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Fuzzy Control of a Low Cost Mobile Robot Based on Vertical Lines in An Edge Detected Image

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Abstract. Edge detection is a computationally efficient and economical image processing technique as this method retains only the edges of surrounding objects for guiding the navigation and localization of a mobile robot. However, present edge detection based methods are heavily dependent on fusion with odometrical data which gradually accumulates localization errors. Moreover, they lack descriptive capabilities. In this paper, a fuzzy view descriptor which fused the information of the detected adjacent primary colours of the vertical lines in the mobile robot's view with the fuzzified digital compass readings was used to ascertain the actual view. This fusion provided a sense of direction in addition to recognizing the frontal view. The fuzzified distance of the base pixel coordinates of the vertical line of interest determined the attraction of the mobile robot towards it or the repulsion from it. A fuzzy control rule base guided the mobile robot towards the vertical line of interest by constantly reducing its deviation in the edge image. The mobile robot managed to execute its consecutive movements in an intuitive manner without a precise mathematical model. The deviations of the vertical lines were kept small and the detection of the correct views was constantly reliable.

1. Introduction

Movement control is one of the important aspects in the navigational task of a mobile robot. This involves maintaining a steady and reasonably smooth trajectory when approaching a landmark of interest. Various vision systems [1] have been researched and developed to facilitate this task. A number of mapping and localization techniques have been applied in indoor and outdoor navigational tasks in structured and unstructured environments. Recent surveys [2] of vision systems discussed recent advances such as visual simultaneous localization and mapping (VSLAM) based techniques. These systems are largely dependent on the quality of the image processing techniques chosen to accomplish the localization and navigational tasks. Capturing of real-time images are done by several types of cameras such as monocular and stereo cameras [3]. These cameras use perspective projection to represent a three-dimensional coordinates of scene points into two-dimensional image plane. Prior to operation calibration has to be carried out to overcome problems such as radial distortion and determination of the optical centres. Monocular cameras are unable to estimate distances of objects. On the other hand, stereo cameras although able to overcome this problem, often encounter correspondence problems and three-dimensional reconstruction tasks. Epi-polar constraints has to be adopted to ensure that the corresponding points between images lie in a straight line. Computationally intensive algorithms



such as the eight-point [4] and five-point algorithms [5] require multiple corresponding points which often overload the matrices calculation. They are used to recover the rotation and translation of the cameras attached to the mobile robot.

Several visual processing models have also been introduced to enable a mobile robot to interpret its environment by utilizing point correspondences. For instance, the point detectors introduced by the Harris [6] and SIFT [7] point detectors. The former is not invariant to scale changes while the latter suffers from problems of localization and computational efficiency. Other perceptual models such as the optical flow model [8] encounters erroneous correspondences between moving scene points when encountering obstacles.

Problems such as the need for calibration, radial distortion, computationally intensive algorithms, erroneous identification of corresponding points in successive images make the aforementioned approaches unsuitable for low cost platforms. Moreover, these approaches lack view descriptors that address issues of uncertainty in interpretation of a view.

In this work, an edge detected based technique with descriptive capabilities is used to control the movement of a mobile robot. A fuzzy view descriptor fuses the location information of the vertical lines with their adjacent primary colours with the digital compass readings to ascertain the mobile robot's actual view. It is known that the detection of colours is a straightforward function of a single image and does not need solving problems of correspondences. The fusion of these information offers a less computationally intensive approach while providing reliability pertaining to the view of the mobile robot by accommodating imprecision of the location of the vertical lines of interest and compass directions.

Sugihara [9] pioneered the use of vertical lines in edge detected images for the purpose of localizing a mobile robot. Huttenlocher [10] used the size of objects in the edge images to determine the distance of traverse of the mobile robot. Akihisa et al. [11] used the difference image produced by comparison of the model and captured edge detected images. Matching vertical lines contained in these models were used for navigation, localization and avoidance of static obstacles. Schuster et al. [12] used the vanishing points of straight edges of a ceiling for the translation and rotational movement of a mobile robot. However, this approach was unsuitable for localization tasks. Talluri and Aggarwal [13] imposed a geometric visibility constraint to find a match between a two-dimensional edge and a stored three-dimensional edge in a database to estimate the pose of a mobile robot. A finite state grammar approach [14] was used to combine extracted edge symbols to determine the direction of landmarks. A text extraction method [15] from edge images which was robust to varying lighting in the surroundings and text sizes from various view angles was attempted as a preparation for mobile robot navigation. An efficient matching rate [16] between groups of vertical lines in edge images with a global model was utilized for localization of mobile robots. Zhou and Li [17] utilized vertical lines to estimate the orientation of a camera attached to a mobile robot. Fan [18] applied morphological operation to extract images which yielded edge images that were richer in details compared to standard edge detection methods. Scaramuzza [19] introduced a descriptor in which gradients on both sides of the vertical lines were used to match the vertical lines of consecutive images. This approach demonstrated robustness to changes in illumination and rotation of the mobile robot's view.

The use of edge based images for the purpose of control and navigation of mobile robots also involved the utilization of fuzzy logic. Pan et al. [20] used the extracted vertical lines representing the walls and junctions of a hallway as inputs to a neural network. The outputs were then fed a fuzzy controller to control the direction and distance of traverse of the FUZZY-NAV mobile robot. A method which involved the maximization of the defuzzified values of 3x3 pixel mask [21] for edge detection and the membership function values of triangular output sets were used to detect white line markings on a road. The gradients of edges [22] of a road were used as antecedents of a rule base to control the navigation of a mobile robot along the road. Lee et al. [23] devised an edge detection method with an automatic thresholding capability to detect edges of door frames along a corridor for the purpose of localization. A fuzzy perceptual model was introduced [24] in which a set of fuzzy rules was used to interpret the horizontal and vertical edges of door frames in terms of size, direction and location to localize a mobile robot. Genetic algorithm [25] was used to tune the fuzzy sets and identify the door

frames from a large database. Gunes and Baba [26] utilized the 3x3 pixel fuzzy mask to extract the edges of a road. The curvature magnitudes of the edges were used for calculating the speed and speed error to navigate along the road. Kato et al. [27] used the vertical lines in edge images for the purpose of alignment of the position of the mobile robot. An 8x8 pixel mask [28] was used to train a back propagation artificial neural network to detect edges for facilitating the navigational task of a mobile robot. However, sensitivity to vertical edges was unsatisfactory.

The present edge based techniques for the control and navigational tasks lack descriptive capabilities to ascertain a mobile robot's view. For instance, if the mobile robot changes direction after a considerable distance, the viewing of a similar edge structure or features coupled with accumulative odometrical errors may cause erroneous views. Some descriptors [25] have been introduced to describe the edge structures but are dependent on a large database which incurs a computational load. The gradient based [19] descriptor is robust to illumination and has invariance capabilities but the problems lies in the unavailability of the omni-directional camera used.

In this project, a simpler approach is implemented on a low cost mobile robot. A fuzzy view descriptor fuses the location of the vertical lines of interest with the digital compass readings to ascertain its current view. The coordinates of the base pixel of the vertical line of interest in the edge image is used as a reference point to attract and repulse the mobile robot based on the perceived distance.

The integrated fuzzy based system implemented here involves the fuzzy edge detection to detect the vertical lines, the use of a fuzzy rule base to detect the adjacent primary colours of the vertical lines for identification, the fuzzy view descriptor to ascertain the mobile robot's view and a fuzzy control rule base to steer the mobile robot towards the consecutive vertical lines of interest.

2. Methodology

Figure 1 shows the physical structure of the low cost mobile robot. It is powered up by the DFRduino microcontroller with a built-in direct current motor driver. The 615 Logitech Web Camera is attached to the front of the mobile robot. Both of these are attached to the USB ports of the M840 Toshiba Sattelite laptop. The Processing software processes the image acquired by the Web Camera. The Arduino software controls the actuation of the pair of wheels of the mobile robot. The HMC 6352 digital compass is attached at the back of the mobile robot to detect the orientation angle of the mobile robot.

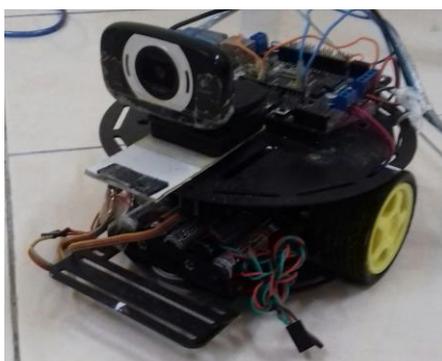


Figure 1. Mobile Robot

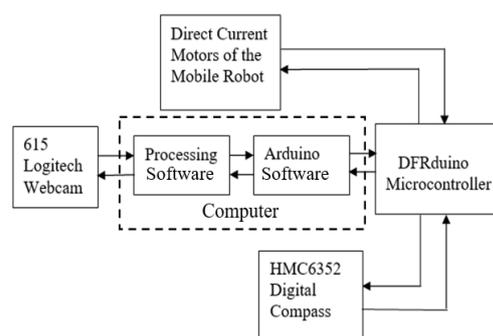


Figure 2. Interfacing of the Complete System

Figure 2 shows the interfacing of the complete system of the mobile robot. The Processing and the Arduino software communicate with each other to enable functionality of the whole system. The real-time image is acquired by the Processing software. The Processing software contains the subroutines and fuzzy rule bases to perform edge detection of the real-time images, to detect the primary colours at the sides of a vertical lines of interest and also to constantly communicate with the Arduino software. It

also contains the fuzzy sets for the perception of the distance to the vertical lines of interest. Most importantly it contains the algorithms of the fuzzy view descriptor and the fuzzy rules bases to control the movements of the mobile robot as it approaches its destination.

The Arduino software contains the subroutines to record the orientation readings of the digital compass and the actuation of the direct current motors. The activation signal of the motor subroutines comes from the Arduino software. In the next section, a brief discussion will be given pertaining to the edge detection, primary colour detection process, the fuzzy view descriptor and the control of the motors of the mobile robot.

2.1 Edge Detection

The first step requires the edge detection of the real-time images acquired by the web camera. The detection of the edges of objects, which is a demarcation of different areas of uniform pixel intensities, is a non-linear and ambiguous process. The fuzzy logic based edge detection method proposed here is suitable to address this issue. A group of three-pixel mask is convolved with the real-time image in four directions. These masks consist of arrangements of consecutive bright and dark pixels which can be represented as a fuzzy rule base to detect edges.

Figure 3 shows the group of fuzzy masks on the left side which is convolved with a 3 x 3-pixel segment of the image. The convolution process starts from the upper left and sweeps to the right and subsequent rows and ends at the bottom right segment of the image. The convolution of the fuzzy masks involves the directions associated with the typical pair of compass directions, viz: - the North-South, East-West, North West-South East and the North East-South West directions. Thresholding is performed to retain the edges.

Figure 4 shows the complete edge detection process in which it retains only the edges in the vertical direction. These vertical lines are used as reference edges for the control movements of the mobile robot. A thin line extending from the rightmost vertical line is a reflection of that line on the floor. An algorithm has been incorporated to minimize the appearance of reflected lines. This makes sure that the reflection is minimal and does not affect the descriptive capabilities of the view descriptor.

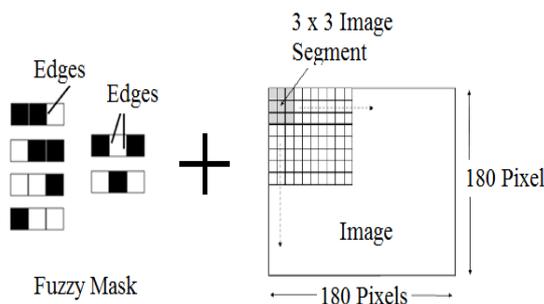


Figure 3. Fuzzy Masks

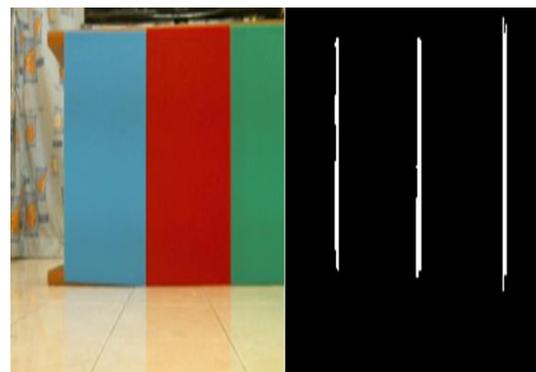


Figure 4. Edge Detection

2.2 Primary Colour Detection

The next stage is the determination of the dominant primary colour of the pixels on the adjacent sides of the vertical lines. The primary colour intensity values are averaged for a width of five pixels on both sides of a vertical line. The left side of Figure 5 shows this procedure clearly. The right side of this figure shows the antecedent sets to fuzzify the primary colour intensity values to obtain their membership functions. Table 1 shows the partial fuzzy rule base to detect the dominant primary colour on both sides

of the vertical line of interest. The consequents represent the dominant detected primary colour. There are 32 rules to implement the colour detection task. As can be seen from Table 1, the resulting detected consequent colour is determined by the dominant antecedent colour.

Table 1. Fuzzy If Then Rules for Primary Colour Identification

ANTECEDENTS (IF)				CONSEQUENT
RULE	RED	GREEN	BLUE	(THEN)
Rule 1	Low	Low	High	Blue
Rule 2	Low	Low	Very High	Blue
Rule 3	Low	Medium	High	Blue
Rule 4	Low	Medium	Very High	Blue
Rule 5	Low	High	Low	Green
Rule 6	Low	Very High	Low	Green
Rule 7	Low	High	Medium	Green
Rule 8	Low	Very High	Medium	Green
Rule 9	High	Low	Low	Red
Rule 10	Very High	Low	Low	Red
Rule 11	High	Low	Medium	Red
Rule 12	Very High	Low	Medium	Red

Figure 6 shows the fuzzy sets to divide the location of a certain vertical line of interest into the left, right and middle portions of the edge image. The resulting membership function indicates the degree of belongingness of a certain vertical line to a certain location range in the image. These values are used by the fuzzy view descriptor.

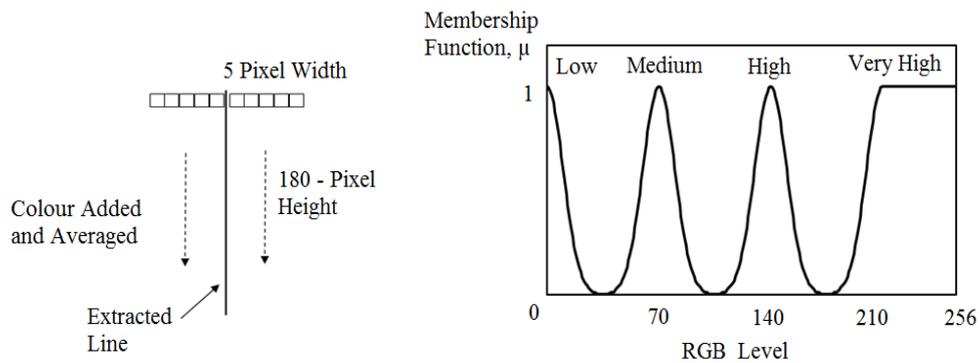


Figure 5. Colour Detection and Antecedents

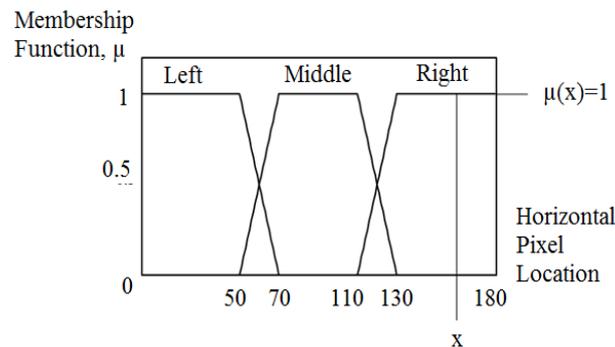


Figure 6. Fuzzification of the Vertical Line Location

2.3 View Descriptor

A fuzzy view descriptor is used to enable the mobile robot to recognize its frontal view. This descriptor fuses the information of the location of the group of vertical lines with similar adjacent primary colours and the fuzzified compass readings. The pseudocodes below show the concept of fusing these two variables to ascertain the actual view. The first group of the pseudocodes detects the presence of the group of vertical lines with the adjacent red colour at the left, middle and right portions of the image.

$$\begin{aligned}
 \text{face1a} &= \min(1, \text{midredhigh}[1], 1); \\
 \text{face1b} &= \min(\text{leftredhigh}[1], 1, 1); \\
 \text{face1c} &= \min(1, 1, \text{rightredhigh}[1]); \\
 \text{viewa} &= \max(\text{face1a}, \text{face1b}, \text{face1c});
 \end{aligned} \tag{1}$$

In the second group of pseudocodes, the maximum value of one of the left-hand side variables indicate the dominant orientation of the mobile robot. For instance, if the variable ‘viewa1’ has a unity value and the variables ‘viewa2’ and ‘viewa3’ have zero values, this indicates the viewing of a landmark with red colours in the north direction. Provisions could also be made for identifying a certain view from various permissible orientations.

$$\begin{aligned}
 \text{viewa1} &= \min(\text{viewa}, \text{compassviewnorth}); \\
 \text{viewa2} &= \min(\text{viewa}, \text{compassviewnorthwest}); \\
 \text{viewa3} &= \min(\text{viewa}, \text{compassviewwest});
 \end{aligned} \tag{2}$$

Figure 7 shows the fuzzy sets that fuzzify the readings of the digital compass into their respective membership functions. The trapezoidal fuzzy sets permit a range of values to be associated with a certain direction. A low overlap between the fuzzy sets ensure the unity membership function in a certain direction in most cases.

2.4 Fuzzy Control Algorithms

Once a certain view has been ascertained, a vertical line of interest within the view is chosen as a reference for control. Its horizontal deviation magnitude in pixel counts is sent to the fuzzy control subroutine. The fuzzy control subroutine will steer the mobile robot until the vertical line of interest is brought to the centre of the image. Figure 8 shows the fuzzy sets for the deviation of the vertical line.

Figure 9 shows the deviation of the vertical line of interest from the middle of the image. The vertical line usually deviates to the left or right of the middle axis of the image. The fuzzy control algorithm constantly steers the mobile robot in such a way so as to reduce the deviation of the vertical line of interest from the centre of the image.

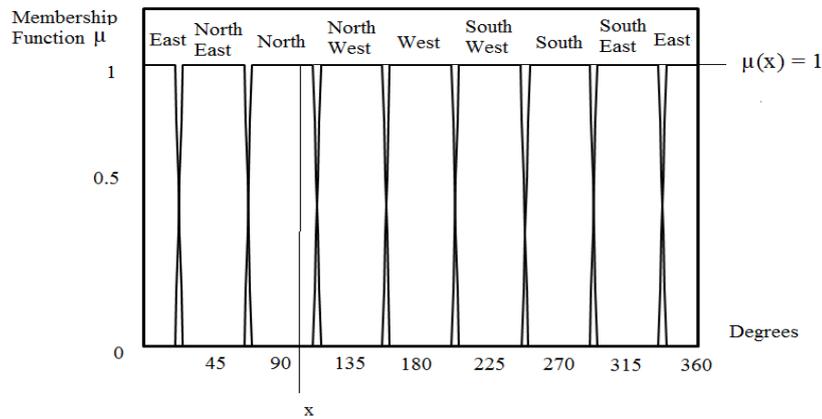


Figure 7. Fuzzification of the Digital Compass Readings

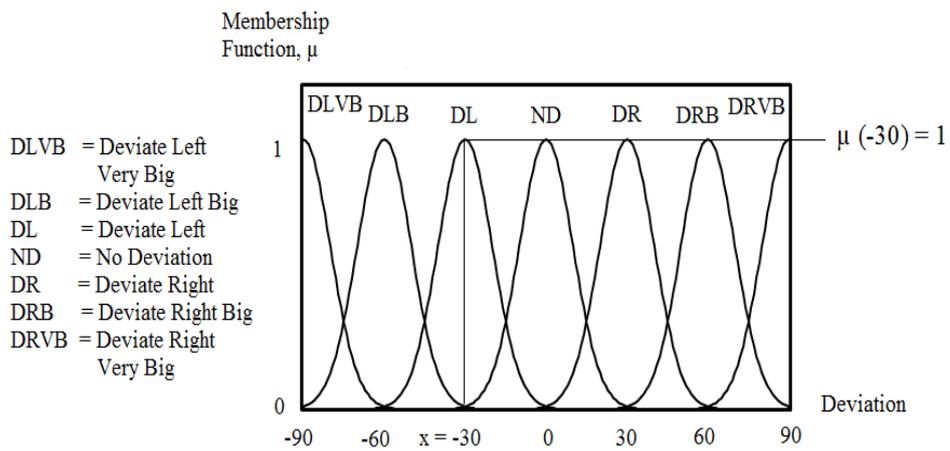


Figure 8. Fuzzification of the Vertical Line Deviation

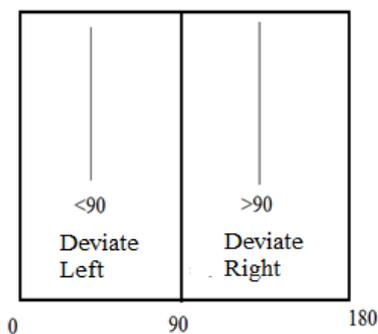


Figure 9. Vertical Line Deviation

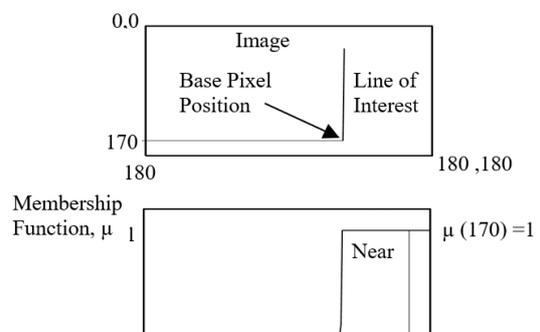


Figure 10. Fuzzification of Base Pixel Position of the Vertical Line

The next important parameter is the vertical pixel coordinates of the base belonging to the vertical line of interest. The vertical pixel position is fuzzified to enable perception of whether the vertical line is considered as near or far. Figure 10 shows this concept. The upper part of this figure shows the vertical pixel coordinate of the vertical line. When this value is fuzzified by the fuzzy set, the resulting unity membership function indicates that the vertical line is perceived to be near the mobile robot.

Another importance of this fuzzy set is that once a unity membership function has been attained, the mobile robot is deemed to have approached the vertical line of interest and is ready to steer and approach the next vertical line in a new view area. The deviation magnitude of the vertical line of interest and the ‘near’ membership function value are sent to a fuzzy rule base for inferencing in order to control the steering of the wheels of the mobile robot. Table 2 shows the rule base for steering the mobile robot when approaching a vertical line of interest. When the mobile robot has approached the vertical line, it will steer to the next view area to detect the relevant vertical line. The steering action at this stage is dependent on the orientation of the mobile robot. The activation of the fuzzy control rule base is also dependent on the status of the current view of the mobile robot. Figure 11 shows the consequent fuzzy sets to execute the steering actions.

Table 2. Fuzzy IF THEN Rules for Steering Control

ANTECEDENT (IF)				CONSEQUENT (THEN)
Rule Number	Distance (Pixel Count)	Deviation (Pixel Count)	Compass Direction	Steering Action (Pixel Counts)
1	Far	None	Don't Care	No Turning
2	Far	Right	Don't Care	Turn Right
3	Far	Right Big	Don't Care	Turn Right Big
4	Far	Right Very Big	Don't Care	Turn Right Very Big
5	Far	Left	Don't Care	Turn Left
6	Far	Left Big	Don't Care	Turn Left Big
7	Far	Left Very Big	Don't Care	Turn Left Very Big
8	Near	Don't Care	North	Turn Left Very Big
9	Near	Don't Care	North East	Turn Left Maximum
10	Near	Don't Care	North West	No Steer

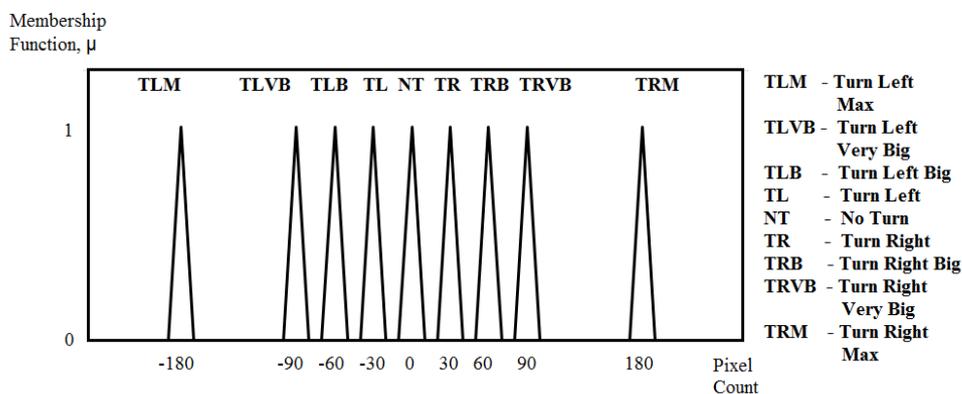


Figure 11. Consequent Sets for Steering Actions

3. Experiment

Figure 12 depicts the path for the pre-planned movement from the ‘start’ to ‘end’ points. The mobile robot moves from its ‘start’ position and goes towards vertical line 1. When it has approached this vertical line, it then steers to the left and goes to the second vertical line. When it has approached the second vertical line, it then steers to the left again and finally goes towards the location considered as the ‘end’ area. The mobile robot halts its movement in this area.

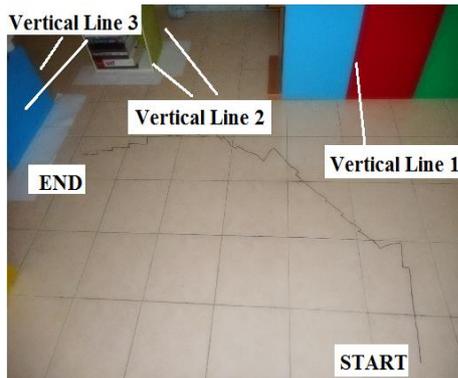


Figure 12. Pre-planned Path

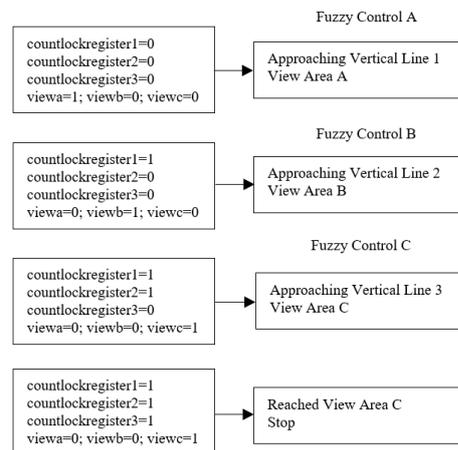


Figure 13. Subroutine Activation

Figure 13 shows the consecutive activation of the fuzzy control subroutines to execute the mobile robot movement from its start to end points. The ‘countlockregister’ variables play a role in this. In the initial stage all the values of these variables are zero. The fuzzy control ‘A’ subroutine is activated and the mobile robot moves towards the first vertical line. At this stage the ‘viewa’ variable value is unity. When it has reached this vertical line, the ‘countlockregister1’ value changes from zero to one. This indicates that the first vertical line has been reached and is ready to go to the next vertical line. The fuzzy control ‘A’ subroutine is deactivated and the fuzzy control ‘B’ subroutine is activated. At this stage, the ‘viewb’ variable value changes to unity value. When the second vertical line is reached, both the ‘countlockregister2’ and ‘countlockregister 1’ values show unity values which indicate that the vertical lines 1 and 2 have been reached. When the second vertical line is reached the mobile robot steers to the left and the fuzzy control ‘C’ subroutine is activated. The ‘viewc’ variable becomes unity. Finally, when the vertical line 3 is reached, all the ‘countlockregister’ variables show unity values which indicate the end of the movement.

4. Results

Figure 14 shows the 10 tracks traced by the mobile robot from the ‘start’ to the ‘end’ points. The tracks exhibit a zigzagging path. A closer inspection of track 8, as shown in Figure 15, indicates this clearly. This was caused by the constant corrective steering actions to move the deviated vertical lines of interest back to the centre of the edge image.

Figure 16 shows the consecutive edge images produced as the mobile robot traverses towards the vertical line with the red colour on its right. The bolded data on the right-side display the coordinates of the base pixel belonging to the vertical line of interest. The reduction of the horizontal coordinate of the base pixel shows that the deviation of the vertical line has been reduced. In addition to that, the reduction in the vertical base coordinate values indicates that the mobile robot is approaching the area containing the vertical line of interest. The unity value of the variable ‘viewa’ indicates that the mobile robot is facing the area which contains the vertical line with the red colour on its right side. The bottom part of the data from photo 1 shows that the mobile robot steers to the right direction by the amount

corresponding to a pixel displacement of 5 pixel counts in order to reduce the deviation of the vertical line.

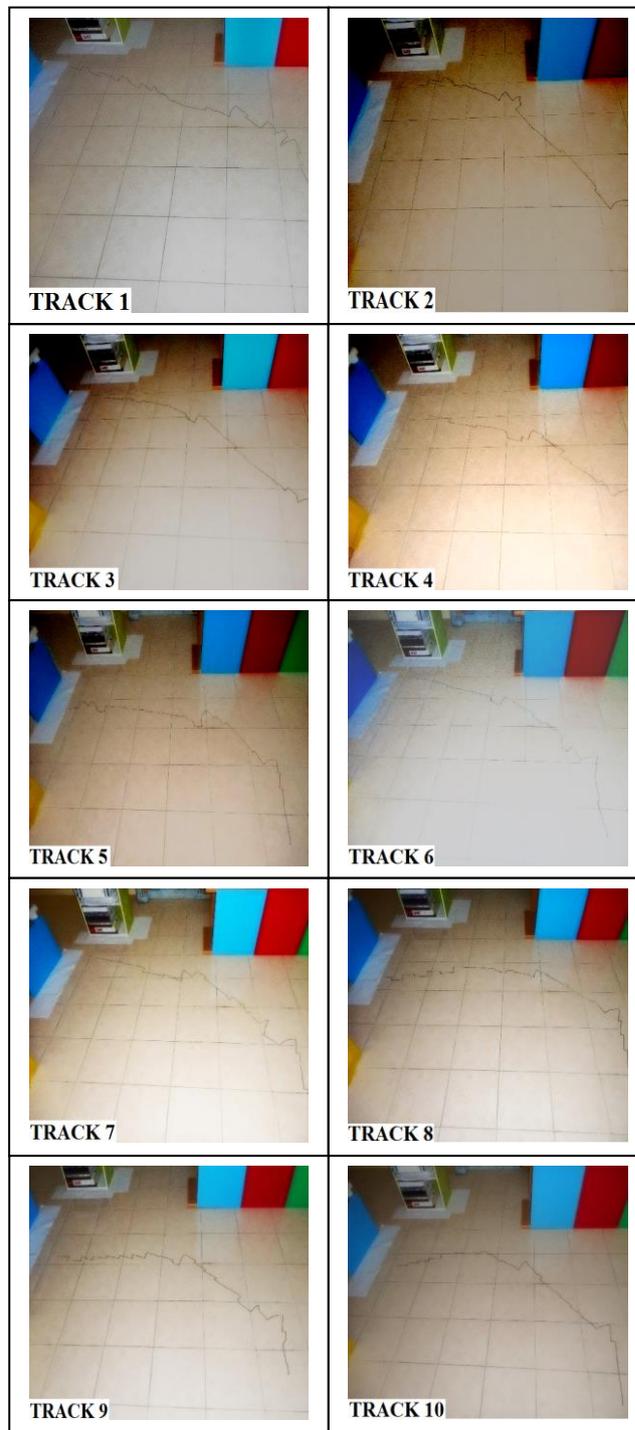


Figure 14. Tracks 1 to 10



Figure 15. Exploded View of Track 8

Photo No	Edge Detected Photographs	Data
1		Setreading = 1 Compass Angle = 93.0 xred1[1]=99.5 yred1[1]=118.5 xgreen[1]=8.0 ygreen[1]=71.0 xblue[1]=43.5 yblue[1]=106.75 xblue1[1]=44.0 yblue1[1]=117.333336 View=1.0 Viewb=0.0 Viewc=0.0 distancea1=118.5 hdistancea1=99.5 Deviation1=9.5 LockRegister1=0.0 LockRegister2=0.0 LockRegister3=0.0 Turn Right =5 Go Straight1 Go Straight1
2		Setreading = 2 Compass Angle = 95.0 xred1[1]=95.5 yred1[1]=112.75 xgreen[1]=159.5 ygreen[1]=122.0 xblue[1]=33.5 yblue[1]=114.25 xblue1[1]=33.5 yblue1[1]=114.25 View=1.0 Viewb=0.0 Viewc=0.0 distancea1=112.75 hdistancea1=95.5 Deviation1=5.5 LockRegister1=0.0 LockRegister2=0.0 LockRegister3=0.0 Turn Right =2 Go Straight1 Go Straight1

Figure 16. Reduction of Deviation of the Vertical Line of Interest

Photo No	Edge Detected Photographs	Data
4		Setreading = 4 Compass Angle = 91.0 xred1[1]=66.5 yred1[1]=128.5 xgreen[1]=138.0 ygreen[1]=128.0 xblue[1]=139.0 yblue[1]=128.0 View=1.0 Viewb=0.0 Viewc=0.0 distancea1=128.5 hdistancea1=66.5 Deviation1=-23.5 LockRegister1=1.0 LockRegister2=0.0 LockRegister3=0.0 Turn Left =2090 Go Straight1 Go Straight1
5		Setreading = 5 Compass Angle = 101.0 xgreen[1]=52.5 ygreen[1]=102.0 xgreen1[1]=74.0 ygreen1[1]=112.0 xblue[1]=55.0 yblue[1]=117.666664 xblue1[1]=131.5 yblue1[1]=125.75 View=0.0 Viewb=1.0 Viewc=0.0 distanceb1=112.0 hdistanceb1=74.0 Deviation2=-16.0 LockRegister1=1.0 LockRegister2=0.0 LockRegister3=0.0 Turn Left =2017 Go Straight1 Go Straight1

Figure 17. Transition of Views

Figure 17 shows the consecutive edge images which indicate how the mobile robot steers to the left after approaching the first vertical line. It can be seen that the vertical coordinate of the base pixel belonging to the first vertical line, from photo 4, is 129. This has exceeded the threshold value of 125 which can be considered near to the mobile robot. At this stage, the ‘lockregister’ value changes to 1 and the mobile robot steers to the left in order to get a new view. From photo 5, it can be seen that the variable ‘viewb’ becomes 1. The pixel coordinates of the vertical lines with the green colour on the left and right sides are displayed. Since the horizontal pixel coordinate of the vertical line of interest, represented by the variable ‘xgreen1[1]’ has deviated to the left side of the middle axis, the mobile robot steers to the left with a corresponding displacement of 17-pixel counts. (ignore the first 2 digits) to reduce the deviation. It is also noticeable that the coordinates of the base pixels of the vertical lines of

interest are displayed in decimal points. The decimal points result from the averaging of the clumped lines with similar adjacent colours.

To evaluate the performance of the fuzzy control algorithms, the average line deviations of the 10 tracks are calculated. Figure 18 shows the deviation pattern of the vertical line of interest in an edge image for track 8. The zigzagging pattern indicates that the mobile robot always attempts to steer itself in such a way so as to enable the reduction of the vertical line deviations. The deviation values appear to hover around the horizontal pixel coordinate of 90, which is considered the middle position of the edge image.

Table 3 shows the deviations for each stage of movement involving all the 10 tracks. The average deviation values for all the tracks are also shown. Most importantly, the overall average deviation value is a small value of 10 pixels, which indicates that the vertical line positions are constantly adjusted to be kept near the middle of the edge image. This ensures directedness of the mobile robot towards a destination point.

Table 4 shows how the fuzzy control algorithm responds by producing the steering magnitudes which approximate the deviations of the vertical lines in pixel counts. The steering actions generally alternate between turning right and left on consecutive step movements. It is also noticeable that the magnitude difference between the steering magnitudes and the deviations of the vertical lines are not more than 5-pixel counts.

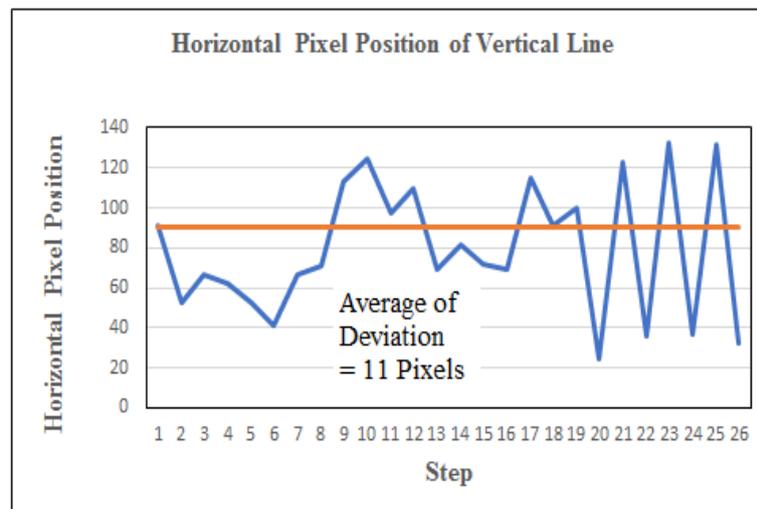


Figure 18. Deviation of Track No.8

Table 3. Absolute Average of Deviation for Each Stage of Movement

Track Number	Absolute Average of Deviation (Start to Line 1)	Absolute Average of Deviation (Line 1 Line 2)	Absolute Average of Deviation (Line 2 to Line 3)	Absolute Total Average of Deviation
1	7	26	14	10
2	12	7	24	14
3	10	1	5	3
4	16	1	4	5
5	3	24	9	12
6	6	14	0	6
7	21	22	3	13
8	28	3	10	11
9	10	12	27	10
10	9	6	34	15
Absolute Average Deviation	11	7	13	10

Table 4. Deviation and Turn Angle (Track 1)

Step Number	Deviation (In Pixels)	Turn Angle (In Pixels)	Difference (In Pixels)	Absolute Difference (In Pixels)
1	-5.0	Turn Left = -1	4.0	4
2	-62.5	Turn Left = -61	1.5	2
3	28.5	Turn Right=+30	1.5	2
4	1.5	Turn Angle =0	1.5	2
5	36.5	Turn Right=+32	4.5	5
6	35.0	Turn Right=+31	4.0	4
7	15.0	Turn Left = -90	Not Applicable	Not Applicable
8	29.0	Turn Right=+30	1.0	1
9	-52.0	Turn Left = -57	5.0	5
10	-69.5	Turn Left = -65	4.5	5
11	39.0	Turn Right=+34	5.0	5
12	-7.7	Turn Left = -90	Not Applicable	Not Applicable
13	-3.75	Turn Left = -1	2.75	3
14	-27.5	Turn Left = -29	1.5	2
15	8.5	Turn Right=+4	4.5	5
16	-21.5	Turn Left = -26	4.5	5
17	-21.0	Turn Left = -26	5.0	5
18	-46.0	Turn Left = -47	1.0	1
19	9.0	Turn Right=+4	5.0	5
20	-53.75	Turn Left = -58	4.25	4
21	16.75	Turn Right=+19	2.25	2
22	-62.75	Turn Left = -61	1.75	2
23	-13.0	Turn Left = -11	2.0	2

5. Conclusions and Recommendations

An integrated fuzzy system has been implemented in this project. The fuzzy edge detection system processed the captured images and retained the vertical lines of objects. The fuzzy colour detection rule base enabled recognition of primary colours on both sides of the vertical lines in the edge image. The fuzzy view descriptor used the information of the location of the vertical lines of interest with the orientation readings of the digital compass. This enabled the mobile robot to ascertain its view and move towards the selected vertical line of interest within its view.

In the future, the fuzzy view descriptor will be refined to enable recognizing landmarks having multiple vertical lines with various combinations and sequences of the adjacent colours. Invariance capabilities will be incorporated to enable recognition of landmarks from various view angles in more challenging environments.

In addition to these features, localization capabilities may be incorporated to enhance the overall capabilities of the mobile robot. This may include simultaneous localization and mapping operations utilizing vision systems. Type-2 fuzzy logic [29] may also be used to improve the control movements by further reducing the deviations of the tracks.

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