Behavior-based Mamdani Fuzzy Controller for Mobile Robot Wall-following

Xiao Li and Dan Wang
Department of Marine Engineering
Dalian Maritime University
Dalian, P. R. China
e-mail: slytton@dlmu.edu.cn

***Abstract*—Most of the researches on mobile robot wall-following problem are focused on straight or continuous smooth wall-following cases. This paper proposes a behavior-based fuzzy controller for multi-type-wall following. The fuzzy controller provides an information fusion mechanism for combining sensor data from all laser range finder sensors. The behavior-based approach is implemented as a coordinator to manage the switching among various behaviors to solve the multi-type-wall following problem. The simulation results demonstrate that the mobile robot can follow the wall with convex corner and concave corner.**

Keywords-Behavior-based fuzzy control; multi-type-wall; wall-following; mobile robot

I. INTRODUCTION

Wall-following is an essential ability for a mobile robot which is exploring in indoor environments. This ability is required for three main tasks:

1) Map building: In unknown environments, wall-following can help to build a precise map of the environments with the data of the wall.

2) Obstacle avoidance: When the planned path of a mobile robot is prevented by an obstacle such as a wall, the mobile robot must execute the wall-following action to avoid the wall collision and to replan a new path to go to the goal.

3) Improvement of the position estimate: By planning the motion of the robot along a known wall, the dead-reckoning error can be reduced by combining the distance data between the wall and robot. [1].

Fuzzy logic was first introduced in 1965 by L.A. Zadeh [2]. Fuzzy control is effective in mobile robot navigation, trajectory control and wall-following [3], [4], [6].

Many researchers designed various wall-following controllers using different approach. But most of the proposed controllers are for straight or smooth wall following. In [1], an Extended Kalman Filter (EKF) was designed for straight wall following. In [3], a fuzzy controller was designed for straight wall following. In [4], wall with obtuse angle corners was followed using a neuro-fuzzy controller. In [5], a smooth and continuous wall was followed using a full state feedback controller and observer-based controller. In [6], a neuro-fuzzy controller was designed for bending wall following. But wall tracking error increases dramatically in the sharp 90-degree corner wall-following case. Comparing with the straight wall, we denote the wall with convex corner and concave corner as 'Multi-type-wall'. By now, to follow a wall with sharp 90-degree corner is still a difficult task. This is the so-called 'convex and concave corner problem' or 'multi-type-wall problem' in wall-following controller design.

II. KINEMATIC MODELLING OF THE MOBILE ROBOT

The robot considered in this paper is a car-like mobile robot with four wheels [7]. The two rear wheels are fixed and the two front wheels are the steering wheels which are responsible for direction change. The movement of the robot is controlled by the steering angle of the front wheels. The kinematics modeling of the robot in indoor environments is shown in Fig. 1.

The posture of mobile robot is denoted with vector p :

$$p = [x \quad y \quad \theta]^T$$

Then, in simulation, the kinematic equations of mobile robot are:

$$\begin{cases} x(\mathrm{k}+1) = x(\mathrm{k}) + v(\mathrm{k}) \cdot \mathrm{T} \cdot \cos(\theta(\mathrm{k}+1)) \\ y(\mathrm{k}+1) = y(\mathrm{k}) + v(\mathrm{k}) \cdot \mathrm{T} \cdot \sin(\theta(\mathrm{k}+1)) \\ \theta(\mathrm{k}+1) = \theta(\mathrm{k}) + \phi(\mathrm{k}) \end{cases} \tag{1}$$

$x(\mathrm{k})$: Position of the robot in the x-direction at time k;

$y(\mathrm{k})$: Position of the robot in the y-direction at time k;

$\theta(\mathrm{k})$: Orientation angle of the robot at time k;

$\phi(\mathrm{k})$: Steering angle of the front wheels at time k;

$v(\mathrm{k})$ and T are velocity of robot and simulation sample time respectively.

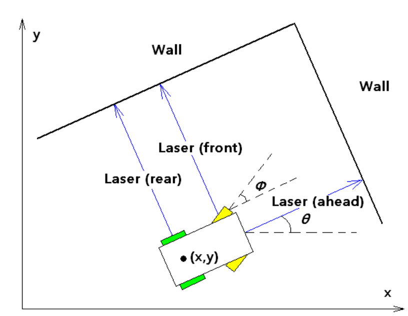

Figure 1. Kinematic of the mobile robot and laser sensor configuration

There are 3 laser range finders mounted on mobile robot. The wall can reflect the laser beam to measure the distance

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between robot and wall. The configuration of laser sensors is depicted in Fig. 1. Two laser sensors detect the distance between robot and flank wall. The distance between robot and wall ahead is measured by a laser sensor mounted on very forepart of mobile robot ('Laser ahead' in Fig. 1).

III. Fuzzy Controller Design for Straight Wall Following

To follow the left straight wall and a wall with obtuse angle corners at a set distance, a fuzzy controller is designed [3]. There are mainly three steps for designing a fuzzy controller: Fuzzification, Inference engine and Defuzzification.

A. *Fuzzification*

Inputs of the controller i.e., distance information from the front and the rear laser sensors are represented by the linguistic variables 'DisLaserF' and 'DisLaserR' respectively and are scaled in range [0, 5] meters. Similarly, the output from the controller i.e., steering angle of mobile robot is represented by the linguistic variable 'SteeringAngle' and is scaled in range [-0.2, 0.2] rad. The ahead laser sensor is absent in straight wall following case. The velocity of the robot is set as 1m/s in constant. So the only one output of controller is steering angle.

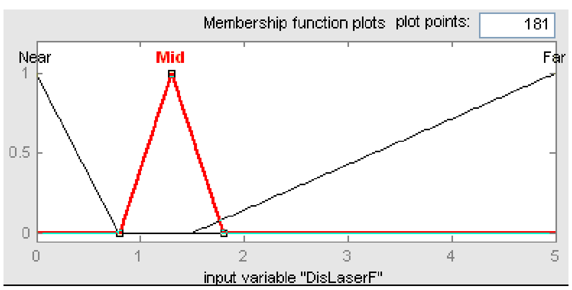

Figure 2. Input variable 'DisLaserF' membership function

The linguistic variables representing the inputs 'DisLaserF' and 'DisLaserR' are described with three fuzzy sets: Near, Mid and Far. We choose triangular membership function as depicted in Fig. 2. To gain better wall-following result, the parameters of the membership function have been changed and tested for plenty of times. So the shape of membership function is different between 'Near' and 'Far'. The input 'DisLaserR' membership function is same as 'DisLaserF'.

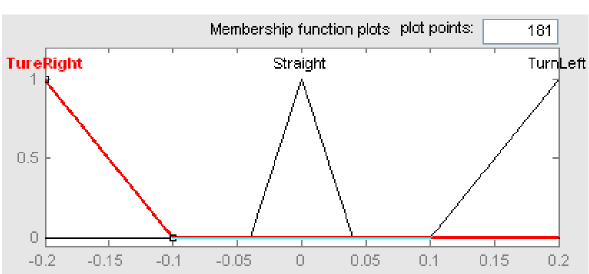

Figure 3. Output variable 'SteeringAngle' membership function

Fig. 3 shows the output 'SteeringAngle' fuzzy membership function. Three fuzzy sets (Turn Right, Straight and Turn Left) describe the linguistic variable. These fuzzy sets do not overlap. The choosing of the parameters of membership function is just according to human's experience. Lots of experiments are needed to determine the parameters in order to gain better control effect.

B. *Fuzzy Inference Engine*

To design a rule base for fuzzy logic controller, various possible cases which the mobile robot can encounter should be considered carefully. By analysing all possible cases, we choose 9 rules shown as table 1. Each rule is in the form of 'If-A-and-B-Then-C'. For instance, If DisLaserF is Near and DisLaserR is Near Then SteeringAngle is TurnRight.

TABLE I. FUZZY RULE TABLE FOR THE STEERING ANGLE CONTROL

		Distance measurement from rear laser (DisLaserR)		
		Near	Mid	Far
DisLaserF	Near	Turn Right	Turn Right	Turn Right
	Mid	Turn Left	Straight	Turn Right
	Far	Turn Left	Turn Left	Turn Left

C. *Defuzzification*

The outputs from the rules that have been activated are aggregated using OR operator. The outputs are fuzzy linguistic variables such as "Turn Right", "Turn Left", and "Straight". To be used by mobile robot controllers, we need a crisp output in the form of radian for controlling the steering angle. Amongst the various methods for defuzzification, center of gravity (COG) method has been used. The crisp value of steering angle calculated by COG method is described as:

$$\phi_{COG} = \frac{\int_{\phi\in U} \phi\mu_F(\phi)d\phi}{\int_{\phi\in U} \mu_F(\phi)d\phi} \tag{2}$$

Where $\mu_F(\phi)$ is the steering angle membership function. ϕ_{COG} is the crisp value of steering angle.

IV. Behavior-based Multi-type-wall Wall-following

Behavior-based controller was first introduced in 1986 by Brooks [8]. The idea is to decompose the whole complex behavior into different simple behavior modules in subsumption architecture. Each behavior is executed independently or in conjunction with the others, and is formulated as a set of fuzzy rule statements.

Because of the trouble caused by 'Convex Corner Problem' and 'Concave Corner Problem', the straight wall-following fuzzy controller designed in section 3 cannot follow the bending wall with sharp 90-degree corners in correct way. In order to solve the 'multi-type-wall problem', behavior-based controller is proposed in this section.

A. Convex Corner Wall Following Problem

Fig. 4 shows the convex corner case. In this case, the laser sensor loses contact with wall. And if you use straight wall following controller, the mobile robot may run away from the wall as shown in Fig. 5. This case is so-called 'Convex corner wall following problem'. To solve this problem, convex corner following behavior controller is used to prevent losing contact with wall by performing a sharp left-turn.

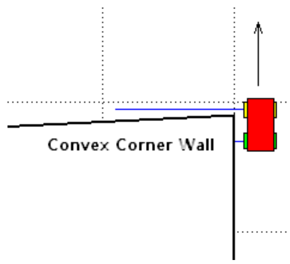

Figure 4. Convex corner

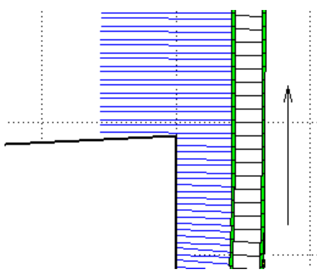

Figure 5. Laser sensor loses contact with wall

B. Concave Corner Wall Following Problem

Fig. 6 shows the concave corner case. In this case, when the mobile robot is close to the concave corner, it cannot forecast or detect the wall ahead without the ahead laser sensor mounted on robot as depicted in Fig.1. So if you still use straight wall following controller, the mobile robot may crash into the wall as shown in Fig. 7. This case is so-called 'Concave corner wall following problem'. To solve this problem, the mobile robot must mount a laser sensor to detect the wall ahead. And concave corner following behavior controller is used to prevent the wall collision by performing a sharp right-turn.

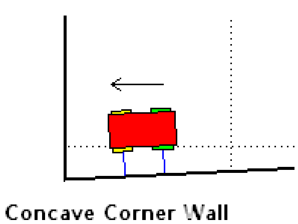

Figure 6. Concave corner

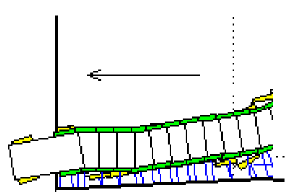

Figure 7. Wall collision in concave corner

C. Behavior Frame for Multi-type-wall Wall-following

To increase the autonomy of the mobile robot, the behavior supervisor can be implemented using a decision function based on sensor inputs to decide upon the right behavior the robot should take. Behavior-based fuzzy controller has 3 behaviors as follows:

1) Straight wall following behavior;
2) Convex corner following behavior;
3) Concave corner following behavior.

Each behavior has its own fuzzy controller to control the task in detail. The fuzzy controller for convex/concave corner following is designed to control the steering angle to perform an effective sharp left/right turn as shown in Fig. 8 and Fig. 9. The turning radius of mobile robot must be considered during the designing of fuzzy controller.

The flowchart of the behavior selection scheme is illustrated in Fig. 10. In each simulation sample cycle, controller make a decision based on sensor inputs at the cycle's beginning, then, the robot performs the right behavior. For instants, if the data get from laser sensors show there is a convex corner near robot, then the robot perform a convex corner following behavior. The flowchart is executed repeatedly in every sample cycle.

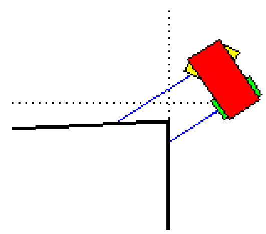

Figure 8. Convex corner following behavior

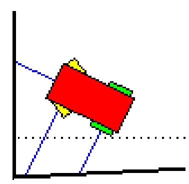

Figure 9. Concave corner following behavior

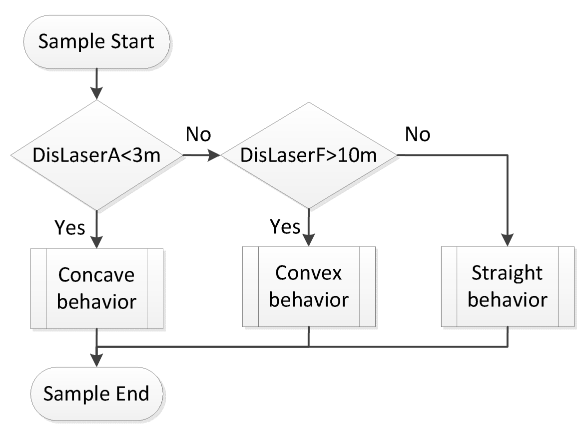

Figure 10. Flowchart of the behavior selection frame

V. SIMULATION RESULT

In order to illustrate the feasibility and effectiveness of the controller, we construct a multi-type-wall simulation environments using Matlab. The multi-type-wall as shown in Fig. 11 includes straight wall, concave/convex corners and obtuse angle corners. There are nine corners in Fig. 11. The mobile robot performs a straight wall following task from corner P_n to corner P_{n+1}. For instants, from P5 to P6 is a straight wall. Traditional fuzzy controller can perform straight wall following task very well. This paper is focus on the wall-following task with concave/convex corners and obtuse angle corners. Corner P1 and Corner P9 are obtuse angle corners. P2, P4, P5, P6 and P8 are convex corners. P3 and P7 are concave corners. So the simulation environment is a typical multi-type-wall. The wall-following track is depicted in Fig. 11. The robot track is very close to wall, no matter what the wall type is. The wall-following error is shown in Fig. 12. The set distance between robot and wall is 1.5m; the wall-following error is about in range (-1, 2.5) meters. Comparing with the wide of the mobile robot 2m, the track error is in the acceptable range. Most important, the behavior-based fuzzy controller can solve effectively the multi-type-wall problem. It can prevent robot running away from the wall or crashing into the wall. By analyzing error data, we can find that the biggest error is mainly caused by two problems: narrow concave corner space or large steering angles. For instants, in corner P2, the robot turns with a large steering angle, so the large error displays in first 10 steps. How to determine the optimal parameters of controller to reduce the error need lots of experiments or using multi objective optimization algorithm. Furthermore, if the narrow concave corner space can be considered in designing controller, maybe it can improve the performance of fuzzy controller.

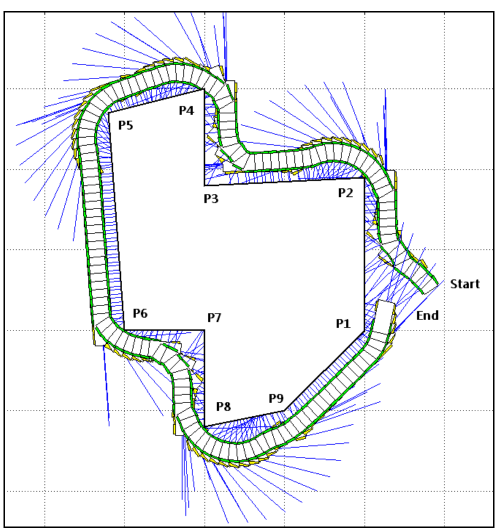

Figure 11. Multi-type-wall following simulation result

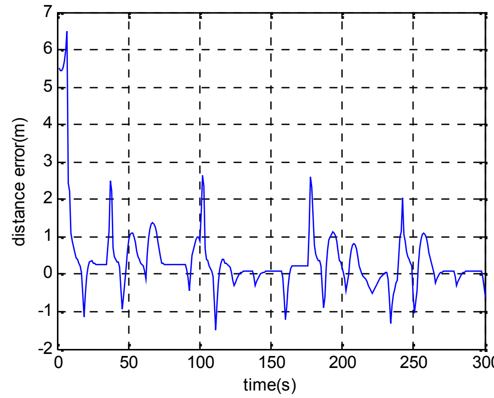

Figure 12. Multi-type-wall following error

VI. CONCLUSIONS

A behavior-based fuzzy controller is presented to solve the multi-type-wall following problem. The wall tracking error is kept in an acceptable range no matter in straight wall case or in sharp convex/concave corner case. In this design, lots of experiments are needed to determine the parameters in order to gain better control effect. Future study may pay attention to this drawback. Furthermore, all cases in this paper are under the assumption that the mobile robot has the invariable speed. If mobile robot traveled with a variable speed, fuzzy controller must consider the speed.

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