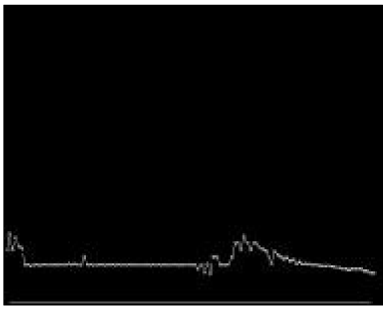
DL- DR of map 5



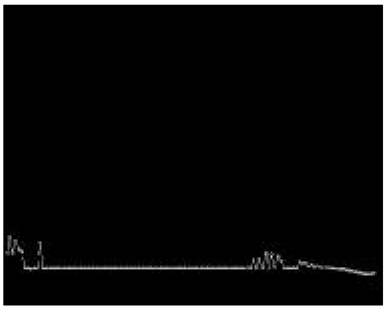
Delta Angle of map 4



Delta Angle of map 5

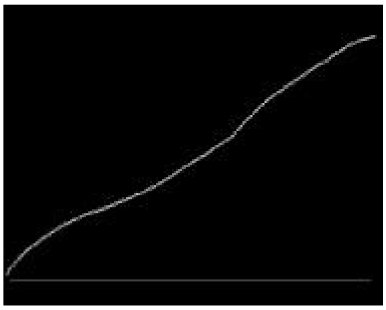


Speed of fuzzy ship of map 4

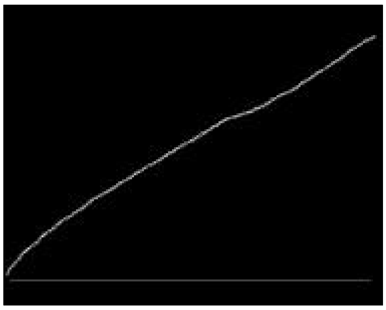


Speed of fuzzy ship of map 5

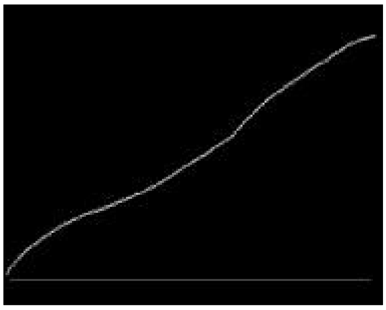
Fig. 28. (continue)



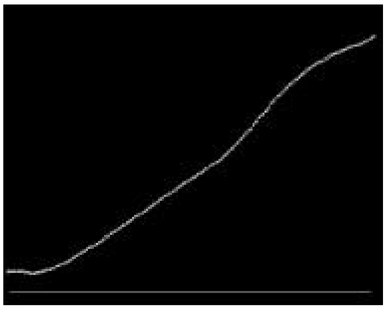
X- coordinate of map 4



X- coordinate of map 5



Y- coordinate of map 4



Y- coordinate of map 5

Fig. 28. (continue)

As shows Fig 28, the plotting graphs of map 4 and map 5 differ each other in spite of the same geographic. DL, DM, DR presents the left distance, the middle distance and the right distance of the fuzzy ship. Before the fuzzy ship leave a dock, DL of map 4 and map 5 is similar. However, after the fuzzy ship leaves a dock, DL graph of map 5 varies more than DL graph of map 4. DM, DR of map 4 and map 5 also has the different result. DL- DR and delta angle of map concern the speed of fuzzy ship. If their change is big, the speed of fuzzy ship is slow and if their change is little, the speed of fuzzy ship is fast. This is proved by the above plotting graphs. In above graphs, because of DL-DR and delta angle of map 4, the map is littler than it of map, the speed of fuzzy ship in map 4 is faster than it of map 5. This is known by the simulation results in section 5.1. X and y coordinates present not vector but scalar of the fuzzy ship. As shown in above graph, the fuzzy ship can know to move at lower place than map 4.

Chapter 6 Conclusion

This paper proposed multivariable fuzzy control system which has a exact decision ability and control technique[5][6]. The proposed multivariable fuzzy control system was used to automatic navigation of ship with dynamic environment.

As shown the results, the ship with multivariable fuzzy control system navigated the various course by itself. The proposed multivariable fuzzy control system was proved that they have a good ability in dynamic environment. Five simulations were shown good results, which were responded to a sudden obstacle.

The fuzzy ship successfully navigated without collision the maps proposed in this paper. Also, the fuzzy ship had different results at map with the same geographic. This was because the dynamic environment of map differed. The plotting graphs shown by simulation result offer an analysis of the multivariable fuzzy control system.

[References]

[1] D. Dubois, H. Prade, Fuzzy Sets and System : Theory and Applications, New York : Academic, 1980.

[2] W. Cheng, S, Jen, C. Wu, and T, Tsuei, " The intersection of fuzzy subsets and the robustness of fuzzy control." in Proc. 1980 Int. Conf. Cybern. Soc., 1980.

[3] E. Czogala and H. J. Zimmermann, " Some aspects of synthesis of probabilistic fuzzy controllers" Fuzzy Sets and Systems, vol. 13, 1984

[4] E. E. Mamdani, "Application of fuzzy algorithms for control simple dynamic plant," in Proc. IEEE Control Sci., vol. 121, no. 12, 1974

[5] A. Shakouri, "Advanced fuzzy controller for multivariable systems," M.Sc. thesis, Dept. of Electrical Engineering, Delft Univershity of Techonology.

[6] M. M. Gupta, G. M. Trojan, J. B Kiszka, and P. N. Nikiforuk, "Solution of multivariable fuzzy equations," Int. J. Fuzzy Sets Syst., to be publishied.

[7] L. Walichiewicz, "Decomposition of linguistic rules in the design of a multidimensional fuzzy control algorithm," in Cybernetics Syst. Res., vol. 2, 1984.

[8] A. Kandel, "Fuzzy Mathematical Techniques with Application", Addison-Wesley Publishing Company, 1986.

[9] G, J, Klir, T. A. Folger, "Fuzzy Sets, Uncertainty, and

Information", Prentice Hall, New Jersey, 1988.

[10] E. H. Mamdani, "Application of fuzzy algorithms for control of simple dynamic plant" in Proc. IEEE control and Science, vol. 121, no. 12, 1974

[11] M. Sugeno, K, Murakami, "An Experimental study on fuzzy parking control using a model car", in Industrial Applications of Fuzzy Control,

[12] M. Sugeno and M. Nishida, "Fuzzy control of model car," Fuzzy Sets Syst., Vol.16, 1985, pp.103-113

[13] J.J. Craig, Introduction to Robotics: Mechanics and Control, 2nd ed. New York, Addison-Wesley Publishing Company, 1989.

[14] C. C. Lee, "Fuzzy Logic in Control Systems: Fuzzy Logic Controller, Parts I and II,"in IEEE Transactions on Systems, Man and Cybernetices, vol. 20, no, 2, pp. 404-435, 1990.

[15] S. Arki, H. Nomura, I. Hayashi and N. Wakami,"A Self-Generating Method of Fuzzy Inference Rules," in Proceeding: 1North Holland, 1985. 991 IFES Conference, pp. 1047-1058, 1991.

[16] E. H. Mamdani, B. R. Gaines, "Fuzzy Reasoning and Its Application", Academic Press, 1981.

[17] L. A. Zadeh, "The concept of a linguistic variable and its application to approximate reasoning," Memorandum ERL-M 411, Berkeley, October 1973.