Fuzzy Logic Steering Controller for a Guided Vehicle

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Abstract - This paper presents the development and implementation of a Fuzzy Logic Steering Controller for a Guided Vehicle based on the visual recognition of a white line on the floor. The Fuzzy Controller is supported by a vision sub-system with a CCD camera. Experimental results obtained with a test platform are presented.

I. INTRODUCTION

The steering control of Autonomous Vehicles has been an area of intensive research in the past few years, [2], combining new control strategies, [5], with the advances in the sensing technology, [7]. The use of different types of sensing devices and the application of new control methodologies lead to an increase of the performance of Guided Vehicles with no major differences on their complexity.

The most common navigation schemes for Automatic Guided Vehicles (AGVs) are based on a network of paths, defined by a buried wire (inductive steering) or by a white guiding line (optical steering) on the floor. In both cases, the path sensing devices provide the necessary information for the vehicle steering controller. PID controllers are commonly used in AGVs.

The advances in the image processing theory have been the framework for the development of visual techniques in the area of robotics, namely those concerned with sensor based navigation and collision avoidance tasks, [3], [4]. Also, during the past several years Fuzzy Logic has emerged as a fruitful research area with potential application on the control of autonomous vehicles, [1].

In this paper we present a Fuzzy Controlled AGV equipped with a CCD camera that acts as a guiding sensor providing the optical information to steer the vehicle along a white line in the floor. The block diagram of the controlled system is represented in Figure 1.

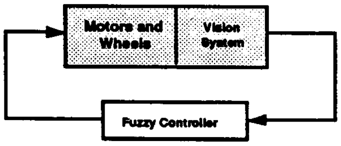

Figure 1: Block Diagram

The experimental tests carried out consider a white strip on a dull black flat ground. This environment avoids optical reflections that may lead to white strip detection problems. The experimental path layout has a topology usually found in industrial plants with curves, straight lines and crossing ways.

The mobile platform used as a test-bed has a rear free wheel and two front drive wheels supported on a transversal axis. It is driven by two electric motors allowing speed and orientation control. The vehicle orientation is controlled through the differential component, v_d, of the velocity applied to each drive wheel. The common component of these velocities, v_c, is the vehicle linear speed, with a maximum value of $0.55 m/s$.

II. VISION SYSTEM

The vision system acts as a smart sensor that acquires and processes the information needed to steer the Mobile Platform along a white line on the floor. To accomplish this task, a CCD camera is used and the difference of contrast between the white line and the black floor is evaluated. The image processing algorithm has a simple structure, with a modest time consumable implementation. It coupes with trajectory junctions, derivations and crossovers. It also overcomes discontinuities and imperfections (e.g., shadows, nastiness) on the white line as well as environment light variations. The vision system, implemented with a modular structure, is composed by the six main blocks represented in Figure 2.

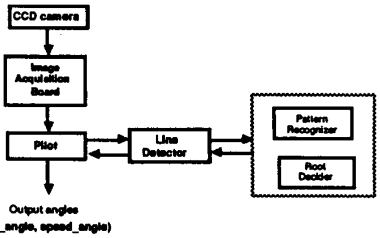

Figure 2: Vision System

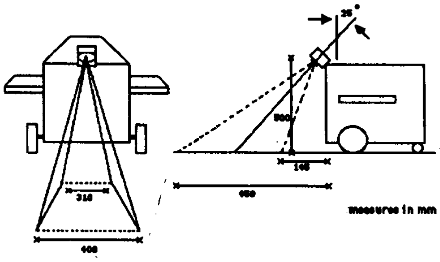

Figure 3: Location of the CCD Camera

CCD Camera

The CCD camera is positioned in the front of the vehicle, along its longitudinal axis, $500 mm$ above the ground, looking ahead with an angle of $25°$ with the vertical axis. The visual field is a trapezoidal area as shown in Figure 3.

Image acquisition

The image acquisition is performed through a DT-IRIS board, that acquires 512 × 512 black and white images with 256 grey-levels. Using the threshold operation supplied with the board, the acquired image is transformed into a binary image with levels 0 and 255 corresponding respectively to black and white colours. The threshold was defined on level 255 after

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the study of some relevant histograms. Any other choice of this level will not improve the white line clearness.

Pilot

This block evaluates the drift of the Mobile Platform relative to the white line.

In operation, the mobile platform must follow as closely as possible the white line above it and a speed reduction is required along a curve path. To achieve this behaviour, it is necessary to evaluate the vehicle's drift relative to the white line in its near vicinity and to predict the path topology ahead of the vehicle. This topology is estimated as the drift of the ahead trajectory relative to the actual one. These drift measures are named as **turn_angle** and **speed_angle**.

At each iteration, k, the Pilot provides the Line Detector with the initial values of the distances $d_{i1}(k)$ and $d_{i2}(k)$, for the image scanning procedure aiming at identifying the white band. After the completion of the scanning procedure, the Line Detector returns the Pilot the distance values $d_{f1}(k)$ and $d_{f2}(k)$ where the line was detected and the coordinates of the middle points, $P_1(k)$ and $P_2(k)$, of the band at the correspondent distances.

At iteration $k+1$ the initial distance values for the search are given by the recursion

$$\begin{cases} d_{i1}(k+1) = -(D_1 - d_{f1}(k))/2 \\ d_{i2}(k+1) = -(D_2 - d_{f2}(k))/2 \end{cases} \tag{1}$$

with $d_{i1}(1) = D_1$ and $d_{i2}(1) = D_2$ are established as a function of the vehicle maximum speed.

The coordinates of the middle point of the white band identified at the distances $d_{f1}(k)$ and $d_{f2}(k)$ are given by

$$\begin{cases} P_1(k) = (x_1(k), d_{f1}(k)) \\ P_2(k) = (x_2(k), d_{f2}(k)) \end{cases} \tag{2}$$

leading to

$$\textbf{turn\_angle} = arctg(x_1(k)/d_{f1(k)}) \tag{3}$$

$$\textbf{speed\_angle} = arctg(x_2(k)/d_{f2(k)}) \tag{4}$$

With the above definition **turn_angle** is the angle between the image longitudinal axis and the line defined by the middle point, of the image bottom line and the point, $P_1(k)$, corresponding to the image line at the distance $d_{f1}(k)$ from the vehicle. The **speed_angle** is similarly defined for $P_2(k)$. These definitions, are illustrated in Figure 4.

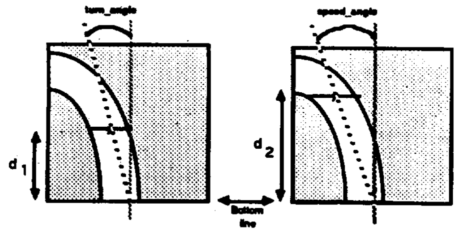

Figure 4: Definition of **turn_angle** and **speed_angle**

Line Detector

The Line Detector implements a sequential search procedure in the binary image. At each iteration, the line search starts at image lines at distances $d_{i1}(k)$ or $d_{i2}(k)$ provided by the Pilot. For each examined line, the Line Detector implements a sequential search on the pixels. As soon as the first white pixel is found, the search is oriented towards the next black pixel. Whenever this black pixel is found, the Line Detector invokes the Pattern Recognizer to decide if the identified gap of white pixels corresponds to a white line. After the recognition, the Line Detector proceeds the analysis at the same image line to identify other possible white line occurrences. If more than one band is found in an image line, e.g., in a cross, the Line Detector invokes the Root Decider to decide which one the vehicle should follow.

There are situations, which occur when the Mobile Platform is entering or leaving a curve path, where there is no white band at the image lines that correspond to the initial distances $d_{i1}(k)$ and/or $d_{i2}(k)$ provided by the Pilot. In these situations, new image lines are analysed corresponding to smaller distances ahead from the vehicle than those initially provided by the Pilot.

Pattern Recognizer

The Pattern Recognizer examines the number of consecutive white pixels found out by the Line Detector in a line in order to decide if they correspond to a white band.

The width of the white band depends on the image line where it was found, due to image perspective. Real experiments lead to the conclusion that the width of the white band in a image varies between 23 and 43 pixels in the image line far from the vehicle ($0.45m$) and between 33 and 83 pixels in the image line nearest from the vehicle ($0.145m$). Between these two image lines the width variation of the white band is considered to be linear.

Root Decider

If more than one white line is recognised in an image line the Root Decider decides the one to follow.

The white line chosen in such a situation is the one that leads to the minimum change of direction on the vehicle current trajectory. Different choice methodologies could have been implemented and tested.

III. FUZZY CONTROLLER

This section describes the vehicle Fuzzy Controller.

The controller receives the signals **turn_angle** and **speed_angle** as inputs and generates, as output, the steering signals, v_c and v_d, to drive the mobile robot. The first one, v_c, represents the vehicle speed in a straight line, whenever $v_d = 0$. The differential component, v_d, defines the positive increment to the left wheel and the negative increment to the right wheel that leads to a vehicle curve path oriented towards its right side.

The Fuzzy Controller structure is represented in Figure 5. The role of each block is the following:

- the *Fuzzification Interface* converts the input crisp values (**turn_angle**, **speed_angle**) provided by the Pilot into linguistic terms of the input fuzzy variables (TURN_ANG and SPEED_ANG), with a correspondent certainty value,
- the *Knowledge Base* stores the data that defines the input and the output fuzzy sets, as well as the fuzzy rules that describe the control strategy,
- the *Decision Logic* block applies the fuzzy rules to the input fuzzy variables to obtain the output values (VC, VD),

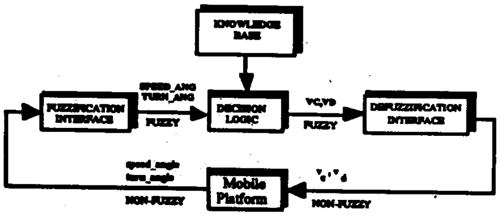

Figure 5: Fuzzy Logic Controller

- the *Defuzzification Interface* achieves crisp output signals (v_c, v_d) based on the output fuzzy sets obtained as the result of fuzzy reasoning.

Linguistic Variables

To drive the Mobile Platform along the desired track, the control actions must impose the behaviour of the vehicle as a function of its actual state quantified by **speed_angle** and **turn_angle**.

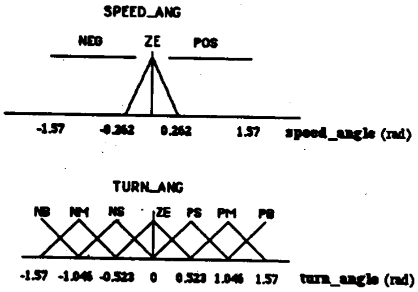

Figure 6: Linguistic terms of the input variables

The universe of discourse and the linguistic terms of the input variable SPEED_ANG represented in Figure 6 are defined to distinguish the situations when the vehicle is following a straight line (linguistic term ZE) or is describing a curve path (linguistic terms NEG, POS). For the Mobile Platform under experiment it revealed adequate to admit a straight line whenever | speed_angle $|\leq 15°(0.262 rad.)$.

The input variable TURN_ANG has an universe of discourse and a set of seven linguistic variables (PB, PM, PS, ZE, NS, NM, NB), experimentally designed and containing the information on the radius of the curve to be described.

The two output linguistic variables, corresponding to the crisp values v_c and v_d are VC (common speed) and VD (differential speed). Their linguistic terms are represented in Figure 7.

The output variable VC and the defuzzification method (minimum-of-maximum), [6], were designed in a such a way that if the inferred value for the speed is "SLOW" (the vehicle is describing a curve) the common speed,VC, will be $0.22m/s$; otherwise VC varies linearly with the inferred certainty.

The output variable VD and the defuzzification method (centre-of-area), [6], were designed in such a way that the differential speed, v_d, defines the increment/decrement of the speed of the left/right wheel as a function of the radius of the curve to be tracked.

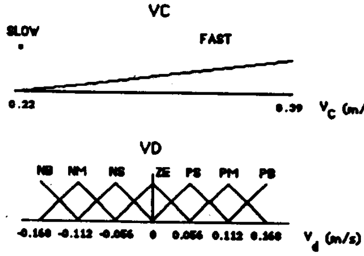

Figure 7: Linguistic terms of the output variables

Fuzzy Rules

The required operation conditions for the Mobile Platform distinguish its behaviour in a straight line and in a curve trajectory. In the first case, the vehicle should accelerate/decelerate linearly as a function of the drift relative to the white band. In a curve path, the vehicle linear velocity should be constant and equal to $0.22m/s$. In fuzzy reasoning this means that the vehicle will travel at "FAST" speed when SPEED_ANG is "ZE" and TURN_ANG is "PS", "ZE" or "NS". This is the case when the vehicle travels along a straight line. When the vehicle is describing a curve the inferred common speed must be "SLOW".

The linguistic variable SPEED_ANG has three linguistic terms while TURN_ANG has seven linguistic terms leading to a maximum number of twenty one terms that can be achieved. The rules designed to control the vehicle, have the general format

if (SPEED_ANG, TURN_ANG) then (VC, VD)

and are listed in the following table, where ',' stands for "also" and '*' stands for "any value".

RULE	IF	SPEED_ANG	TURN_ANG	THEN	VC	VD
1	IF	POS NEG	PS, PS	THEN	SLOW	PS
2	IF	ZE	PS	THEN	FAST	PS
3	IF	*	PM	THEN	SLOW	PM
4	IF	*	PB	THEN	SLOW	PB
5	IF	ZE	ZE	THEN	FAST	ZE
6	IF	POS NEG	ZE, ZE	THEN	SLOW	ZE
7	IF	POS NEG	NS, NS	THEN	SLOW	NS
8	IF	ZE	NS	THEN	FAST	NS
9	IF	*	NM	THEN	SLOW	NM
10	IF	*	NB	THEN	SLOW	NB

IV. EXPERIMENTAL RESULTS

The proposed steering technique was tested in a mobile platform equipped with a CCD camera.

The ideal choice of D_2 is the one that for which a curve path is detected a distance ahead that allows a smooth deceleration before entering the curve. Due to the small vision field of the camera used in the experiments, the best choice is to take D_2 at the top image line. However, as it is displayed in the results, this value revealed insufficient and differences are verified between the reference trajectory and the one followed by the vehicle.

The value of D_1 results from a trade-off between the computational time for each iteration and the vehicle common speed.

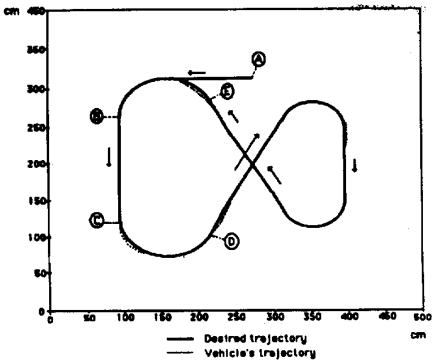

Figure 8: Trajectory of the vehicle

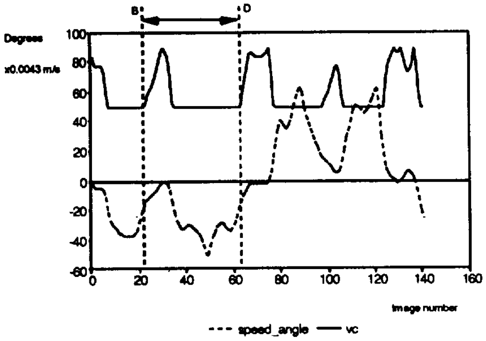

Figure 9: Evolution of common speed

For this experimental set-up D_1 also coincides with the image top line.

Figure 8 represents, with a solid line, a real path used for the vehicle test and, with a dashed line, the trajectory actually performed. The unmatched situation near the curves results from the small value of D_2 which is a direct consequence of the reduced field of vision of the camera. With this restriction, a curve path is detected when the vehicle is too near from it leading to high deceleration values imposed by the controller.

Figures 9 and 10 display the evolution of **VC**, **speed_angle**, **VD** and **turn_angle** during a test along the real trajectory starting in point **A**, visiting **B**, **C**, **D** and finishing in **E**. The labeled region in both Figures corresponds to the track between **B** and **D** in Figure 8.

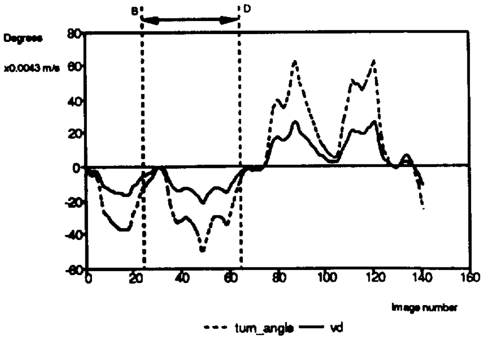

Figure 10: Evolution of differential speed

Figure 9 displays the control actions imposed to the vehicle in terms of v_c. In **B** the vehicle enters a straight line being subjected to an acceleration whose value is a function of the drift relative to the ideal trajectory. When the vehicle detects the curve path (**C** → **D**) it is subject to a deceleration until a minimum value of v_c is reached. In the curve (**C** → **D**) the common speed is constant and equal to $0.22m/s$. Figure 10 confirms, trough experience, the linear relation between **turn_angle** and v_d imposed by the Fuzzy Rules.

V. CONCLUSIONS

The motion control of an autonomous vehicle is presented. A Fuzzy Logic Controller generates the steering signals to drive the mobile robot based on environment information provided and processed by a vision system. A set of twenty one fuzzy rules and a linguistic description of the input and output variables are derived to define the knowledge base of the Fuzzy Controller.

The almost perfect matching between the real trajectory and the desired one shows the performance of the proposed steering system. The small errors in the vehicle trajectory when entering or leaving a curve path are related to the sensing device and are easily overcomed by replacing the CCD camera by another one with an higher vision field.

The efficiency, low cost and easy implementation of the proposed controller lead to the conclusion that Fuzzy Logic is an adequate and promising framework for the project of steering mechanisms of mobile robots. Future work in this project includes the integration of a path planner and a root decider as well as mechanisms for the detection of unexpected obstacles left on the vehicle trajectory.

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