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Behavior-Based Autonomous Robot Navigation on Challenging Terrain: A Dual Fuzzy Logic Approach

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Abstract - **A robot navigation system based on combined two fuzzy logic controllers is developed for a mobile robot. Eight ultrasonic sensors, a GPS sensor and two fuzzy logic controllers with separate 81 rules were used to realize this navigation system. The data from sensors are used to the input of each fuzzy controller. The outputs of fuzzy controllers control the speed of two servo motors. The robot with this navigation system chooses one of two controllers based on the information from the sensors while navigating for the targets. Fuzzy controller1 has functions that are target steering, avoiding obstacles and following the edge of obstacles. Fuzzy controller2 has a function that makes the robot keeps following the edge of obstacles. Simulation results show that a mobile robot's escaping ability from U-shaped obstacle was improved and steering ability for a target by avoiding obstacles was also improved with this combined fuzzy logic controller.**

Keywords: Robot navigation, fuzzy logic controller, U-shaped obstacle

1. INTRODUCTION

A main issue in mobile robots is robot navigation in an uncertain and complex environment and considerable research has been done for making an efficient algorithm for the mobile robot navigation. Among them, adaptive control and behavior-based control are most popular control algorithms and driving research in robot navigation. Adaptive navigation control is a method using pre-defined equations that represent the robot's moving path to reach targets and show strong ability in well-known environment [1]. However it is hard to build precise path generating equation for unknown and complex environment. Behavior-based control is putting a number of behavior units in a mobile robot's navigation system to improve navigation ability under the various conditions of environment [2]. Behavior-based control shows a good performance in making a robot to take motions which are instructed from each behavior unit corresponding to the information obtained from the surroundings; however, it has two major problems: the combination of behavior units, and the integration of behaviors with higher-level processes [3].

Such disadvantages of behavior-based control should be overcome so that the mobile robot navigation algorithm would satisfy the following navigation skills: target steering, avoiding obstacles, following the edge of obstacles and escaping from U-shaped obstacles in order to reach a specified target without collision with obstacles.

A useful approach to implementing behavior-based control is the use of fuzzy logic. Fuzzy logic provides many advantages to mobile robot navigation because of its robustness in dealing with large variability and uncertainty of parameters. This characteristic can satisfy the need of navigation system where many navigation skills can be combined to show good performances in uncertain and complex environment [2 - 5].

A drawback of using fuzzy logic in mobile robot navigation is that a robot tends to get trapped inside U-shaped obstacles [6 - 7]. Once a robot enters a U-shaped obstacle, it keeps roaming because of conflict of the behavior rules that instruct the robot to move toward target and to avoid or follow obstacles at the same time.

In this paper, a combined fuzzy logic controller is designed for a mobile robot's navigation system to solve the problem of trapping inside U-shaped obstacles and to improve navigation ability of the mobile robot.

A combined fuzzy controller consists of two different fuzzy controllers. Fuzzy controller1 has functions of target steering, avoiding obstacles, following the edge of obstacles, while Fuzzy controller2 has a function which makes the robot keep following the edge of obstacles without proceeding to targets. Each controller has 81 fuzzy rules and 4 inputs from sensors. The output from each fuzzy controller controls the velocity of two wheels of mobile robot. The difference in the velocity between the two wheels makes the robot turn right or left.

In normal conditions, the robot just uses Fuzzy controller1 to reach a target. Once the robot perceives that it gets trapped inside a U-shaped obstacle, it starts to use Fuzzy controller2 to find an exit by following the edge of the obstacle. The robot needs to keep tracking the edge of obstacles until the robot escapes from the obstacle. As a result, the robot with Fuzzy controller2 doesn't have any interruption from the GPS sensor and has a tendency that makes the robot approach the edge of obstacles without collision.

This paper is organized as follows. Section 2 describes the scheme of sensors in this navigation system. Section 3 presents the functions of two fuzzy controllers. Section 4 presents the design of a combined fuzzy controller. Section

5 shows simulation results. Section 6 presents the conclusion.

2. SENSORS

The sensors perceive surroundings. Eight ultrasonic sensors and 1 GPS sensor are mounted on the robot.

While the robot navigates in an unknown environment, ultrasonic sensors measure the distance from the obstacles, and a GPS sensor detects the present position of robot. Eight ultrasonic sensors are divided into 3 groups. Two ultrasonic sensors are placed on the front of the robot and three ultrasonic sensors are placed on each side of the robot to measure the distances from the left and right obstacles, respectively.

Before the data from the sensors are used as inputs to a fuzzy controller, they go through a procedure which reduce the number of distance data from 8 ultrasonic sensors to 3 distance data which are the smallest distance values of each sensor group in front, left, and right side of robot and are denoted by L_distance, F_distance, R_distance, as shown in Fig. 1. This procedure is effective to reduce the number of fuzzy rules because it uses only 3 meaningful distance values, therefore lightening the burden on designing fuzzy rules from all combination of 8 variables.

Based on the data from GPS, the difference angle between robot's heading direction and target position is calculated and it is used to an input to a fuzzy controller. The positive and negative value of the difference angle is denoted by θ. If θ has a positive value, it means the robot is on the right side of a target. If θ has a negative value, it means the robot is on the left side of a target. This process is illustrated in Fig. 2.

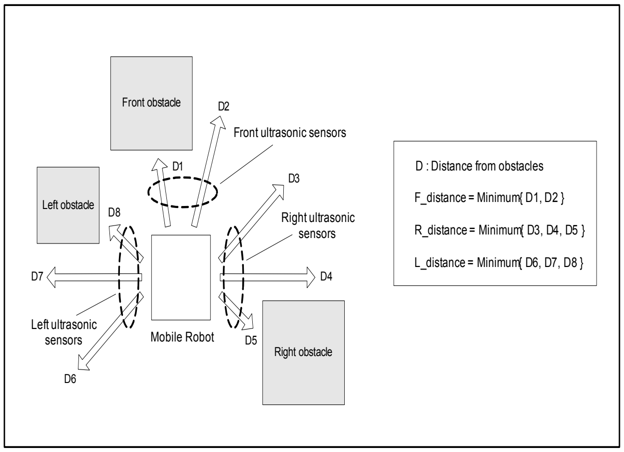


Fig. 1. Scheme of data processing of ultrasonic sensors

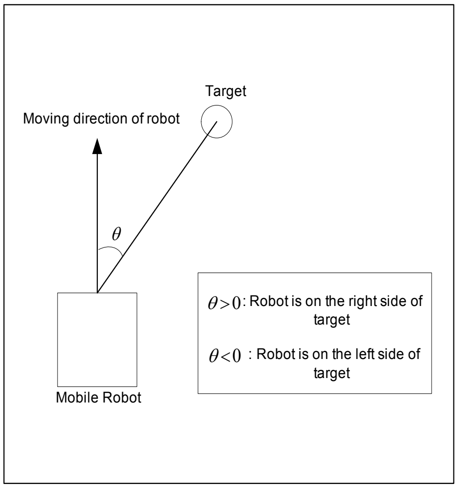


Fig. 2. Scheme of data processing of GPS sensor

3. NAVIGATION SYSTEM WITH A COMBINED FUZZY CONTROLLER

In order to reach a specified target, a mobile robot needs the following navigation skills: target steering, avoiding obstacles and following the edge of obstacles. A conventional robot possessing the above skills has a good navigation performance in unknown and uncertain environment; however, the robot usually gets trapped in U-shaped obstacles and it is directly connected to navigation failure. Once a robot gets trapped in a U-shaped obstacle, it oscillates between target steering rules and following edge rules [5]. Fig. 3 illustrates this situation with a U-shaped obstacle configuration.

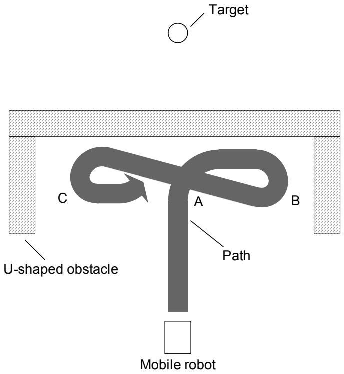


Fig. 3. Example of navigation failure in U-shaped obstacle

At the beginning of navigation, the U-shaped obstacle is too far away to have an effect on the robot's moving direction, hence the robot moves toward the target in a straight line under the effect of target steering rules. On point A, the front ultrasonic sensors detect an obstacle placed in front of the robot, and the avoiding obstacle rules veer the robot to the right to avoid the obstacle. The robot moves along the edge of the obstacle from point A to point B by using the following edge of obstacles rules because the target is placed behind the obstacle. On point B, because the obstacle is placed on the left-hand side and the target is placed on the right-hand side, the robot turns to right and moves toward the target. When the robot is faced with the obstacle around point A again, the robot uses the avoiding obstacle rules, and then it uses the following edge of obstacles' rules until it arrives at point C. On point C, the target is placed on the left-hand side of the robot, and there are no obstacles on the left-hand side of robot, the robot turns to left and moves toward the point A again. The robot keeps on oscillating this way, between points A, B and C endlessly.

To improve this drawback, a navigation system based on two combined fuzzy logic controllers is designed. Fig. 4 shows the schematic diagram of this navigation system.

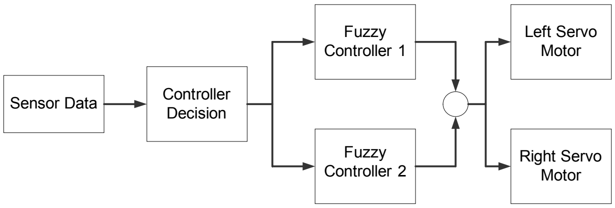


Fig. 4. Scheme of navigation system with a combined fuzzy controller

In the navigation system, a controller decision process is conducted based on the data from two front ultrasonic sensors. When the mobile robot with Fuzzy controller1 is surrounded by obstacles or the robot's path is blocked by an obstacle, the robot quickly tries to make big turns to avoid collision. While the robot is taking such an avoiding action, the front part of robot usually approaches to the obstacle closely. When either distance value from two front ultrasonic sensors is smaller than a predefined value in the controller decision process, this situation is regarded as getting trapped inside an obstacle and the navigation system starts to use Fuzzy controller2.

While Fuzzy controller2 is operating, the robot only follows the edge of obstacles without taking any action of target steering and avoiding obstacles. The reason for putting the second fuzzy controller to this navigation system is to give the robot an ability to find an exit of U-shaped obstacle. The navigation system keeps using Fuzzy controller2 until the robot finds an exit inside the obstacle.

The finding exit process is also conducted by controller decision process of navigation system based on the data from front ultrasonic sensors. While the robot moves along the edge of obstacles, a front ultrasonic sensor, which is close to the edge of obstacles, keeps transmitting smaller values of distance data to controller decision process than the other front ultrasonic sensor. When both distance values of front ultrasonic sensors are bigger than a predefined value, that point is regarded as an exit.

After the robot finds an exit of the U-shaped obstacle, the robot doesn't use Fuzzy controller1 immediately because the data from sensors still direct the robot to move inside the U-shaped obstacle. To solve this problem, the controller decision process has a counter to give a delay between finding an exit and changing controller to Fuzzy controller1 until the robot escapes from the condition that makes the robot to move inside the U-shaped obstacle. While the counter counts certain time, the robot keeps using Fuzzy controller2 and can get out of the trapped condition.

4. FUZZY CONTROLLERS

Two fuzzy controllers designed in this paper have the same input and output membership functions. The difference between two controllers is the rule evaluation part. After a fuzzy controller is chosen based on the information obtained from the surroundings, the fuzzy controller has a process, which consists of three stages: fuzzification, rule evaluation and defuzzification. The outputs of fuzzy controllers control the velocity of two wheels of the mobile robot and they are denoted by L_velocity and R_velocity as linguistic variables in fuzzy rules. Fig. 5 shows the process of combined fuzzy controller in detail.

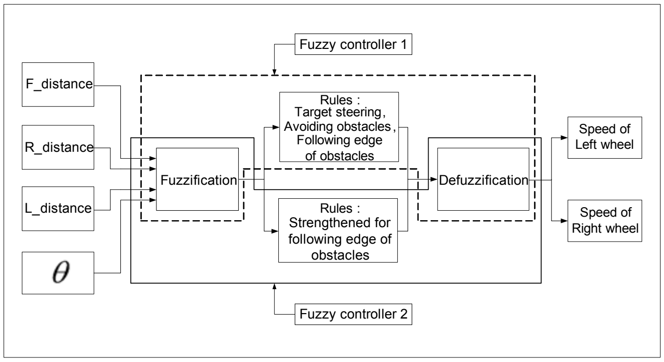


Fig. 5. Scheme of combined fuzzy controller

4.1 FUZZIFICATION

Two fuzzy membership functions are designed to fuzzify the data from sensors. Membership function shown in Fig. 6 is used to fuzzify the value of variables "F_distance, R_distance, L_distance" from the ultrasonic sensors.

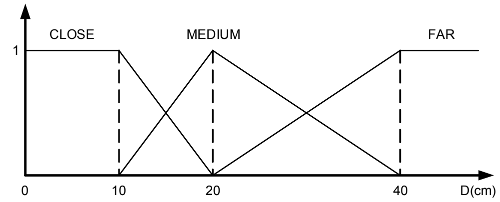


Fig. 6. Membership function for linguistic variables "F_distance, R_distance, L_distance"

Membership function shown in Fig. 7 is used to fuzzify the difference angle (θ) between robot's heading angle and target's position. If θ is bigger than $+90^\circ$ or smaller than -90°, it is denoted by R_position and L_position respectively. If the difference angle is within the range of $\pm 90^\circ$, it will be denoted by S_position.

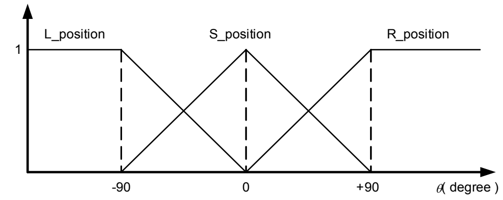


Fig. 7. Membership function for variable "θ"

With these membership functions, the distance information and position information from sensors are converted to fuzzy values.

4.2 RULE EVALUATION

With 4 fuzzy inputs, each fuzzy controller has two outputs that are denoted by linguistic variables: L_velocity, R_velocity. Those linguistic variables represent the speed of each wheel, and they are classified by three range of speed: SLOW, MED, and FAST.

The fuzzy rules have two parts: condition part that consists of IF statements and behavior part which consists of THEN statements. Condition part is designed to represents all possible environmental condition which the robot with the proposed sensor system can meet while it navigates and the speed of each wheel is represented in THEN statement to control robot's motion coping properly with the environmental conditions.

4.2.1 RULES IN FUZZY CONTROLLER 1

Fuzzy controller1 has 81 rules for navigation skills: Target steering, avoiding obstacles and following the edge of obstacles. To realize these navigation skills, following rules are designed.

<Rules for target steering>

Rule 1: If (L_distance is FAR and F_distance is FAR and R_distance is FAR and θ *is S_position) then (L_velocity is FAST and R_velocity is FAST)*

Rule 2: If (L_distance is FAR and F_distance is FAR and R_distance is FAR and θ *is L_position) then (L_velocity is FAST and R_velocity is SLOW)*

Rule 3: If (L_distance is FAR and F_distance is FAR and R_distance is FAR and θ *is R_position) then (L_velocity is SLOW and R_velocity is FAST)*

<Rules for avoiding obstacles>

Rule 5: If (L_distance is MEDIUM and F_distance is CLOSE and R_distance is CLOSE and θ *is any) then (L_velocity is SLOW and R_velocity is FAST)*

Rule 6: If (L_distance is CLOSE and F_distance is CLOSE and R_distance is MEDIUM and θ *is any) then (L_velocity is FAST and R_velocity is SLOW)*

Rule 7: If (L_distance is CLOSE and F_distance is MEDIUM and R_distance is CLOSE and θ *is any) then (L_velocity is MED and R_velocity is MED)*

<Rules for following edge of obstacles>

Rule 8: If (L_distance is FAR and F_distance is FAR and R_distance is CLOSE and θ *is L_position) then (L_velocity is MED and R_velocity is MED)*

Rule 9: If (L_distance is CLOSE and F_distance is FAR and R_distance is FAR and θ *is R_position) then (L_velocity is MED and R_velocity is MED)*

Rule 10: If (L_distance is FAR and F_distance is MEDIUM and R_distance is CLOSE and θ *is L_position) then (L_velocity is MED and R_velocity is MED)*

Rule 11: If (L_distance is CLOSE and F_distance is MEDIUM and R_distance is FAR and θ *is R_position) then (L_velocity is MED and R_velocity is MED)*

4.2.2 RULES IN FUZZY CONTROLLER 2

Fuzzy controller2 also has 81 rules. Different from rules in Fuzzy controller1, the rules in Fuzzy controller2 are designed for the robot to follow the edge of obstacles in order to find any exit inside obstacles. These rules are a fortified form of following edge rules in fuzzy controller1. With these rules, the mobile robot approaches to the edge of obstacles, making adequate distance, and keeps following the edge of obstacles without consideration of compensating the difference angle (θ). With these rules, in most case, the robot moves at low speed. However, when the robot reaches a corner of obstacle, it makes turns towards the obstacle at high speed because the robot usually misses obstacles at that point, so such quick approaching motion toward obstacle prevents the robot from getting away from obstacle. To realize this navigation skill, following rules are designed.

<Rules for fortified following edge of obstacles>

Rule 12: If (L_distance is FAR and F_distance is FAR and R_distance is MEDIUM and θ *is any) then (L_velocity is FAST and R_velocity is SLOW)*

Rule 13: If (L_distance is FAR and F_distance is FAR and R_distance is CLOSE and θ *is any) then (L_velocity is MED and R_velocity is MED)*

Rule 14: If (L_distance is FAR and F_distance is MEDIUM and R_distance is MEDIUM and θ *is any) then (L_velocity is FAST and R_velocity is MED)*

Rule 15: If (L_distance is FAR and F_distance is MEDIUM and R_distance is CLOSE and θ *is any) then (L_velocity is MED and R_velocity is MED)*

Rule 16: If (L_distance is MEDIUM and F_distance is MEDIUM and R_distance is CLOSE and θ *is any) then (L_velocity is MED and R_velocity is MED)*

Rule 17: If (L_distance is MEDIUM and F_distance is FAR and R_distance is CLOSE and θ *is any) then (L_velocity is MED and R_velocity is MED)*

4.3 DEFUZZIFICATION

In this paper, the weighted-average defuzzification method and a membership function shown in Fig. 8 are used.

The weighted-average defuzzification method can be expressed as follows.

$$x^i = \frac{\sum_{i=1}^{number\ of\ rules} m^i \times w^i}{\sum_{i=1}^{number\ of\ rules} m^i} \qquad (1)$$

x^i = defuzzified output

m^i = the member of output of each rule

w^i = weight associated with each rule

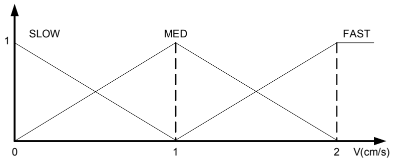


Fig. 8. Output membership function

5 SIMULATION AND RESULTS

In the simulation results, the robot's navigation path to reach specified targets shows that the navigation system is working properly. The path is represented by the overlapped motion of mobile robot in each step. In order to prove the performance of the combined fuzzy controller, various shapes of obstacles are put in the simulation environment.

The dense part of path means that the robot moves at lower speed compared to the other parts of path. Especially, when it avoids obstacles or follows the edge of obstacles, it is shown that the robot reduces its speed.

Fig. 9. (a) shows robot's motion when it meets scattered obstacles on its way to a target. The result shows that the robot with combined fuzzy controller steers for a target without collision with obstacles.

Fig. 9. (b) shows robot's motion when a target is placed inside a U-shaped obstacle. The result shows that the robot with combined fuzzy controller reaches a target inside a U-shaped obstacle using following edge rules.

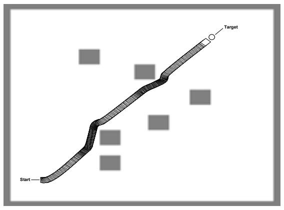


Fig. 9. (a)

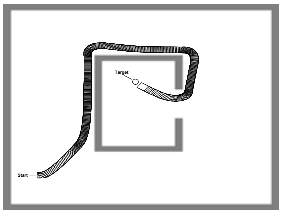
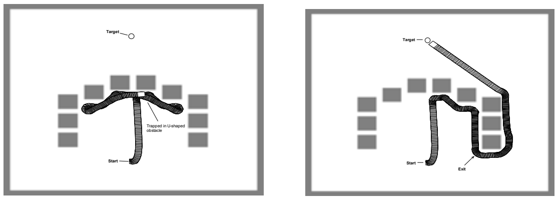
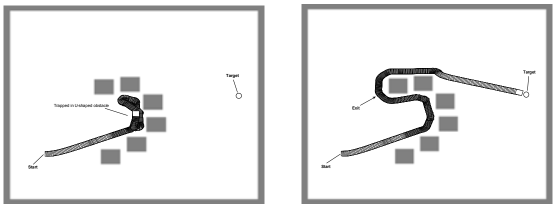


Fig. 9. (b)

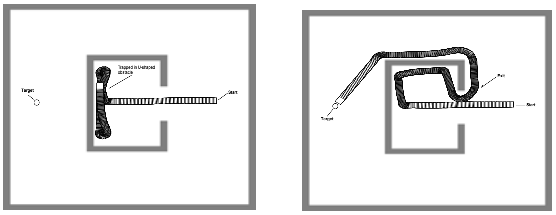
Fig. 10 shows robot's escaping motion for various shapes of U-shaped obstacle. In each case, two simulation results are presented. One is the robot's motion with Fuzzy controller1 only, and the other is the robot's motion with the combined fuzzy controller. In all cases, the robot equipped with Fuzzy controller1 fails to escape from the U-shaped obstacle. On the other hand, the robot equipped with the combined fuzzy controller finds out the exits from U-shaped obstacles and reaches the targets successfully.



(a) – Using controller1 (b) – Using combined controller



(c) – Using controller1 (d) – Using combined controller



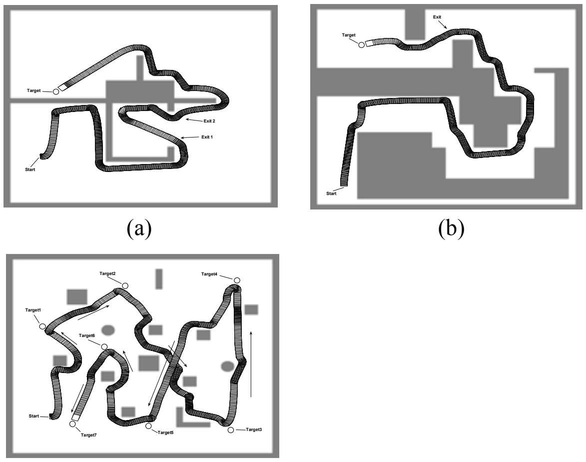
(e) – Using controller1 (f) – Using combined controller

Fig. 10. (a)-(f): Robot's motion in various shaped of U-shaped obstacles

In Fig. 11 (a), when the robot with combined fuzzy controller is initially faced with the obstacle, it will turn to right automatically and starts to use Fuzzy controller2 until it finds Exit 1. As soon as the robot finds Exit 1, Fuzzy controller1 starts to operate to steer for target. When the robot perceives that it gets trapped in U-shaped obstacle again, Fuzzy controller2 is operated again until it finds Exit 2. Such alternation between two controllers keeps occurring until it reaches the target to prevent it from getting trapped in the U-shaped obstacle.

In Fig. 11 (b), the robot with the combined fuzzy controller reaches the target passing through the obstacles along the narrow road.

Fig. 11 (c) shows the robot's motion in an environment, which has a number of scattered obstacles. In this simulation, the robot has to pass six sub-targets in order to reach the final target. From the result, the robot with combined fuzzy controller reaches each target without collision and controls moving speed. When it passes obstacles it reduces the speed.



(a) (b)

(c)

Fig. 11. (a) The robot reaches a target with escaping from a U-shaped obstacle. (b) The robot having a target lower speed at curved and narrow road. (c) The robot reaches more targets in a cluttered environment.

6 CONCLUSIONS

A navigation technique using a combined fuzzy controller has been proposed in this paper. From the simulation result, the mobile robot with the combined fuzzy controller demonstrates an improved navigation in unknown or uncertain environment. A number of behavior units are well combined and show good responses to the various sensor data through fuzzy logic

In the complex environment where there are various shaped obstacles, the robot with the combined fuzzy controller reached specified targets without collision with the obstacles, and the robot also showed smooth navigation paths by reducing its moving speed while it bypasses obstacles. This shows that the fuzzy logic, which imitates human's reasoning, is suitable to control the robot's motion in complex environment and thus simplifies the navigation system without using any dynamic equations to generate robot's path corresponding to surrounding information.

NONMENCLATURE

L_distance$_p$: distance data from left ultrasonic sensors
F_distance : distance data from front ultrasonic sensors
R_distance : distance data from right ultrasonic sensors
θ : difference angle between robot's heading direction and target position
L_velocity : rotating speed of left wheel of robot
R_velocity : rotating speed of right wheel of robot

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