A Fuzzy Inference System for the Front Steering Control of an Autonomous Mobile Vehicle

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Abstract: - This Paper presents a Fuzzy Inference System as a path tracking controller for the front steering of an autonomous mobile vehicle. The Paper focuses on the application of a Fuzzy Inference System to a mobile vehicle kinematics model, and on developing a Graphical User Interface (GUI) to simulate the path tracking by steering the front wheels. Here it is demonstrated that the proposed Fuzzy Inference System leads the vehicle to move precisely along a predefined path in both straight line and curve sections.

Key-Words: - Fuzzy Inference Systems, Neuro-Fuzzy Control, Kinematic Control, Autonomous Vehicles

1 Introduction

In many urban environments, the usage of the private vehicles has led to severe problems with respect of pollution, noise, safety and general degradation of the quality of life. Alternative solutions to the private vehicles with the same flexibility now appear with a new concept of mobility: the vehicle is part of the public transportation system and is used as a complement to mass transit and non-motorised transportation [3], [4], [5].

A previous work presented in [2] provides an autonomous vehicle (cybernetic car) controller architecture. Its main component includes 4 modules for: the front steering, rear steering, velocity and the look-ahead distance controller. The controller proposed in [2] includes two major kinematics (straight line and curve) models which have their own fuzzy membership functions and rules. Under the curve section, there are two subsystems to manipulate the vehicle movement inside and outside the track.

In this Paper, a Fuzzy Inference System for the steering control of an autonomous cybernetic vehicle. However, here unlike the work in [2]:
(a) Only one controller is used for steering the whole mobile vehicle;
(b) A more detailed set of fuzzy logic rules are used. These refined rules (37 rules for the straight line movement; 25 rules for the curve movement) enable smoother vehicle movement and steering;
(c) Only one controller layer is utilized to steer the front wheel.

This paper presents a strategy and a Fuzzy Inference System for path tracking through the vehicle front steering control system. Here it is shown that the path tracking results reflect good performance and accurate path tracking in simulation. This is due to the smooth transitions between rules and the interpolation between different actions. Although there may be a smooth movement concern in the curve sections, this problem can be solved by reducing the vehicle velocity.

Furthermore, here it is also demonstrated that the vehicle can move precisely along the predefined path in both straight line and curve sections.

2 The Vehicle Kinematic Models

In this paper, a pre-defined path is established as a test bed. This path includes 2 straight lines and 2 arcs and the autonomous mobile vehicle will steer the front wheel to follow the pre-defined path. The path is represented as a green line in the simulation in the Figure 1, and the vehicle initial orientation (+45° degrees) and position (0, 45) is illustrated in Figure 9.

Here two kinematic models are considered: Vehicle Kinematics Model on the Straight Path; and Vehicle Kinematics Model on the Curve Path.
2.1 Vehicle Kinematic Model- Straight Path

The vehicle kinematics can be simply represented in the Figure 2, as shown in [2]. Point A is the present vehicle position with the lateral deviation $E_{LR}$ and the orientation deviation $E_{\theta}$. The vehicle will move from A to C and then continue to move far away from the predefined path if fuzzy logic controller does not have an effect on the front wheel steering.

$$L = (L(m + \text{step}) - L(m))$$
$$X_{B} = X_{C} + L; \quad Y_{B} = Y_{C} + L \cdot \tan(E_{\theta}); \quad E_{\theta} = \text{phi}$$

2.1 Vehicle Kinematic Model- Curve Path

For the vehicle running outside the track:

Similarly, the kinematics model along the curve can be represented in the Figure 3, leading to the following relationships:

The vehicle present distance to the centre of the arc is:

$$OB = \sqrt{(x_{B} - x_{O})^2 + (y_{B} - y_{O})^2}$$

$$\angle CBF = \text{phi} + \phi - \angle IBC$$

$$\angle IBH = \text{phi}^\prime$$: The initial (previous) direction;

$$\angle HBF = \text{phi}^\prime$$: The steering angle adjustment after fuzzy inference control;

$$\angle IBC$$: Since line BC is parallel to the line AG which is the tangent of the curve at point A, therefore $\angle IBC$ is known.

$$\angle OBC = 90^\circ$$,  \quad \angle OBE = 90^\circ - \angle CBF$$

$$\angle BOE = \text{delta_angle} = \text{track}_\theta(m) - \text{track}_\theta(m + \text{step})$$

From the triangle sine law, we have:

$$\frac{\sin \angle OBE}{\sin \angle BFO} = \frac{\sin \angle CBF}{\sin \angle BFO}$$

$$r \cdot (x_{B} - x_{O})^2 + (y_{B} - y_{O})^2 \approx \frac{\sin \theta}{\sin (90^\circ - \angle CBF)} \sin (90^\circ - \angle CBF) \sin (90^\circ - \angle CBF)$$

$$\Delta D = r \cdot \Delta F$$

$$\Delta x \approx \frac{\sin \theta}{\sin (90^\circ - \angle CBF)} \sin (90^\circ - \angle CBF) \sin (90^\circ - \angle CBF)$$

where $r$ is the radius of the curve.

When the delta angle is very small, the distance:

$$DF = \Delta x \approx \frac{\sin \theta}{\sin (90^\circ - \angle CBF)} \sin (90^\circ - \angle CBF) \sin (90^\circ - \angle CBF)$$

where $\Delta x$ is the new x position deviation comparing to the nominal.
Instead of moving to the point F, the vehicle turns at the point E. We will see that the vibration can be greatly decreased.

For the vehicle running inside of the track:
The vehicle present distance to the centre of the arc is:
\[
OB = \sqrt{(x_a - x_o)^2 + (y_a - y_o)^2}
\]
\[
\angle EBG = -\phi_i + \phi + \angle GBI
\]
\[
\angle HBE = \phi_i' : \text{The initial (previous) direction};
\]
\[
\angle HBI
\]
\[
\phi
\]
\[
\phi_i
\]
\[
\angle IBE
\]
\[
\angle IBG
\]
\[
\text{Since line BC is parallel to the line AG which is the tangent of the curve at point A, therefore } \angle IBC \text{ is known.}
\]
\[
\angle OBG = 90^\circ
\]
\[
\therefore \angle FBO = 90^\circ + \angle EBG = 90^\circ - \phi_i + \phi + \angle GBI
\]
\[
\angle BOE = \text{delta_angle}\cdot\text{delta_angle}\cdot\text{track_thet}(m)\cdot\text{track_thet}(m+\text{step})
\]
\[
\sin\angle FBO \cdot \sin\angle 80 \cdot \angle FBO - \angle BOB
\]
\[
\frac{\sin\angle FBO}{\angle FBO}
\]
\[
\frac{\sin\angle 80 - \angle FBO - \angle BOB}{\angle FBO}
\]
\[
\frac{\sin\angle FBO}{\angle FBO}
\]
\[
\frac{\sin\angle 80 - \angle FBO - \angle BOB}{\angle FBO}
\]
\[
\text{Figure 4. Vehicle inside of the curve path}
\]

Another point DE’ is set up, which is equivalent to the distance of DE.

During the movement, the vehicle will stop at the point F rather than point E. Then it turns to the point E’. As the result, the deviation of the vehicle is very little and the vibration will be reduced as well.

3 Controller Input, Output
In this Paper also Fuzzy Logic is used for developing a Fuzzy Inference System for the steering control of a mobile vehicle. However, here unlike as in [2], it is considered the following:
(a) Only one controller is used for steering the whole mobile vehicle; whereas in [2], 4 controllers are used.
(b) A more detailed set of fuzzy logic rules are used; whereas, in [2] only 4 rules are used for front wheel steering. These refined rules (37 rules for the straight line movement; 25 rules for the curve movement) enable smoother vehicle movement and steering;
(c) Only one controller layer is utilized to steer the front wheel; using 2 fuzzy files for straight line and curve separately. Whereas, 2 layers of the controller to steer the front wheel are used in [2].

Here, the main elements of the proposed Fuzzy Inference System (FIS) are presented. First, the inputs and outputs to this FIS are established; followed by the set up of the FIS corresponding membership functions and Fuzzy Logic rules.

A. On the Straight Path

• Inputs:
The Lateral Error (LE) membership function is a fifth-pronged triangular membership functions and two trapezoidal membership functions, representing lateral distances conditions: High Negative LE (HNLE), Negative LE (NLE), Low Negative LE (LNLE), Zero LE (ZLE), Low Positive LE (LPLE), Positive LE (PLE) and High Positive LE (HPLE).

• Outputs:
The FrontSteering (FS) membership function is a fifth-pronged triangular membership function and two trapezoidal membership functions, representing the Front Steering commands: High Negative FS (HNFS), Negative FS (NFS), Low Negative FS (LNFS), Zero FS (ZFS), Low Positive FS (LPFS), Positive FS (PFS) and High Positive FS (HPFS).

• Rules:
The following rules constitute part of the knowledge bade of the PTC and express how the system would react:
If LE is LPLE and AE is LNAE then FS is LNFS;
If LE is LNLE and AE is LPAE then FS is LPFS;
If LE is LPLE and AE is LPAE then FS is LNFS;
If LE is LNLE and AE is LNAE then FS is LPFS.
The Figures 5 and 6 illustrate the inputs, outputs and rules based on the above description. 37 rules have been established to control the mobile vehicle movement.

### A. On the Curve Path

**Inputs and Outputs:**
Besides the Lateral Error (LE) and the Angle Error (AE), one more input is added into the system – Delta Angle Error (DAE). Unlike the AE along the straight line, the curvature of the arc will change the AE in the next step. Therefore DAE has to be considered in the curve section movement.

Its membership functions include AE Decreasing (DDAE), AE Constant (CDAE) and AE Increasing (IDEA). The output is the same as the ones on the straight path.

**Rules:**
The following rules are part of the knowledge base of the PTC and express how the system would react:
- If LE is LPLE and AE is LNAE and DAE is DDAE then FS is INFS;
- If LE is LPLE and AE is HNAE and DAE is IDEA then FS is NFS;
- If LE is LNLE and AE is HPAE and DAE is IDEA then FS is PFS;
- If LE is PLE and AE is PAE and DAE is IDEA then FS is LNFS.

### 4 Simulation

In this Paper, a pre-defined path as in Figure 1 is established prior to the simulation. This path includes 2 straight lines and 2 arcs and the autonomous vehicle will steer the front wheel to follow the pre-defined path. The path is represented as a green line in the simulation. The vehicle initial orientation (+45° degrees) and position (0, 45) is illustrated in detail in the Figure 8.

The developed FIS in Matlab is used to simulate the dynamic moving status of the vehicle. The FIS controller computes the Lateral Error (LE) and Angle Error (AE) and triggers a fast recovery from the initial pose. Then the vehicle merges precisely into the pre-defined path as shown in Figure 9.

The Matlab FIS program also simulates the vehicle movement in the curve section. Comparing the straight line section movement, the car has less smoothness because of the additional DAE.
In order to recover faster, the vehicle has to turn larger angles along the curve as shown in the Figures 10, and 11. However this problem is overcome by reducing the step size, in the other words, decreasing the vehicle speed. It is shown in the figure 12, that the vehicle has less vibration when the speed is reduced from 1m/s to 0.45m/s.

A graphical user interface is also built in order to enable the users to easily select the initial position, orientation and stop stations along the track. By using the Matlab 6.5 GUIDE tool box, a template is designed to contain the following figures, slides, radio buttons and push buttons.

A Matlab program is designed as the interface between the GUI and the FIS execution vehicle movement programs. After the user selects the initial pose inputs (includes both position and orientation) and stop station, the program will transfer this information to the executable programs to trigger the vehicle first movement.

From the simulation of the entire (line and curve) path, presented in Figure 13, it can be easily observed that the vehicle can quickly match the path and move smoothly along the path.
5 Error Analysis
In order to evaluate the developed FIS performance for the mobile vehicle movement, data is collected to compare the actual stopping pose to the desired ones at each station. Based on this criterion, the vehicle is tested to start from the initial point with the maxim deviation (+18.2m, +60 degrees) and reach one of the stations (10 times for each station).

The Table 1 details the desired and actual position and orientation, relative errors and the speed when reaching the three different stations.

The table reveals that the x deviation at station 1 and orientation deviation at station 2 are relatively larger comparing to the other deviations. These are due to the high speed when the vehicle stops. After it is reduced the 1st straight line and 1st curve section speed to 10x and 5x respectively, the actual position and orientation are greatly improved when it reaches the desired stations. As we can see from the above table, the x deviation error is reduced from 5.44% to 0.49% at station 1 and orientation error is reduced from 14.08% to 0.12% at station 2.

Therefore, a conclusion can be made that the error will be dramatically decreased by reducing the vehicle velocity during the movement.

6 Conclusions
In this Paper a strategy and a Fuzzy Inference System as a control for path tracking through of an autonomous mobile vehicle front steering control system it is presented. Here it is shown that the path tracking results reflect good performance and accurate path tracking in simulation; this is due to the smooth transitions between rules and the interpolation between different actions. It has been demonstrated that the vehicle can move precisely along the predefined path in both straight line and curve sections.

Although there may be a smooth movement concern in the curve sections, this problem can be solved by reducing the vehicle velocity. More importantly, here it is also demonstrated that the vehicle can move precisely along the predefined path in both straight line and curve sections.

Here also a Graphical User Interface (GUI) for simulation purposes has been developed. This GUI enables the user to select the start point, initial orientation and the stations visually and perform the simulation effectively.

Future Tasks
The velocity control based on the path status and the obstacles is a big challenge for the overall control system. The on-line communication between the external signals and the internal reactions has to be considered carefully under the real working environment.

REFERENCES