International Journal of
Advances in Scientific Research and Engineering (ijasre)

E-ISSN : 2454-8006

DOI: 10.31695/IJASRE.2020.33678

Volume 6, Issue 1
January - 2020

Fuzzy-Based Obstacle Avoidance Control of Mobile Robots Using 3D Camera

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ABSTRACT

This research develops a novel method of generating the velocities of the right and left motors of the two-wheeled mobile robot base on the distances of the detected objects according to the image processing technique using the Fuzzy Logic Controller for obstacle avoiding system. The aim of this research is to build a controller for avoiding some obstacles with distance information obtained from the 3D camera or depth sensor which is mounted on a mobile robot. This sensor is used in this study due to its double integrated sensor, namely vision and distance. The fuzzy controller is designed for obstacles avoiding the system to control the mobile robot. The position of the obstacle is generated by using a contour operation on a captured image, together with a Canny edge detector and morphological operation. The distance between the robot and the obstacle is obtained from a depth frame. According to these data, the velocities of the left and right motors of the two-wheel-drive mobile robot are generated from the fuzzy controller. The effectiveness of the proposed approach was verified through several experiments.

Key Words: *Image-Based Visual Serving, Fuzzy Logic Controller, Obstacle Avoidance, Trajectory Generation, Velocity Generation*

1. INTRODUCTION

Development of an obstacle avoiding system has become an important issue in commercial environments such as industrial applications for achieving robots autonomy. The automatic obstacle avoiding systems of two-wheeled drive mobile robots have attracted a great deal of attention from research organization and automobile industry. For the development of autonomous mobile robots, several aspects must be taken into consideration, such as the type of application and the basic robot platform and sensors adopted, which compose the robot's hardware is presented in [1] and [2]. [3], used a laser range finder to detect an obstacle and measuring the distance, and generated a path for obstacle avoidance system using polar coordinate. Many formal methods and techniques have been proposed for solving the obstacle avoiding problem. Moreover, natural vision comes with living beings like humans who use their eyes and their brains to control the word around them. Computer vision, artificial vision comes in the similar way by imitating human vision with artificial intelligence techniques which involve the development of a theoretical and algorithmic basis to achieve automatic visual understanding. In particular, vision sensor is an important sensor for autonomous robotic system because it can be used for the environmental measurement without physical contact.

Vision sensors and digital image processing technology become effectively accessible with the advancement of computer innovation in recent years. Among these technologies, visual servoing is one of a control technique for deciding the robot behavior by utilizing the data acquired through eyes like human. Visual servoing can be generally separated into two strategies: i.e., position-based visual servoing (PBVS) and image based visual servoing (IBVS). The PBVS is a strategy for controlling the robot straightforwardly, where the characteristics of the acquired image are controlled on the image. The IBVS is a technique for in a roundabout way controlling the robot, where the attributes of the obtained picture are controlled on the picture. For research on IBVS, Kurashiki and Fukao [4] extracted the tangent of a curve, which was drawn on the ground, by the camera mounted on an autonomous mobile robot, and achieved curve tracking control by controlling the slope and intercept on the image coordinates. The advantages of IBVS when contrasted with PBVS are that the computational expense is low and it is controllable by a biomimetic approach. On the other hand, a disadvantage is that there is no special idea to connect the data on the features, which is gotten from the image, to the control. Many techniques along with different vision sensors have been used for computer vision applications including Stereovision, LIDAR (Light Detection and Ranging) and RADAR (Radio Detection Ranging) is presented in [5], but still each of them has its own advantages and disadvantages.

In this research, IBVS by a fuzzy controller is used for the obstacle avoidance system for two-wheeled mobile robot using 3D camera. The accuracy of obstacle avoidance is improved by obtaining the distance information through 3D camera or depth sensor. Finding the trajectory line between the camera and detected objects within camera's field of view and generate the robot velocity to avoid the obstacles which are the main purpose of the present research, is an ongoing field of research given the fact that there is not a perfect solution yet and computer vision prefers to use depth cameras rather image intensity cameras since depth information makes the variety of applications more feasible and robust. In this research depth sensor is used to make experiences for detecting objects in its field of view and measuring how far away they are from the sensor. Such depth sensors have recently become widely available, enabling affordable, accurate 3D sensing. A fuzzy logic controller (FLC) with reactive behavior was implemented for obstacles avoiding system and tested on a mobile robot platform.

2. PROBLEM SETTING

The objectives of this research is to generate the trajectory line that the robot to be followed and robot. The slope and intersection of the trajectory line is calculated by image processing techniques. From the depth image, the distance between the objects and the robot is obtained and then an image-based fuzzy controller is implemented for an obstacle avoiding mobile robot. The design of obstacles avoiding system for autonomous robot using image based processing in which an Intel D435 depth camera is mounted on the robot to detect the objects. In this research, the 3D camera is used to detect the objects and to inform the distance of the objects.

2D computer vision applications have been limited because of the lack of an important third dimension: depth. To avoid the obstacles, the distance between the object and the robot is the important information. By using 3D camera, this problem can solve easily and unlike 2D, 3D vision enables machines to accurately understand shapes, sizes, distances and to maneuver in the real 3D world. So, Intel®RealSense™ Depth Camera D435 is used in this research to get the distance information between the object and the robot. Fig 1 shows the Intel®RealSense™ Depth Camera D435.

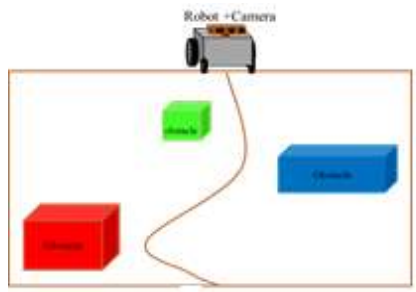

Figure1. Operating environment of the system

Figure 1 shows the operating environment of the system. In this obstacle avoiding system, a 3D camera is mounted on the two-wheeled mobile robot. From the color image and depth image of the 3D camera, the object coordinates and distance are calculated. Based on these data, the slope and intersection of the target line for free path is calculated. These values are compared to the desired values and the compared values are used as the inputs of the fuzzy logic controller. The controller determines the control inputs (δ, λ,) from the image features in the image coordinate to drive the mobile robot in an appropriate robot velocity. If the robot can follow the target line, it can be said that the robot the can avoid the obstacles correctly. The block diagram of the image-based fuzzy controller for obstacle avoiding mobile robot is shown in Figure 2.

DOI: 10.31695/IJASRE.2020.33678

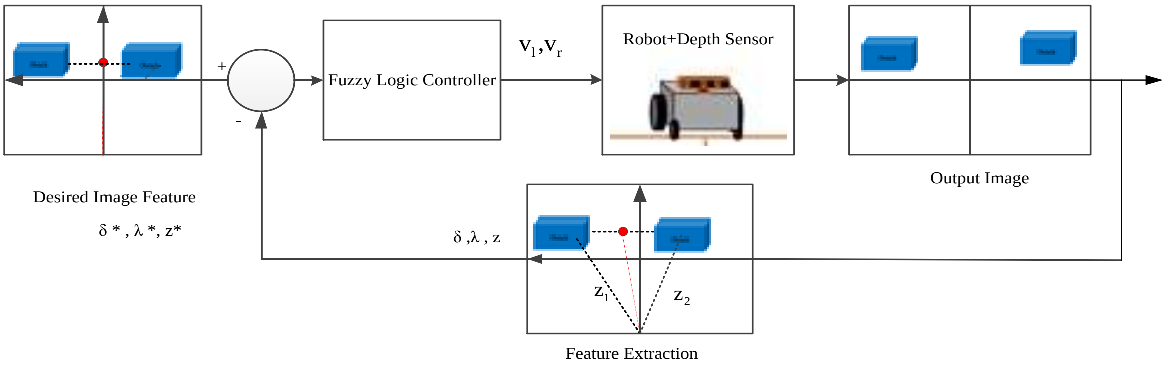

Figure2. System block diagram of obstacle avoiding mobile robot

3. GENERATION OF INPUTS VARIABLES FOR FUZZY LOGIC CONTROLLER

In the present, image processing is widely used for detection in intelligent autonomous mobile robot because it is one of the quick and accurate methods for obstacle avoiding system. In this section, the steps of image processing on a captured image are explained to detect obstacles and generate the trajectory line of an obstacle avoiding system.

3.1. Calculation of Slope and Intersection of Trajectory Line for Obstacle Avoiding System

To generate the trajectory line that the robot to be followed, the slope and intersection are calculated from the color image using image processing algorithms and the distances of the obstacles are getting from the depth image to avoid the obstacle. The slope and intersection of the trajectory line and the distances between the robot and the object are used as the control inputs to build an image-based fuzzy controller.

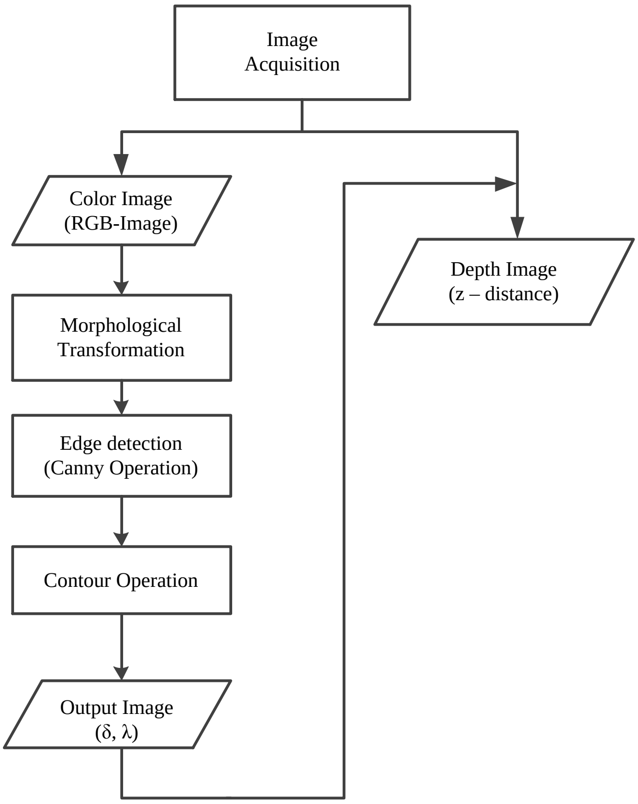

Figure3. Flow chart for image processing algorithm

At first, a preprocessing is executed on the captured image to generate the slope and intersection of trajectory line and the distance between the robot and the objects for an obstacle avoiding system. Figure 3 shows the flow chart for image processing algorithm**.** For the color image, the smoothing and filtering operation is used to smooth the captured image and to filter the noise of the image. Morphological Transformation such as erosion and dilation process is used when the number of pixels added or removed from the object in an image. Canny edge detector is used to detect the wide range of edges in an image. The contour is an image processing technique for extracting features of particular shapes, such as lines, circles, or ellipses. In this paper, contour (mini-enclosing circle) is used to create the bounding boxes for contour.

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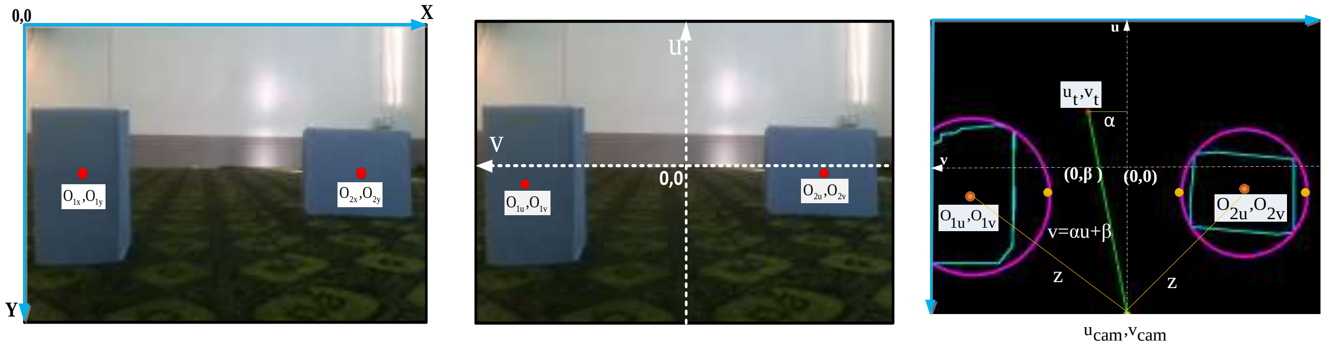
In this research, depth camera is used to make experiment for detecting objects in its field of view and measuring how far away they are from the camera. The obstacles in the environment are detected from the 3D camera equipped on the two-wheel drive mobile robot by the image processing. The world coordinate is represented by X-Y coordinate; the changed image coordinate for the camera is represented by u-v coordinate and the features extraction for calculating control inputs are shown in figure 4. The original image coordinate is the X-Y axis, but it is modified to a new image coordinate as u-v axis by Equation (1) and (2). The image size is W (width) x H (height) in pixel. The W (width) of the image is 640 pixels and the H (height) of the image is 480 pixels. The distance values can be obtained from the image processing algorithm. These values are used as input variables to the fuzzy controller and then controller determines the output variables such as the velocities of the right and left motors of the mobile robot (v_r, v_l) to avoid the obstacles. The following equations (3) and (4) are represented the coordinates values of the center point of the detected objects. Equation (5) and (6) show the slope and intersection of the trajectory lines on the image coordinates.

$$v = \frac{W}{2} - X \qquad \text{---------------- (1)}$$

$$u = \frac{H}{2} - Y \qquad \text{----------------- (2)}$$



(a) (b) (c)

Figure4. (a) Original image axis (X, Y) (b) Changed image axis (u, v) (c) Feature extraction

$$O_u = \frac{W}{2} - O_x \qquad \text{---------------- (3)}$$

$$O_v = H - O_y \qquad \text{---------------- (4)}$$

$$\delta = \frac{v_t - v_{cam}}{u_t - u_{cam}} \qquad \text{---------------- (5)}$$

$$\lambda = \frac{u_{cam} v_t - u_t v_{cam}}{u_t - u_{cam}} \qquad \text{--------------- (6)}$$

Where, the endpoints of the trajectory line is defined as (u_t,v_t) and (u_{cam},v_{cam}). The trajectory line is calculated using the following equation (7).

$$v = \delta u + \lambda \qquad \text{---------------- (7)}$$

Figure 5 shows the system flow chart of the obstacle avoiding mobile robot. From the image processing algorithms the slope, intersection and distance (δ, λ and z) are obtained. If the detected object’s distances are greater than 2m, the robot will move to the forward with constant speed and if the detected object’s distances are less than 2m the fuzzy controller is operated and control the robot’ left and right motor velocities.

DOI: 10.31695/IJASRE.2020.33678

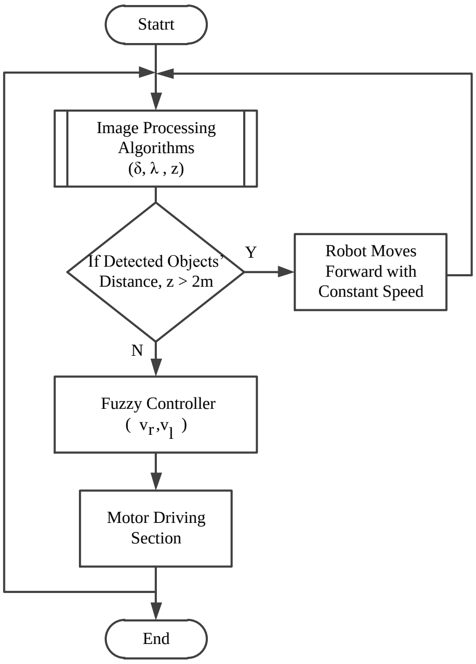


Figure5. System flow chart for obstacle avoiding mobile robot

3.2. Proposed fuzzy controller

In this section, obstacle detection and avoiding mobile robot using the proposed fuzzy controller is discussed. Fuzzy control loop for mobile robot is shown in figure6. The fuzzy controller determines the control inputs through mainly three steps:

(a) Fuzzification of state variables
(b) Calculation of grade of each rule and
(c) Defuzzification of input values

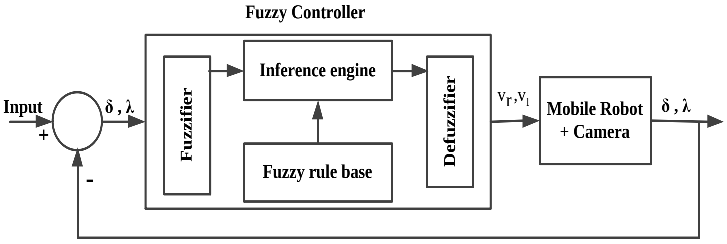


Figure6. Fuzzy control loop for mobile robot

3.2.1. Fuzzification of state variables

The fuzzification module turns real input values into fuzzy values which are linguistic representations with grades which are given by membership functions. To develop the system, the inputs variables (δ, λ) are assigned into five triangular membership functions and the outputs (v_r, v_l) are assigned into three singletons membership functions. It uses multiple membership functions like membership function of the input variable and the output variable.

Input variable is value of the slope (δ) and the intersection (λ), which includes:

- Slope (δ) is divided into three fuzzy sets, namely: Negative (N), Zero (Z), and Positive (P)
- Intersection (λ) is divided into three fuzzy sets, namely: Negative (N), Zero (Z), and Positive (P)

Output variable is the value of the right motor speed (V_r) and the left motor (V_l), which includes:

- v_r is divided into three fuzzy sets, namely: Stop (S), Medium fast (M), and Fast (F)
- v_l is divided into three fuzzy sets, namely: Stop (S), Medium fast (M), and Fast (F)

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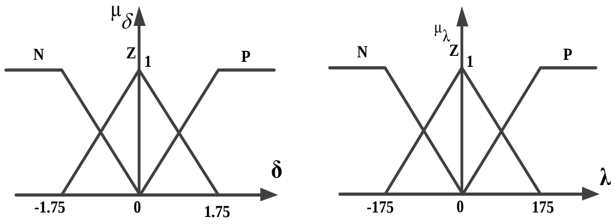
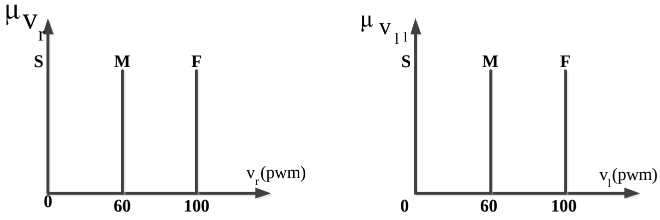


(a) (b)

Figure7. Membership functions for inputs (a) Slope (δ) and (b) Intersection (λ)



(a) (b)

Figure8. Membership functions for outputs (a) Right motor velocity (v_r) (b) Left motor velocity (v_l)

Figure.7 shows the membership function of input variables (slope and intersection) and Figure.8 shows the membership function of output variables (right motor velocity and left motor velocity). Fuzzy logic rules for right motor velocity and left motor velocity are illustrated in Table 1.

Table1. Fuzzy rules for the speeds of motors

Rule	Inputs		Outputs	
	δ	λ	v_l	v_r
0	N	N	F	M
1	N	Z	M	S
2	N	P	M	M
3	Z	N	M	S
4	Z	Z	F	F
5	Z	P	S	M
6	P	N	M	M
7	P	Z	S	M
8	P	P	M	F

3.2.2. Calculation of grade of each rule

The fuzzy rules for the right motor velocity v_r and left motor velocity v_l are shown in Table I. In this table, the number of fuzzy rules is nine rules (0 to 8). One of the corresponding linguistic meanings is that "if δ is NB, λ is NB, then v_r is F and v_l is F". This phenomenon denotes that the robot should go with maximum velocity to the forward. The grade of each control rule is the same as the minimum value among the degrees of truth of the fuzzified state variables related to the rule. Although the degree of truth of each rule is adopted as the degree of truth of the control input, if other rules have the same values, then the maximum value among these degrees of truth is adopted (min–max algorithm).

3.2.3. Defuzzification

The defuzzification is the conversion of fuzzy output to crisp output. The output crisp value of this module is given by the weighted average for singletons defuzzification method and is described as:

$$v_r = \frac{60 \times \mu_{v_r,M} + 100 \times \mu_{v_r,F}}{\mu_{v_r,S} + \mu_{v_r,M} + \mu_{v_r,F}} \quad \text{------------------------ (8)}$$

$$v_l = \frac{60 \times \mu_{v_l,M} + 100 \times \mu_{v_l,F}}{\mu_{v_l,S} + \mu_{v_l,M} + \mu_{v_l,F}} \quad \text{------------------------ (9)}$$

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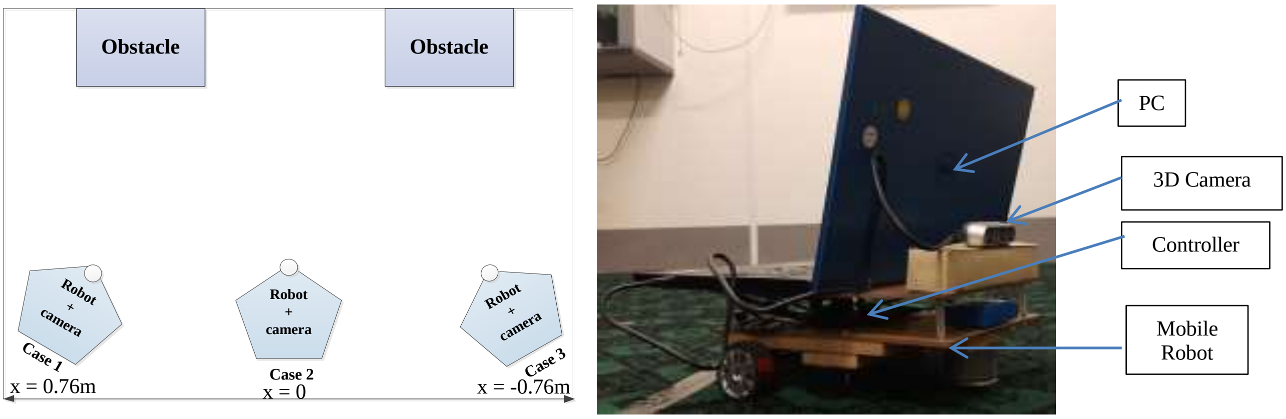
Where $\mu_{v_r,S}$ is the grade of conformity with the consequent "$v_r = S$" and $\mu_{v_l,S}$ is the grade of conformity with the consequent "$v_l = S$". As presented above, the fuzzy controller determines the input (v_r, v_l) from the parameters of input variables.

4. EXPERIMENTAL RESULTS FOR OBSTACLE AVOIDING SYSTEM

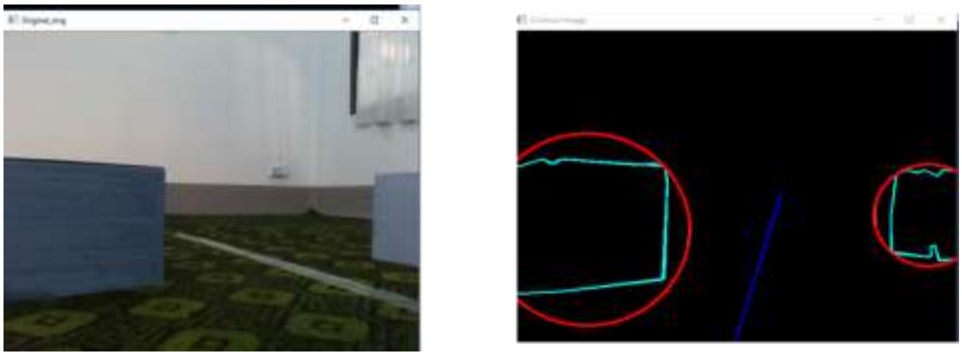
For obstacle avoiding and generating trajectory lines based on image processing is tested in this experiment. A 3D camera is used to detect the objects of the frame and the laptop PC mounted on the robot executes the image processing to extract δ and λ from the captured image. In this experiment, the robot captured the obstacles from three initial positions as shown in Figure 9, (in which the robot is located at the position x= 0.76m in the case 1, x=0 in the case 2 and x=-7.6m in the case 3) and experimental robot of the system.



(a) (b)

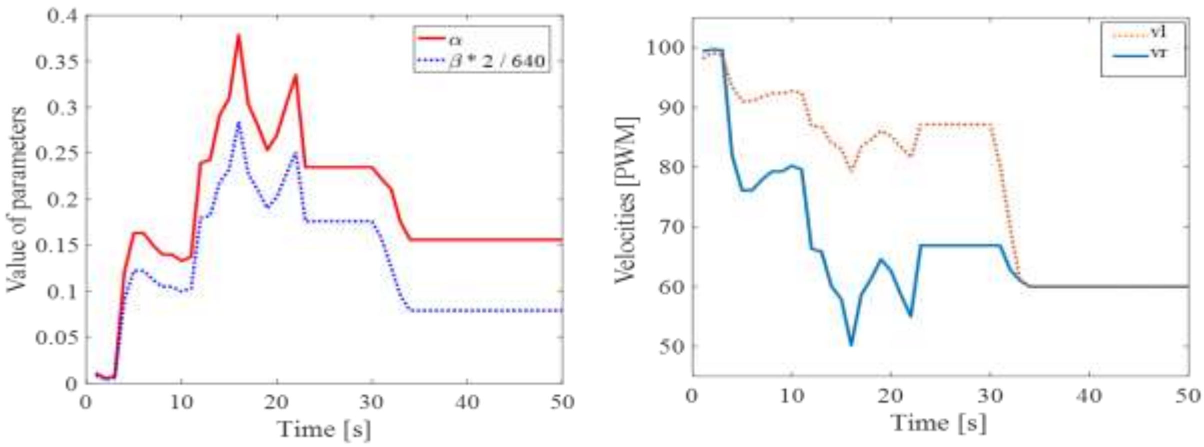
Figure9. (a) The Experimental testing positions for case 1, case 2 and case 3(b) Experimental robot

The experimental results for generating time-varying trajectory lines of the obstacle avoiding system for case 1 is shown in Figure.10 and 11 respectively. Figure.12 and 13 are shown for case 2 and Figure14 and 15 are shown for case 3.



(a) (b)

Figure10. Resultant image for case 1(a) Original image (c) Contour image



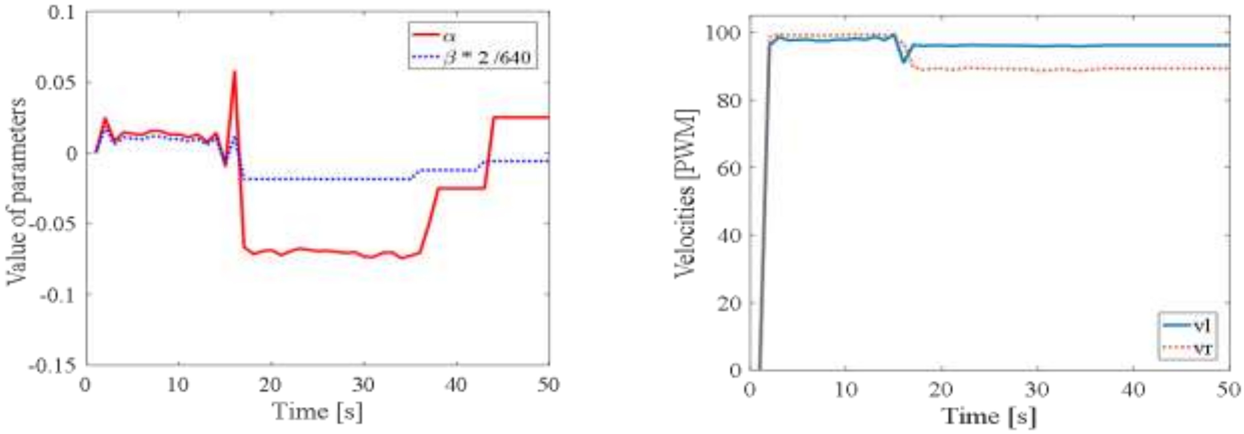
(a) (b)

Figure11. Experimental results for case 1 (a) Input parameters (δ, λ) (b) Output parameters (v_r, v_l)

DOI: 10.31695/IJASRE.2020.33678

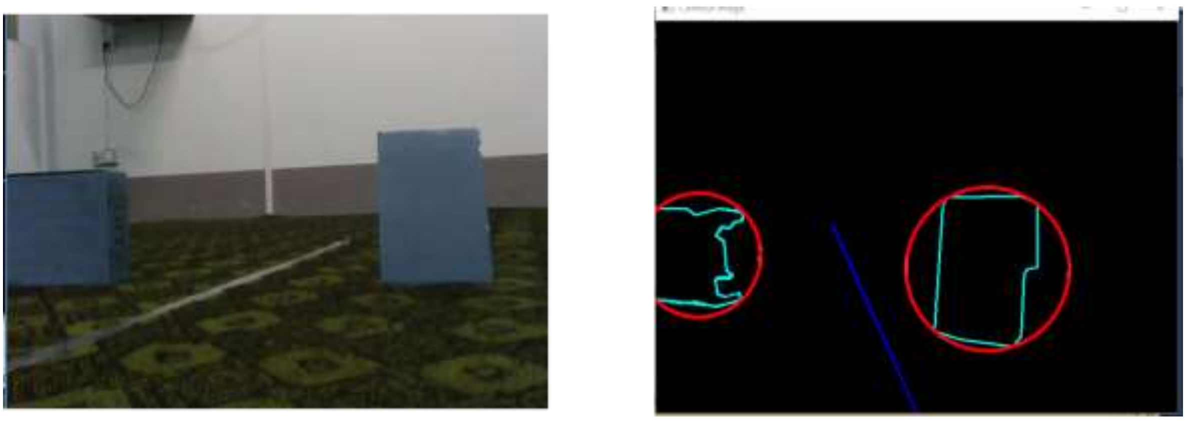
(a) (b)

Figure12. Resultant image for case 2(a) Original image (c) Contour image



(a) (b)

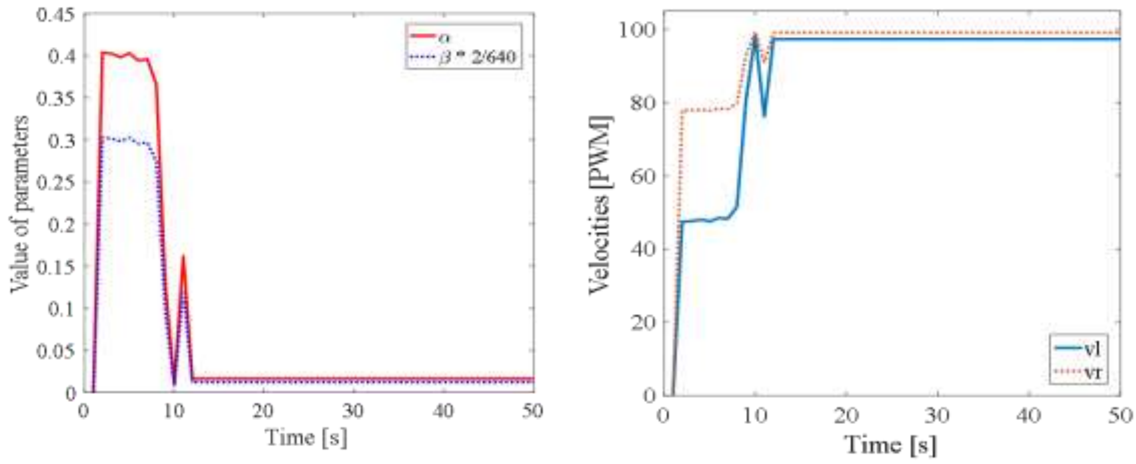
Figure13. Experimental results for case 2 (a) Input parameters (δ, λ) (b) Output parameters (v_r, v_l)



(a) (b)

Figure14. Resultant image for case 2(a) Original image (c) Contour image

DOI: 10.31695/IJASRE.2020.33678



(a) (b)

Figure15. Experimental results for case 3 (a) Input parameters (δ, λ) (b) Output parameters (v_r, v_l)

CONCLUSIONS

A fuzzy controller for the obstacles avoiding system of a mobile robot was described, where the robot equipped with a depth camera to detect the object. Based on 3D image information, the controller determined the control inputs, the left and right motors' speeds for the two-wheeled drive mobile robot. In this system, not only 2D data but also the distance between the obstacles and the robot are always measure whether the detected obstacle is near or far.

Based on the experimental results, the robot will move to right according to the slope and intersection in the case 1. The robot's right motor velocity moved with the maximum speed and left motor velocity moved with medium speed from 0s to 30s. After 30s, there has no detected object the robot will move with constant velocity in this case. Therefore, the robot avoids the obstacles for this case. In the case 2, the robot's left and right motor velocities are nearly same and moved with maximum speed within 0s to 13s and there has a little variation at the 15s , after that the robot moved with steady speed. In the case 3, at first 10s the robot move to left with robot' right motor speed is maximum and left motor speed is medium. After 10s, the robot moved to the forward with same speeds because of detecting no object.

According to the results of motors' speeds, the image processing technique worked well to generate the robot motors speeds of obstacle avoiding system for autonomous mobile robot.

ACKNOWLEDGMENT

The author is very thankful to Dr. Ei Ei Htwe, Pro-Rector of Mandalay Technological University, for his encouragement, invaluable permission and his kind support in carrying out this paper work.

The author is deeply grateful to Dr.Wut Yi Win, Professor and Head, Department of Mechatronic Engineering, Mandalay Technological University for supplying all necessary things.

The author is extremely grateful to Dr. Yin Yin Aye, Professor, Department of Precision Engineering, University of Technological Yadanarpon Cyber City, for her valuable suggestion, accomplished supervision, sharing experience and correction on this research.

The author especially appreciates and thanks all her teachers for paper support, and guidance during theoretical study and paper preparation durations.

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DOI: 10.31695/IJASRE.2020.33678