Speed and position control of autonomous mobile robot on variable trajectory depending on its curvature

Mahit Gunes and A Fevzi Baba

1Department of Electrical-Electronics Engineering, Kahramanmaras Sutcu Imam University, K.Maras/Turkey
2Electronics and Computer Department, Technical Education Faculty, Marmara University, Istanbul/Turkey

Received 07 July 2008; revised 13 March 2009; accepted 19 March 2009

This paper presents design of autonomous mobile robot MBR-01 for speed and position control on variable trajectory depending on trajectory curvature. MBR-01 can communicate reciprocally with host computer using RF data transceiver. Road data image is captured by CCD camera mounted on vehicle and transferred to host computer using RF data link unit. Applying image processing on trajectory, reference speed has been produced depending on curvature of trajectory. Reference speed is applied to fuzzy controller unit and output is sent to vehicle by wireless transmitter unit. Received control signal by vehicle is transferred to DC motor drive system with Pulse Width Modulation techniques. Position control is realized by microprocessor-based units mounted on vehicle. Equipped 7 optical sensors detect trajectory deviation and wheel angle of vehicle for track detection and wheel angle detector unit.

Keywords: Autonomous mobile robot, Fuzzy edge detection, Position control, Speed control

Introduction

Autonomous mobile robots are characterized by nonlinear and complex dynamics, such as turning and static friction, and noisy and typical harsh outdoor environments. Robot navigation in outdoor environment requires a real-time image processing at variable natural illumination, bright sunlight, clouds, etc. Different methods on mobile robot navigation include behavioral-based of vehicle from combination of several behaviors including trajectory tracking, target tracking, obstacle avoidance, landmark recognition systems, soccer robots navigation, model-based and feature-based methods are used for trajectory-tracking and navigation toward objects. Methods on fuzzy logic based mobile robot navigation include numerous studies as indoor laboratory environments while some of them discuss outdoor navigation using fuzzy systems. Generally, indoor applications include corner detection, door detection, wall-following, path planning, seeking the goal position. Outdoor applications consist of garage-parking, parallel parking, stair climbing, scrambling over rubble, human-like driving using GPS systems.

Under unknown and dynamic real world conditions, Internet allows users to connect to a website and remotely control a robot manipulator or a mobile robot. A number of limitations and difficulties (restricted bandwidth, image transmission delays, and packet lost or error), influence performance of Internet-based robot navigation systems.

This paper proposes a vision-based speed and position control on variable trajectory of developed autonomous mobile robot (MBR-01), which can be remotely controlled by host computer with wireless image transferring unit mounted on MBR-01 for different applications.

Materials and Methods

A. System Structure

Developed vehicle (Fig. 1) weighs 11 kg and has maximum speed of 4 m/s. It is equipped with 12VDC 4Ah battery power supply unit, to navigate for 6 h. Vehicle has two electrical motors; steering motor provides orientation of driving wheel, and second motor provides driving torque. A wireless image transmitter unit (2.4 GHz carrier frequency) captures trajectory information with a CCD camera and transfers image data to computer. There is a reciprocal RF data transmitter unit for controlling signals between robot and computer (Fig. 2). At the mobile
Fig. 1—Developed autonomous mobile robot (MBR-01)

Fig. 2—Simplified control diagram of the system
robot side, a fuzzy controller unit performs position control by getting angle of steering wheel and deviation information. Road data image is received from video receiver mounted on computer, and then video interface unit captures this image from receiver output. After completion of this process, fuzzy edge detection and line extraction algorithms are activated.

After line extraction process on trajectory, reference speed is determined depending on curvature of trajectory. Speed error and its derivative values are applied to fuzzy controller. Control signal is modulated at 433 MHz carrier radio frequencies and then transmitted back to vehicle side, where control signal is received by video receiver unit and applied to speed controller unit. Steering control unit is processed on vehicle side by microprocessors based on fuzzy algorithm unit. For this process, vehicle is equipped with 7 sensors to take its position deviation according to desired trajectory. Position error is applied to fuzzy position controller.

B. Fuzzy Edge Detection

In robot navigation, edge detection methods (Sobel, Prewitt, Roberts and Gradient) are not robust to noise and environment changes, since a robot requires image processing in real-time. Fuzzy reasoning classifies a pixel in an image into a border region or a uniform region based on luminance differences between this pixel and its neighboring pixels. Detecting edges by fuzzy inference classifying every pixel in an image into white or black is based on: i) If a pixel points on border region then make it black, else make it white; and ii) If a pixel points to a uniform region then make it white, else make it black. To decide whether a pixel belongs to a border or a uniform region, luminance differences between pixel and its neighboring pixels have to be computed (Fig. 3). In processed image, it is started to compute from upper left corner point (0, 0) to bottom right corner point (X, Y). Through entire line, every U pixel and its neighboring luminance differences are calculated individually and then decided to whether pixel is on edge or not. It is possible to define 8 different rules (Fig. 3). C++ software was developed to implement this process. If resolution is 640 x 480 pixels then 307200 calculations will be required and it reduces overall speed of the system. This is a disadvantage for a big resolution image. Each pixel on processed image is composed of RGB values and each color has 8 bit resolution. Thus maximum value of each color will be hexadecimal FF and maximum value of each pixel will be hexadecimal FFFFFF (= .6777215). Using black/white CCD camera, there is no important difference between 8 bit gray image or 32 bit color image to make decision in edge calculation.
So in this study 8-bit gray level is used to obtain maximum image processing speed. Maximum value 255 corresponds to white, and minimum value 0 corresponds to black. U value of 255 is black and value of -255 is white. For control input, luminance difference membership function is defined by triangular function (Fig. 4). Two fuzzy sets are defined in input function. NEG corresponds to negative, POZ corresponds to positive, BLK corresponds to black and WHT corresponds to white. As a result of defined rules, output membership function of each U point will be white if point is a plane, or black if it is an edge. Membership functions of outputs based on gray level intensity of pixel Q are determined by following 8 fuzzy rules.

1. If (f1 is neg) and (f2 is neg) and (f4 is poz) and (f5 is poz) and (f6 is poz) and (f8 is neg) then (u is black).
2. If (f2 is neg) and (f3 is neg) and (f4 is neg) and (f6 is poz) and (f7 is poz) and (f8 is poz) then (u is black).
3. If (f2 is poz) and (f3 is poz) and (f4 is poz) and (f6 is neg) and (f7 is neg) and (f8 is neg) then (u is black).
4. If (f1 is neg) and (f3 is poz) and (f4 is poz) and (f5 is poz) and (f7 is neg) and (f8 is neg) then (u is black).
5. If (f1 is poz) and (f3 is poz) and (f4 is neg) and (f5 is neg) and (f6 is neg) and (f8 is poz) then (u is black).
6. If (f1 is poz) and (f2 is poz) and (f4 is neg) and (f5 is neg) and (f6 is neg) and (f7 is poz) then (u is black).
7. If (f1 is poz) and (f3 is neg) and (f4 is neg) and (f5 is neg) and (f7 is neg) and (f8 is poz) then (u is black).
8. If (f1 is poz) and (f2 is poz) and (f3 is poz) and (f5 is neg) and (f6 is neg) and (f7 is neg) then (u is black).

Luminance of each pixel is computed by Centroid Defuzzification Method as defined in Eq. (1).

\[ Q = \frac{\sum_{i=1}^{n} u_i \mu_{out}(u_i)}{\sum_{i=1}^{n} \mu_{out}(u_i)} \] …(1)

In this study, it is evident that determining limit value of input membership functions is very important. Changing limit values affects output defuzzification process, as indicated in original processed image (Fig. 5) and different membership functions (Fig. 6). Membership functions were defined with changeable limit values, which were determined by average luminance difference value of processed image.

C. Fuzzy Speed Control of MBR-01

In speed control process of mobile robot, reference speed has been determined according to curvature of trajectory. To get this process, firstly fuzzy edge detection algorithm was applied on image and then developed line extraction algorithms from image determined trajectory. According to specified trajectory curvature, reference speed was determined by software defined by slope-speed transfer curve. After determining reference speed, speed error and error change were applied to fuzzy controller unit. Speed error and error deviation are input variables of fuzzy controller, which has two inputs in the range of -10 to +10 pulse per second. This pulse was produced from encoders equipped with rear wheels of the vehicle. Fuzzy output was applied to pulse width modulation (PWM) unit. Membership functions were defined (Fig. 7). According to these descriptions, rules of the fuzzy controller are stated as

1. If (e N) and (de NE) then (u Y)
2. If (e Z) and (de NE) then (u H)
3. If (e P) and (de NE) then (u H)
4. If (e N) and (de ZE) then (u Y)
5. If (e Z) and (de ZE) then (u NR)
6. If (e P) and (de ZE) then (u H)
7. If (e N) and (de PE) then (u Y)
8. If (e Z) and (de PE) then (u Y)
9. If (e P) and (de PE) then (u H)

D. Position Controller

Position controller has been implemented on mobile robot by microcontroller units. Actual steering wheel angle of mobile robot was measured by a mechanism. Deviation information from trajectory was detected by 7 optical sensors. If vehicle is in middle of trajectory, 4th sensor
Fig. 6—Fuzzy edge outputs for different membership functions

<table>
<thead>
<tr>
<th>MBF</th>
<th>N=[-10.1] [-10.1] [0.0] [0.0]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Z=[-10.0] [0.1] [0.1] [10.0]</td>
</tr>
<tr>
<td></td>
<td>P=[-10.0] [0.0] [10.1] [10.1]</td>
</tr>
</tbody>
</table>

Fig. 7—Membership functions

<table>
<thead>
<tr>
<th>MBF</th>
<th>NE=[-10.1] [-10.1] [0.0] [0.0]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ZE=[-10.0] [0.1] [0.1] [10.0]</td>
</tr>
<tr>
<td></td>
<td>PE=[-10.0] [0.0] [10.1] [10.1]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MBF</th>
<th>Y=[0.1] [0.1] [127.0] [127.0]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S=[0.0] [127.1] [127.1] [255.0]</td>
</tr>
<tr>
<td></td>
<td>H=[127.0] [127.0] [255.1] [255.1]</td>
</tr>
</tbody>
</table>
detects white stripe. When vehicle moves to right side, white strip is detected by 3rd, 2nd and 1st sensors. Similarly, when vehicle moves to left side, white strip is detected by 5th, 6th and 7th number of sensors, respectively. If vehicle passes through all sensors, robot keeps last sensor information so vehicle moves to opposite direction. Microcontroller board on vehicle scans white strip detectors continuously and saves its status in memory to learn vehicle position. This information gives vehicle deviation from trajectory. If vehicle loses trajectory, last sensor information in memory is taken into consideration. Reference designator produces a reference steering angle according to received position errors. Reference angle is determined according to information of sensors.

- If (Position=1) Then (Angle 45°)
- If (Position=2) Then (Angle 22.5°)
- If (Position=3) Then (Angle 12.5°)
- If (Position=4) Then (Angle 0°)
- If (Position=5) Then (Angle -12.5°)
- If (Position=6) Then (Angle -22.5°)
- If (Position=7) Then (Angle -45°)

Difference between reference angle and feedback angle was applied to fuzzy controller as error input. Input and output membership functions were defined (Fig. 8). In position controller, basic rules are defined as

1. If (e N) Then (u RIGHT)
2. If (e Z) Then (u STRAIGHT)
3. If (e P) Then (u LEFT)

Developed microcontroller board mounted on mobile robot implemented all these operations.

Results and Discussion

Realized experiments were classified in two stages. In first stage, fuzzy speed controller has been tested. In this stage, image processing was disabled and control was performed at a different desired reference speed (Fig. 9a, where SV represents speed set value and PV represents speed procure value). Speed controller algorithms have been implemented in PC side. Controller output was sent to mobile robot by wireless RF signals and feedback signal was transferred back to controller in same way. Second experiment in first stage has been performed at high-speed test of controller. In this experiment, when vehicle reached at high speed, DC motor produced noises as a result of arc problem. These noises affected RF communication unit and caused fluctuations on actual speed (Fig. 9b).

In second stage of experiments, reference speed was calculated according to curvature of trajectory. Reference error and error deviations were applied to controller. Output of controller was transferred in form of 433 MHz RF modulated signal to mobile robot. Experiments in this stage were speed and position control according to a random variable trajectory (Fig. 10), different color of trajectory strip (Fig. 11) and discrete trajectory strip (Fig. 12). Experiment on variable trajectory shows that reference speed changes depending on each captured image. In this experiment, higher curvature means lower speed, whereas lower curvature means higher speed. In position control (Fig. 10), reference trajectory (REF) is trajectory tracked and position error (ERR) is deviation in millimeters from trajectory (deviation from the middle of optical sensors). When vehicle losses trajectory, it means that deviation error is bigger than 72 mm. In this experiment, maximum deviation was approx. 48 mm (Fig. 10). In different color experiment, whether trajectory color was white or not, image processing didn’t affect position controller. In random variable discrete strip trajectory experiment, vehicle speed fluctuated and position...
Fig. 9—Experimental result of fuzzy speed controller at: a) Low speed; b) High speed

Fig. 10—Experimental result of fuzzy speed and position controller on variable trajectory
controller has not been affected excessively.

**Conclusions**

Autonomous mobile robot was developed with control of speed and position on variable trajectory using CCD camera and optical sensors in conjunction with fuzzy edge detection and line extraction algorithms. Position controller was observed not to depend on image processing algorithms, because position controller has been operated independently from speed controller and run very quickly using microprocessors based optical sensors mounted on vehicle. Optical sensors continuously record vehicle position status in the memory, even if vehicle losses its...
trajectory, it can find its trajectory again by these recorded data. In image processing stages, fuzzy edge detection and position controller has not been found affected unless trajectory tracked color is not close to black. Also, dark and light scenes, does not affect fuzzy edge detection control. Using headlamps mounted on mobile robot, vehicle can be guided in dark conditions. With wireless image transferring and remote controllability of vehicle, various applications can be carried on: i) Security and monitoring applications with the capability of wireless image transferring, Internet base long range remote control and short range remote controlling by PC; ii) Material transfer applications; iii) Measuring radiation, magnetic field or harmful chemical gases; and iv) Useful for bomb destruction and mine sweep vehicle.

References