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碩 士 論 文

利用超音波訊號分析與模糊控制技術作室內自動車學習與導航之研究

A Study on Automatic Learning and Guidance for Indoor Autonomous Vehicle Navigation by Ultrasonic Signal Analysis and Fuzzy Control Techniques

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摘 要

本研究提出了一套智慧型自動車系統，利用超音波訊號分析，讓自動車能具有跟隨使用者行走，並同時學習路徑、與人互動、做路徑分析，以及進行智慧型導航等功能。我們利用一台具有超音波感測器的自動車作為實驗平台，使其航行於室內走廊環境中。針對跟隨人物，我們提出了一個利用超音波和模糊控制來讓自動車動態跟隨使用者的方法。另外，為了能讓使用者與自動車互動以下達控制指令，我們提出了一個分析使用者的行為以取得控制指令的方法，先以超音波偵測使用者的行走軌跡和特定姿勢，再利用投票的方式來決定使用者對自動車所下達的控制指令。在學習完路徑後，我們提出了一個自動分析路徑的方法，能經由學習過的路徑分析出導航時所需的轉彎參數等資訊。接著，我們提出了一個利用超音波和模糊控制進行導航的方法，在導航時，利用牆壁資訊作為環境特徵，並使用所設計的模糊控制器結合路徑資訊和超音波訊號，來調整自動車的方向。我們還提出了一個能在導航時利用轉彎參數和超音波以判斷是否抵達轉彎點的方法。最後我們以成功的學習和導航實驗證明了本系統的完整性與可行性。

A Study on Automatic Learning and Guidance for Indoor Autonomous Vehicle Navigation by Ultrasonic Signal Analysis and Fuzzy Control Techniques

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ABSTRACT

An intelligent autonomous vehicle system for learning and vehicle guidance in indoor environments is proposed. The system has several capabilities: learning paths by person following, interaction with humans, path analysis, and navigation as a guide. An autonomous vehicle equipped with ultrasonic sensors is used as a test bed. First, a method for person following in an environment is proposed, which has two fuzzy controllers for following a person dynamically. The fuzzy controllers adjust the vehicle's direction and speed. Furthermore, to interact with humans, a technique for analyzing human behaviors is proposed, which analyzes a person's walking trajectory by ultrasonic signals and uses a voting technique to obtain human commands implied by the walking postures. After learning, a method for path analysis is proposed, which analyzes the learned path data to estimate certain turning parameters for navigation. In addition, a method for vehicle navigation guidance by the use of the ultrasonic signal sequence and a fuzzy controller is proposed. The main environment feature used for navigation is wall. The fuzzy controller combines some information obtained from path analysis with ultrasonic signals to adjust the vehicle's navigation direction. A technique for detecting learned turning points is also proposed, which decides whether the vehicle arrives at a turning point or not, using learned data and ultrasonic signals as well. Good experimental results show the flexibility and feasibility of the proposed system for the applications of person following, path analysis, and people guiding in indoor environments.

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Finally, The author also extend her profound thanks to her family for their lasting love, care, and encouragement. The author dedicates this dissertation to her beloved parents.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1
Introduction

1.1 Motivation

In recent years, autonomous vehicles have more and more applications. It is not only convenient but also effective to use autonomous vehicles in many human works. For example, they can used to patrol in buildings, monitor important objects, and become security guards.

When we visit an office in a building, we usually desire some guidance to introduce the environment to us. The most common way is to set up a sign with some explanation. Sometimes, a staff will act as a guide. Furthermore, in an exhibition, visitors can reserve a guide to introduce the exhibition, but this may not be convenient. This problem may be solved if we use an autonomous vehicle to act as a guidance.

In order to do the above-mentioned tasks, an autonomous vehicle should have the abilities to navigate in indoor environments and guide visitors. The work to build an autonomous vehicle to have such abilities can be separated into two parts: the first is that the vehicle has to learn a guiding path, and the second is that it should be able to navigate and guide visitors.

In an office or an exhibition, the decoration may be changed after a period. It will be very inconvenient if a vehicle has to learn new environments in a repetitive way. This problem can be solved if the vehicle can follow a person and learn an indoor environment in the mean time. Furthermore, it may not be smart for a vehicle to navigate by following a learned trajectory step by step in a precise way, because the trajectory might be rough and curvilinear. It is so desired also that the vehicle, after learning, can plan a navigation path to follow the sequences of objects which it has to introduce without hitting walls in a narrow environment. In order to achieve the above goals, we will use an autonomous vehicle equipped with ultrasonic sensors to learn a corridor and keep it navigating in the learned paths safely. In addition, we will implement the above ideas by fuzzy logic control techniques because such techniques can be utilized to control a vehicle more smoothly in general.

In summary, our research goal of this study is to design an intelligent autonomous vehicle system with the following capabilities:

1. learning corridors environments automatically by following a person;
2. controlling the vehicle by fuzzy logic control techniques;
3. analyzing learned information to plan appropriate paths to navigate; and
4. navigating automatically in corridors and guiding people.

1.2 Survey of Related Studies

To learn a guidance map, it is desired that an autonomous vehicle have the abilities of following a person and recording a map in the mean time. To achieve the mission of person following in indoor environments, cameras may be used as sensors. Wang and Tsai [1] proposed a method for person following, which uses an elliptic skin model to detect human faces by color and shape features in images. Tsai and Tsai [2] proposed a method for the same purpose in environments where the luminance is not uniform.

In addition, Ku and Tsai [3] proposed a sequential pattern recognition method to decide the location of a person with respect to a mobile robot and to detect a rectangular shape attached on the back of the person to achieve smooth person following. Kwolek [4] proposed a method of visual head tracking and person following by a mobile robot. They used laser readings to determine the position of the vehicle and a particle filtering technique to track the human head. Chueh, Yeung, Lei, and Joshi [5] proposed a method to integrate information provided by the behavioral cues of the leader to enhance the reliability and the performance of following. They utilized a Kalman filter to estimate the predicted position of the leader as the robot moves, and then direct the following robot to the predicted position. Takemura, Ito, and Mizoguchi [6] proposed a method to detect a target person according to the colors of the followed person's clothes and the H-S Histogram of the color based on the HIS color model.

For applications of fuzzy logic control techniques, some studies used them on person following and some used them for navigation control of mobile robots. Tarokh and Ferrari [7] proposed a method for a mobile robot to follow a person using a fuzzy controller. They utilized image colors, shape characteristics, and a region growing technique in a person identification process, and used image features such as the mass, the center of mass, and their rates of changes as inputs to the fuzzy controller. Peri and Simon [8] proposed a fuzzy control method to control an autonomous wall-following robot equipped with ultrasonic sensors. The robot can navigate along a predefined path. Xin, et al. [9] proposed a fuzzy control method for an unmanned exploration vehicle equipped with ultrasonic sensors. They used a fuzzy logic algorithm to fuse the vehicle's behaviors and self-tuning membership functions to control the vehicle. Datta, Banerji, and Mukherjee [10] proposed a method for mobile robot localization using laser-based maps. They also proposed a fuzzy controller for obstacle avoidance.

Furthermore, some studies used fuzzy logic control techniques to control a mobile robot in unknown environments. Islam, et al. [11] proposed a fuzzy control algorithm to guide a mobile robot to navigate in an unstructured environment and avoid any encountered obstacle without human intervention. Tan and Yang [12] proposed a fuzzy-inference controller for navigation control of a mobile robot in dynamic environments. They also described a good idea for avoiding moving obstacles: like a person driving a car at an intersection and facing another moving car, when a mobile robot faces a moving obstacle, it can stop instead of turning in other directions to avoid the moving obstacle. In this way, the mobile robot might be able to find an even shorter path to the target.

Meng and Liu [13] proposed a behavior-based navigation strategy for autonomous robots. Li and Zong [14] proposed a hierarchical fuzzy controller to improve the problem that a designed fuzzy rule base may be too large in a single fuzzy controller. Yang, Moallem, and Patel [15] proposed a layered goal-oriented fuzzy motion planning strategy to control a mobile robot in an unknown and dynamically-changing environment. In addition, some studies [16, 17] used neuro-fuzzy techniques to control an autonomous vehicle in unknown environments.

For navigation and guidance, Tsai and Tsai [2] proposed a guidance method using sequences of ultrasonic signals in an indoor environment. They used an autonomous vehicle to learn the information of path data and point data. Then, the vehicle can analyze the ultrasonic signals which are detected during navigation and guide people on the learned path.

1.3 Overview of Proposed Approach

The overall framework of the proposed system with the four capabilities mentioned previously are illustrated in Figures 1.1, in which several methods have been proposed to deal with various works.

The first proposed method for person following using ultrasonic sensors includes three major stages. The first stage is human leg detection. In order to follow a person, the vehicle detects the person's leg and computes accordingly the distance between the person and itself. The second stage is to follow the person. After the vehicle obtains the distance between the person and itself, it can analyze such information to decide its velocity, including the speed and direction.

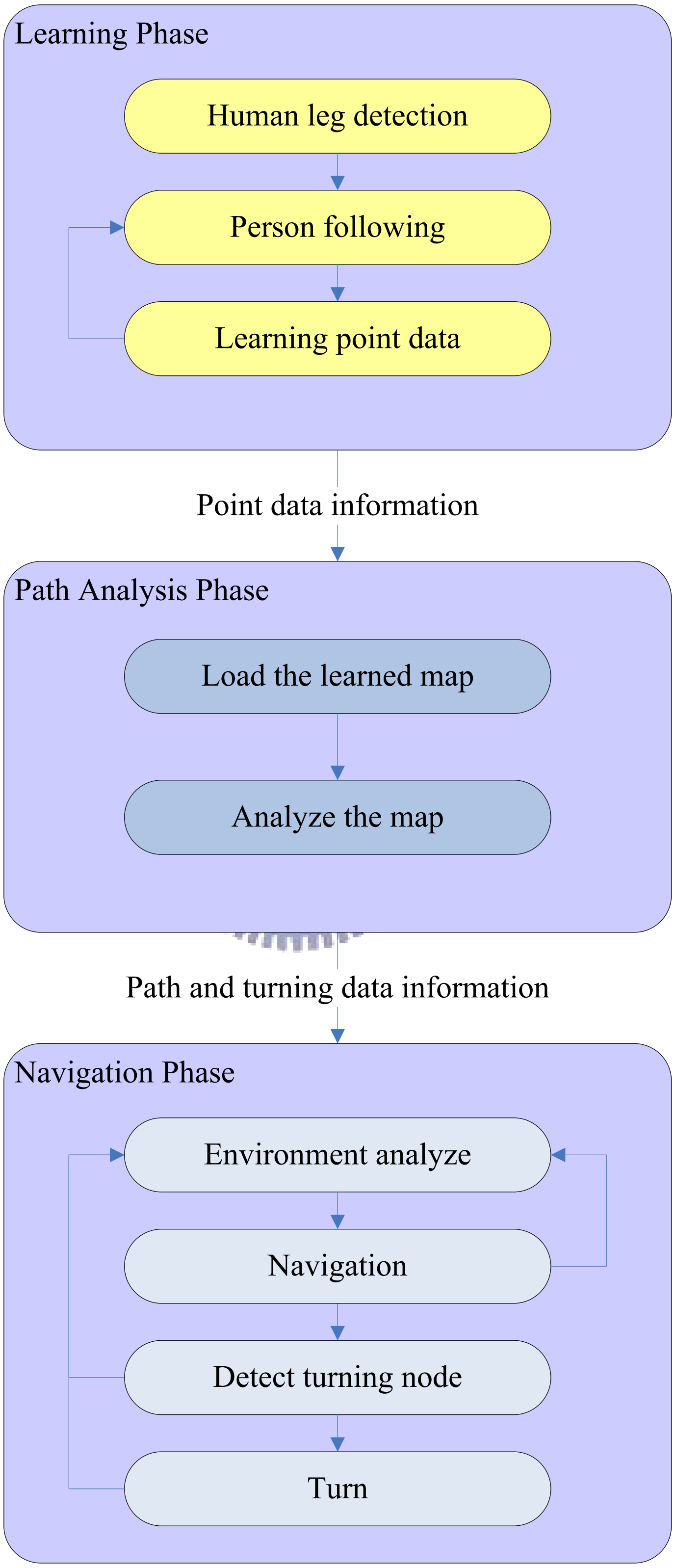


Figure 1.1 Flowcharts of proposed systems.

Besides, we also use fuzzy logic control techniques to help deciding the vehicle's velocity during the learning and navigation phases. The third stage is to learn the path data in the last stage. The vehicle needs to learn three kinds of data. The first is the data of path nodes which are used for path analysis. The second is the data of the person's instructions issued during the learning phase. The final one is the data used to introduce objects or places during navigation. The details will be described in Chapter 3.

The second proposed method is for path analysis. In the method, the vehicle analyzes the record obtained in the learning phase by applying the last method to get some guiding information, including wall widths in environments, when to turn, when to introduce objects, etc. The details will be described in Chapter 4.

The third proposed method is for controlling an autonomous vehicle by ultrasonic sensors and fuzzy logic control techniques to navigate as a guide in indoor environments. The method deals with four major stages in the navigation process. The first stage is environment analysis in which the vehicle analyzes the signal detected from the ultrasonic sensor. In the second stage, the analysis result of the last stage, the path data analyzed by the last method, and some fuzzy logic control techniques are combined to navigate the vehicle. In the third stage, whether the vehicle has arrived at a turning node or not is decided. If so, then it turns in the fourth stage. The details will be described in Chapter 5.

1.4 Contributions

The major contributions of this study are summarized as follows.

(1) A method for following a person using sequences of ultrasonic signals and fuzzy logic control techniques is proposed.

(2) A method for learning paths in corridors environments by way of person following is

proposed.

(3) A path analysis method which can be adapted to different corridors is proposed.

(4) A method for guiding the vehicle is proposed, which uses sequences of ultrasonic signals detected during the navigation phase, information obtained in the phase of path analysis, and some techniques of fuzzy logic control.

(5) A method for environment learning, path analysis, and vehicle guidance in corridors is proposed.

1.5 Thesis Organization

The remainder of this thesis is organized as follows. In Chapter 2, we describe the system configuration of the vehicle and the ideas of the proposed methods for person following and environment learning, path analysis, and vehicle navigation. In Chapter 3, the proposed method for person following using sequences of ultrasonic signals and fuzzy logic control techniques is described. In Chapter 4, the proposed method for analyzing learned data to get some guiding information and adapting to different environments is described. In Chapter 5, the proposed method for vehicle guidance using sequences of ultrasonic signals and fuzzy logic control techniques is described. Furthermore, some satisfactory experimental results are shown in Chapter 6. Finally, some conclusions and suggestions for future works are given in Chapter 7.

Chapter 2
System Configuration and Navigation Principles

2.1 Introduction

When we visit an unfamiliar place like an office in a building, we usually desire some guidance to introduce the environment to us. It will be very convenient if we use an autonomous vehicle instead of asking a person to act as a guide. The vehicle may hit walls or objects in the environment during navigation if the available paths of the environment are narrow in space. In order to solve this problem, we use an autonomous vehicle equipped with ultrasonic sensors in this study. Ultrasonic sensors in general can detect distances to walls or objects around. Therefore, the vehicle can use the measured distance information to avoid hitting walls or objects in the environment. The entire hardware equipments and software of the autonomous vehicle used in this study are described in Section 2.2.

In addition, in order to use the vehicle to act as a guide in different environments, it is desired that the vehicle can learn some information of the environment. For this, it is inconvenient to conduct the learning work by keying in the information of the environment by hand. One way out is to enable the vehicle to follow a person automatically, and learn the route the person walks through, also in an automatic way. We will introduce the main idea of this approach to *learning by person following* in Section 2.3. Then, the vehicle also needs a method to transform the learned information into some guidance information, including, for example, corridor widths in environments, when to turn, when to introduce objects, etc. These goals can be achieved if we can design a method for path analysis. We will introduce the main idea of a path analysis method we propose in this study in Section 2.4. Finally, in order to use the vehicle to navigate more smoothly, we design further a navigation method using fuzzy logic control techniques. We will introduce the main idea of this method in Section 2.5.

2.2 System Configuration

In the proposed vehicle system, we use the Pioneer 3, a vehicle made by ActiveMedia Robotics Technologies Inc., as a test bed. A diagram illustrating the configuration of this system is shown in Figure 2.1.

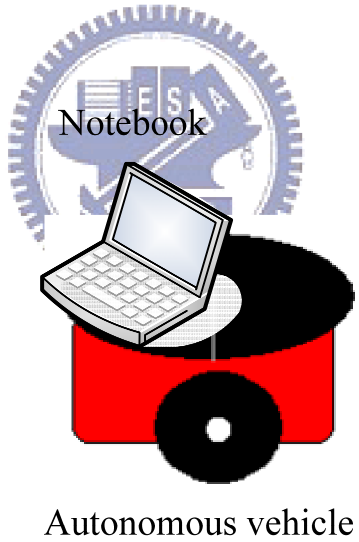


Figure 2.1 Equipment of vehicle system used in this study.

2.2.1 Hardware configuration

The hardware equipments we use in the proposed system include two parts. The first is a notebook which we use to run programs. A kernel program can be executed on the notebook to control the vehicle by issuing commands to the vehicle. It also can be used to obtain the status information of the vehicle.

The second part is the vehicle itself which has an aluminum body. The size of it is 44cm×38cm×22cm with two drive wheels and a caster. The diameter of each drive wheel is 16.5cm. In the vehicle, there are three 12V batteries which supply power to the vehicle to run 18-24 hours by one charge. The vehicle can reach a forward speed of 160cm per second and a rotation speed of 300 degrees per second. The embedded control system can be used to control the vehicle to move forward, backward, and turn around by the user's commands. The vehicle is also equipped with two range devices. Each one of them includes 8 sonars. The appearance of the vehicle is shown in Figure 2.2.

2.2.2 Software configuration

The ActiveMedia Robotics provides an application interface ARIA to control the vehicle used in this study. The ARIA is an object-oriented interface which is usable under Linux or Win32 in the C++ language and can dynamically control the velocity, heading, and other navigation settings of the vehicle. We use the ARIA to communicate with the hardware embedded system of the vehicle. Also, we use the Borland C++ Builder as the development tool in our experiments.

2.3 Idea of Proposed Person Following and Learning Method

The proposed learning method is based on human following by ultrasonic signals, as mentioned previously. When the vehicle follows a person, it uses the distance between the person's leg and itself to decide if it has to conduct fine tuning of its direction or not. Then it has to handle two kinds of situations. If it detects the situation that the person does not stop, it uses the distance as input to the fuzzy controller we design to decide if it has to adjust its running angle and speed or not. However, if the person stops, the vehicle has to stop and then it has to know what the person commands it to do. For this, the following four kinds of situations are handled by the vehicle, as proposed in this study.

(a) (b)

Figure 2.2 The vehicle Pioneer 3 with a notebook used in this study. (a) A front view of the vehicle. (b) A back view of the vehicle.

The first is that the vehicle should turn left or right. The second is that the vehicle should learn the information of objects or places which will be introduced by the vehicle as a guide during navigation. The third is that the person is just too close to the vehicle at the current moment, but the person does not want to stop. In this situation, the vehicle is designed to do nothing and continue learning. In the just-mentioned three kinds of situations, the vehicle is designed to learn the path data in the mean time. The final situation is the end of learning.

These major steps are shown in Figure 2.3.

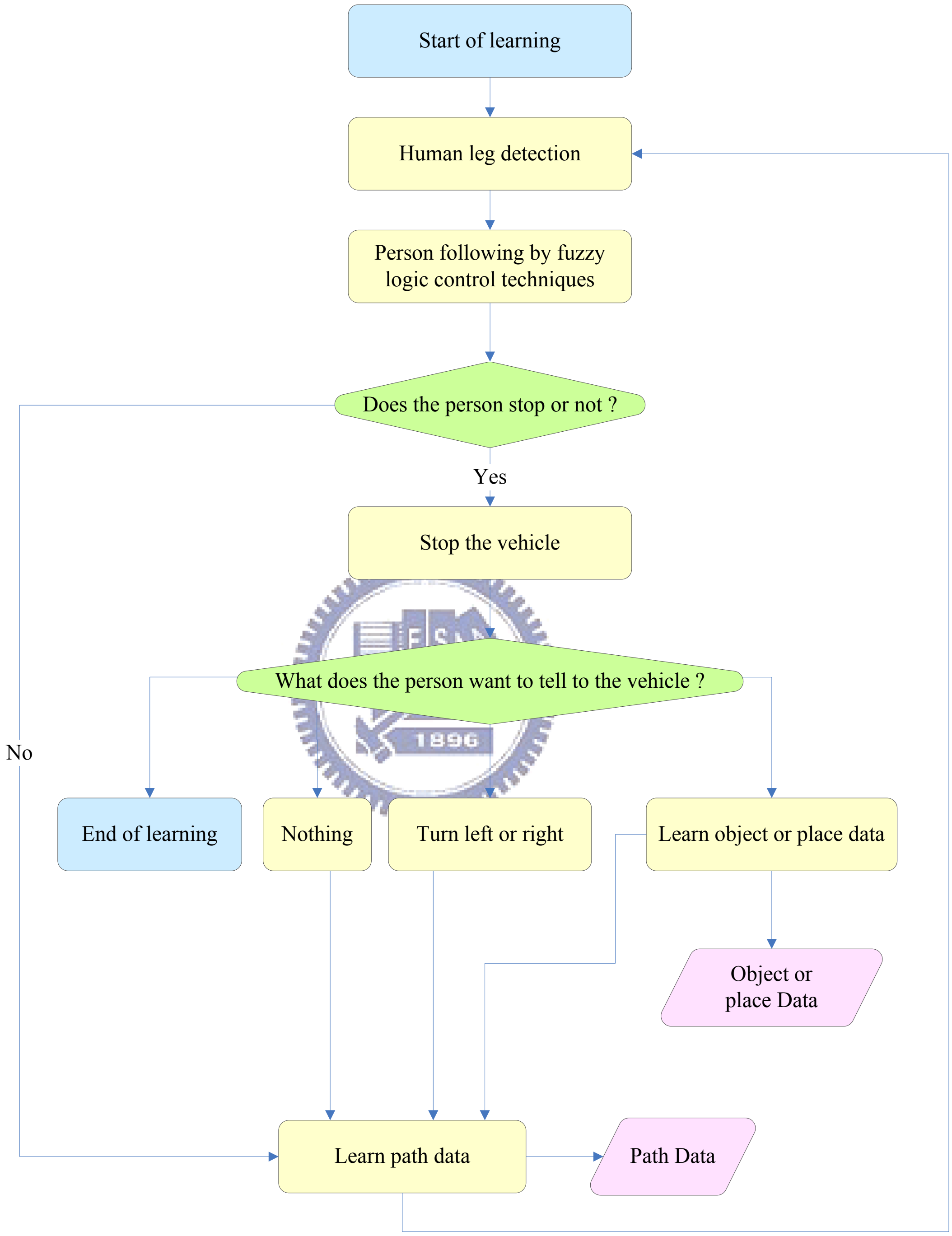


Figure 2.3 An illustration of proposed process of automatic learning by person following and fuzzy logic control techniques.

2.4 Idea of Proposed Path Analyzing and Guiding Method

After the vehicle learns the data of paths, objects, and places in the learning stage, it has to analyze the learned data. For this, five kinds of information are identified in this study for use during navigation, as described in the following.

The first is when the vehicle has to turn. If it turns just according to the originally learned position, it may turn too early or too late possibly because of incremental mechanic errors. This may cause the vehicle to hit the wall or to go too close to it after turning. Therefore, we propose a method for deciding when the vehicle has to turn, and combine this method with the result of path analysis.

The second kind of information for use in navigation is the distance between walls in environments. An indoor navigation path usually includes several different environments, like a corridor, an entrance hall, etc. The wall distances in these environments may be not the same. Therefore, the vehicle has to know the wall distances in environments and when to use them. We have designed the fuzzy controller mentioned previously to have such an ability, which will be described in Chapter 5.

The third kind of information for use in navigation is the intolerable distance between the vehicle and obstacles in front of the vehicle. When the vehicle is on a place where it has to turn at the learning stage, it may be blocked by a wall in front of it. Therefore, the vehicle needs to know the intolerable distance to keep itself from hitting the wall. Besides, when a person walks in the front of the vehicle and the person's leg is detected by ultrasonic sensors, the vehicle also needs to have an idea about how to deal with such a situation.

The fourth kind of information for use in navigation is when to stop. If the vehicle does not have to turn, it needs to know the timing for this action. The final kind of information is when to introduce to objects or places as a guide. The major steps are illustrated in Figure 2.4.

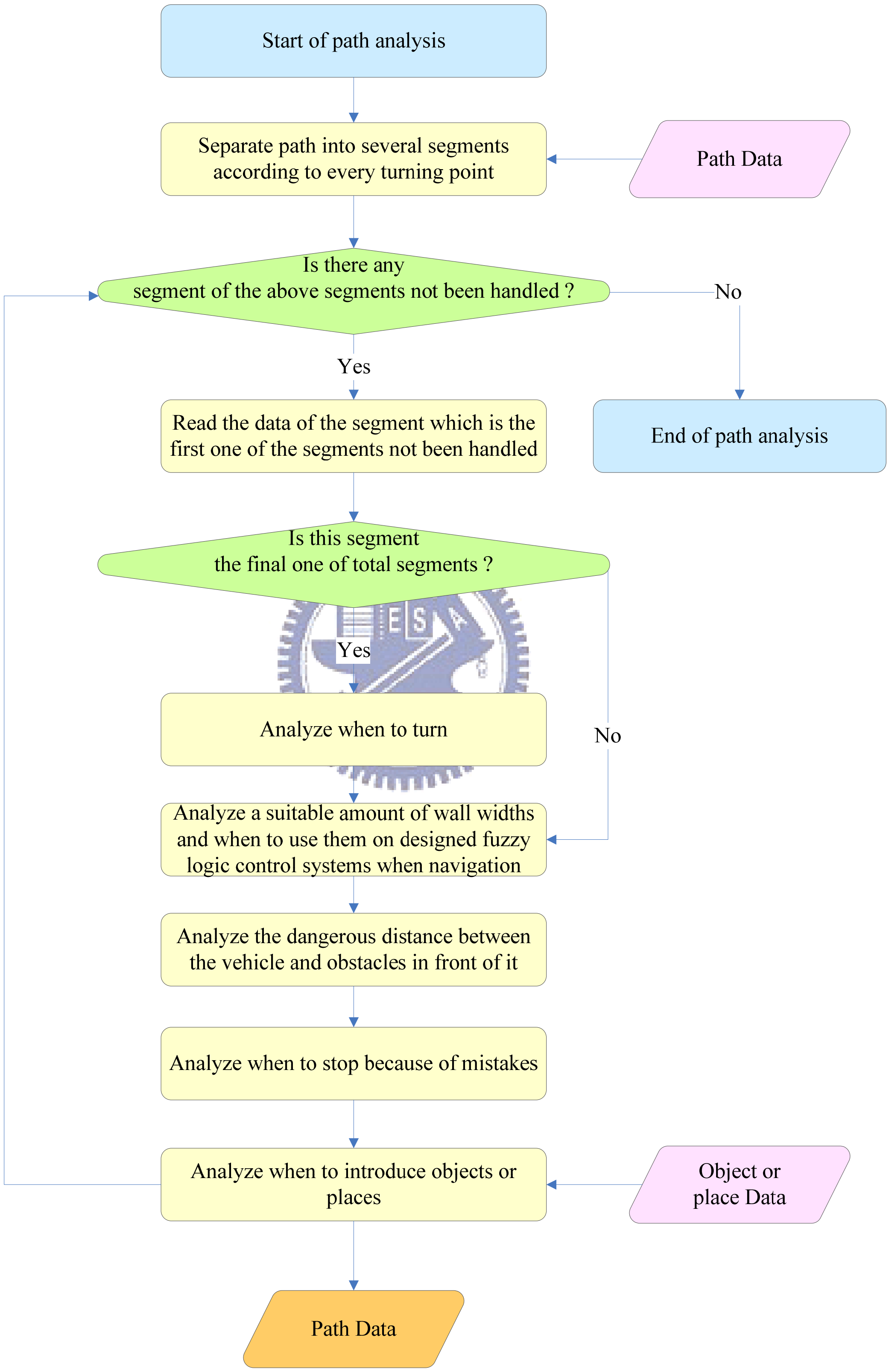


Figure 2.4 Illustration of proposed path analysis process.

2.5 Idea of Proposed Vehicle Navigation Method

After analyzing the learned path, the vehicle will have the path data of the environment. Then, it can use such information to navigate. The proposed navigation method has two major steps and conducts three tasks. The first step is reading the data of the navigation path which is separated into several segments by the turning nodes obtained from analyzing the learned path. Accordingly, the vehicle can navigate and work as a guide. The second step is navigation in the environment by proposed fuzzy logic control techniques.

In addition, the vehicle is designed in this study to perform three tasks at every path segment. The first task is finding the position of the turning node if this segment is not the final one. The second task is introducing objects or places as a guide if necessary. The third task is stopping navigation when one of the following two situations happens. The first is that an unexpected mistake happens. The second is that this segment is the final one where the vehicle arrives at the end of navigation. These major steps are illustrated in Figure 2.5.

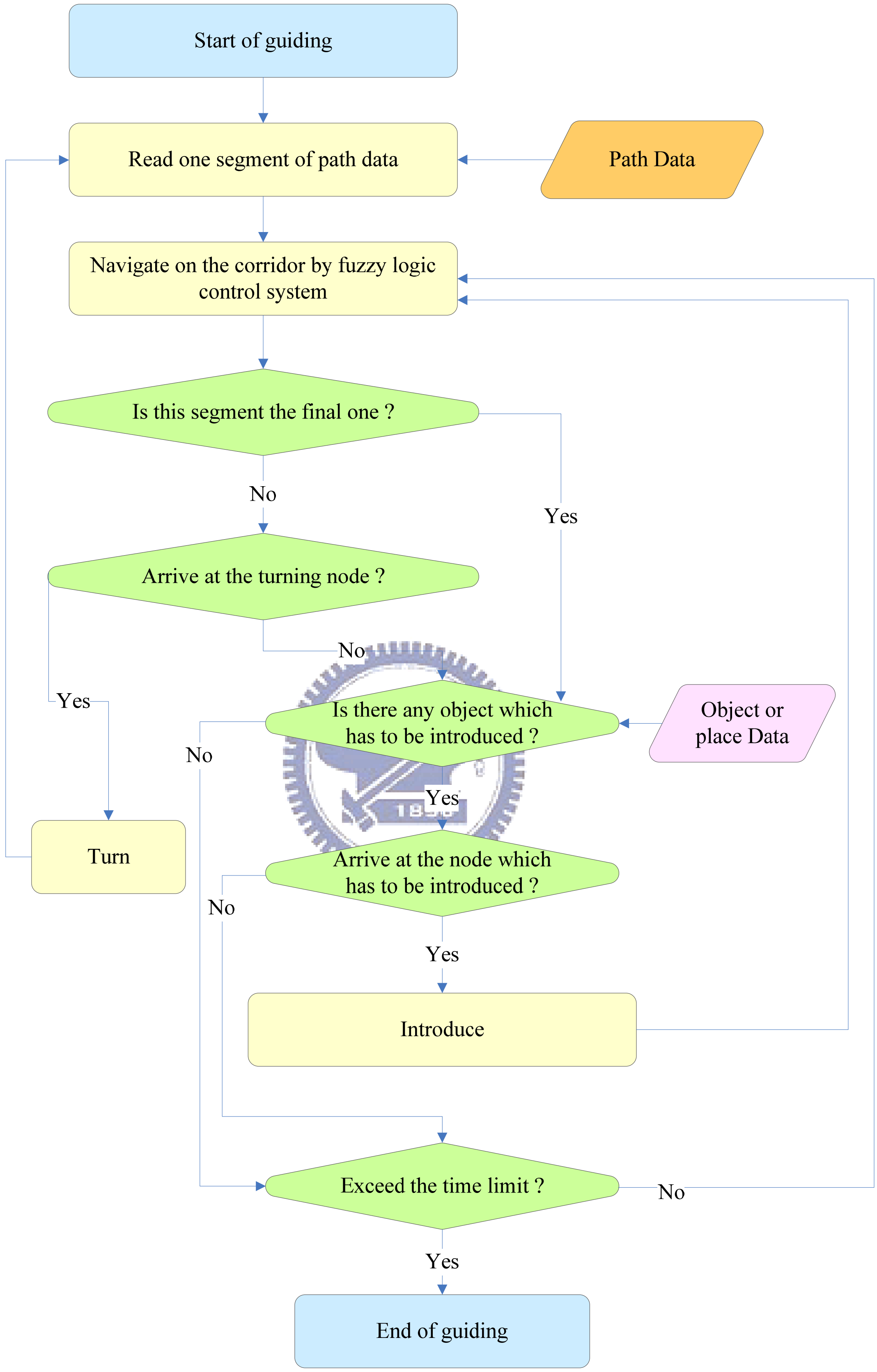


Figure 2.5 Illustration of proposed navigation process.

Chapter 3
Human Following by Fuzzy Logic Control for Path Learning

3.1 Introduction

In this chapter, we introduce the details of the proposed learning procedure. The environmental feature used for learning in this study is path data. In the learning procedure, the vehicle follows a person and learns path data in the mean time. In Section 3.2, we describe how to gather path data when the vehicle follows a person in an indoor environment. In Section 3.3, we review the fundamental fuzzy control theory and describe the principle of a fuzzy logic controller which we design for this study. In Section 3.4, we describe how to use fuzzy logic control techniques in the proposed method. Furthermore, we describe how to detect and handle three kinds of situations which happen when the person stops and after the vehicle stops in Section 3.5. Finally, we summarize the above-mentioned techniques and describe an algorithm of the proposed learning procedure in Section 3.6. An illustration of the learning procedure is shown in Figure 3.1.

3.2 Learning of Path Data

While the vehicle follows a person, it learns path data in the mean time. For this, it will obtain four kinds of information from different sources, as identified in this study.

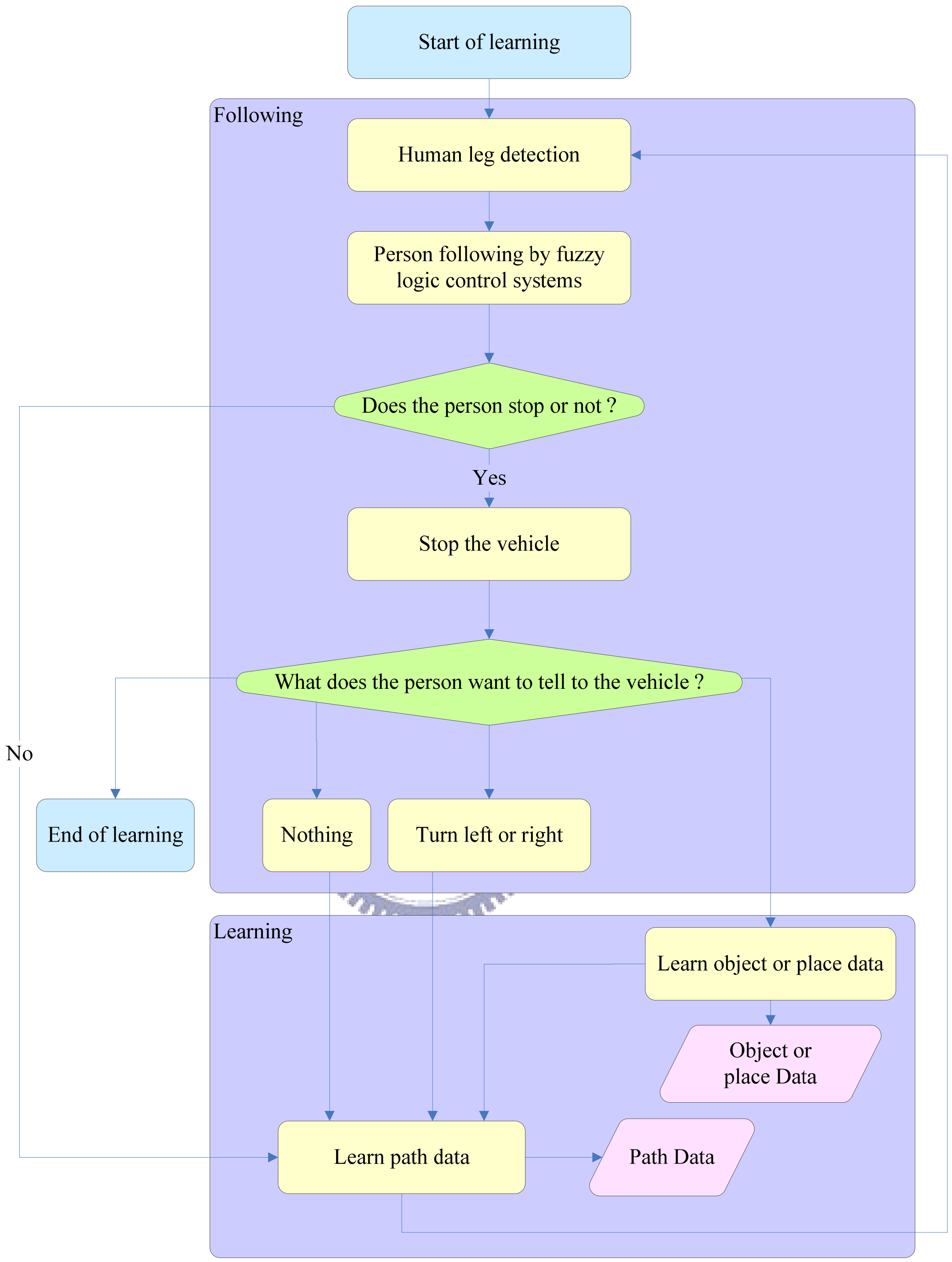


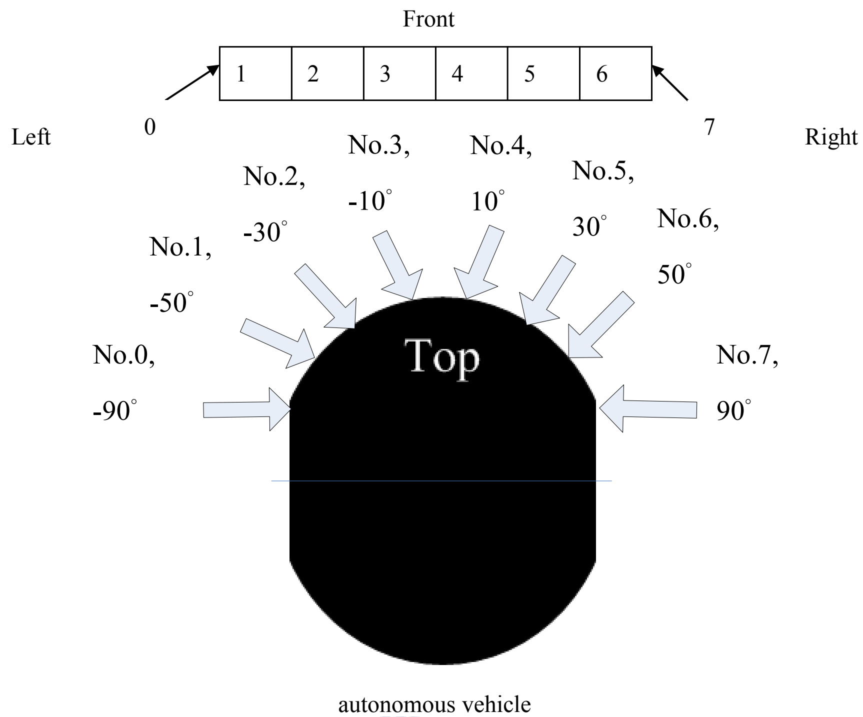
Figure 3.1 Illustration of proposed learning procedure.

First, the odometer provides the speed information of the vehicle. Second, the computer provides the information of the running time of the program which controls the vehicle. Third, the ultrasonic sensors provide the distance information with respect to surrounding objects and walls. The ultrasonic sensors equipped in the vehicle include fore and aft sonar arrays. The sonar positions in all sonar arrays are fixed: one on each side and six facing outward at 20-degree intervals. The fore sonar array of the vehicle is shown in Figure 3.2(a). A simple illustration of the fore and aft sonar arrays is shown in Figure 3.2(b). Fourth, the person provides the command information with regard to surrounding environments. The command information is that describing the ways the person interacts with the vehicle. For example, if the vehicle detects that the person stops, it will stop, too. In other words, the command information does not mean the information which the operator of the vehicle keys in by hand.

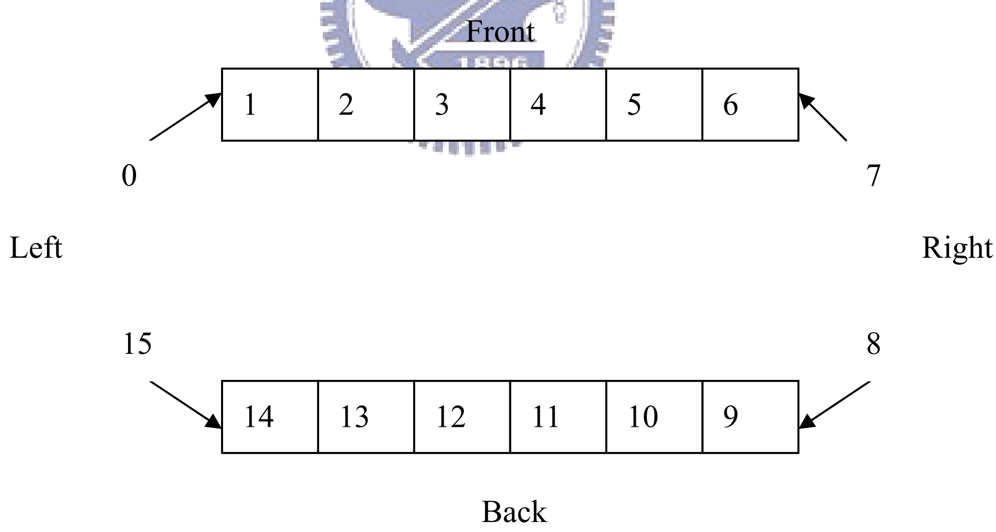
Besides, in order to draw a map to show on the screen of a computer, the vehicle also records the position information which consists of the coordinates (x, y, θ) in the world coordinate system provided by the odometer. A list of all kinds of the learned information is shown in Table 3.1.

Table 3.1 *All kinds of the learned information.*

Type	Explanation
Command 1	This item records that this node is the first or final one of a path or not.
Command 2	This is the person's command. The vehicle receives it by analyzing the ultrasonic signals and the person's behaviors. It includes going front, stopping, restarting, turning, and introducing objects.
Speed	This is the speed of the vehicle.
Coordinate (x, y, θ)	x and y are coordinates on Cartesian coordinate system. θ is the direction of the vehicle.
Time	This is the information of running time of the program which controls the vehicle.
Angle	This is part of the person's command and represents the angle which the vehicle has to turn
Distances	This is an array with 16 elements and represents every distance which detected by the respective ultrasonic sensors.



(a) The fore sonar array of the vehicle.



(b) The fore and aft sonar arrays.

Figure 3.2 Illustration of sonar arrays

3.3 Review of Design Principle of Fuzzy Logic Control System

3.3.1 Fuzzy sets and membership functions [18]

According to Lin and Lee [18], a classical (crisp) set is a collection of distinct objects that can be separated into two groups, *members* and *nonmembers*, by a characteristic function defined as Eq. (3.1):

$$\mu_A(x) = \begin{cases} 1 & \text{if and only if } x \in A; \\ 0 & \text{if and only if } x \notin A. \end{cases} \tag{3.1}$$

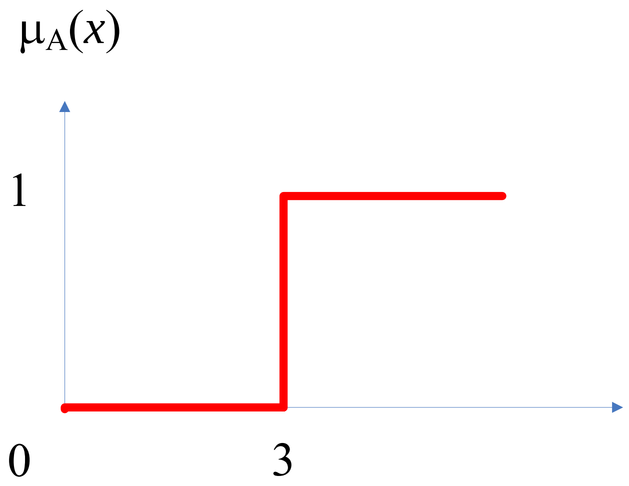
In Eq. (3.1), *A* is a classical set, *x* is an element, and μ is a characteristic function of *A*. Furthermore, the boundary of a classical set *A* is rigid and sharp.

On the other hand, a fuzzy set introduces vagueness by eliminating the sharp boundary that divides members from nonmembers in the group. It is defined as a set of ordered pairs by:

$$\tilde{A} = \left\{ \left(x, \mu_{\tilde{A}}(x) \right) \middle| x \in U \right\}. \tag{3.2}$$

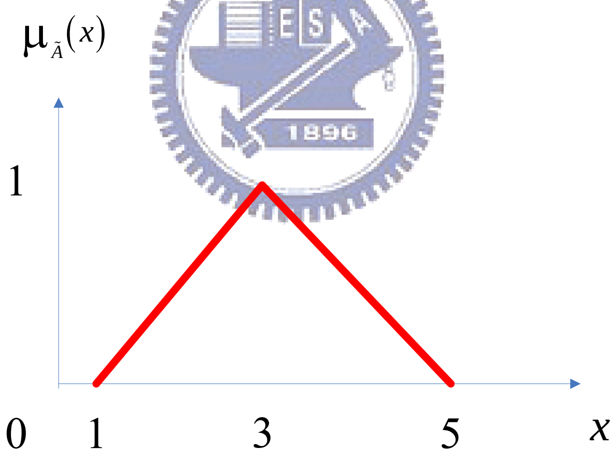
In Eq. (3.2), $\tilde{A}$ is a fuzzy set in the universe of discourse U, and *x* is an element of U. In addition, μ is a membership function (characteristic function) of $\tilde{A}$ and $\mu_{\tilde{A}}(x)$ is the grade (or degree) of membership of *x* in $\tilde{A}$, which indicates the degree that *x* belongs to $\tilde{A}$. The range of μ is a subset composed by the nonnegative real numbers whose supremum is finite.

An example of characteristic functions of a classical set *A* and a fuzzy set $\tilde{A}$ is shown in Figure 3.3.



$$\mu_A(x) = \begin{cases} 1 & if\ x \geq 3; \\ 0 & if\ x < 3. \end{cases}$$

(a) An example of characteristic function of a classical set *A*.



$$\mu_{\tilde{A}}(x) = \begin{cases} \dfrac{x-1}{2} & if\ x \geq 1\, and\ x < 3; \\ \dfrac{3-x}{2}+1 & if\ x \geq 3\, and\ x < 5; \\ 0 & if\ x < 1\, or\ x > 5. \end{cases}$$

(b) An example of membership function (characteristic function) of a fuzzy set $\tilde{A}$

Figure 3.3 An example of characteristic functions of a classical set *A* and a fuzzy set $\tilde{A}$.

3.3.2 Basic architecture of a fuzzy logic controller [18]

According to Lin and Lee [18], the basic architecture of a fuzzy logic controller is shown in Figure 3.4. It is comprised of four principle components. The first is *fuzzifier*. The observed data are usually crisp. Therefore, a fuzzifier will be utilized to convert the data into fuzzy numbers (fuzzy data) using membership functions.

The second is *fuzzy rule base*. It is a collection of fuzzy control rules characterized by fuzzy IF-THEN rules. In the case of multi-input-single-output systems, the general form of the fuzzy control rules is:

$$R^i\text{: IF } x \text{ is } A_i, \ldots, \text{ AND } y \text{ is } B_i, \text{ THEN } z = C_i,\ \mathrm{i} = 1, 2, \ldots, n, \quad (3.3)$$

where x, …, y are linguistic variables representing the process state variables, and z is a linguistic variable representing the control variable. A_i,…, B_i, and C_i are linguistic values of the linguistic variables x, …, y, and z.

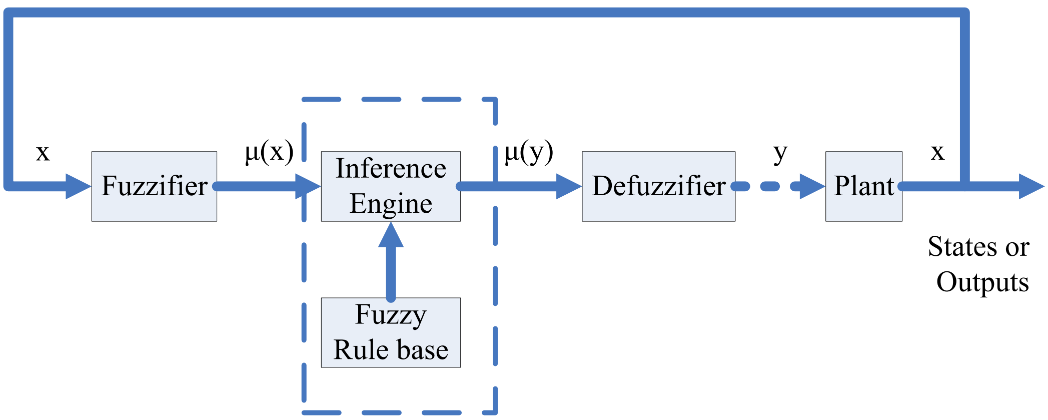


Figure 3.4 Basic architecture of a fuzzy logic controller. [18]

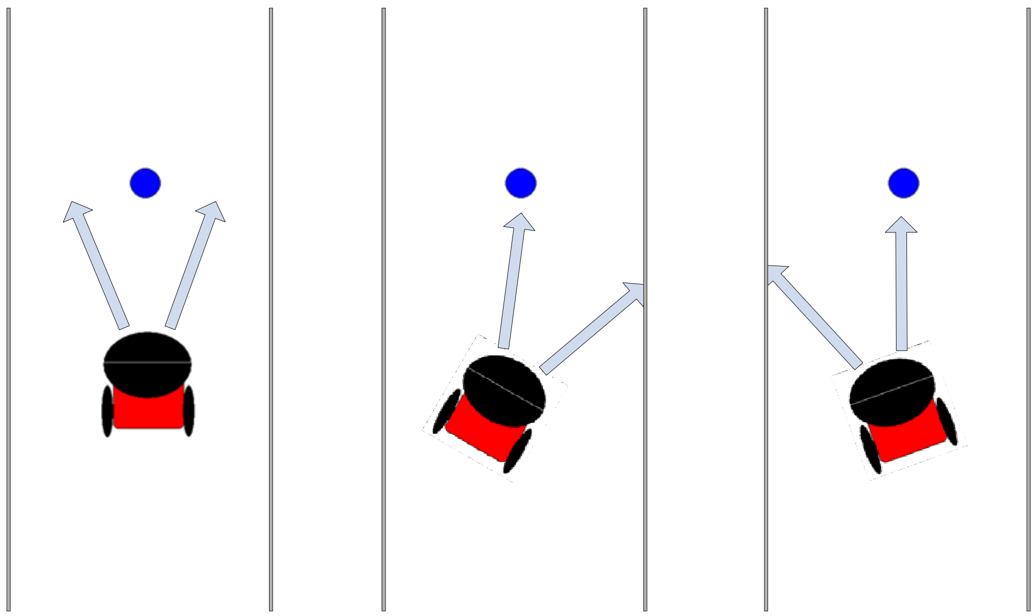
The operation AND which we used for fuzzy sets in this study is defined as the minimum function. It is a basic operation of fuzzy sets.

The third is *inference engine*. It imitates people to make decisions according to fuzzy if-then rules and fuzzy reasoning. The forth is *defuzzifier*. It transforms the result in the space of fuzzy control actions into some actions in the space of nonfuzzy (crisp) control actions.

3.4 Proposed Fuzzy Logic Control Techniques for Human Following

3.4.1 Proposed method for controlling vehicle direction

The sonar positions in the sonar arrays shown in Figure 3.2 are not directly in front of the vehicle. Therefore, if the vehicle moves straight and follows a person as shown in Figure 3.5(a), it can not detect the person by ultrasonic sensors. However, if it moves on a curve path as shown in Figures 3.5(b) or 3.5(c), it will detect the person by ultrasonic sensors. In order to keep following the person, the vehicle has to keep the person’s position directly in front of it. However, it may move on a curve path because of incremental mechanic errors or the person may not walk on a straight path. For this, if it detects that the person is on the left hand side of it as shown by Figure 3.5(b), then it can know that it is moving on a curve path and adjusts its direction by turning left. Similarly, if it detects that the person is on the right hand side of it as shown by Figure 3.5(c), then it can know that it is moving on a curve path and adjusts its direction by turning right. In addition, in order to improve the chance that it can detect the person by ultrasonic sensors, the values detected from ultrasonic sensors No. 2, 3, 4, and 5 will be used as the inputs of the proposed fuzzy controller.

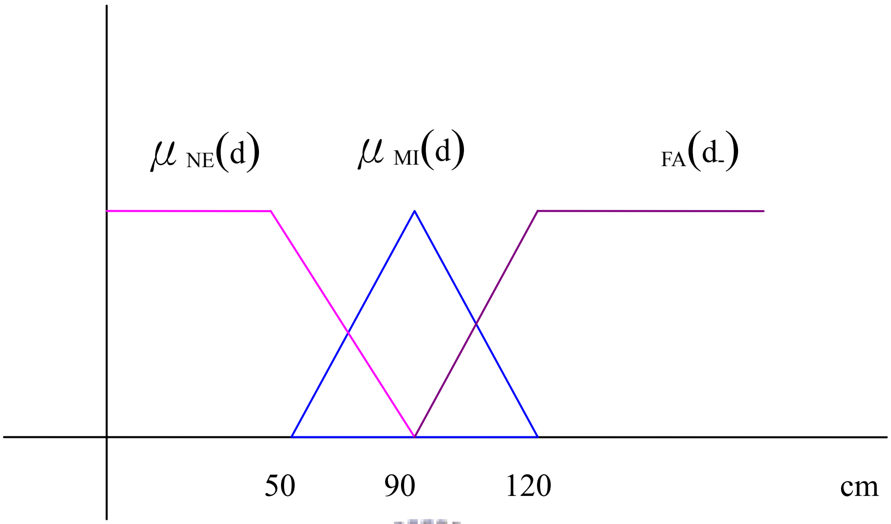


(a) (b) (c)

Figure 3.5 Three kinds of relative positions of the vehicle and a person. The blue circle represents the person and the arrows represent the signals of the ultrasonic sensors equipped in front of the vehicle. (a) The vehicle moves on a straight path. (b) The vehicle moves on a curve path. (c) The vehicle moves on a curve path.

According to this idea, the input variables for the proposed fuzzy controller are D_2, D_3, D_4, and D_5, which represent the values measured from ultrasonic sensors No. 2, 3, 4, and 5. The controlled linguistic variable is denoted as *ANGLE*, which represents the angle and direction of the vehicle's rotation. Three fuzzy terms are defined for each input variables. They are near (NE), middle (MI), and far (FA). The membership functions of the three fuzzy terms, NE, MI, and FA, are illustrated in Figure 3.6. Furthermore, seven fuzzy terms are denoted for the controlled linguistic variable. They are from negative large to positive large. The negative large means that the vehicle turns a large angle to the left. Similarly, the positive large means that the vehicle turns a large angle to the right. The membership functions of the seven fuzzy terms of the linguistic variable *ANGLE* is illustrated in Figure 3.7.

The degree that d belongs to NE, MI, or FA.



d : The distance detected from ultrasonic sensor No. 2, 3, 4, or 5.

Figure 3.6 The membership functions of the three fuzzy terms, NE, MI, and FA.

A total of 81 fuzzy rules are represented as a fuzzy rule matrix which is shown in Table 3.2, and the fuzzy terms of the output variable *ANGLE* is represented as seven numbers which are described in Table 3.3. The form of each fuzzy rule is:

$$R^i: \text{IF } D_2 \text{ is } A_k, D_3 \text{ is } B_k, D_4 \text{ is } C_k, \text{ AND } D_5 \text{ is } E_k, \text{ THEN } ANGLE \text{ is } F_j. \quad (3.4)$$

In Eq. (3.4), A_k, B_k, C_k, and E_k represent the linguistic values of the three fuzzy terms, NE, MI, and FA, respectively. Furthermore, F_j represents the linguistic values of the seven fuzzy terms of the output variable.

Table 3.2 *The fuzzy rule matrix for controlling the vehicle direction.*

Left \ Right	D_5	NE_5			MI_5			FA_5		
D_2	D_3 \ D_4	NE_4	MI_4	FA_4	NE_4	MI_4	FA_4	NE_4	MI_4	FA_4
NE_2	NE_3	3	2	2	3	2	2	3	2	2
	$MI_{\cdot 3}$	4	3	2	4	3	1	4	3	1
	FA_3	4	4	3	4	5	1	4	5	0
MI_2	NE_3	3	2	2	3	2	2	3	2	2
	MI_3	4	3	1	4	3	1	4	3	1
	FA_3	4	5	5	4	5	3	4	5	0
FA_2	NE_3	3	2	2	3	2	2	3	2	2
	MI_3	4	3	1	4	3	1	4	3	1
	FA_3	4	5	6	4	5	6	4	5	3

Table 3.3 *The fuzzy terms of the output variable ANGLE.*

ANGLE						
Left-hand rotation----------------------------- straight --------------------------- Right-hand rotation Large angle of rotation ------------------------zero------------------------- Large angle of rotation						
0	1	2	3	4	5	6

Finally, the method used to defuzzify the fuzzy output is the discrete fuzzy centroid defuzzification.

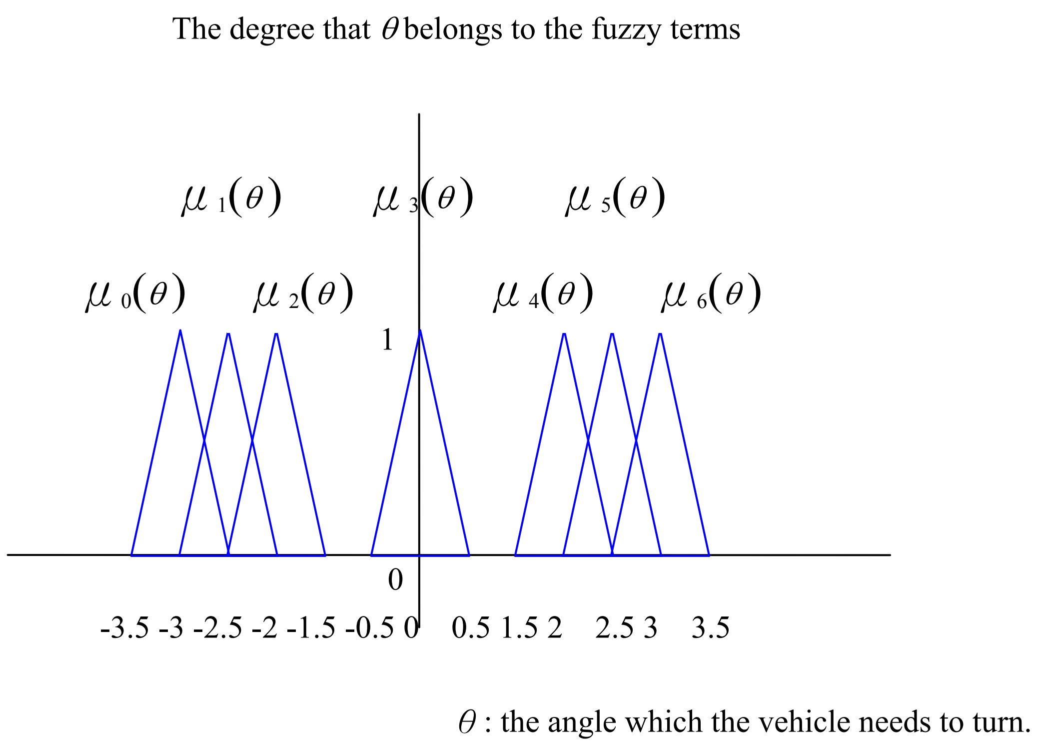


Figure 3.7 The membership functions of the seven fuzzy terms of the controlled linguistic variable *ANGLE*.

3.4.2 Proposed method for controlling vehicle speed

When the vehicle follows a person, the moving speed of the person may not be a constant. For this, after adjusting its direction, it still has to adjust its speed to keep following the person. The relationship between the person's speed and the vehicle's speed is an important factor in the proposed method. For example, if the person walks faster than the vehicle, the vehicle should speed up. The proposed system retrieves the distance information D_i which includes the values ($d_{2,i}$, $d_{3,i}$, $d_{4,i}$, $d_{5,i}$) measured respectively from ultrasonic sensors No. 2, 3, 4, and 5 at time *i*. The person's speed is estimated by the two variables, D_i and D_{i-1}.

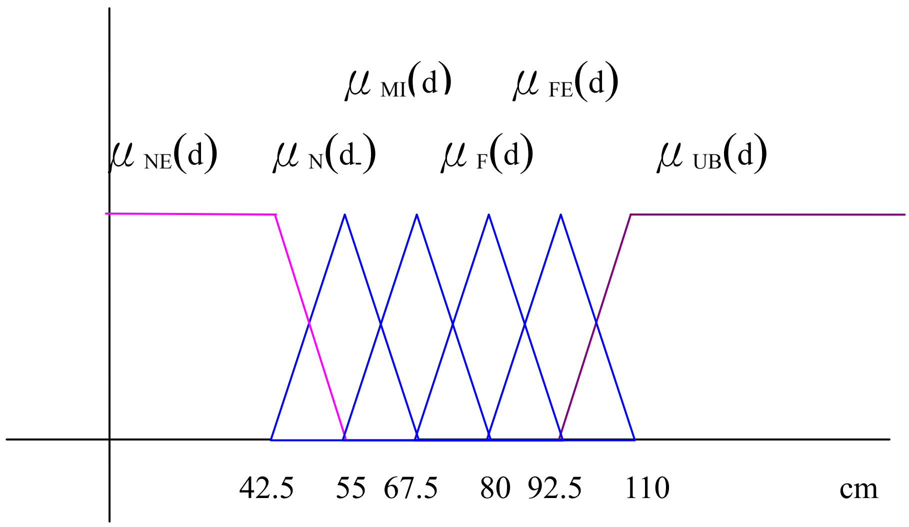
Three input linguistic variables are used in the designed fuzzy controller. They are the distance d_i measured at time i (D_N), the distance d_{i-1} measured at time $i-1$ (D_L), and the speed of the vehicle at time i (S_V). In the learning stage, we assume that only one person is in front of the vehicle. Therefore, at time i, the input value d_i of the variable D_N is the minimum values of $d_{2,i}$, $d_{3,i}$, $d_{4,i}$, and $d_{5,i}$, and the input value d_{i-1} of the variable D_L is the minimum values of $d_{2,i-1}$, $d_{3,i-1}$, $d_{4,i-1}$, and $d_{5,i-1}$. However, a wall may also be in front of the vehicle when the vehicle is at a corner. In order to deal with this situation, the variables, D_N and D_L, have the fuzzy terms respectively to do this work. This fuzzy term is UB which will be defined in the following paragraph. The main idea to define this fuzzy term is that if the input value d is very large, then it belongs to this fuzzy term with a large degree, because it can not be used to decide what in front of the vehicle is, the person or a wall.

Six fuzzy terms are defined for each of the input variables, D_N and D_L. They are nearer (NE), near (N), middle (MI), far (F), farther (FE), and unbelieving (UB). The term UB is used when the distance is too far to decide whether it is to the person or a wall. The membership functions of these fuzzy terms are illustrated in Figure 3.8.

Furthermore, five fuzzy terms are defined for the input variable S_V. They are slower (SE), slow (S), middle (MD), fast (FS), and faster (FR). The membership functions of these fuzzy terms are illustrated in Figure 3.9.

The output linguistic variable which is denoted as *SA* represents speed. If the vehicle's speed is V_i at time i and the controller outputs a result *sa* which is the output value of *SA*, then the vehicle's speed at time i+1 is represented as V_{i+1} and obtained by $V_{i+1} = V_i + sa$. In other words, the result of the controller is a difference of the vehicle's speeds at time i and i+1. Eleven fuzzy terms are defined for the output variable. They are from negative large (0) to positive large (10). The negative value means that the vehicle has to decrease its speed. The membership functions of these fuzzy terms are illustrated in Figure 3.10.

The degree that d belongs to NE, N, MI, F, FE, or UB.



d : the distance obtained by the above-mentioned way.

Figure 3.8 The membership functions of the six fuzzy terms, NE, N, MI, F, FE, and UB.

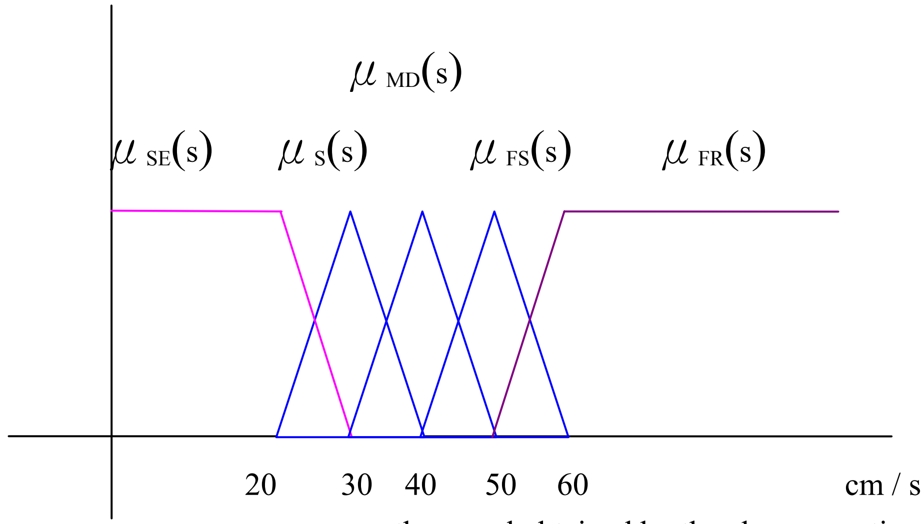
A total of 180 fuzzy rules are represented as a fuzzy rule matrix which is shown in Table 3.4, and the fuzzy terms of the output variable *SA* are described in Table 3.5. The form of each fuzzy rule is:

$$R^i: \text{IF } D_N \text{ is } A_k,\ D_L \text{ is } B_k, \text{ AND } S_V \text{ is } C_k, \text{ THEN } SA \text{ is } E_j, \tag{3.5}$$

In Eq. (3.5), A_k and B_k represent the linguistic values of the six fuzzy terms NE, N, MI, F, FE, and UB, respectively. C_k represent the linguistic values of the five fuzzy terms SE, S, MD, FS, and FR. Furthermore, E_j represents the linguistic values of the seven fuzzy terms of the output variable.

Finally, the method used to defuzzify the fuzzy output is the discrete fuzzy centroid defuzzification.

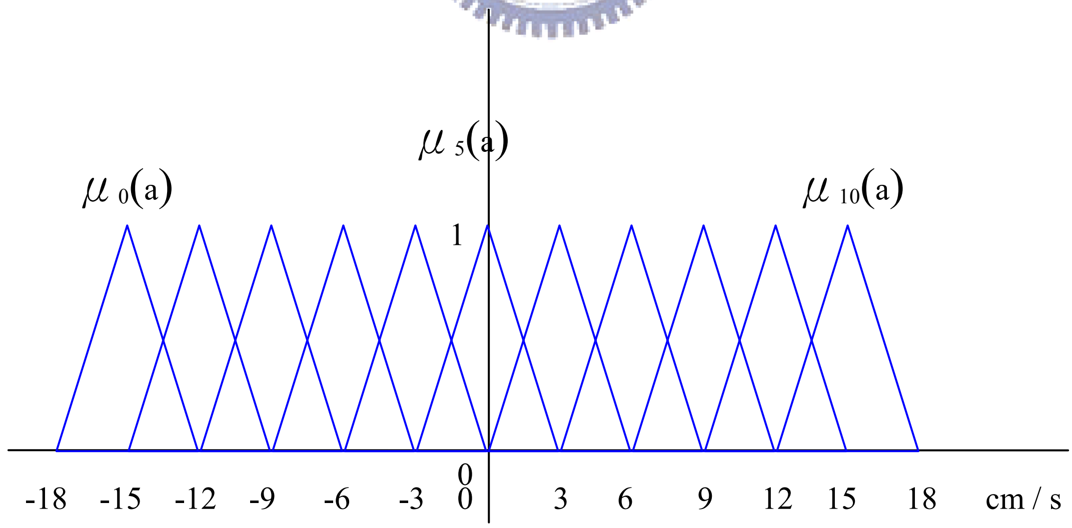
The degree that s belongs to SE, S, MD, FS, or FR.



s: the speed obtained by the above-mentioned way.

Figure 3.9 The membership functions of the five fuzzy terms of the input variable S_V.

The degree that a belongs to the fuzzy terms of the output variable *SA*



a: difference of the vehicle's speeds at time *i* and *i*+1

Figure 3.10 The membership functions of the eleven fuzzy terms of the output variable *SA*.

Table 3.4 *The fuzzy rule matrix for controlling the vehicle's speed.*

D_N	$D_L \setminus S_V$	SE	S	MD	FS	FR
NE	NE	5	4	2	1	1
	N	4	4	2	1	0
	MI	4	3	1	0	0
	F	3	3	1	0	0
	FE	3	2	1	0	0
	UB	4	3	2	0	0
N	NE	6	5	3	2	2
	N	5	5	3	2	1
	MI	4	4	2	1	1
	F	4	4	2	1	0
	FE	3	3	2	1	0
	UB	6	5	3	1	1
MI	NE	8	6	5	4	3
	N	7	6	5	4	3
	MI	6	5	4	3	2
	F	6	5	4	3	2
	FE	5	4	4	3	2
	UB	8	7	5	3	1
F	NE	10	8	7	7	6
	N	10	8	7	6	5
	MI	9	8	7	6	5
	F	9	7	6	5	4
	FE	8	7	6	5	3
	UB	9	8	6	5	4
FE	NE	10	9	8	8	7
	N	10	9	8	7	6
	MI	10	9	8	7	6
	F	10	8	7	6	5
	FE	9	8	7	6	5
	UB	10	9	7	6	5
UB	NE	4	3	2	1	0
	N	5	4	3	2	1
	MI	6	5	4	3	2
	F	7	6	5	4	3
	FE	8	7	6	5	4
	UB	5	5	5	4	4

Table 3.5 *The fuzzy terms of the output variable SA.*

SA										
Decrease speed more -------------------------Zero--------------------------- Increase speed more										
0	1	2	3	4	5	6	7	8	9	10

3.5 Vehicle Stopping, Turning, and Restarting Techniques

3.5.1 Stopping technique

When the vehicle follows a person, if the person stops, the vehicle has to stop, too. It is desired that if the person is near the left- or right-hand side of the vehicle, then the vehicle should stop. In other words, if the distance detected from ultrasonic sensors Nos. 0, 7, 8, or 15 is smaller than a preselected value, then the vehicle should stop.

3.5.2 Turning technique

If the vehicle stops according to the stopping technique mentioned in Section 3.5.1, it has to know what the person commands it to do. In this study, it can receive four kinds of commands by analyzing the ultrasonic signals and the person’s behaviors. These commands are represented as *TURN*, *RECORD, WALK,* and *END*. The command *TURN* means that the vehicle is at a turning node and it has to turn. The command *RECORD* means that the vehicle is at a node where it will introduce an object or a place as a guide during navigation. In order to achieve this task, it records this node. The command *WALK* means that the vehicle is not at a node where it turns, a node where it will introduce an object or a place as a guide, or a node which is the end of this path. Therefore, it continues to follow the person without turning or recording any object's position. The command *END* means that the vehicle is at the end of the learning path. Therefore, it should record this node and finish learning.

In order to obtain the just-mentioned commands, the vehicle uses a voting technique to analyze the ultrasonic signals and the person's behaviors. It detects the person's position by the ultrasonic sensors. After it stops, it still receives values from the ultrasonic sensors n times and these values are represented as SD_1, SD_2, …, SD_n, where n is a threshold we set in advance. Each SD_i includes 16 values (sd_0, …, sd_{15}) from the respective 16 ultrasonic sensors. If sd_k in SD_i is less than 40% of sd_k in SD_1, then ultrasonic sensor No. k gets a vote. After voting, if the votes got by ultrasonic sensor No. k are the most and more than a threshold T we set, the vehicle will execute a command which is represented by ultrasonic sensor No. k. Ultrasonic sensors Nos. 0, 1, 2, 5, 6, and 7 represent the command *TURN*. Ultrasonic sensors Nos. 8 and 15 represent the command *RECORD*. Ultrasonic sensors Nos. 3 and 4 represent the command *WALK*. In addition, if several ultrasonic sensors get the same number of votes and their respective votes are all more than the threshold T, a sequence of priority of the commands is used. This sequence of priority is *TURN* > *RECORD* > *WALK*. However, if all of these three commands, *TURN, RECORD,* and *WALK* are not selected, the vehicle will execute the command *END*. A list of the ultrasonic sensors and the commands represented by them respectively is shown in Table 3.6. The algorithm of the turning technique is shown in Algorithm 3.1.

3.5.3 Restarting technique

After the vehicle executes the person's command as mentioned previously, it detects if the person is in front of it or not. If the answer is yes, then it restarts to follow the person. However, if the answer is no, it waits a period of time and continues to detect during this period of time. Afterward, if the answer does not change, then it will finish learning.

Table 3.6 *List of the ultrasonic sensors and commands represented by them, respectively*.

k (Ultrasonic sensor No. k)	Command
0	*TURN* : Turn an angle of $90°$ to left.
1	*TURN* : Turn an angle of $50°$ to left.
2	*TURN* : Turn an angle of $30°$ to left.
3	*WALK*
4	*WALK*
5	*TURN* : Turn an angle of $30°$ to right.
6	*TURN* : Turn an angle of $50°$ to right.
7	*TURN* : Turn an angle of $90°$ to right.
8	*RECORD*
15	*RECORD*
Other	*END*

Algorithm 3.1 *Getting a command by analyzing the ultrasonic signals and the person's behaviors*.

Input: The ultrasonic signals SD_1, SD_2, …, SD_n measured after the vehicle stops.

Output: One of the four kinds of commands *TURN*, *RECORD, WALK,* and *END*.

Steps:

Step 1. Set $i = 1$.

Step 2. If sd_k in SD_i is less than 40% of sd_k in SD_1, then ultrasonic sensor No. k gets a vote, $k = 0, 1, 2, \ldots, 15$.

Step 3. Repeat Step 2 until $i = n$.

If $i > n$, then go to step4.

Step 4. Compute how many votes got by every ultrasonic sensor respectively.

Step 5. Compute which ultrasonic sensor gets the most votes.

Step 6. If only an ultrasonic sensor gets the most votes and these votes are more than the threshold T, then go to Step 7. (Assume that this ultrasonic sensor's number is k1). If more than one ultrasonic sensor gets the most votes and the votes of each sensor are more than the threshold T, then go to Step 8. (Assume that these ultrasonic sensors' numbers are k1, k2, …, and kj).
If no ultrasonic sensor gets enough votes which are more than the threshold T, then output the command *END* and finish this procedure.

Step 7. Set w = k1, and then go to Step 9.

Step 8. According to the sequence of priority of the commands *TURN* > *RECORD* > *WALK*, set w = kx, where x = 1, 2, …, or j and go to Step 9.

Step 9. According to the ultrasonic sensor's number w and Table 3.4, output the command represented by w.

3.6 Algorithm of Proposed Method for Path Learning

In this section, an integral algorithm of the proposed learning procedure is described. As mentioned previously, the proposed learning procedure includes two major tasks, following a person and learning a path in the mean time. At first, the vehicle follows a person and adjusts its direction and speed by the ultrasonic signals and fuzzy logic control techniques. If the person stops, it stops to detect what the person commands it to do by analyzing the ultrasonic signals and the person's behaviors. Then it continues learning until the person commands it to finish. The integral algorithm of proposed method for path learning is shown in Algorithm 3.2.

Algorithm 3.2 *Learning a path by following a person.*

Input: A vehicle and a user.

Output: A guiding path data.

Steps:

Step 1. Follow the user.

Step 2. Adjust its direction and speed by the proposed fuzzy controllers described in Section 3.4 and save the information of each node. All kinds of information of a node to learn are shown in Table 3.1.

Step 3. If the person stops, then stop and go to step4, else go to Step2.

Step 4. Analyze the person's behaviors and obtain a command by Algorithm 3.1.

Step 5. Execute this command and save the information of this command.

If this command is not *END*, go to Step 6, else go to Step 7.

Step 6. Wait until the person stands in front of it.

If the person stands in front of it, go to Step 1.

If the person never stands in front of it during a period of time, go to Step 7.

Step 7. Save the information of this node and finish learning.

Chapter 4
Path Analysis Using Ultrasonic Signals

4.1 Introduction

We introduce the details of the proposed procedure of path analysis in this chapter. The environmental feature obtained from path analysis and used for navigation is path data. When the vehicle learns path data by following a person, the trajectory of the path may be rough and curvilinear. After learning, it is so desired also that the vehicle can plan a navigation path to follow the sequences of objects which it has to introduce as a guide without hitting walls in environments. For this, the path data for navigation are identified by five kinds of information in this study. In other words, the structure of the learned path data is not the same as that of the path data for navigation. We describe the structure of the path data for navigation in Section 4.2. In Section 4.3, we describe how to analyze the learned path data mentioned in Section 3.2 and obtain the path data for navigation described in Section 4.2. Finally, we summarize the above-mentioned techniques and describe an integral algorithm of the proposed procedure of path analysis in Section 4.4. An illustration of the proposed procedure of path analysis is shown in Figure 4.1.

4.2 Path Data for Navigation

As just-mentioned, the path data for navigation are identified by five kinds of information in this study. In this section, we describe the details of these kinds of information. They are denoted as *TTURN*, *WDIS*, *IDIS*, *TSTOP*, and *TOBJECT*.

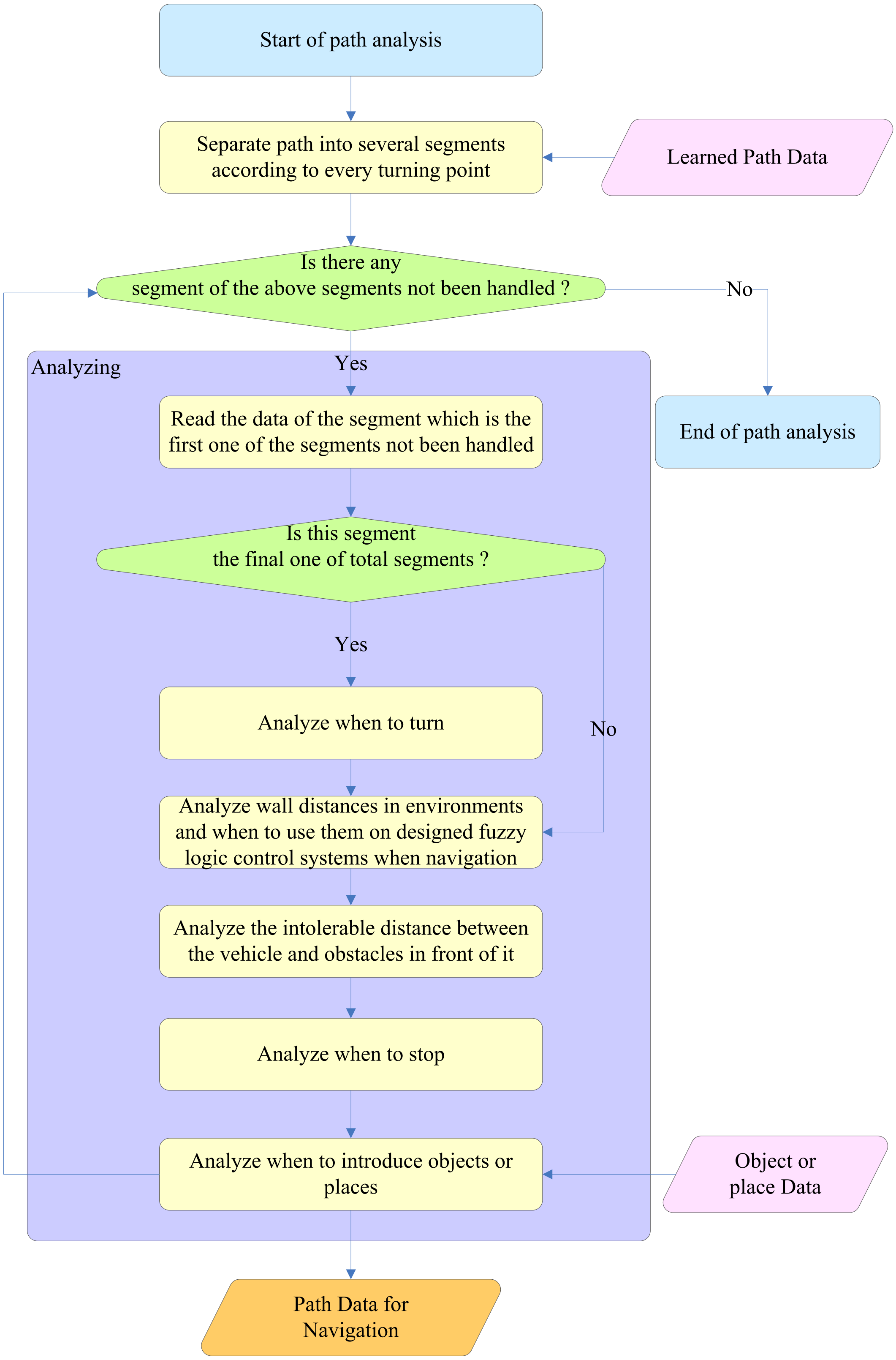


Figure 4.1 Illustration of proposed procedure of path analysis.

The first kind of information *TTURN* is about when to turn. It includes three major items. The first item is *TDIRECT*. It records the tuning direction of a turning node obtained from the learned path data directly. The second item is *NDETECT*. Consider the case that the vehicle turns left on a turning node during learning. It should not detect anything on its left-hand side for a period of time from arriving at the turning corner to arriving at the turning node. This period of time is just what is meant by the second item. If the vehicle navigates on the same path next time, it can use this information to know when to turn. However, this information is not enough to deal with all situations. Sometimes, when the vehicle desires to turn left on the same turning corner by itself after learning, it may detect nothing on its left-hand side for the same period of time as specified by *NDETECT* even if it does not arrive at the turning corner, because walls in environments are not always connected everywhere. Therefore, an item is used to deal with such the situation, which is the third item of *TTURN*, named *BEFORE*. It means that the vehicle can not turn when its running time is not over this value. In other words, the vehicle is not regarded close to the turning corner before the period of time specified *BEFORE* elapses. An example of *TTURN* is illustrated in Figure 4.2.

The second kind of information *WDIS* is distances between walls in environments. It includes three major items named as *WNUM*, *WVALUE*, and *WTIME*. Wall distances in different environments may not be the same. Therefore, the vehicle has to know the wall distances in learned environments and when to use them. Furthermore, environments between two turning nodes may also be different. For this, the first item *WNUM* is defined as the number of distinct wall distance values. The second item *WVALUE* records each value of the wall distances. The item *WTIME* records when to use the respective wall distances of *WVALUE*.

The third kind of information *IDIS* is the intolerable distance between the vehicle and obstacles in front of the vehicle. The vehicle should know this information to keep itself from hitting obstacles or walls in front of it. The fourth kind of information *TSTOP* is when to stop.

If the vehicle does not have to turn, it needs to stop at the end node of a path of navigation.

The fifth kind of information *TOBJECT* is when to introduce objects or places as a guide and includes two major items. They are named *ONUM* and *OTIME* and represent the number of objects which the vehicle needs to introduce and the time when to introduce the objects, respectively. All above-mentioned kinds of the information of the path data for navigation are listed in Table 4.1.

4.3 Techniques for Path Analysis

In this section, we describe how to obtain the five kinds of information as mentioned in Section 4.2.

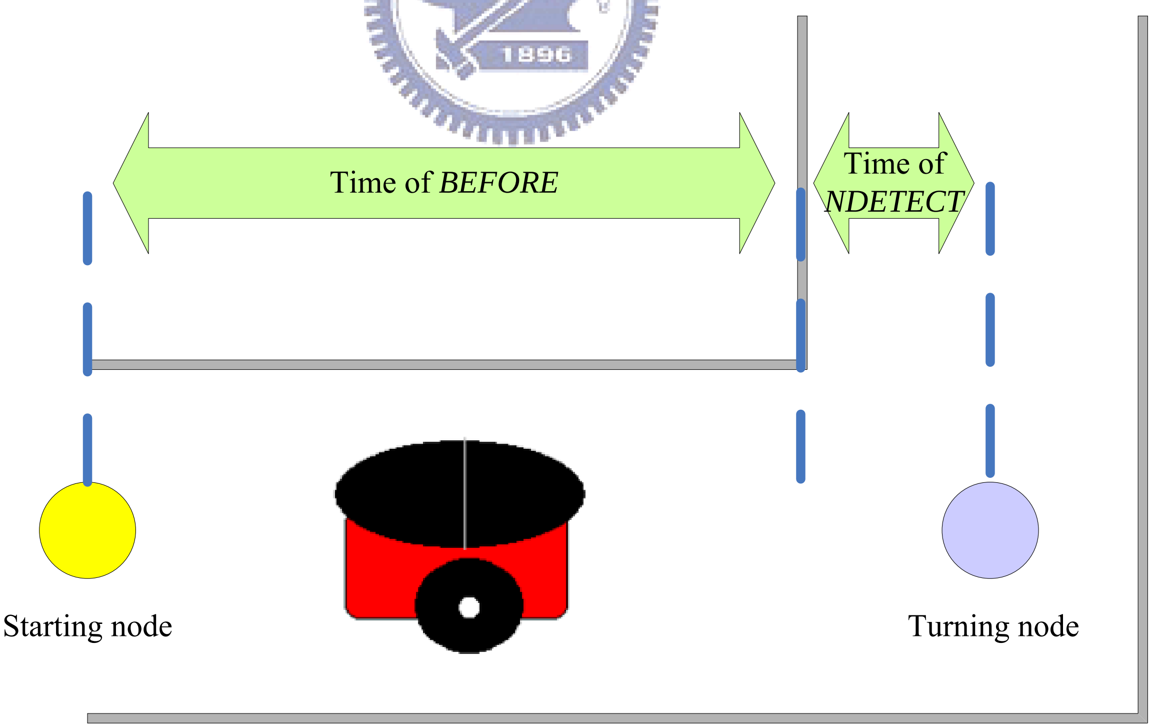


Figure 4.2 Illustration of when to turn.

At first, a learned path is segmented into several pieces by the turning nodes before being analyzed, and each segment is given a record in this study, which includes these five kinds of information.

Table 4.1 *All kinds of the information of the path data for navigation.*

Type	Items (if exist)	Meaning
TTURN	*TDIRECT*	This is the turning direction obtained from the learned path data directly.
	NDETECT	This is a period of time from arriving at a turning corner to arriving at the turning node.
	BEFORE	The period of time before which the vehicle can not turn.
WDIS	*WNUM*	The number of the wall distances.
	WVALUE	This records each value of the wall distances.
	WTIME	This records when to use the respective wall distances of *WVALUE*.
IDIS	(no item)	This is the intolerable distance between the vehicle and obstacles in front of the vehicle.
TSTOP	(no item)	This is when to stop.
TOBJECT	*ONUM*	The number of objects which the vehicle needs to introduce.
	OTIME	This records when to introduce the objects, respectively.

4.3.1 Turning

In this section, we describe how to obtain the information *TTURN*. The turning direction is obtained from the learned path data directly. Denote the distance from a turning corner to the turning node as D_{turn}. Then, presumably the vehicle should detect very large distance values by ultrasonic sensors on the turning direction from the position of the turning corner to that of the turning node. Therefore, we can obtain D_{turn} by computing the recorded information of its running time and speed from the turning node back to the starting position of the turning corner. In other words, if the starting position of the turning corner is represented as P_c, the position of the turning node is represented as P_t, the speed of the vehicle is represented as SV_i, and the vehicle's running time between the position i to i+1 is represented as T_i, then we have

$$D_{\text{turn}} = P_t - P_c = \sum_i((SV_i + SV_{i\text{-}1}) / 2) \times T_i,$$

where i is from c to t. However, the vehicle may also detect very large distance values by ultrasonic sensors before arriving at P_c, for example, when a door in an environment is opened, or when the environment includes more than one crossroad, etc. In these situations, if the vehicle detects very large values by ultrasonic sensors continuously for a period of time in an environment, then we should deal with them additionally. Let the distance, which the vehicle goes across during the period of time in such a kind of situation, be represented as $D_{\text{space}, j}$, where j is the number of such special environments. A segment of the learned path data may have several such distances. The maximum value of all $D_{\text{space}, j}$ is denoted as D_{space}. Note that all $D_{\text{space}, j}$ must occur before D_{turn}, because a turning node is the last node of a segment of a learned path. Figure 4.3 is an example to explain the just-mentioned idea.

In Figure 4.3, this segment includes an opened door and two crossroads. The opened door is from the position P_{s1} to the position P_{s2}, the first crossroad is from P_{s3} to P_{s4}, and the second crossroad is the turning corner. $D_{\text{space}, 1}$ is the distance between P_{s1} and P_{s2}, $D_{\text{space}, 2}$ is the distance between P_{s3} and P_{s4}, and D_{space} is the maximum value of $D_{\text{space}, 1}$ and $D_{\text{space}, 2}$. In the proposed method for navigation, the vehicle will use D_{turn} as its turning condition.

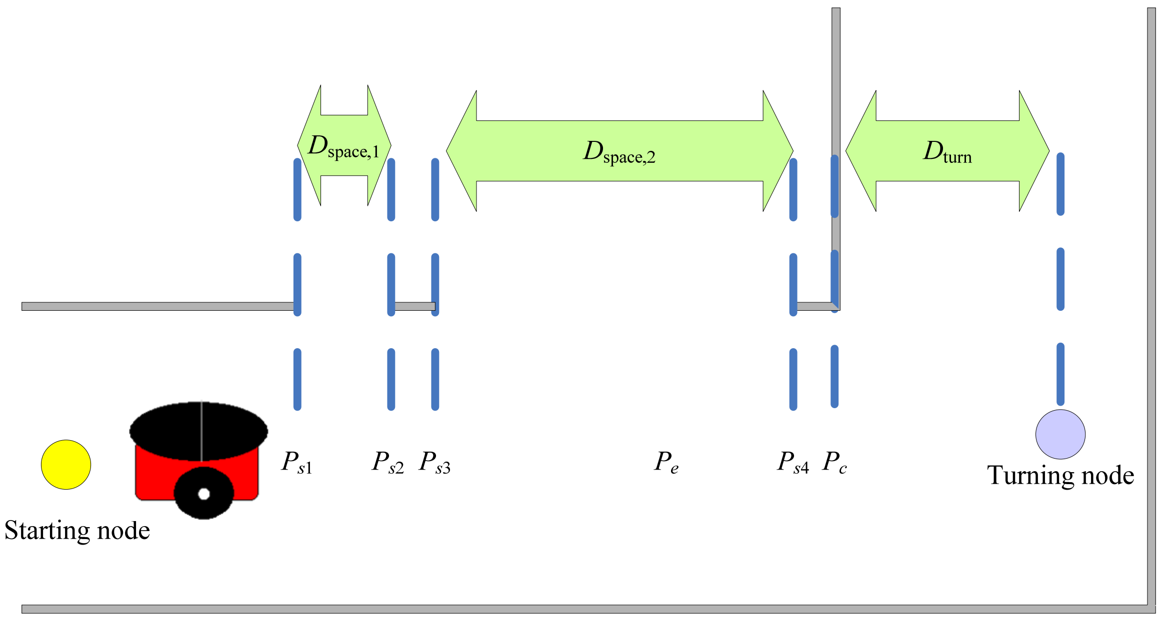


Figure 4.3 An example to explain the idea of turning.

According to the relationship between D_{turn} and D_{space}, the system needs to consider three kinds of situations. The first is $D_{space} < D_{turn}$. In this situation, the vehicle can decide that the distance which it goes across is D_{turn} or $D_{space,\,j}$ during navigation, because D_{turn} is larger than all $D_{space,\,j}$. The second is $D_{space} \geq D_{turn}$. As shown in Figure 4.3, if $D_{space,\,1} < D_{turn}$ and $D_{space,\,2} > D_{turn}$, then $D_{space} > D_{turn}$. In this situation, a position P_e which is between P_{s3} and P_{s4} exists and it satisfies that $P_e - P_{s3} = D_{turn}$. If the vehicle only uses D_{turn} to decide whether it needs to turn or not, it will turn at the position P_e. However, it should not do so, because P_e is not the correct turning node. In order to deal with this situation in general cases, a condition is used, that is, the vehicle can not turn when it is not over a position P_B, and the position P_B has to satisfy the constraint that all $D_{space,\,j}$ must occur before P_B. In the just-mentioned second situation, the system can set $P_B = P_c$. However, if D_{turn} is too large as shown in Figure 4.3, the vehicle may not continuously detect very large values by ultrasonic sensors from P_c to P_t

because of some noise. Therefore, the maximum value of D_{turn} needs to be limited by a threshold DT, as conducted in this study. In other words, if $t - c$ is smaller than DT, then we set $D_{\text{turn}} = P_t - P_c$; else, we set $D_{\text{turn}} = P_t - P_{t-DT}$.

The detail of the techniques mentioned previously is described in Algorithm 4.1.

Algorithm 4.1 *Getting the information TTURN of a segment.*

Input: A list of learned data of a path segment k with starting position P_{start} and the speed S_{navi} of the vehicle for navigation where P_i means the coordinates of the vehicle on recorded node i.

Output: The values of the respective items of *TTURN*.

Steps:

Step 1. Set *TDIRECT* = *left* or *right* by the learned data.

Step 2. Compute the starting position P_c of the turning corner.

Step 3. If $t - c$ is large than a preselected threshold DT, then set $c = t - DT$.

Step 4. Compute $D_{\text{turn}} = P_t - P_c = \sum((SV_i + SV_{i-1}) / 2) \times T_i$, $i = t, t-1, \ldots, c$.

Step 5. Compute $NDETECT = D_{\text{turn}} / S_{\text{navi}}$.

Step 6. Set $P_B = P_c$.

Step 7. For any position i from P_B to $P_B - TH$, if the detected values of ultrasonic signals on the direction the same as *TDIRECT* are all smaller than a preselected value WA, then reset $P_B = P_B - TH$, where TH is a preselected value.

Step 8. Compute $D_B = P_B - P_{start} = \sum((SV_i + SV_{i-1}) / 2) \times T_i$, $i = B, B-1, \ldots, start$.

Step 9. Compute $BEFORE = D_B / S_{\text{navi}} - cy$ where cy is a constant.

Step 10. Save the information *TTURN*.

In Algorithm 4.1, if a wall is before the turning corner, then the position P_B, which the vehicle can not turn when it is not over, should be more far to the turning corner in order to reduce the effects of errors of running time.

4.3.2 Computing distances between walls

In order to adapt the navigation path of the vehicle to different environments, the information of wall distances is very important. In this section, we describe how to obtain this information specified by the wall distance information *WDIS*.

The main idea is to make an estimate of the wall distance at position i by considering the data of the positions $i+1$, $i+2$, …, $i+w$, where w is a preselected value. If w is too large, the estimate of the wall distance is rougher. However, if w is too small, it may be affected by noise greatly. In order to solve this problem, a two-pass method is used. In the first pass, a large w preselected and represented as *TWL* is used to make estimates. After the first pass, if some estimates are not obtained for some positions, then a smaller w preselected and represented as *TWS* is used in the second pass.

In order to make an estimate, the system constructs an array *CR* and each element CR_i in *CR* records if the values detected from ultrasonic sensors are *credible* or not. A *credible* value means that it is not too large and its difference between times i and $i-1$ is large enough for decision making. A value of CR_i can represent four kinds of message, which are: (1) ultrasonic sensors Nos. 0 and 15 (ultrasonic sensors on the left-hand side of the vehicle) are credible, (2) ultrasonic sensors Nos. 7 and 8 (ultrasonic sensors on the right-hand side of the vehicle) are credible, (3) they are all not credible, and (4) they are all credible. These messages are represented as CR_i = *left*, *right*, *no,* and *all*, respectively.

If CR_i = *all*, two situations needs to be handled. Let the value of ultrasonic sensor No. m on position i be represented as $V_{m,i}$, and $ABS(V_{m,i} - V_{n,i})$ represent the absolute value of $V_{m,i} - V_{n,i}$. The first situation is that $ABS(V_{0,i} - V_{7,i}) \leq T_{abs}$, where T_{abs} is a preselected threshold.

In this situation, it means that the person goes across a node which is on the middle of two walls when learning. Therefore, the system makes an estimate of the distance between the two walls as $V_{0,i} + V_{7,i}$. The second is that $ABS(V_{0,i} - V_{7,i}) > T_{abs}$. In this situation, it means that the person goes across a node which is on either the left or the right hind side of two walls when learning. Therefore, the system makes an estimate of the distance between the two walls as a double of the minimum value of $V_{0,i}$ and $V_{7,i}$. The detail of the technique of this section is described in Algorithm 4.2.

Algorithm 4.2 *Getting the information of distances between walls along a path segment.*

Input: A list of learned data of a path segment k with starting position P_{start}, the speed S_{navi} of the vehicle for navigation, and a turning position P_t, where P_i means the coordinates (x_i, y_i) of the vehicle on recorded node i.

Output: The values of the respective items of the wall distance information *WDIS*.

Steps:

Step 1. Compute the *credible* value for each node respectively in this segment.

Step 2. For every node m from the start node *start* to the turning node t, do the following steps.

2.1. Consider nodes m through $m + JT - 1$, where JT is preselected.

2.2. If not all elements at these nodes include large *credible* values on the same side, then do the following steps.

2.2.1. Estimate the first wall distance of this segment k according to the following rules.

2.2.1.1. If the ultrasonic signals on the left-hand side of the vehicle are credible, set the wall distance as a double of the value of ultrasonic sensor No. 0 on the node m into the record of wall distances, *WDIS*.

2.2.1.2. If the ultrasonic signals on the right-hand side of the vehicle are credible, set the wall distance as a double of the value of ultrasonic sensor No. 7 on the node *m* into the record of wall distances, *WDIS*.

2.2.1.3. If the ultrasonic signals on both the left- and right-hand sides of the vehicle are credible, set the wall distance as the sum of the values of ultrasonic sensors No. 0 and No. 7 on the node *m* into *WDIS*.

2.2.1.4. If the ultrasonic signals on both sides of the vehicle are all not credible, give up all the following steps and redo Steps 2.1 and 2.2.

2.2.2. If the record of wall distances, *WDIS*, includes no element, set a default value into it and finish this algorithm.

2.3. If node $m+TWL-1$ is not at the turning node t yet, where *TWL* is a preselected threshold, then do the following steps.

2.3.1. For every node i from the current node m to node $m + TWL - 1$, do the following steps.

2.3.1.1. Compute an estimated value e_i of the wall distance for node i according to one of the following rules.

2.3.1.1.1. If the ultrasonic signals on the left-hand side of the vehicle are credible, estimate the wall distance e_i as a double of the value of ultrasonic sensor No. 0.

2.3.1.1.2. If the ultrasonic signals on the right-hand side of the vehicle are credible, estimate the wall distance e_i as a double of the value of ultrasonic sensor No. 7.

2.3.1.1.3. If the ultrasonic signals on both sides of the vehicle are credible, then do the following steps.

2.3.1.1.3.1. If the absolute difference between the values of ultrasonic sensors Nos. 0 and 7 is smaller than a preselected threshold T_{abs}, then estimate the wall distance e_i as the sum of the values of ultrasonic sensors No. 0 and 7; else, as a double of the minimum of the values of ultrasonic sensors Nos. 0 and 7.

2.3.1.1.4. If the ultrasonic signals on both sides of the vehicle are not credible, estimate the wall distance as zero.

2.3.2. Compute the mode e_{mode} as the most frequently-occurring value in the above-computed values e_i, with i being from m to $m + TWL - 1$ where TWL is a preselected threshold. And obtain e_{num} as the numbers of e_i's whose values are e_{mode}.

2.3.3. If e_{num} is large (i.e., if many of the estimated values of the wall distances are almost the same) and e_{mode} is not equal to the last wall distance recorded in the record *WDIS* of wall distances, then do the following steps.

2.3.3.1. If $e_{mode} = 0$, set the estimated wall distance as -1 into the record *WDIS* of wall distances; else, as e_{mode} into *WDIS*.

2.3.4. If e_{num} is small and the last wall distance recorded in *WDIS* is not -1, then set the estimated wall distance as -1 into *WDIS*.

Step 3. If any estimated wall distance in *WDIS* is equal to -1, then use *TWS* instead of *TWL* to estimate wall distances again in Step 2.3.

Step 4. Take the information of wall distances in *WDIS* as output.

In Step 2.3.2 and the following steps in Algorithm 4.2, if the absolute difference between two estimated values e_i and e_j is smaller than a preselected threshold, then we regard them to be equal. Furthermore, if an estimated wall distance in *WDIS* is equal to −1, it means that the system cannot estimate a credible wall distance for this position. Therefore, the vehicle will utilize the credible wall distance estimated at the last position before this one to navigate. In addition, *WTIME* on position *m* is computed as follows:

$$WTIME_m = (P_m - P_{start}) / S_{\mathrm{navi}} = (\textstyle\sum_i(((SV_i + SV_{i\text{-}1}) / 2) \times T_i)) / S_{\mathrm{navi}},$$

where P_i means the coordinates of the vehicle on recorded node *i* so that $P_m - P_{start}$ means the distance between P_m and P_{start}; *i* is from the current node *start* to the node *m*; SV_i is the speed of the vehicle on node *i*; T_i is the vehicle's running time between node *i* to *i*+1, and S_{navi} is the speed of the vehicle for navigation.

In general, the left- and right-hand sides of the vehicle are both walls. However, it may be possible that just one of the two sides of the vehicle is a wall and the other is not in an environment. In this situation, the system estimates the wall distance to be a double of the distance between the one-side wall and the vehicle. This is the main idea of handling such a situation in Steps 2.3.1.1.1 and 2.3.1.1.2 in Algorithm 4.2 above.

4.3.3 Computing intolerable distance to obstacles in front of the vehicle

When the vehicle arrives at a turning node, it may be blocked by a wall in front of it. However, the person usually stands in front of the vehicle at all time in the learning stage. Therefore, the vehicle cannot detect the distance between the wall in front of it and itself by ultrasonic sensors Nos. 3 and 4 directly. But, after turning, it can detect this distance by ultrasonic sensors which are on its left- or right-hand side. If this distance is large, it is not necessary to set the intolerable distance to be this value because it may cause the vehicle to stop frequently. If this distance is too small, the vehicle may not stop even it is too close to an obstacle. Therefore, after obtaining an estimate for this distance by ultrasonic sensors which are on its left or right hand side, a range is used to adjust this estimate. If this estimate is large or smaller than the range, we use a default value to replace this estimate. The detail of this technique is described in Algorithm 4.3 below.

Algorithm 4.3 *Getting the information of the intolerable distance of a path segment.*

Input: A list of learned data of a segment k with starting position P_{start}, the speed S_{navi} of the vehicle for navigation, turning position P_t, and the starting position of the next segment $P_{restart}$ where P_i means the coordinates of the vehicle on recorded node i.

Output: The value of the intolerable distance, *IDIS*.

Steps:

Step 1. If this segment is the final, set the intolerable distance *IDIS* to be the default value and go to Step 4.

Step 2. If the vehicle turns left on the node t and the values of ultrasonic sensors Nos. 7 and 8 of the nodes *restart*+1, *restart*+2, …, and *restart*+n are *almost* the same, where n is a preselected threshold, set the intolerable distance *IDIS* as

$$IDIS = w \times \text{value of ultrasonic No. 7 at node } restart,$$

where w is a preselected threshold.

If the vehicle turns right on the node t and the values of ultrasonic sensors Nos. 0 and 15 of the nodes *restart*+1, *restart*+2, …, and *restart*+n are *almost* the same, set *IDIS* as

$$IDIS = w \times \text{the value of ultrasonic No. 0 of the node } restart.$$

Step 3. If *IDIS* is too large or small than a range, set *IDIS* to be the default value.

Step 4. Take the information of the intolerable distance *IDIS* as output.

In Step 2 in Algorithm 4.3, if the absolute difference between two ultrasonic signals *a* and *b* is smaller than a preselected threshold, then we regard them to be *almost* the same.

4.3.4 Stopping

The vehicle needs to know when to stop at the final segment of the learned path. When the running time is over this value, the vehicle will stop itself. If a segment is not the final of the learned path, this value is estimated as a double of the total running time of this segment. The detail of the technique mentioned previously is described in Algorithm 4.4 below.

Algorithm 4.4 *Getting the information TSTOP of a path segment.*

Input: A list of learned data of a segment *k* with starting position P_{start}, the speed of the vehicle for navigation S_{navi}, turning position P_t, the speed SV_i of the vehicle on position *i*, and the vehicle's running time T_i from position *i* to *i*+1 where P_i means the coordinates of the vehicle on recorded node *i*.

Output: The value of *TSTOP*.

Steps:

Step 1. Compute the total distance of this segment as

$$D = P_t - P_{start} = \sum((SV_i + SV_{i\text{-}1}) / 2) \times T_i$$

where $i = t, t{-}1, \ldots, start$.

Step 2. If this is the final segment, compute $TSTOP = D/S_{\text{navi}}$; else, compute $TSTOP = 2\times(D/S_{\text{navi}})$.

Step 3. Save the information *TSTOP* as output.

4.3.5 Introducing objects or places as a guide

It is easy to know if the vehicle needs to introduce an object as a guide or not at a node. Therefore, this information can be used to estimate when the vehicle needs to introduce objects or places as a guide. The detail is shown in Algorithm 4.5 below.

Algorithm 4.5 *Getting the information TOBJECT of a path segment*.

Input: A list of learned data of a segment k with starting position P_{start}, the speed of the vehicle for navigation S_{navi}, turning position P_t, the speed SV_i of the vehicle on position i, and the vehicle's running time T_i from position i to i+1 where P_i means the coordinates of the vehicle on recorded node i.

Output: The values of the respective items of *TOBJECT*.

Steps:

Step 1. For every node j from the start node *start* to the turning node t, if the record of the node j says that the vehicle needs to introduce an object as a guide on this node, then compute the distances

$$D = P_j - P_{start} = \sum_i((SV_i + SV_{i\text{-}1}) / 2) \times T_i,$$

$i = j, j-1, \ldots, start$; and append an *introduction time period* as D/S_{navi} into the item *OTIME*.

Step 2. Save the information *TOBJECT* as output.

4.4 Algorithm of Proposed Method for Path Analysis

In this section, an integral algorithm of the proposed procedure of path analysis is described. As mentioned previously, a learned path is separated into segments by the turning nodes. Each segment is given a record with five kinds of information by path analysis in this study. The path data for navigation is a collection of these records. The integral algorithm of the proposed method for path analysis is shown in Algorithm 4.6.

Algorithm 4.6 *Path analysis*.

Input: A learned path data with n turning nodes.

Output: A path data for navigation in the form of an array R with n elements with each element being a record including the five kinds of information as mentioned in Section 4.2.

Steps:

Step 1. Separate the learned path data into n segments by the turning nodes, where n is the number of turning nodes.

Step 2. For every segment k from the start segment 1 to the final segment n, use the data of segment k as the inputs and perform Algorithms 4.1, 4.2, 4.3, 4.4, 4.5, and combine their output information into an array R.

Step 3. Save the information of R as output.

Chapter 5
ALV Navigation by Ultrasonic Signal Sequence and Fuzzy Logic Control

5.1 Introduction

After the vehicle finishes the learning work and obtains the path data for navigation by path analysis, it will utilize them to act as a guide. In this chapter, we introduce the details of the proposed navigation procedure. In Section 5.2, we describe how to use fuzzy logic control techniques in the proposed method. Furthermore, we also describe how to combine the path data for navigation with the proposed fuzzy controller.

In Section 5.3, we describe how to use the path data for navigation to detect whether the vehicle arrives at a turning node or not. The path data for navigation includes five kinds of information and these five kinds are described in Section 4.2. We also describe how to use other kinds of information during navigation in this section. These kinds of information include intolerable distances between the vehicle and obstacles in front of the vehicle, when to introduce objects or places as a guide, and when to stop.

Finally, we summarize the above-mentioned techniques and describe an algorithm of the proposed navigation procedure in Section 5.4. An illustration of the navigation procedure is shown in Figure 5.1.

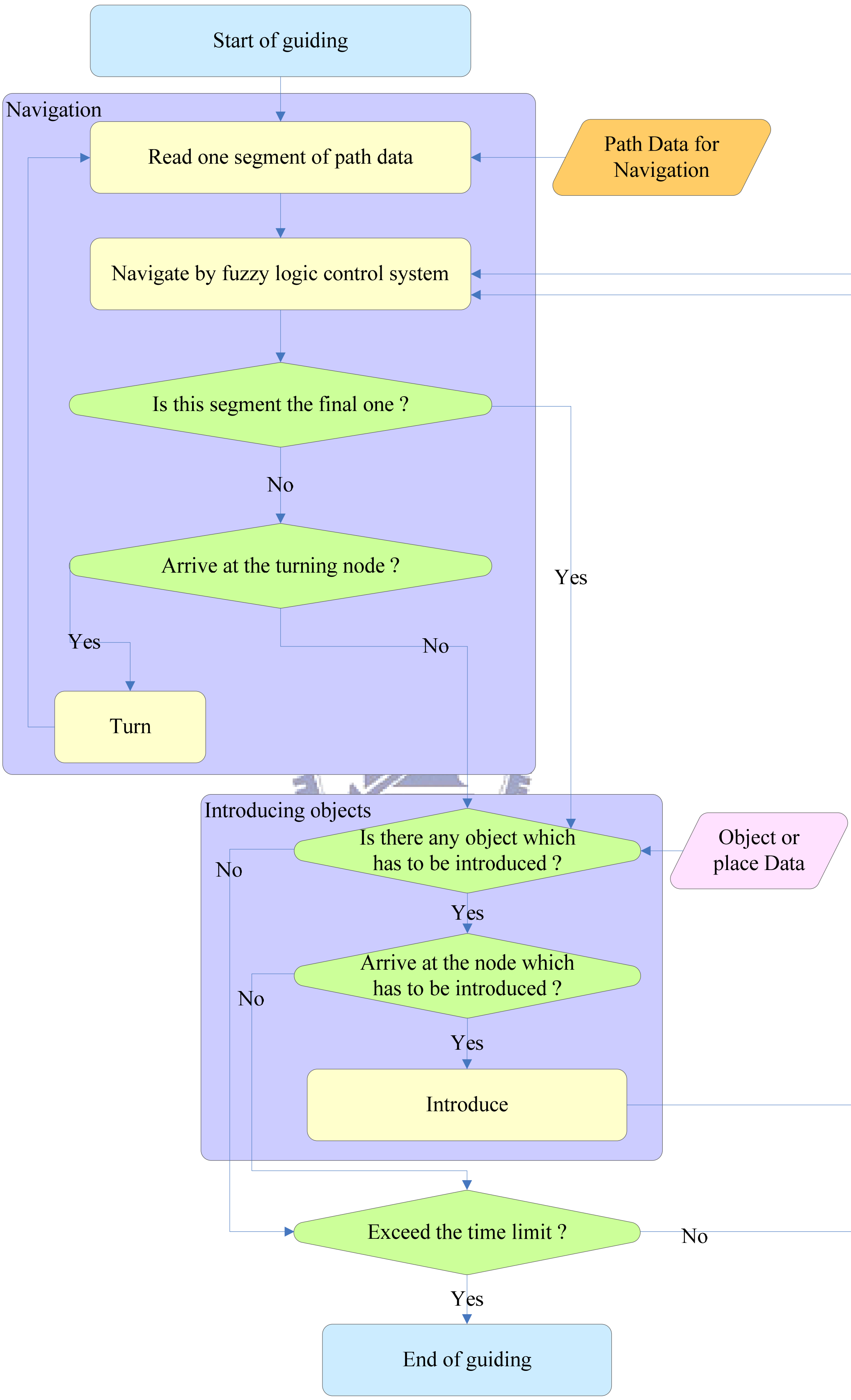


Figure 5.1 Illustration of proposed navigation procedure.

5.2 Proposed Fuzzy Logic Control Techniques for Navigation

5.2.1 Proposed method for controlling vehicle direction

When the vehicle navigates on an environment like a corridor, etc, we desire that it can go straight and does not hit walls. However, the vehicle may go on a curve path because of incremental mechanic errors. Therefore, it needs to correct its direction by some other information during navigation. The environmental feature used to correct the vehicle's direction is walls. If an environment includes both walls on its left- and right-hand sides, we desire that the vehicle can navigate in the middle of the walls in the environment.

However, the vehicle may go across some environments like an entrance hall, etc. These environments may not include walls continuously. For example, an elevator, an opened door, a sofa, a potted flower, etc, may be in these environments. The vehicle can detect some information of walls in such environments, but the information is not very much. In this situation, if the information is enough to some degree, we desire that the vehicle can also navigate almost in the middle of them in the environments. These are the main ideas to design the fuzzy controller for use in this study.

If the vehicle cannot detect any information of walls in an environment or if an environment includes too many objects so that the vehicle cannot detect any useful information of walls in the environment, these situations are out of our assumptions in this study.

In the proposed fuzzy controller for controlling the vehicle's direction, some situations are handled. The first is that if the vehicle is on or close to the left- or the right-hand side of an environment, then it has to conduct fine tuning. In this situation, wall distances in environments are very important. As mentioned previously, if the environment includes walls both on its left- and right-hand sides, we desire that the vehicle can navigate in the middle of the walls in the environment. Therefore, the vehicle needs the information of the wall distances in the environment to decide whether it is in the middle of the walls in the environment or not. However, if the environment includes only a wall on its left- or right-hand side, the vehicle has to keep the same distance as it learned from the wall. Therefore, the information of wall distances obtained from path analysis is used to denote the membership functions of the designed fuzzy controller.

The second is that if a deviation from the vehicle's direction is large, then it should not turn to the same direction again, because it may hit walls or objects and cannot conduct fine tuning by ultrasonic sensors. In order to deal with this situation, the system uses two kinds of features, which are distances obtained from ultrasonic sensors and an accumulated angle from the system's commands issued so far. Distances obtained from ultrasonic sensors can used to estimate the relative directions between walls and the vehicle. However, they are not always credible. For example, if the vehicle goes across an edge of a door, the estimated relative direction between the wall and the vehicle may be very large because of the depth of the door. In this situation, the vehicle should keep going straight and not turn. Therefore, a variable is used to record whether the estimated relative direction is credible or not.

Furthermore, if the vehicle is in a wide environment, it may turn to the same direction many times so that the estimated relative direction is not correct. The accumulated angle from the system's commands is another feature to deal with such a situation. However, the accumulated angle may not always be correct because the vehicle has mechanical errors. Therefore, a method is proposed to correct the accumulated angle. The idea of this method is that if the vehicle finds out that it is almost parallel to the walls, then it resets the accumulated angle to be zero.

5.2.2 Proposed fuzzy controller

According to the just-mentioned idea, the input variables for the proposed fuzzy controller are D_L, D_R, and *DIR*. D_L and D_R are represent as the distances between the vehicle and the respective walls of the left- and right-hand sides of the vehicle. The values of D_L and D_R are measured from ultrasonic sensors Nos. 0 and 7.

Five fuzzy terms are denoted for each of the input variables, D_L and D_R. They are nearer (NE), near (N), middle (MI), far (F), and farther (FE). The membership functions of these fuzzy terms are illustrated in Figure 5.2.

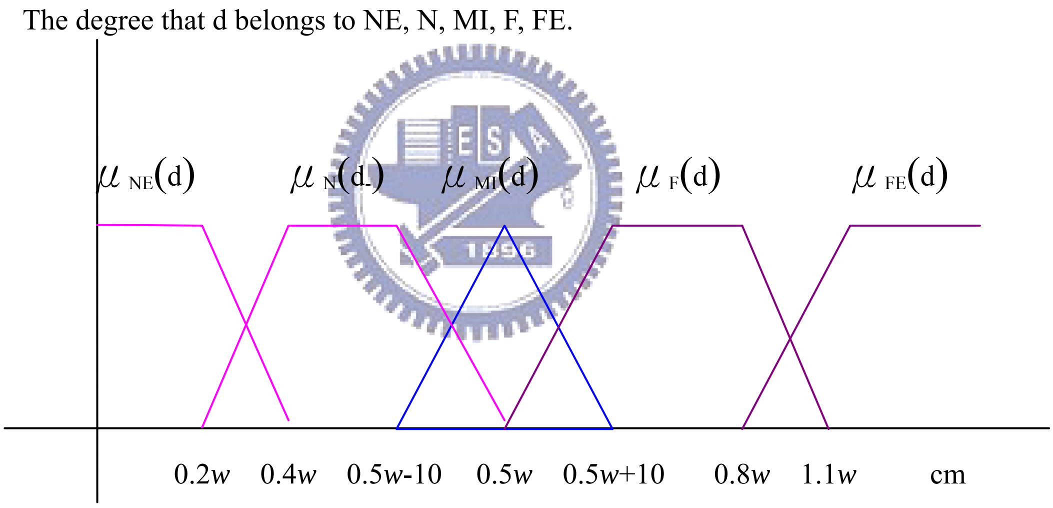


Figure 5.2 The membership functions of the five fuzzy terms, NE, N, MI, F, and FE, where *d* is the distance obtained by ultrasonic sensor No. 0 or 7, and *w* is the distance between walls.

DIR represents the deviation from the vehicle's direction. The value of *DIR* is obtained from combining with the detected values of ultrasonic sensors Nos. 0, 7, 8, 15, and an accumulated angle from the system's commands issued before. Six fuzzy terms are denoted for the input variable, *DIR*. They are very left (*VL*), left (*LE*), parallel (*PA*), right (*RI*), very right (*VR*), and unbelieving (*UB*).

Each of the fuzzy terms of the input variable *DIR* is obtained from operating several fuzzy sets. These fuzzy sets can be separated into three groups. The first is the estimated angle from ultrasonic signals on the left-hand side of the vehicle. The second is the estimated angle from ultrasonic signals on the right-hand side of the vehicle. The third is the accumulated angle from the system.

Using distances obtained from two parallel ultrasonic sensors can compute an estimated relative angle between the vehicle and a wall on its left- or right-hand side. Assume that the distance between ultrasonic sensors Nos. 0 and 15 is *DUS*, which is the same as the distance between ultrasonic sensors Nos. 7 and 8. An illustration of *DUS* is shown in Figure 5.3. According to *DUS* and the distances detected by ultrasonic sensors Nos. 0 and 15, the system can compute the deviation from the vehicle's direction. Similarly, according to *DUS* and the distances detected by ultrasonic sensors Nos. 7 and 8, the system can obtain another value of the deviation. The former is represented as θ_L and the latter is represented as θ_R. They are obtained as follows:

$$\tan \theta_L = (V_{0,i} - V_{15,i}) / DUS;$$

$$\tan \theta_R = (V_{8,i} - V_{7,i}) / DUS, \tag{5.1}$$

where $V_{m,i}$ is the value detected from ultrasonic sensor No. *m* on position *i*. A minus value of θ_L or θ_R means that the direction of the vehicle is left. In order to avoid computing "/ *DUS*" repeatedly, two variables, VE_L and VE_R, are denoted as follows:

$$VE_L = (V_{0,i} - V_{15,i}) = \tan \theta_L \times DUS;$$

$$VE_R = (V_{8,i} - V_{7,i}) = \tan \theta_R \times DUS. \tag{5.2}$$

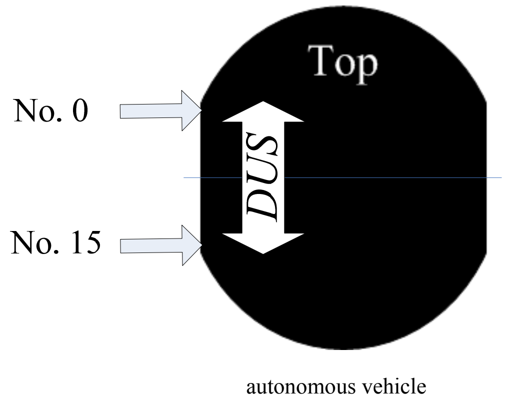


Figure 5.3 An illustration of *DUS*, the distance between ultrasonic sensors Nos. 0 and 15.

Five fuzzy sets are used to decide whether the estimated relative angle, VE_L or VE_R, is very left (*D1*), left (*D2*), straight (*D3*), right (*D4*), or very right (*D5*). The membership functions of these five fuzzy sets are shown in Figure 5.4. However, as mentioned previously, if the vehicle goes across an edge of a door, the estimated relative angle between the wall and the vehicle may be very large because of the depth of the door. In other words, if an environment changes suddenly, the vehicle may not obtain a correct estimated relative angle between the wall and itself. Therefore, two more fuzzy sets, CR_L and CR_R, are used for deciding whether the estimated relative angle from ultrasonic signals on the left- or right-hand side of the vehicle is credible or not respectively.

The just-mentioned two fuzzy sets are both obtained from five fuzzy sets respectively. The main idea for designing these five fuzzy sets can be categorized into three situations. The first is whether the distance detected from ultrasonic sensors Nos. 0, 7, 8, or 15 is too large or not. If the answer is yes, then the estimated relative angle is not credible, because the vehicle cannot detect any wall. The second is comparing the values of the ultrasonic signals on the current node with the values on the last node. If the differences between these two kinds of values are not small, then the estimated relative angle is not credible, because the environment may change suddenly. The third is comparing the values from two parallel ultrasonic sensors on the current node. If the differences between the values from the two parallel ultrasonic sensors are not small, then the estimated relative angle is not credible, because the environment may change suddenly, too. Two fuzzy sets are used to deal with the above-mentioned three kinds of situations and their membership functions are shown in Figure 5.5. The membership function in Figure 5.5(a) is for the second and third situations, and the membership function in Figure 5.5(b) is for the first situation.

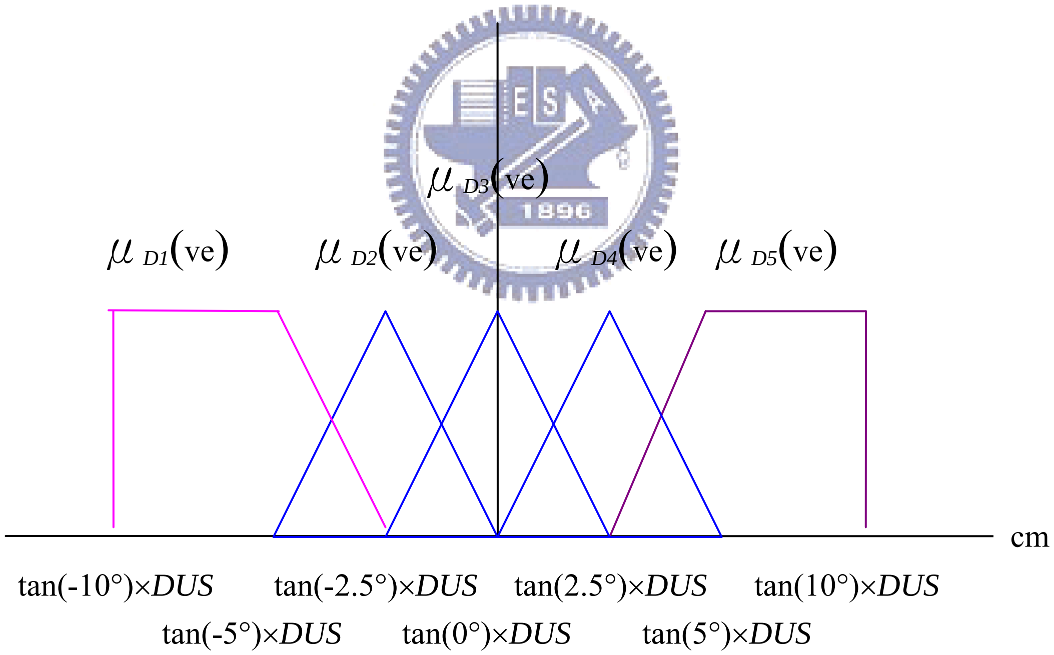
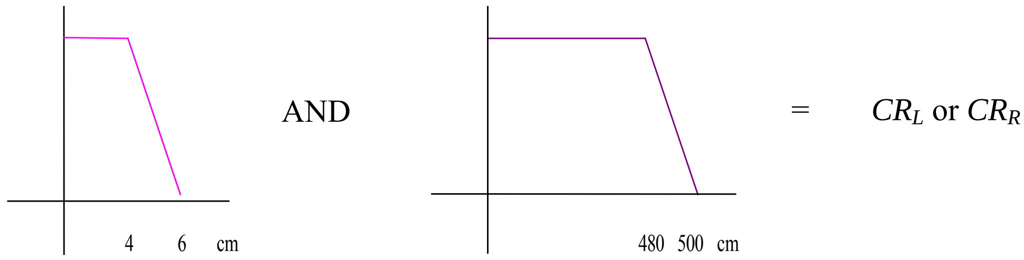


Figure 5.4 Membership functions of the estimated relative angle, VE_L or VE_R, and represented as very left (*D1*), left (*D2*), straight (*D3*), right (*D4*), or very right (*D5*).



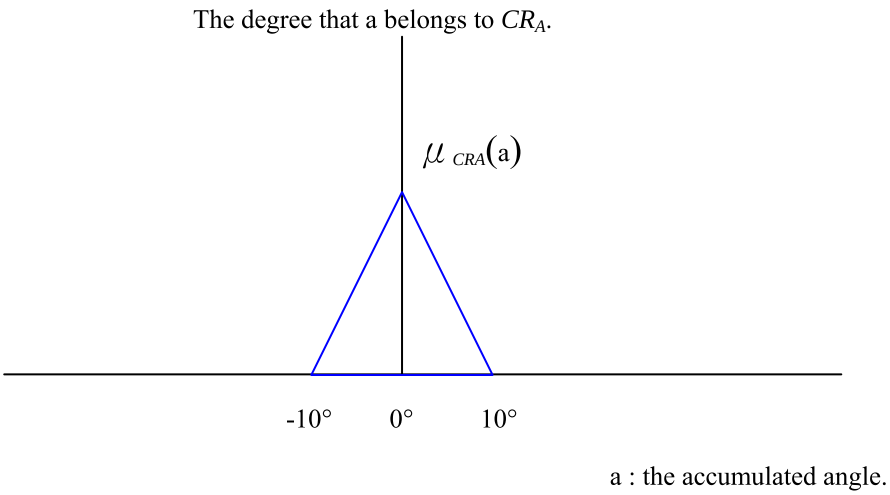
(a) (b)

Figure 5.5 Membership functions of credibility CR_L and CR_R.

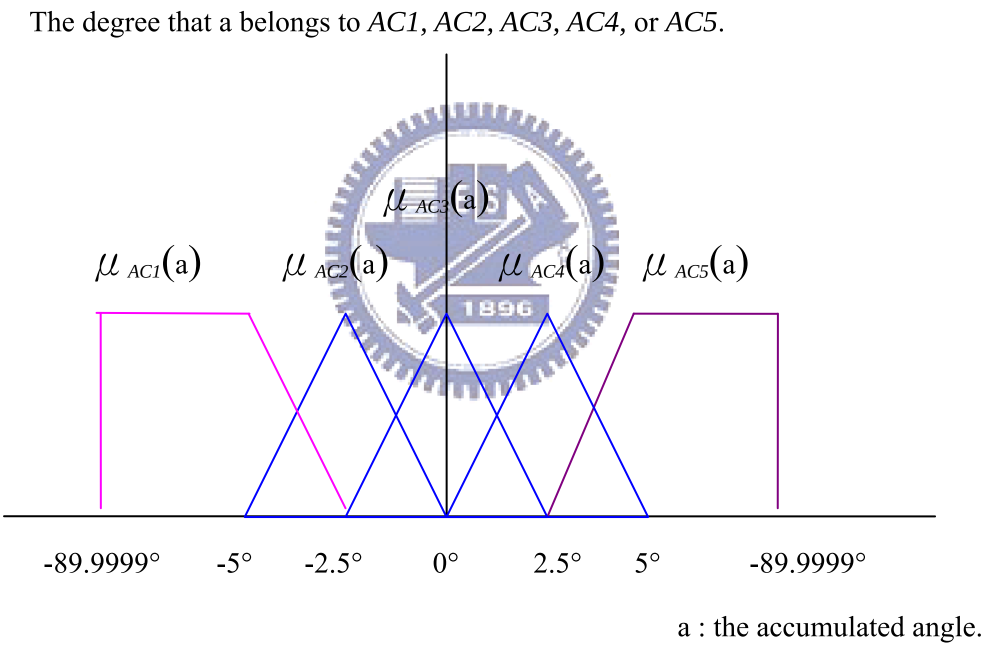
In addition, as mentioned previously, if the vehicle is in a wide environment, it may turn to the same direction many times so that the estimated relative direction is not correct. The accumulated angle from the system's commands is another feature to deal with such a situation. Five fuzzy sets are used to decide whether the accumulated angle is very left *(AC1)*, left *(AC2)*, straight *(AC3)*, right *(AC4)*, or very right *(AC5)*. The membership functions of these five fuzzy sets are shown in Figure 5.6(a). However, the accumulated angle may not always be correct because the vehicle has mechanical errors. Therefore, a fuzzy set CR_A is used to decide whether the accumulated angle is credible or not. The membership function of CR_A is shown in Figure 5.6(b).

VL (very left) is one fuzzy term of the input variable *DIR* (the deviation from the vehicle's direction). The main steps which are used to obtain the degree of an input value which belongs to *VL* from the above-mentioned fuzzy sets and the idea are shown in Algorithm 5.1. The other fuzzy terms of *DIR* are denoted in a similar way except the fuzzy term *UB* (unbelieving).

The main idea in defining the fuzzy term *UB* is that if an input value satisfies the constraint that the estimated relative angle is not credible and the accumulated angle is not credible, then the degree of this input value belongs to *UB* is large.



(a) The membership function of CR_A.



(b) The membership functions of the fuzzy sets, *AC1, AC2, AC3, AC4,* and *AC5*.

Figure 5.6 The membership functions of the just-mentioned fuzzy sets.

In Algorithm 5.1, *FL*, *FR*, and *FA* are three fuzzy sets preselected to decide three situations: whether the estimated relative angle from ultrasonic sensors Nos. 0 and 15 is very left or not, whether the estimated relative angle from ultrasonic sensors Nos. 7 and 8 is very left or not, and whether the accumulated angle from the system's commands before is very left or not. CR_L, CR_R, and CR_A are three fuzzy sets preselected to decide whether the above-mentioned three kinds of detected values are credible or not, respectively.

Algorithm 5.1 *Obtaining a degree of an input value which belongs to VL (very left).*

Input: the value of the input variable *DIR* (the deviation from the vehicle's direction), which includes the detected values of ultrasonic sensors Nos. 0, 7, 8, 15, and the accumulated angle from the system's commands issued before; the just-mentioned three fuzzy sets, *FL*, *FR*, and *FA*, preselected for decide whether the estimated relative angles or the accumulated angle is very left or not; the three fuzzy sets, CR_L, CR_R, and CR_A, preselected to decide whether the above-mentioned three kinds of detected values are credible or not, respectively.

Output: The degree of the input value belonging to *VL*.

Step 1. Decide whether the ultrasonic signals from ultrasonic sensors Nos. 0 and 15 are credible or not by using the fuzzy set CR_L.

Step 2. Decide whether the ultrasonic signals from ultrasonic sensors Nos. 7 and 8 are credible or not by using the fuzzy set CR_R.

Step 3. Combine the above-mentioned six fuzzy sets to be the fuzzy set *VL* according to one of the following rules.

3.1 If the ultrasonic signals on the left-hand side of the vehicle are credible, set *VL* as $VL = CR_L \cdot FL + CR_A \cdot FA$.

3.2 If the ultrasonic signals on the right-hand side of the vehicle are credible, set *VL* as $VL = CR_R \cdot FR + CR_A \cdot FA$.

3.3 If the ultrasonic signals on both sides of the vehicle are credible, set *VL* as $VL = (CR_R \cdot FR + CR_L \cdot FL) + CR_A \cdot FA$.

3.4 If the ultrasonic signals on both sides of the vehicle are credible, set *VL* as $VL = CR_A \cdot FA$.

Step 4. Use the input value of the input variable *DIR* into *VL* and output the degree of the input value which belongs to *VL*.

In Algorithm 5.1, the operator " + " is the operator of the *algebraic sum* operation on fuzzy sets, and the operator " · " is the operator of the *algebraic product* operation on fuzzy sets.

The output linguistic variable is denoted as *ANGLE*, which represents the angle and direction used to adjust the vehicle's direction. Eight fuzzy terms are denoted for the controlled linguistic variable. The first seven fuzzy terms are from negative large to positive large. The negative large means that the vehicle turns a large angle to the left. Similarly, the positive large means that the vehicle turns a large angle to the right. The membership functions of the seven fuzzy terms of the linguistic variable *ANGLE* are illustrated in Figure 5.7. The last fuzzy term means that the vehicle should stop.

A total of 150 fuzzy rules are represented as a fuzzy rule matrix which is shown in Table 5.1, and the fuzzy terms of the output variable *ANGLE* is represented as eight numbers which are described in Table 5.2. The form of each fuzzy rule is:

$$R^i: \text{IF } D_L \text{ is } A_k, D_R \text{ is } B_k, \text{ AND } DIR \text{ is } C_k, \text{ THEN } ANGLE \text{ is } F_j. \quad (5.3)$$

where A_k and B_k represent the linguistic values of the five fuzzy terms *NE*, *N*, *MI*, *F*, *FE*, respectively; C_k represent the linguistic values of the six fuzzy terms *VL*, *LE*, *PA*, *RI*, *VR*, and *UB*; and F_j represents the linguistic values of the eight fuzzy terms of the output variable.

Finally, the method used to defuzzify the fuzzy output is the discrete fuzzy centroid defuzzification.

5.3 Vehicle Turning Technique

A learned path is segmented into several pieces by the turning nodes before being analyzed, and each segment is given a record, which includes the five kinds of information, as mentioned in Section 4.2. In other words, if the learned path includes *n* turning nodes, and then the path data for navigation includes *n*+1 records. Furthermore, each record includes five kinds of information. These five kinds of information are listed again in Table 5.3.

The degree that θ belongs to the fuzzy terms

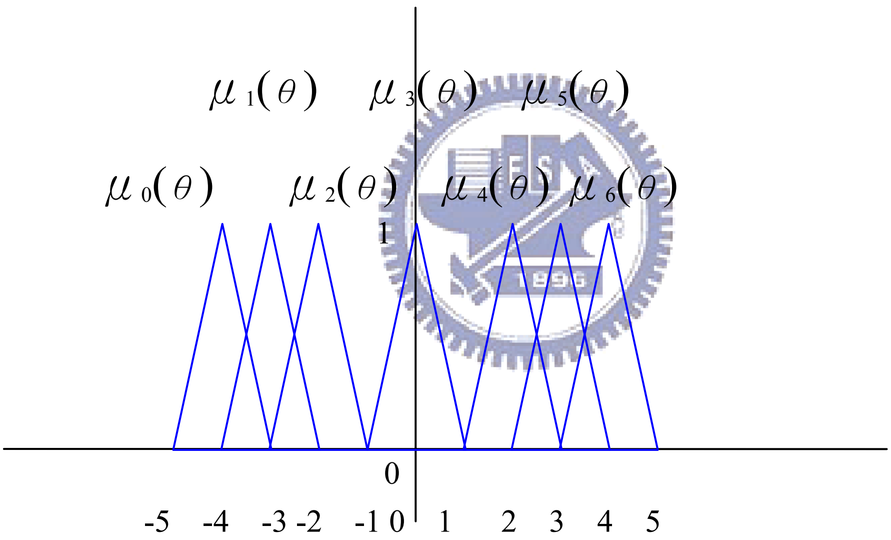


Figure 5.7 The membership functions of the seven fuzzy terms of the output linguistic variable *ANGLE* where θ is the angle which the vehicle needs to turn.

The vehicle can know when to turn by using the information *TTURN* of the path data for navigation. Therefore, if the system's running time is less than *BEFORE*, the vehicle uses the designed fuzzy controller to adjust its direction. If the system's running time is over *BEFORE*, the vehicle detects whether walls on its left- or right-hand side or not by ultrasonic sensors. If the vehicle cannot detect any wall on the side as recorded in *TDIRECT* for a period of time continuously and this period of time is over *NDETECT*, then it turns to the direction as *TDIRECT* and read the information of the next segment. The detail of the turning technique is described in Algorithm 5.2.

Table 5.1 *The fuzzy rule matrix for controlling the vehicle direction.*

D_L	DIR \ D_R		NE		N		MI		F		FE	
NE	*VL*	*RI*	7	7	5	3	5	4	6	4	6	4
	LE	*VR*	7	7	5	2	5	2	6	2	6	2
	PA	*UB*	7	7	4	3	4	4	5	4	5	4
N	*VL*	*RI*	4	1	5	2	5	3	6	4	6	4
	LE	*VR*	3	1	4	1	4	2	5	1	5	1
	PA	*UB*	2	3	3	3	4	3	4	4	5	4
MI	*VL*	*RI*	4	1	4	2	5	2	5	2	5	2
	LE	*VR*	2	1	3	1	4	1	4	1	4	1
	PA	*UB*	2	2	2	3	3	3	4	4	3	4
F	*VL*	*RI*	4	0	4	1	5	2	5	2	5	2
	LE	*VR*	2	0	2	0	4	1	4	1	4	1
	PA	*UB*	1	2	2	2	2	2	3	3	3	2
FE	*VL*	*RI*	4	0	4	1	5	2	5	2	5	2
	LE	*VR*	2	0	2	0	4	1	4	1	4	1
	PA	*UB*	1	2	1	2	3	2	3	4	3	3

In addition, if the vehicle detects any obstacle to be in front of it by ultrasonic sensors and the information *IDIS*, then it stops for a period of time for the obstacle, which may be a person or a moving object in this case, to move away. Afterward, the vehicle restarts to navigate.

Table 5.2 *The fuzzy terms of the output variable ANGLE*.

<table>
<tr><td colspan="8">ANGLE</td></tr>
<tr><td colspan="7">Left-hand rotation---------------------- straight --------------------- Right-hand rotation
Large angle of rotation ------------------zero-------------------- Large angle of rotation</td><td>Stop</td></tr>
<tr><td>0</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td></tr>
</table>

Table 5.3 *All kinds of the information of the path data for navigation*.

Type	Items (if exist)	Meaning
TTURN	*TDIRECT*	This is the turning direction obtained from the learned path data directly.
	NDETECT	This is a period of time from arriving at a turning corner to arriving at the turning node.
	BEFORE	The period of time before which the vehicle cannot turn.
WDIS	*WNUM*	The number of the wall distances.
	WVALUE	This records each value of the wall distances.
	WTIME	This records when to use the respective wall distances of *WVALUE*.
IDIS	(no item)	This is the intolerable distance between the vehicle and obstacles in front of the vehicle.
TSTOP	(no item)	This is when to stop.
TOBJECT	*ONUM*	The number of objects which the vehicle needs to introduce.
	OTIME	This records when to introduce the objects, respectively.

Algorithm 5.2 *Deciding whether to turn or not on a node by the information TTURN of a segment.*

Input: A node *I* with a list of the data for navigation of a path segment *k* with the information *TTURN*; *RT* which represents the running time of the system from the starting node of this segment to the current one; *RN* which represents the period of time that the vehicle cannot detect any wall on the side as recorded in *TDIRECT*.

Output: One of the two messages, *turning* and *not turning*.

Steps:

Step 1. If the system's running time *RT* is less than *BEFORE*, which is the recorded running time before the turning corner, then output the message, *not turning*, and finish this algorithm.

Step 2. If the vehicle cannot detect any wall on the side as recorded in *TDIRECT*, compute *RN* = *RN* + the running time from the last node to this node; else, reset *RN* = 0.

Step 3. If the period of time *RN* is large than *NDETECT*, which is the running time from the turning corner to the turning node, then output the message, *turning*; else, output the message, *not turning*.

If the running time of the system arrives at the time recorded by *OTIME*, the vehicle broadcasts the introduction of the objects recorded by *ONUM*, respectively.

If the running time of the system is over *TSTOP*, then the vehicle finishes the navigation procedure.

5.4 Algorithm of Proposed Method for ALV Navigation

In this section, an integral algorithm of the proposed navigation procedure is described. The proposed navigation procedure includes two major tasks, navigating on the learned path and introducing the learned objects as a guide in the mean time. At first, the vehicle navigates on the learned path. In this situation, the vehicle uses the path data for navigation and the proposed fuzzy controller to adjust its direction. It also decides whether it arrives at a turning node or not in the mean time. If it arrives, then it turns to the recorded direction. If any moving obstacle goes across the front of it during navigation, it will stop to wait the moving obstacle leaving. If it arrives at a position where it has to introduce an object as a guide, it broadcasts the recorded introduction to the object. The integral algorithm of the proposed method for navigation is shown in Algorithm 5.3.

In Algorithm 5.3, the system will record information *NAVI*, which includes the detected values of ultrasonic sensors, the vehicle's coordinates of each node, the system's running time, etc. The information can be used to draw a map of the path where the vehicle navigated on.

Algorithm 5.3 *Navigation on a learned path*.

Input: Path data for navigation, which is analyzed from a learned path data by the method described in Algorithm 4.6 and is composed of *n* segments with each segment with index *k* including a starting node $start_k$, a turning node *t*, and the information *TTURN*, respectively; *RT* which represents the running time of the system from the starting node $start_k$ to the current node; *RN* which represents the period of time that the vehicle cannot detect any wall on the side as recorded in *TDIRECT*.

Output: A record of the above-mentioned information *NAVI* of the vehicle during navigation.

Steps:

Step 1. For every segment indexed by *k* from 1 to the final segment *n*, do the following steps.

1.1. Reset the running time of the system *RT* = 0 and *RN* = 0.

1.2. For the starting node of this segment through the turning node of this segment, do the following steps.

1.2.1. If the distance of an obstacle detected from ultrasonic sensors Nos. 3 or 4 is smaller than the intolerable distance *IDIS*, then stop and do Step 1.2.2; else, do Step 1.2.3.

1.2.2. If the obstacle moves and is not in front of the vehicle after a preselected period of time, then restart to navigate, deduct this period of time from the running time *RT*, and go to Step 1.2; else, go to Step 2.

1.2.3. Decide whether to turn or not on this node by Algorithm 5.2 and obtain a message *M* from Algorithm 5.2.

1.2.4. If *M* is *not turning*, then adjust the vehicle's direction by the fuzzy controller described in Section 5.2; else, turn to the direction as *TDIRECT*, which is the item of the turning information of the record, and go to Step 1.

1.2.5. If the vehicle has to introduce any object as a guide in this segment and the running time *RT* arrives at the time recorded by *OTIME*, then broadcast the introduction to the object.

1.2.6. If this segment is the final one and the running time *RT* is over *TSTOP*, then go to Step 2.

Step 2. Stop and save all information *NAVI*.

Chapter 6
Experiment Results and Discussions

6.1 Experimental Results

In this section, we will show some experimental results of applying the proposed person following, learning, navigation techniques of the proposed autonomous vehicle system in indoor environments. We perform experiments for this study at the hallway out of the Computer Vision Laboratory and the entrance hall at the Department of Computer Science in Engineering 3 Building in National Chiao Tung University.

The user interface of the person following and learning system is shown in Figure 6.1.

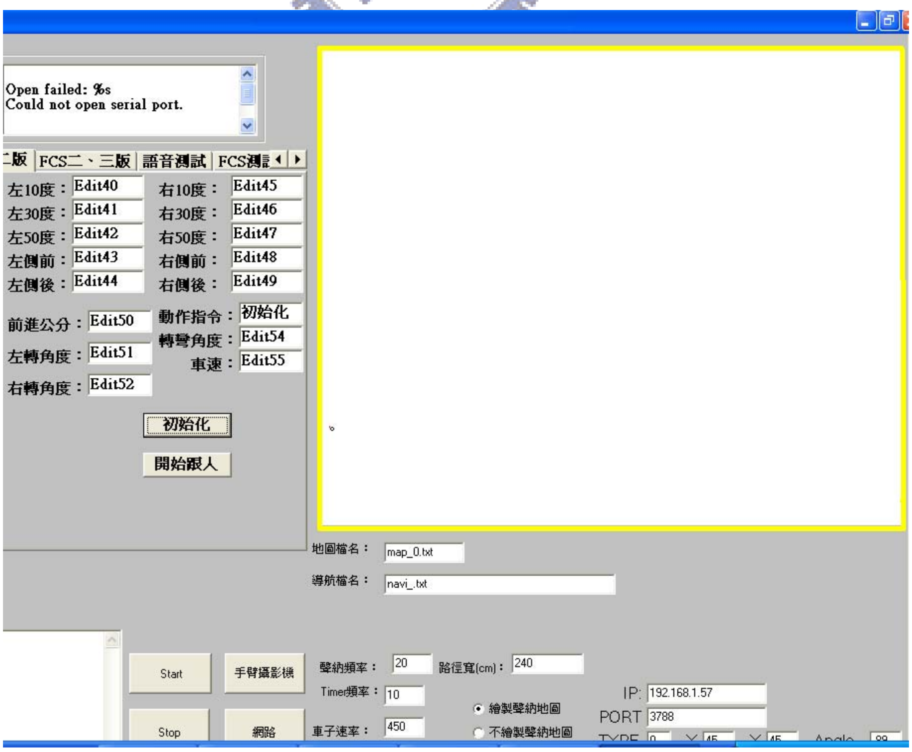


Figure 6.1 An interface of the experiment with yellow box shows a draft of environment map.

The proposed system has five major tasks: detection, following, learning, stopping, and turning. After a user presses the start button, the system will start to detect any person's leg by ultrasonic sensors, as shown in Figure 6.2.

(a)

(b)

Figure 6.2 An experiment result of detecting a person. (a) The person stands in front of the vehicle. (b) The vehicle detects the person and starts to follow the person.

Then the vehicle utilizes the distance between the person and itself to follow the person and learns the path data in the mean time, as shown in Figure 6.3.

(a) (b)

(c)

Figure 6.3 An experiment result of following a person. (a) The vehicle follows the person. (b) The vehicle's direction is with some deviation and it detects the person. (c) The vehicle adjusts its direction to keep following the person.

If the person stops, then the vehicle stops, too, as shown in Figure 6.4. Then it analyzes the person's behaviors and obtains the person's commands. If the command is *turning*, then it turns left or right accordingly, as shown in Figure 6.5.

(a)

(b)

Figure 6.4 An experiment result of stopping. (a) The vehicle follows the person. (b) If the person stops, then the vehicle stops, too.

Furthermore, if the command is *learning an object*, then it learns the position of an object. If the command is *nothing*, then it restarts to follow the person and does not do any other thing.

(a) (b)

(c)

Figure 6.5 An experiment result of turning. (a) The vehicle analyzes the person's command. (b) The vehicle turns according to the person's command *turning*. (c) The vehicle restarts to follow the person.

Finally, if the command is *finish*, then it finishes the process of learning and following the person. After the learning process, the vehicle will collect the learned path data, as shown in Figure 6.6, and save these data into a text file. An illustration of the experimental process is shown in Figure 6.7.

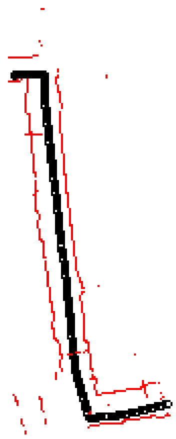


Figure 6.6 An experiment result of a learned path. The black circles are spots specified by the coordinates obtained from the odometer and the red lines are the distances obtained from ultrasonic sensors.

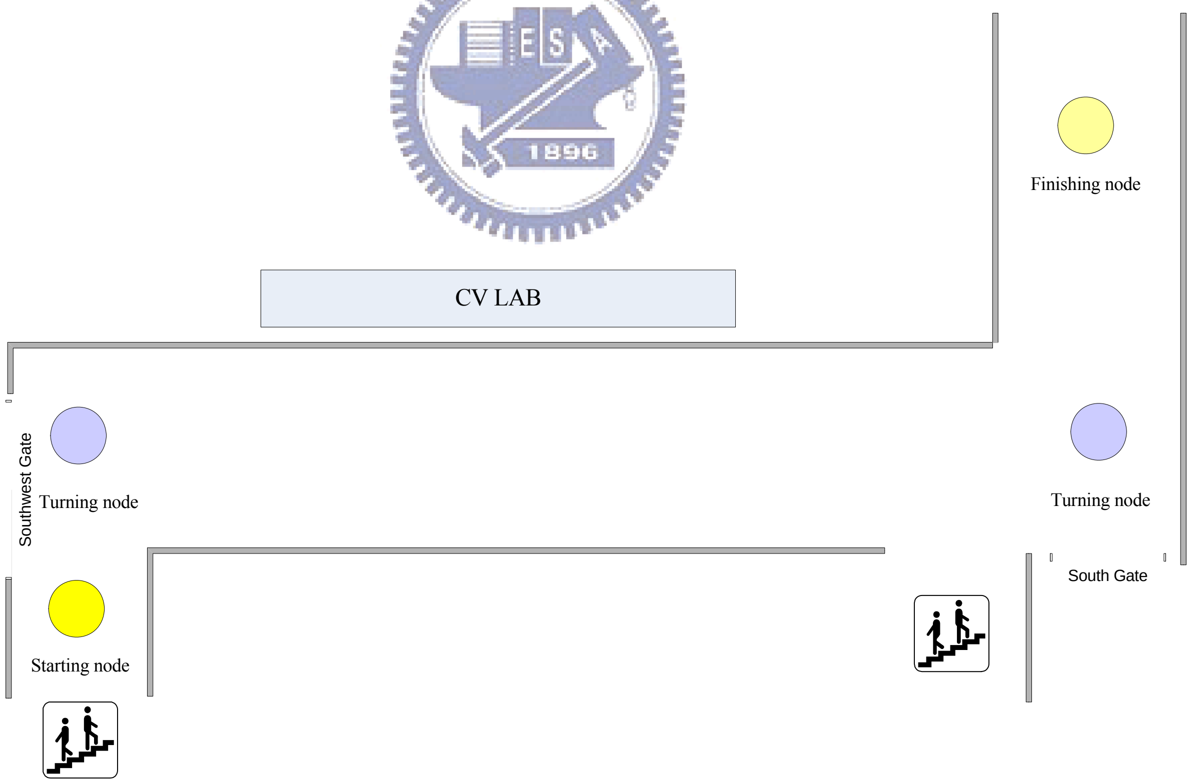


Figure 6.7 An illustration of the path of following a person in an experiment.

The user interface of the path analysis system is shown in Figure 6.8. A file of learned path data is taken as the input to the system. After loading the input file, the system will analyze the learned path data and output a file with the path data for navigation. The just-mentioned files are text files.

Figure 6.8 An interface of the experiment.

When the vehicle arrives at a node which includes any object it needs to introduce, then it broadcasts the introduction to the object as a guide. If it goes across an entrance hall, it should keep its direction straight and not hit walls. Note that the just-mentioned entrance hall needs to include some useful information of walls. The useful information of walls means that the vehicle can detect somewhere the distances between the walls and itself by the ultrasonic sensors. If an environment includes no useful information of walls, this situation is out of our assumption in this study.

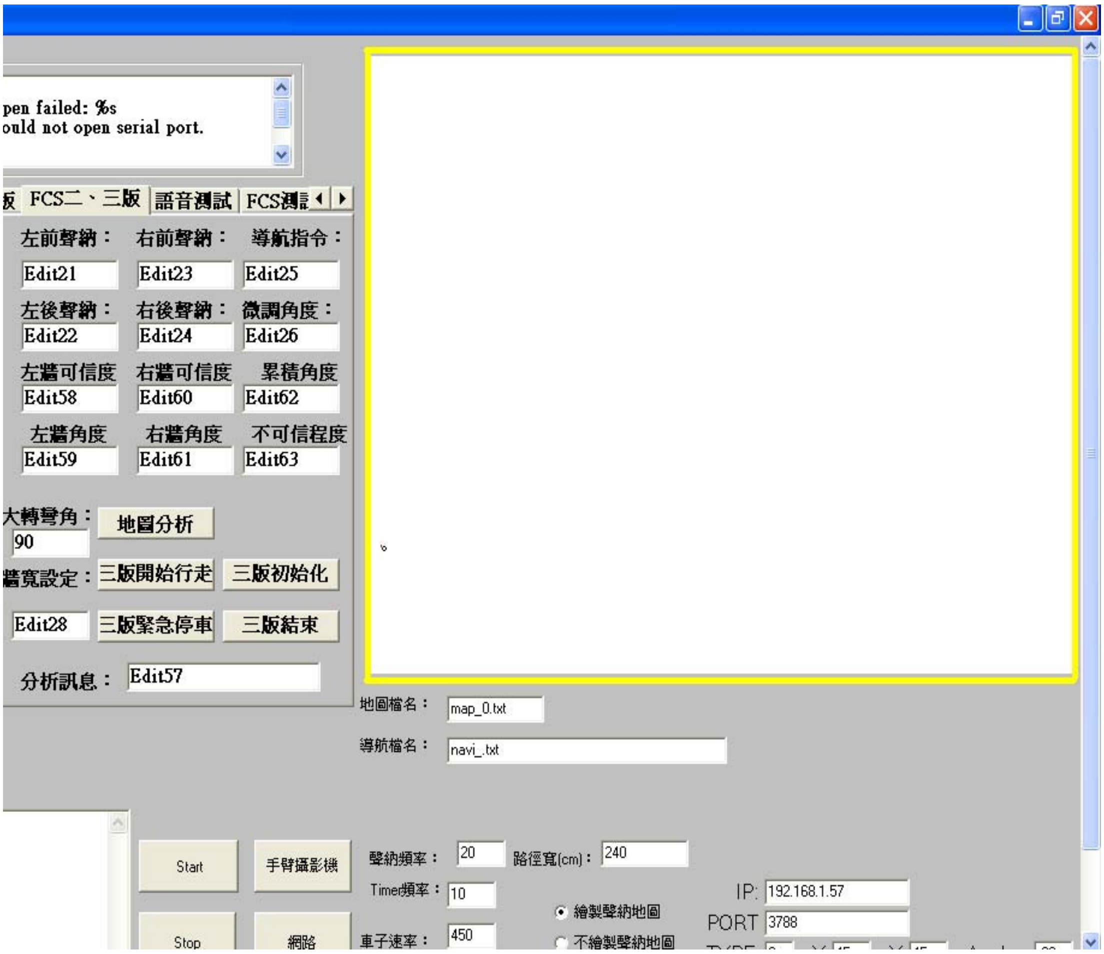


Figure 6.9 An interface of the experiment with yellow box showing a draft of environment map.

An illustration of the experimental process is shown in Figure 6.10. Some experimental results of the proposed navigation system on the path as shown in Figure 6.10 are shown in Figure 6.11. The recorded path data obtained from the odometer and ultrasonic sensors during navigation is shown Figure 6.12.

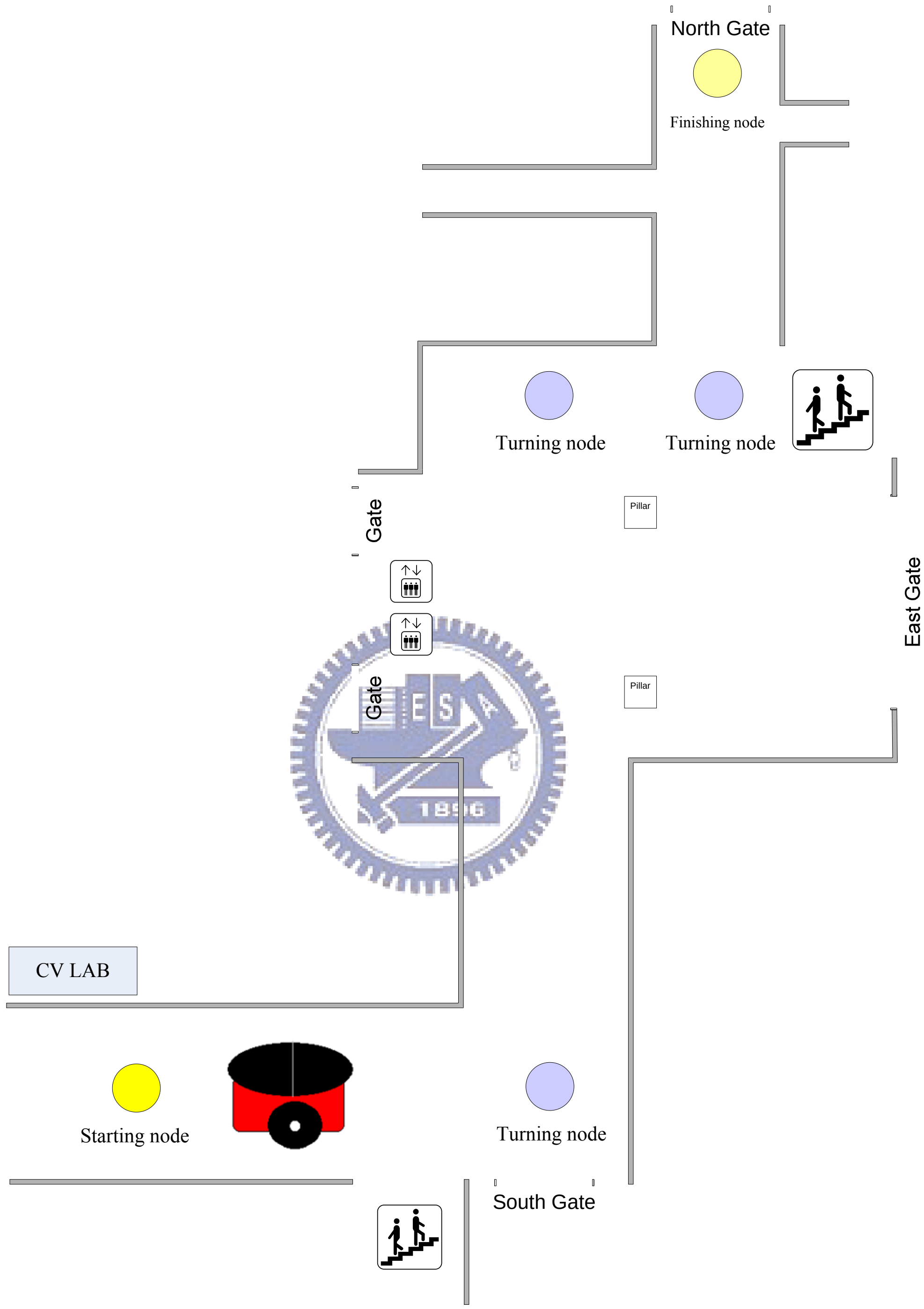
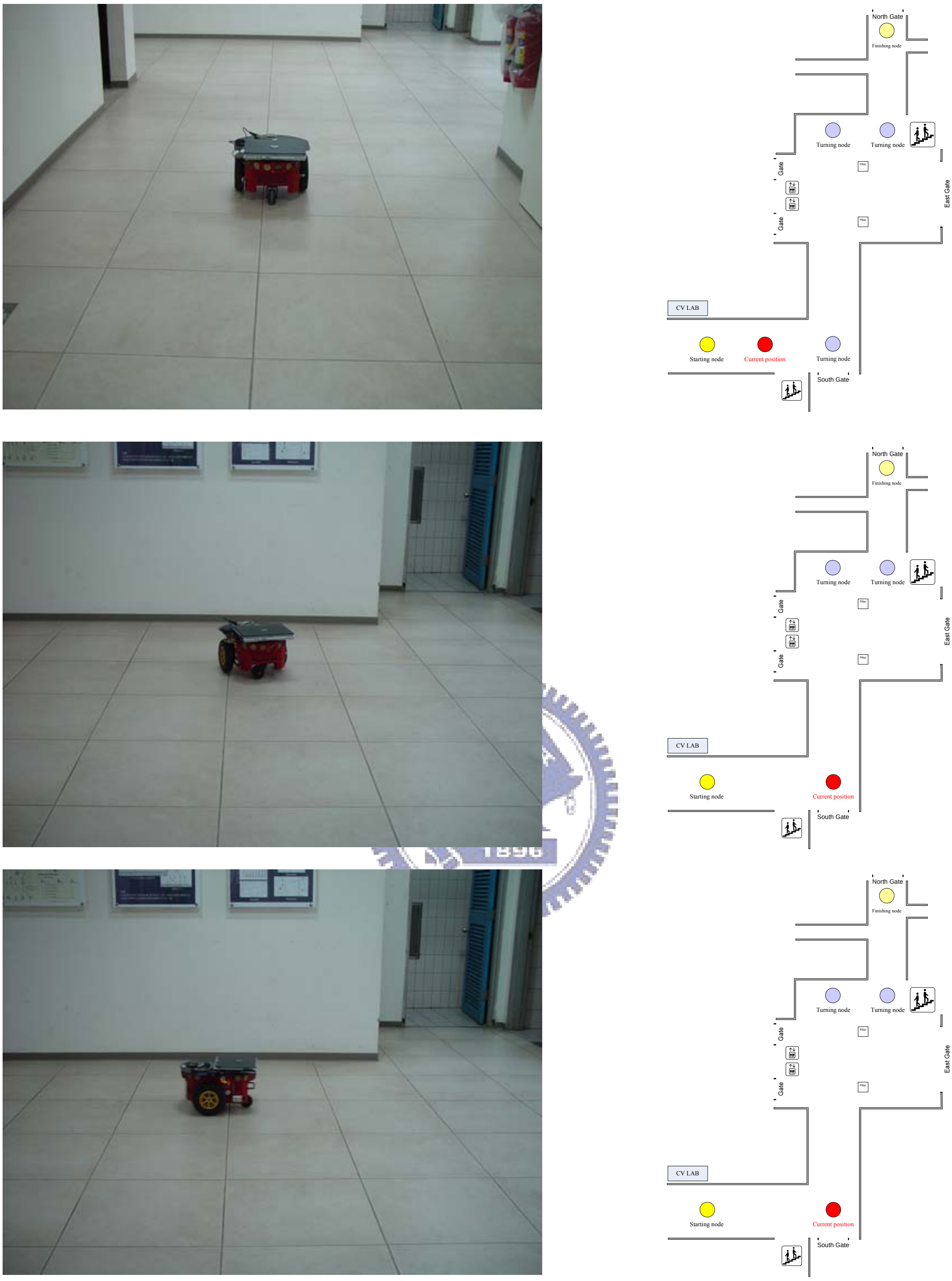
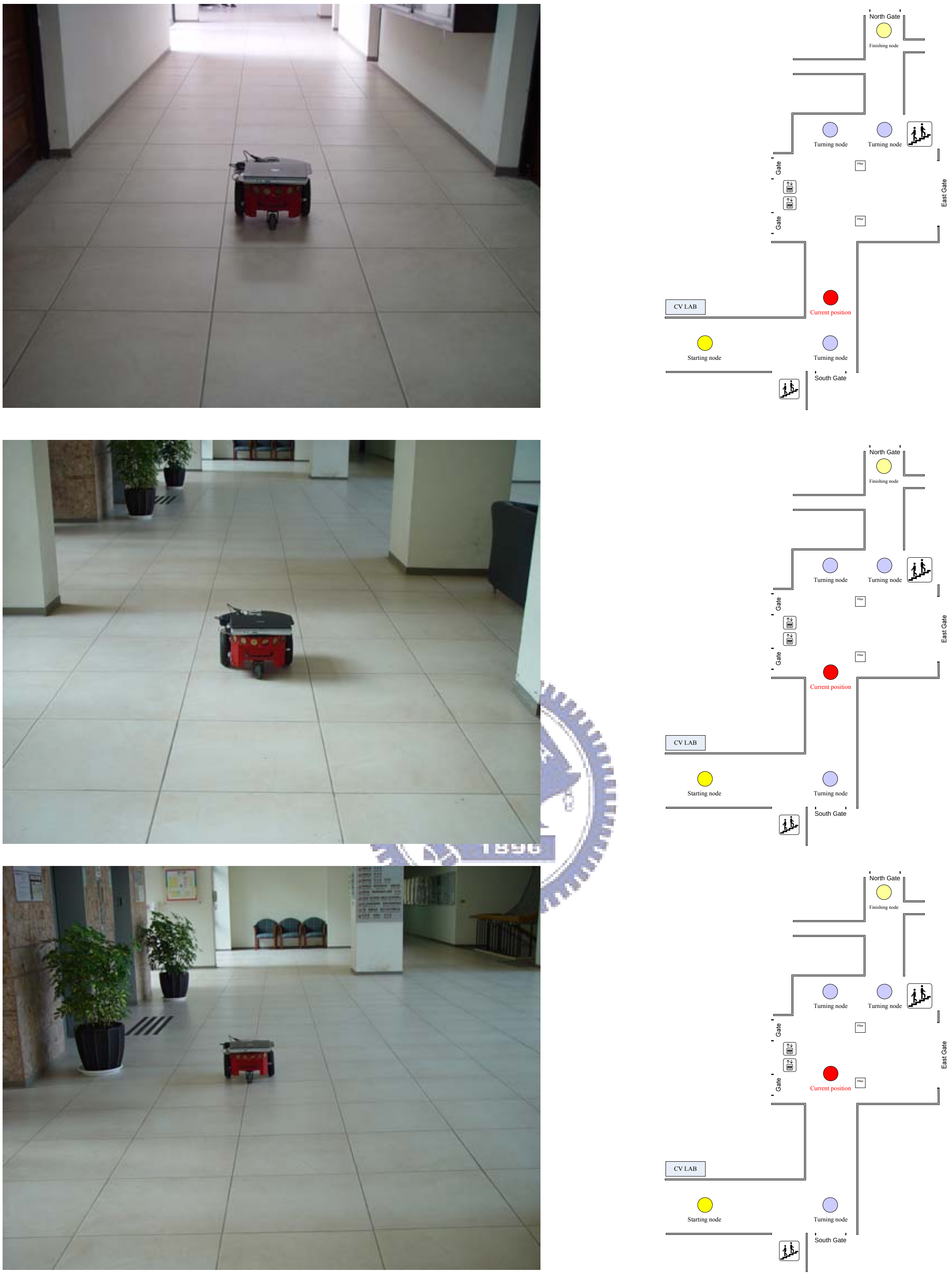


Figure 6.10 An illustration of the path of navigation in an experiment.



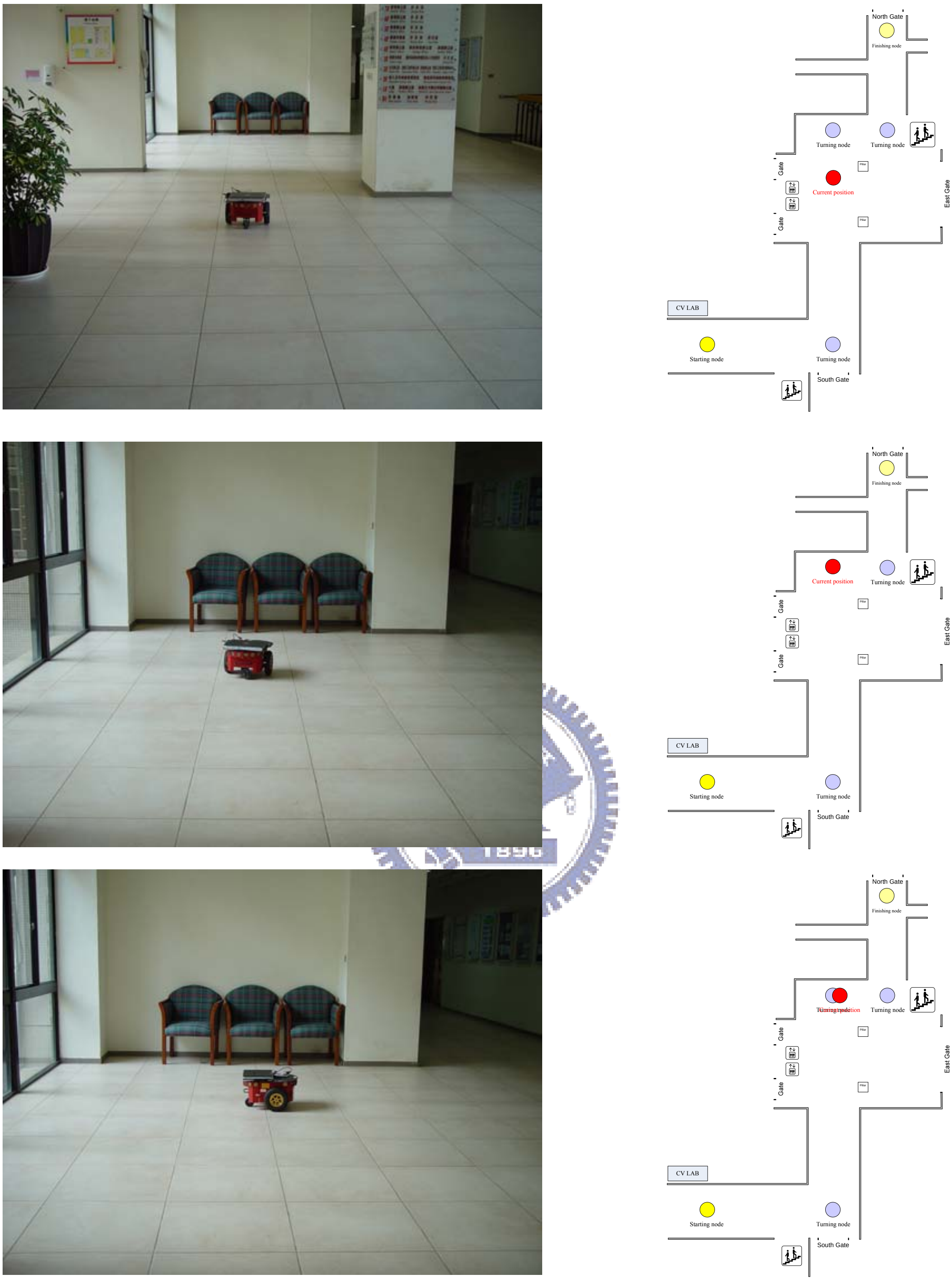
(a) (b)

Figure 6.11 An experimental result of navigation in an indoor environment. (a) The vehicle navigates on the path. (b) The navigation map with red circle indicating the current position.



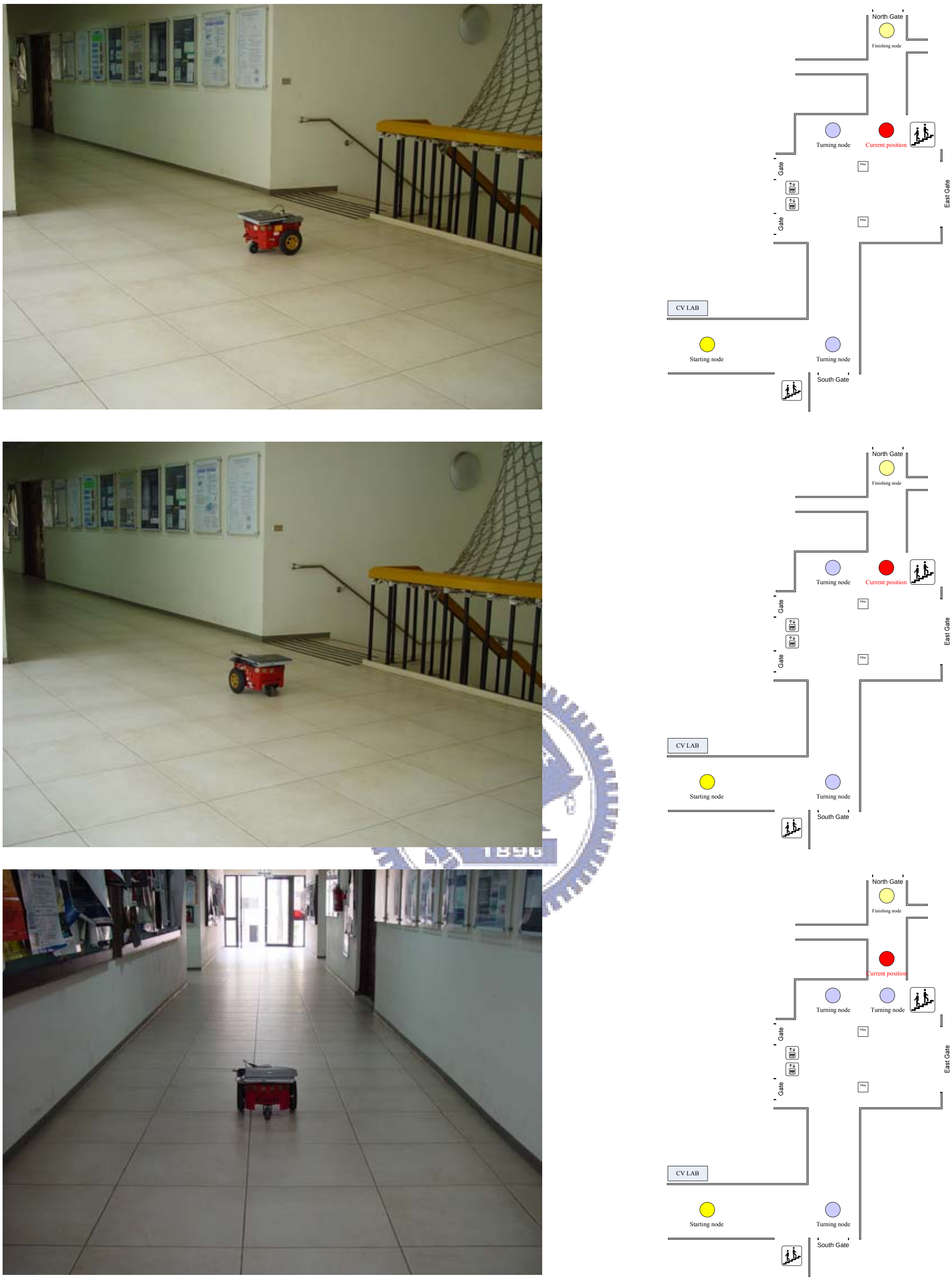
(a) (b)

Figure 6.11 An experimental result of navigation in an indoor environment. (a) The vehicle navigates on the path. (b) The navigation map with red circle indicating the current position (continued).



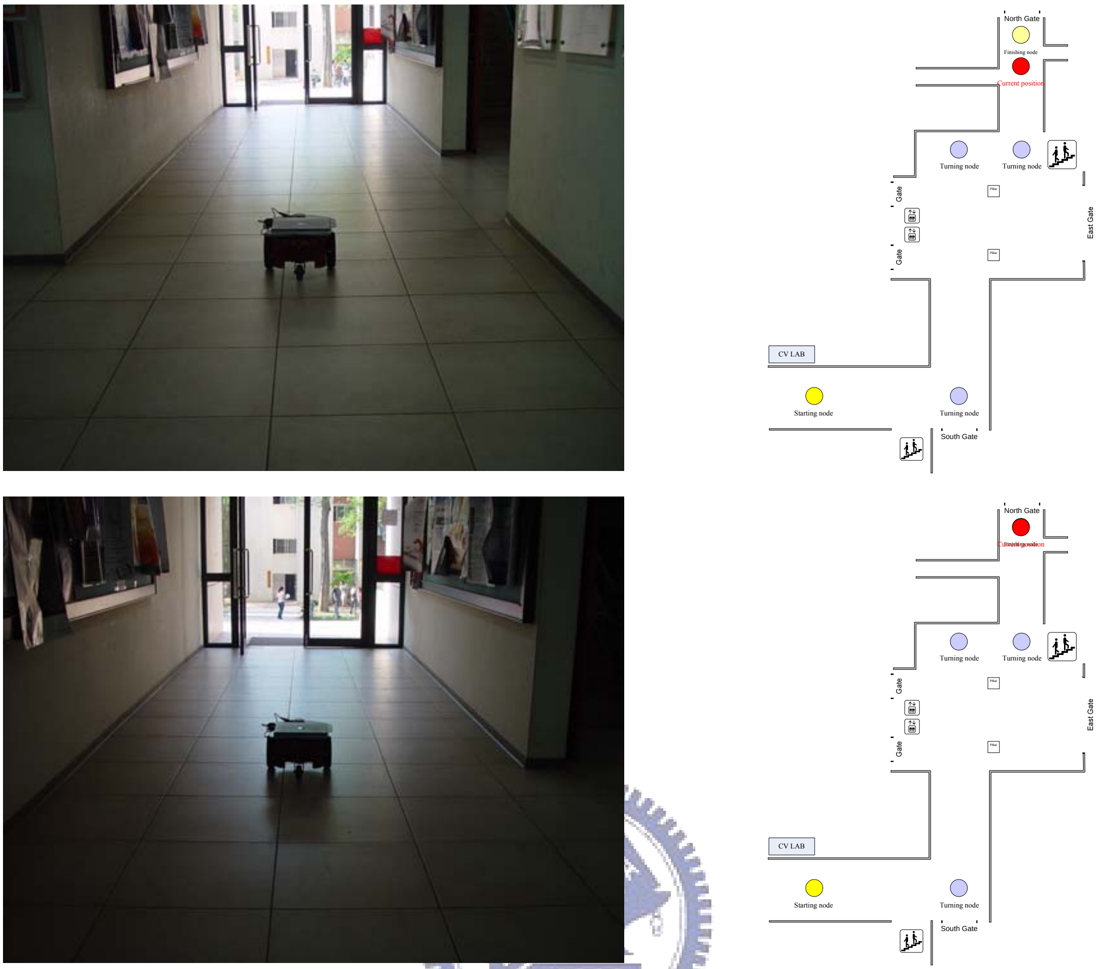
(a) (b)

Figure 6.11 An experimental result of navigation in an indoor environment. (a) The vehicle navigates on the path. (b) The navigation map with red circle indicating the current position (continued).



(a) (b)

Figure 6.11 An experimental result of navigation in an indoor environment. (a) The vehicle navigates on the path. (b) The navigation map with red circle indicating the current position (continued).



(a) (b)

Figure 6.11 An experimental result of navigation in an indoor environment. (a) The vehicle navigates on the path. (b) The navigation map with red circle indicating the current position (continued).

6.2 Discussions

By analyzing the experimental results of person following and guidance, some problems are identified as follows.

Figure 6.12 An experiment result of a navigation path. The black circles are spots specified by coordinates obtained from the odometer and the red lines are the walls plotted according to the distances obtained from the ultrasonic sensors.

(1) When the vehicle follows a person, if the person walks very fast suddenly or is far away from the vehicle, then the vehicle may fail to track the person, because it can not detect the person by ultrasonic sensors then.

(2) If the person walks near a wall and the vehicle's direction is not straight, then it may not distinguish between the person and the wall.

(3) If the person walks too near to or too far from a wall during learning, the path analysis system may not be able to plan a suitable path for navigation. The main environmental feature used for navigation is wall. We desire that the vehicle can navigate in the middle of two walls and will not hit the walls. However, another main task of the navigation procedure is following the learned path. Therefore, if the

person walks too near to or too far a wall during learning, then the vehicle can not obtain the correct path. In order to deal with this problem, we have to add more environmental features for use by the navigation system in the future.

Chapter 7
Conclusions and Suggestions for Future Works

7.1 Conclusions

Several techniques and methods have been proposed in this study and integrated for use on an autonomous vehicle system for learning and navigation in indoor environments. The system includes four kinds of capabilities. They are: following a person, learning a path, analyzing the learned path, and navigating on the learned path.

At first, a method of person following has been proposed. The vehicle uses ultrasonic sensors to detect the distance between a person and itself. Two fuzzy logic controllers have been proposed. The fuzzy controllers are used to control the vehicle's direction and speed during following the person. Therefore, if the relative direction between the vehicle and the person changes, the vehicle can adjust its direction to keep following the person. In addition, if the person's speed changes, the vehicle can also adjust its speed to keep following the person.

Besides, a method for vehicle turning has been proposed. The vehicle can analyze some of the person's behaviors by a voting technique. For example, if the vehicle detects the condition that the person stands on its left-hand side for a period of time, it means that the person commands the vehicle to turn left.

When the vehicle follows the person, it should learn the path data in the mean time. It collects the path data of the system's running time, speed, distances from ultrasonic sensors, the person's commands, and positions.

Then a method for path analysis has been proposed. The main environmental feature used for navigation is path data. However, learned path data may be rough. Therefore, we use the proposed method to analyze the learned path data into the path data for navigation. When the vehicle navigates on the learned path, it should know when to turn. We have proposed a technique to analyze the time for vehicle turning. The environmental feature used to correct the vehicle's direction is wall. In order to adapt to different environments, the vehicle should know wall distances in the environments. We have proposed a technique to analyze information of wall distances in different environments. Furthermore, the vehicle also needs to know when to stop, when to introduce objects or places as a guide, etc. We have proposed some techniques to analyze the just-mentioned information.

After analyzing a learned path, the vehicle needs to navigate on the learned path to act as a guide. A method for navigation for this purpose has been proposed. Also, we have proposed a fuzzy controller which combines ultrasonic signals obtained during navigation with the information of wall distances obtained from path analysis to control the vehicle's direction. Therefore, the vehicle can navigate in the middle of the learned path.

We also have proposed a method for detecting learned turning points. According to the path data for navigation, the vehicle can have some information about the learned turning points. Therefore, it can utilize the information and the ultrasonic signals to decide whether it arrives at one of the learned tuning points or not. In addition, the vehicle can also utilize the path data for navigation to introduce objects or places in the mean time. Therefore, the system can act as a guide in an office environment, a museum, an art gallery, etc. It can guide visitors and make some introductions to them.

The experimental results shown in the previous chapters have revealed the feasibility and practicality of the proposed system.

7.2 Suggestions for Future Works

The proposed strategies and methods, as mentioned previously, have been implemented on a vehicle system. Several suggestions and related interesting issues worth further investigation in the future are stated as follows.

(1) Following a person by use of not only the feature of ultrasonic signals, but also images to recognize the person, for improving the ability of identifying the person.

(2) Improving the controlling abilities of fuzzy controllers, such as adding more features, like images from top view cameras, information of coordinates from the odometer, etc., into the fuzzy controllers.

(3) Improving the learning abilities of the system, such as using the neuro-fuzzy system (NFS) to follow a person and learn a path in the mean time.

(4) Improving the controlling abilities of the fuzzy controller for navigation, such as using the NFS. The fuzzy controller we have proposed has some parameters that can be adjusted automatically. If a neural network can be applied to the designed fuzzy controller, it may improve the ability of adjusting the controller's parameters automatically so that it can improve the controlling abilities of itself.

(5) Adding the capability to detect more danger conditions and the abilities to deal with these situations.

(6) Reducing the number of ultrasonic sensors and achieving the same functions of person following.

(7) Combining the two fuzzy controllers for following a person into one controller and improving the controlling abilities.

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