Design of Hierarchical Fuzzy Logic Control for Mobile Robot System

Lon-Chen Hung, Hung-Yuan Chung
Department of Electrical Engineering
National Central University
Jhongli City, Taoyuan County 320, Taiwan (R.O.C.)
hychung@ee.ncu.edu.tw

Abstract—This paper studies the problem of motion and control law design for a mobile robot that moves inside a partially unknown environment, under the assumption of parametric uncertainty in the model that describes the motion of the robot. This paper deals with a fuzzy-based intelligent mobile robotic system by hierarchical structure that requires various capabilities normally associated with intelligence. The proposed method is applied for a path planning problem of a mobile robot; the effectiveness of the method is illustrated through some experiment.

Keywords—fuzzy, mobile, robot

I. INTRODUCTION

A behavior-based control system, which can intelligently construct a controlled system for a mobile robot or robot manipulator according to the interaction between the robot and the environment, is now becoming attractive in the field of robotics [3-8,10]. One very interesting approach is known as subsumption architecture, which has been proposed by Brooks [9]. The control system, based on the subsumption architecture, decomposes itself in parallel into several elemental behaviors, and then the results from the elemental behaviors are competed or cooperated to fuse them, whereas the conventional controlled system of the robot is serially decomposed into several elemental functions. The behavioral fusion is performed with a fixed relationship based on a priority in [12-14]. However, Xu [15] proposed the dynamical fusion method, which selects an action by activation or suppression of each elemental behavior. In behavior-based control system, behavioral fusion is important, but each elemental behavior, too, is important. The present authors have already developed a fuzzy behavior-based control system [15-19], realized in the framework of soft-computing, in which each elemental behavior is expressed by fuzzy rules. Behavioral fusion is formulated using a sign function and a saturation function. The method has been applied for a terminal control problem of a mobile robot with two independent driving wheels [1,2].

For classes of methods to derive the fuzzy rule base stand out [11], they are based upon: (a) expert experience, (b) the operators control actions, (c) a fuzzy model of the process, and (d) learning. The first one that consists in verbalizing the human expertise and expressing it under the form of fuzzy rules is the most widely used and it is the one that has been selected in order to set up the fuzzy rule base of the execution monitor. Besides, following [4,16,20], it was decided to use a behaviour-based approach. In other words, the overall reactive behaviour of the vehicle results from the combination of several basic behaviours. From a practical point of view, behaviours are implemented through a modular organization of the fuzzy rule base (like [18] or [19]). Each basic behaviour is encoded by a subset of the fuzzy rule base and it is the fuzzy control mechanism that straightforwardly handles the problems of behaviour arbitration and command fusion. However, in order to better manage the interactions between the basic behaviours and between the rules of a given basic behaviour, it was decided to attach weighing coefficients to the rules (like [19]), thus permitting a fine tuning of their respective influence.

This paper proposed a hierarchical fuzzy logic controller (HFLC) for navigate the WMR from initial position to desired position with desired orientation. For the practicality and completeness of the proposed controller. The problem of extracting the IF-THEN rule base is carried out via an evolutionary programming method, and the hierarchical structure can reduce the fuzzy rule.

The paper is organised as follows. In Section 2, the dynamic model of the mobile robot is described. In Section 3, previous methods of HFLC are given. In Section 4, Experiment results that demonstrate the efficiency of the proposed methodology are given. Finally, in Section 5, some concluding remarks are stated.

II. SYSTEM DESCRIPTION

Consider a robot system having an n-dimensional configurations space $C$ with generalized coordinates $\mathbf{q} = (q_1, \ldots, q_n)$ and subject to $m$ constraints of the following from:

$$A(q)\mathbf{q} = 0 \quad (1)$$

where $A(q) \in \mathbb{R}^{m \times n}$ is the matrix associated with constraints. Let $N(A)$ be the null space of $A(q)$, a set of smooth and linearly independent vector fields $s_1(q), \ldots, s_{n-m}(q)$ can be obtained. If we let $S(q) = [s_1(q), \ldots, s_{n-m}(q)]$ be the full rank matrix consists of the these vectors, then the following equation holds

$$A(q)S(q) = 0 \quad (2)$$

The dynamic equation of the mobile robot system with nonholonomic constraints (1) can be described as follows:

$$M(q)\ddot{\mathbf{q}} + V_n(q, \dot{\mathbf{q}}) + F(\dot{\mathbf{q}}) + \tau_d = B(\mathbf{q})\tau - A^T(q)\lambda \quad (3)$$

where $M(q)$ is the mass matrix, $V_n(q, \dot{\mathbf{q}})$ is the Coriolis and centrifugal force, $F(\dot{\mathbf{q}})$ is the friction force, $\tau_d$ is the disturbance torque, $B(\mathbf{q})$ is the input matrix, $A(q)$ is the null space matrix, $\lambda$ is the control input, and $\tau$ is the control input.
where \( M(q) \in R^{n \times n} \) is a symmetric, positive define inertia matrix, \( V_a(q, q) \in R^{n \times n} \) is the centripetal and Coriolis force term, \( F(q) \in R^{n \times 1} \) denotes the surface friction. \( \tau_d \) denotes non-bounded unknown external disturbance vector, \( B(q) \in R^{n \times r} \) is the input transformation matrix, \( r \in R^{n \times 1} \) is the input vector. \( \lambda \in R^{n \times 1} \) is the vector of constraint forces.

We consider the mobile robot a two-wheeled type. It is located in the two-dimensional \( X-Y \) coordinate word. \( C \) is the origin for the local coordinate \( X_0, Y_0 \) of the mobile robot. \((x_c, y_c)\) is the position of the world \( X-Y \) coordinate. \( \theta_c \) is the angle between the \( X \)-axis and is representing a heading direction of the mobile robot. The posture of the mobile robot can be described by three parameters \((x_c, y_c, \theta_c)\) which is defined as \( q \), i.e.,

\[
q = [x_c, y_c, \theta_c]^T (4)
\]

The mobile robot has the nonholonomic constraints that the driving wheels purely roll and do not ship. This nonholonomic constraint is written as the following equation:

\[
y_c \cos \theta - x_c \sin \theta - d \dot{\theta} = 0 \quad (5)
\]

where \( d \) is the distance from \( C \) to the axis of the driving wheel. For the mobile robot described in Figure 1, \( n = 3 \) and \( m = 1 \). Therefore, \( v \) becomes two-dimensional and defined as follows:

\[
v = [v_x, w_c]^T (6)
\]

where \( v_c \) represents linear velocity of \( C \) and \( w_c \) represents angular velocity of \( C \). Then the Eq. (4) is derived as follows:

\[
q = S(q)v \quad (q = S(q)v)
\]

\[
\begin{bmatrix}
x_c \\ y_c \\ \theta_c
\end{bmatrix} =
\begin{bmatrix}
\cos \theta & -\sin \theta & 0 \\
\sin \theta & \cos \theta & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
v_c \\ w_c
\end{bmatrix} (7)
\]

where \( |v_c| \leq V_{\text{max}} \), \( |w_c| \leq W_{\text{max}} \), \( V_{\text{max}} \) and \( W_{\text{max}} \) represent the maximum linear velocity and the maximum angular velocity of the mobile robot. \( S(q) \) is given by

\[
S(q) =
\begin{bmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta \\
0 & 1
\end{bmatrix} (8)
\]

System (11) is called the steering system of the mobile robot. Most researches on the motion planning of mobile robot have been considered this steering system (11) only while neglecting the remaining dynamics (7) of the mobile robot. If we define the tracking error as (13) and if we apply the velocity command in Eq. (14) to the (11), then the kinematic model (11) is asymptotically stable. That is, \( e_1, e_2 \) and \( e_3 \) goes to zero as \( t \to 0 \). 

\[
e_p = T_c(q_r - q) (9)
\]

\[
\begin{bmatrix}
e_1 \\ e_2 \\ e_3
\end{bmatrix} =
\begin{bmatrix}
\cos \theta & \sin \theta & 0 \\
\sin \theta & -\cos \theta & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
x_r - x \\ y_r - y \\ \theta_r - \theta
\end{bmatrix} (10)
\]

\[
v_i =
\begin{bmatrix}
v_c \cos e_1 + k_e e_1 \\
-w_r + k_i v_c e_2 + k_v \sin e_1
\end{bmatrix} (11)
\]

\[
v_d = f_c(e_p, v_r, K) (12)
\]

One can obtain the necessary control \( \tau \) for (7) which guarantees perfect velocity tracking using the computed-torque control as done in [4]. One of the drawbacks of this work is that the complete knowledge of the mobile robot dynamics is necessary, which is not always possible.

### III. DESIGN OF THE PROPOSED CONTROLLER

Most commercial fuzzy logic control (FLC) implementations feature a single layer of inferencing between two or three inputs and one or two outputs. For autonomous vehicles, however the number of inputs and outputs are usually large and the desired control behaviours are more complex. If we assume that each input will be represented by three fuzzy sets and each output by four fuzzy sets, using a single layer of inferencing will lead to rules exponent increased which would be difficult, if not impossible to determine. However, by using a fuzzy hierarchical approach the number of rules required can be significantly reduced.

As Figure 1 shows, all components of the relative robot posture \((u_1, u_2, d_c)\) are required to achieve all actions. If the three components are elaborated into one fuzzy controller, the number of rules could be very large because it increases by the factor of the number of term sets of each input variable. So the controller is decomposed into two sub-controllers that take only two input variables.

#### 3.1 The hierarchical fuzzy logic control

Fuzzy logic has become a mean of collecting human knowledge and experience and dealing with uncertainties in the control process. Fuzzy control is by far the most useful application, but its successful solutions to a variety of consumer products and industrial systems, helped to attract growing attention and interests. Thereafter, a situation for which the vehicle tries to reach an end point is examined. From its design simplicity, its implementation, and its robustness properties, a hierarchical fuzzy logic controller is used in order to control the navigation behavior of an autonomous mobile robot. If we consider the vehicle moving in a free obstacle environment, then the optimal trajectory from its current position to its end configuration is naturally a line joining these two extreme points as it is depicted for instance by Figure 2. The distance \( d_e \) becomes zero when the vehicle stabilizes at its final configuration. Figure 1 gives a schematic block diagram of this architecture.

#### 3.2 The proposed control for path planning

A key issue for a mobile autonomous robot is its navigation control in uncertain and complex environments. If the robot is moving among unknown fixed and/or mobile obstacles seeking a goal location, and it must avoid collision, sensors must be used to acquire information from the
environment. Fuzzy logic use for control has increased during the last few years and has become one of the most active research areas. Fuzzy logic control has become the best scheme to represent knowledge of a process. The application of fuzzy logic control in robotics is to produce an intelligent robot with the ability of autonomous behavior and decision. The path planning controller is for generating a path by calculating desired robot’s heading angle $\theta_i$ at each position. It is again divided into three sub-block: destination block and mode selection block.

### 3.3 Destination mode block

This is for getting desired heading angle at each robot position without considering obstacles. For getting the input variable, we define $u_1 = \theta_d - \theta_s$ and $u_2 = \theta_s - \theta_i$ to be input variables, which are relative posture between the robot and the destination point. According to the posture between the robot and the destination point, we can find desired robot’s heading angle $\phi$, which is the output variable. Table I and Figure 3–Figure 5 are the membership function and the fuzzy rules of $u_1$, $u_2$ and $\phi$, respectively.

#### Table I. Fuzzy rules for $\phi$.

<table>
<thead>
<tr>
<th>$u_1$</th>
<th>$u_2$</th>
<th>$\phi$</th>
</tr>
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<tbody>
<tr>
<td>NB</td>
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<td>NM</td>
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#### Figure 1. Overall fuzzy control structure

#### Figure 2. The distance $d_s$ becomes zero when the vehicle stabilizes at its final configuration.

#### Figure 3. Membership function of $u_1$ (deg.).

#### Figure 4. Membership function of $u_2$ (deg.).

#### Figure 5. Membership function of $\phi$ (deg.).

### IV. EXPERIMENT RESULTS

The position and heading angle of the robot, which are the inputs to the controller, are obtained from the captured image only. Figure 6 shows a functional block diagram of the closed loop control system. The WMR has no embedded
position sensor, as shown in Figure 7 and its RF receiver only listens to commands from the host computer. The position information is obtained by recognizing the color mark on top of each WMR. In view of the low resolution of the camera (320×240 pixels), the readings of the robots’ positions and heading angles are subject to tolerances. In practice, for a stationary WMR, the tolerance of position would be about three pixels, whereas that of the heading angle will be even greater (sometimes more than 20°). Errors of input signals are therefore inevitable. This is because the velocity is estimated by dividing a pixel count by time, which is inherently inaccurate when the pixel reading itself has errors.

4.1 Position control

Case 1: The WMR initial location (58 cm, 30 cm, -46°), The target location is (150 cm, 80 cm), experiment result as shown in Figure 8 and Figure 9.

Case 2: The WMR initial location (59 cm, 120 cm, 30°), The target location is (160 cm, 70 cm), experiment result as shown in Figure 10 and Figure 11.
4.2 The trajectory tracking control

Case 1: The WMR initial location (34 cm, 36 cm, 58 cm) desire to track the trajectory line \( y = 100 \), experiment result as shown in Figure 12 and Figure 13.

Case 2: The WMR initial location (18 cm, 46 cm, 78 cm) desire to track the trajectory line \( y = 0.4x + 120 \), experiment result as shown in Figure 14 and Figure 15.

Case 3: The WMR initial location (20 cm, 81 cm, -140°), desire to track the trajectory line \( y = -30\sin(\frac{x}{25}) + 90 \), experiment result as shown in Figure 16 and Figure 17.

V. CONCLUSION

This paper presents a hierarchical fuzzy logic controller including a path planning method for WMR navigation from an initial position to a desired position and orientation. Moreover, with existence of obstacle, the proposed fuzzy controller also can handle the situation without colliding with obstacles. The result of simulation and experiment demonstrates that the proposed fuzzy controller has satisfactory behavior. The future objective will stress the ability of obstacle avoidance, ex. Mobile obstacles, optimal path planning, reduce the travel time, etc.

REFERENCES


