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Mobile Robot Controller Based on Fuzzy Logic System in Uneven Terrain

Zati Hanani Ismail[1] , Syibrah Naim[2] , Ahmad Faisal Ayob[3] and Azam Che Amat[4]
[1]*School of Informatics and Applied Mathematics, Universiti Malaysia Terengganu, 21030 Kuala Terengganu, Terengganu*
[2 and 4]*School of Computer Science, Universiti Sains Malaysia, 11800 Pulau Pinang*
[3]*School of Ocean Engineering, Universiti Malaysia Terengganu, 21030 Kuala Terengganu, Terengganu,*
[1]zatihanani93@yahoo.com, [2]syibrah@usm.my, [3]ahmad.faisal@umt.edu.my, [4]zackfortune70@gmail.com

ABSTRACT

In many environments, mobile robot navigation is not always feasible as the environment can lack of features and dynamic obstacles. Fuzzy logic control system is well suited for controlling a mobile robot because of its capability for making inferences in vague environments. It assists rules generation and decision making. In this paper, we will use mobile robot, mBot V1.1 as an experimental robot to be tested for obstacles avoidance using ultrasonic sensor. MBot consists of two wheels and is equipped with ultrasonic in front of its main body. The ultrasonic sensor will calculate the distance by emitting high frequency sound pulse and then times how long it takes for the echo of the sound to reflect back. The fuzzy logic controller will be implemented in the MBot microcontroller to maximize efficiency of the Mbot in uneven terrain for obstacle avoidance method. Fuzzy logic will then determine the speed of the MBot if any obstacles is presented while keeping it on the track. Conventional controller without fuzzy logic will also be tested alongside the system that has fuzzy logic implementation on the same area and data will be collected and compared to each other at the end of the project. These data findings will contribute significant impact for fuzzy logic implementation on mobile robot system for obstacle avoidance testing in uneven terrain. In the future, we plan to increase the number of sensors or variables which not only focuses on path towards the target and apply the mobile robot controller in challenging real-time unstructured areas.

Keywords: Fuzzy logic controller, Mobile robot navigation, MBot V1.1, Uneven terrain

INTRODUCTION

Mobile robot navigation in real-world unstructured environments which is the environments that have not been specifically engineered for a robot is a local path planning problem based on sensory information with no knowledge of the form and locations of obstacles (Baklouti, John, & Alimi, 2012). According to Baklouti et al. (2012), precise end-effector and positioning accuracy are required in the navigation process as the real-world environments are not ideal as they can produce random errors that change unpredictably. In addition, Chen et al. (2009) stated that, a mobile robot is a small robot mainly equipped with wheels to move and various sensors to perform tasks such as navigation, obstacle avoidance and other. Due to this characteristic, many achievements have been accomplished by mobile robot outside human’s league includes venturing into small or dangerous place, collecting data from far distance and other (Chen, Chen, & Chase, 2009).

Mobile robot navigation is not always feasible as there are many uncertainties that the robot need to cope with in order to navigate in unstructured environments. Therefore, the choice of an adequate method is important in order to make the robot to move smoothly. Hagras (2007) has clarified in his paper, a fuzzy logic control as the most widely used application of fuzzy logic.

Fuzzy Logic Controller (FLC) is credited with being an adequate methodology for designing robust controllers that are capable of delivering a better performance while facing the uncertainty and imprecision. Besides that, a FLC also provides a method to construct controller algorithms in a user-friendly way closer to human thinking and perception (Hagras, 2007).

The first implementation of FLC was by Mamdani and Assilian in 1974 (Mamdani & Assilian, 1975). Since then, the implementation of FLC in real-world applications have been applied by many researchers where the FLCs have given satisfactory performance similar to the human operators (Hagras, 2007). For example, Chao et al. (2009) had developed one fuzzy control system for target tracking and obstacle avoidance of a mobile robot. The fuzzy control strategy based on the sensed environment using a stereo vision information has been proposed in order to handle the decision making of the mobile robot (Chao, Hsueh, Hsiao, Tsai, & Li, 2009). Moreover, Boubertakh et al. (2008) also has proposed a new fuzzy logic based navigation method for movement of mobile robot in an unknown environment. A fuzzy logic controller based on human sense and a fuzzy reinforcement algorithm is used to fine tune fuzzy rule base (Boubertakh, Tadjine, Glovennec, Labiod, 2008).

Fuzzy logic control system is a control system based on fuzzy logic concept that analyzes input values in terms of logical variables that take on continuous values between 0 and 1 (Zadeh, 1965). Such concept is different to classical or digital logic, which operates on discrete values of either zero or 1 (false or true, respectively). According to Mendel (1995), fuzzy logic system can be defined as a nonlinear mapping of an input data set to a scalar output data. He also stated that there are four main stages namely; fuzzification, fuzzy rules, inference and defuzzification.

Most of mobile robot is equipped with sensors for purpose of doing thing autonomously such as navigation and automatically avoid the obstacle. The sensor presents in the MBot is an ultrasonic sensor that used to detect and avoid the obstacles if detected by the sensor. The obstacles avoidance method shows the intelligent behavior of the mobile robot. The current intelligent behavior of the mobile robot is capable only to be operated or moved on a smooth terrain of flat terrain where the path is simple with fully sighted of obstacles presented. However, with such current intelligent behavior, the mobile robot was having a difficulty to move on an uneven terrain which is the area full of uncertainty challenges includes the random appearance of obstacle and different type of path.

Besides, Yan and Li (2016) also states that the weakness of the conventional algorithm implemented in the system is the source of this problem. It operates component line follower sensor normally where the line follower sensor and ultrasonic sensor detection function is limited to only two binary input of 0 and 1 (Yan & Li, 2016). The reason for the implementation of the conventional algorithm is because of the cheap cost and minimum power consumption as the mobile robot only can detect two inputs, the operation of mobile robot is limited (Yan & Li, 2016). As a result, the mobile robot may suffer from many problems as incomplete information is denied from collecting it. Consequently, the mobile robot might collide with the random obstacles that appear and may damage the mobile robot as calculation of distance is not precise enough. Besides, the mobile robot may also suffer from the inability to stay in path for example narrow path and stray out without any guide in uneven terrain (Yan & Li, 2016).

In this paper, we proposed one algorithm of fuzzy logic controller for obstacles avoidance controller in an uneven terrain while moving towards the target. An uneven terrain presents many challenges for example, dead end path, sudden obstacles appearance and other. It is the same as research conducted in the paper by Faisal et al. (2013) where the uneven terrain is referring to a dynamic environment where traditional mobile robot planning approaches (conventional system) remain not robust and unable to overcome these challenges (dynamic environment) (Faisal, Hedjar, & Sulaiman, 2013). This means that the nature of uneven terrain will cause the MBot to not work very well when moving in that area with the current system. Therefore, fuzzy logic control (FLC) will be implemented to handle the problem. FLC is taken into consideration as fuzzy logic capable of reasoning with vague information and dealing with higher uncertainty in uneven terrain so FLC is the best optimal solution. In order to prove the effectiveness of the FLC system over a conventional system without FLC, two tests will be conducted with both system and data will be collected.

FUZZY SET THEORY

Fuzzy set was first introduced by Zadeh (1965) which characterized an object with degree of membership. In classical set theory, a set, C, is comprised of elements, $x \in U$, whose membership in C is described by the characteristic, or membership function (Zadeh, 1965)

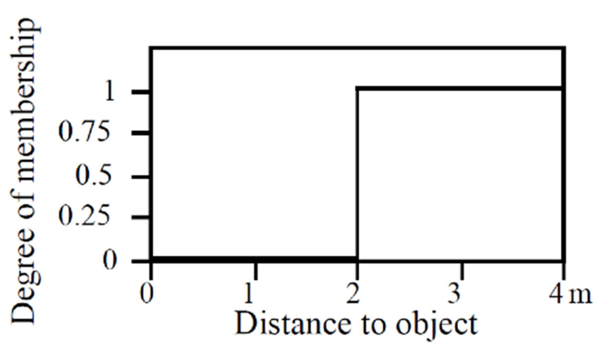
$$\mu_C(x): U \to \{0,1\} \tag{1}$$

where U is the universe of discourse, a collection of elements that can be continuous or discrete. The membership function $\mu_C(x)$ implies that the element x either belongs to the set $(\mu_C(x) = 1)$ or it does not $(\mu_C(x) = 0)$. In fuzzy set theory, a fuzzy set, $\tilde{F}$, is described by the membership function (Zadeh, 1965)

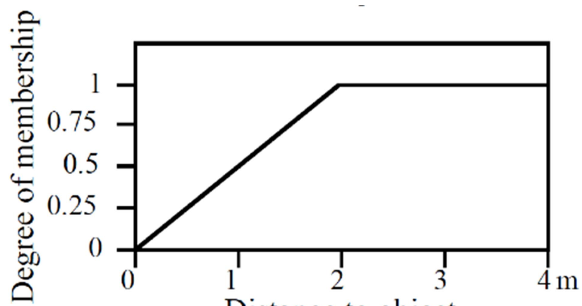
$$\mu_{\tilde{F}}(x): U \to [0,1] \tag{2}$$

where elements, $x \in U$, have degrees of membership in $\tilde{F}$ with any value between 0 and 1 inclusive. Note that a fuzzy membership function is a so-called possibility function and not a probability function. A membership value of 0 corresponds to the case where in the detail, the element is definitely not a member of the fuzzy set. A membership value of one corresponds to elements with full membership in the fuzzy set (Zadeh, 1965). According to Tunstel et al. (1996), the membership values in the open interval (0, 1) correspond to partial membership and indicate a measure of uncertainty or imprecision associated with the element.

A comparative example of a crisp set and a fuzzy set can be illustrated by using the usage of linguistic term 'near' in reference to the relative distance between mobile robot and obstacles (Jamshidi, Ross, & Vadiee (Eds.), 1993). The term 'near' can take on different meanings to different individuals, and in different contexts. For illustrative purposes, let 'near' be 2 meters (approximately 2 meters in the fuzzy set case). A graphical representation of a crisp set and a fuzzy set for 'near' is shown in Figure 1 below (Jamshidi, Ross, & Vadiee (Eds.), 1993).



(a) Crisp set



(b) Fuzzy set

Figure 1: Graphical representation of 'near'

Tunstel et al. (1996) also stated that, the membership functions can be defined as functions which take on a variety of possible shapes determined at the discretion of the fuzzy system designer. In addition, also stated that the common used function shapes (fuzzy logic terminology given in parentheses) include triangular (Λ), trapezoidal (Π), delta (singleton), positively sloped ramp (Γ), and negatively sloped ramp (L). These are shown in Figure 2. The ramp functions are sometimes referred to as right shoulders (Γ) and left shoulders (L) (Tunstel, Lippincott, & Jamshidi, 1996).

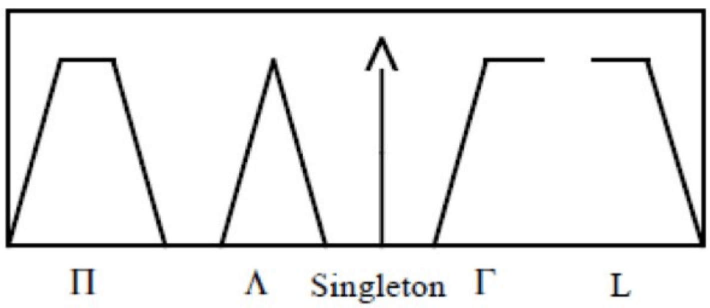


Figure 2: Common fuzzy membership functions

Fuzzy sets, like classical crisp sets, are subject to set operations such as union, intersection, and complement (Zadeh, 1965) which are used to express logic statements or propositions. The union of two fuzzy sets $\tilde{A}$ and $\tilde{B}$ with membership function $\mu_{\tilde{A}}(x)$ and $\mu_{\tilde{B}}(x)$ is a fuzzy set $\tilde{C} = \tilde{A} \cup \tilde{B}$ whose membership function is related to those of $\tilde{A}$ and $\tilde{B}$ as follows (Zadeh, 1965):

$$\mu_{\tilde{C}}(x) = \mu_{\tilde{A}\cup\tilde{B}}(x) = \max[\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)] \tag{3}$$

The operator in this equation is referred to as the max-operator and is represented by the logical term OR. The intersection of $\tilde{A}$ and $\tilde{B}$ is a fuzzy set $\tilde{D} = \tilde{A} \cap \tilde{B}$ whose membership function is given by Zadeh (1965):

$$\mu_{\tilde{D}}(x) = \mu_{\tilde{A}\cap\tilde{B}}(x) = \min[\mu_{\tilde{A}}(x), \mu_{\tilde{B}}(x)] \tag{4}$$

The operator in this equation is referred to as the min-operator represented by the logical term AND.

Consider the Cartesian product of two universes U and V defined by

$$U \times V = \{(u, v) | u \in U; v \in V\}$$

which combines elements of U and V in a set of ordered pairs. A fuzzy relation **R** is a mapping (Zadeh, 1965):

$$\mathbf{R}: U \times V \rightarrow [0,1]$$

where

$$\mu_{\mathbf{R}}(u,v) = \mu_{\tilde{A}\times\tilde{B}}(u,v) = \min[\mu_{\tilde{A}}(u), \mu_{\tilde{B}}(v)] \tag{5}$$

The composition of two relations, **R** (u, v) and **S** (v, w), is denoted by $\mathbf{T} = \mathbf{R} \circ \mathbf{S}$. Its membership value can be determined by the following expression

$$\mu_{\mathbf{T}}(u,w) = \max[\mu_{\mathbf{R}}(u,v) \circ \mu_{\mathbf{S}}(v,w)] \tag{6}$$

which is called the max-product composition. Another common compositional rule inference is the max-min composition (Yanik, Ford, & McDaniel, 2010).

According to Tunstel et al. (1996), the fuzzy relations can be represented linguistically by natural language statements in the form of fuzzy if-then rules. A collection of such rules is referred to as a rule-base. Accompanied by suitable membership functions, the rule-base is a core ingredient of any fuzzy rule-based expert system (Tunstel, Lippincott, & Jamshidi, 1996).

FUZZY LOGIC CONTROLLER

Sufficient solution is needed to solve the problem in the project. It is noted that the robot's behavior can be changed if their "hardware, control program (the task) or the environment is changed" (Ali, 2011). This quote has proven that by changing the system of mobile robot, failure working in uneven terrain can be overwritten to successful one (Ali, 2011).

In this paper, the fuzzy logic controller (FLC) is expected to overcome the problems approaches by Mbot in uneven terrain as fuzzy logic (FL) is capable of making a decision based on the vague and ambiguous information. The concept of FL is similar as mimicking human mind. FL is introduced by Zadeh (Zadeh, 1965). In his works, the concept of a linguistic variable or "fuzzy" was introduced. Rather than using number, it is easy to express the facts or rules by using word (linguistic) form Peri (2002). For example, Peri (2002) defined the line follower sensor as the input, based on degree detection of the left path and the right path. In term of the linguistic variable, it can be defined as 'slightly to the right', 'less to the left' and many other variables as the fuzzy sets range from 0 to 1.

According to Yanik et al. (2010), fuzzy logic controller consists of four main stages, namely; fuzzification, fuzzy rules, inference, and defuzzification. In details, fuzzy logic system takes a crisp set of data as input. Then, in fuzzification stage, the fuzzifier will convert the crisp input into fuzzy set using linguistic terms that are characterized on the closed interval [0, 1] according to their levels of membership in fuzzy sets in order to illustrate how the membership functions relates to each other (Yanik, Ford, & McDaniel, 2010). After that, in the inference engine stage, the engine will draw a conclusion based on the set of rules as known as Rule Base. The Rule Base is characterized by a set of IF-THEN rules in which antecedents (IF parts) and the consequents (THEN parts) involve linguistic variables (Yanik, Ford, & McDaniel, 2010). Lastly, in the defuzzification stage, it will extract a crisp command output from inferences drawn from fuzzy rules by mapping the resulting fuzzy output (Yanik, Ford, & McDaniel, 2010). Figure 3 below shows the block of fuzzy logic control system (Yanik, Ford, & McDaniel, 2010).

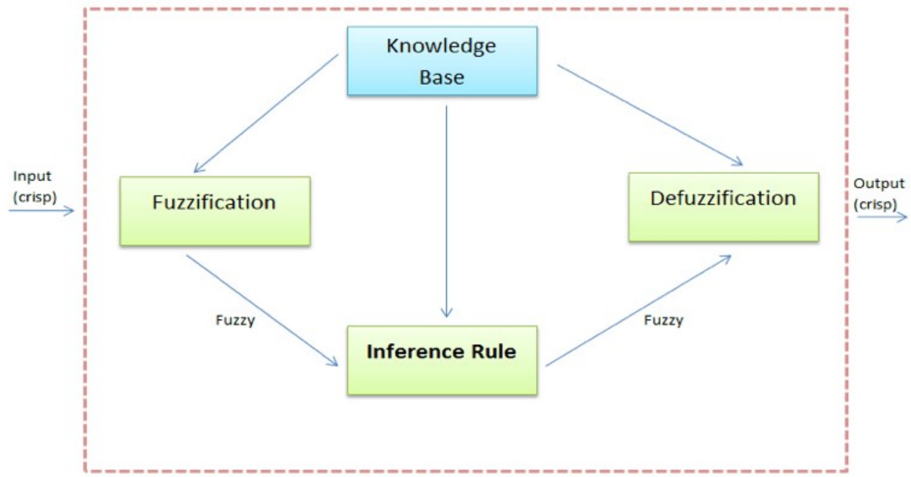


FIGURE 3: Fuzzy Logic System Block Diagram

MOBILE ROBOT APPLICATION

Tunstel et al. (1996) in their paper stated that, mobile robots are typically equipped with several sensor modalities which may include range sensors, tactile/contact sensors, encoders, and vision systems. Furthermore, they added that by giving such sensor modalities, the usual procedure for fuzzy control synthesis consists of first defining linguistic terminology for the inputs and outputs. Then partition the sensor space and actuator space using appropriate fuzzy sets (membership functions), and lastly, formulating fuzzy rules that satisfactorily govern the desired response of the robot in all practical situations (Tunstel, Lippincott, & Jamshidi, 1996).

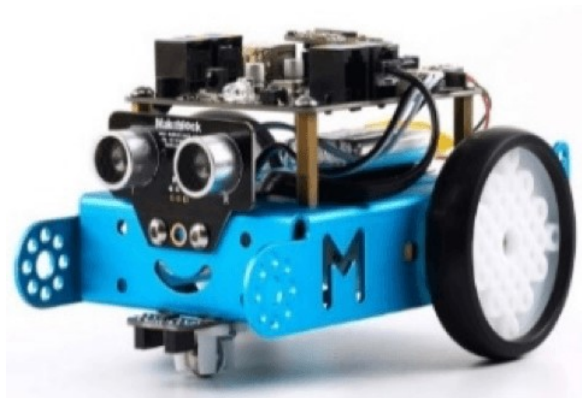
In this paper, we will use MBot V1.1 robot kit in order to apply the fuzzy logic controller to the mobile robot. mBot V1.1 robot kit is an educational robot kit that can be used in order to experience the hands-on experience about programming, electronics, and robotics. To program this robot, there are two types of programming that can be used which are Arduino programming and Scratch programming.

The MBot V1.1 bluetooth module used in this paper was controlled by mCore board which is the main control board specially design for MBot and Arduino programming. The MBot is equipped with sensors such as line follower used for detect, moving following the path and ultrasonic sensor used for obstacles avoidance. Ultrasonic sensor works by calculate distance by emitting high frequency sound pulse and then times how long it takes for the echo of the sound to reflect back. For the line follower sensor, it detects path by measuring the intensity of light reflected by the terrain.

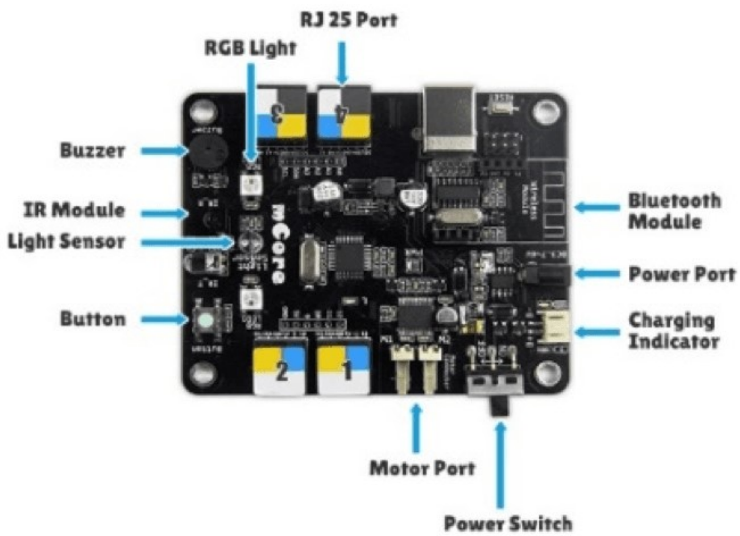
Besides, MBot also has been equipped with two wheels to move around. The other important component of Mbot includes:

- Two servo motor used to rotate the wheels.
- AA Battery holder to hold the battery to power all component of Mbot
- Chassis, the body that hold all the component of the Mbot.
- Bluetooth module, small board that provides wireless network to the Mbot

Figure 4a and Figure 4b below shows the mBot V1.1 robot and the features of mCore board respectively.



(a) MBot V1.1



(b) MCore board

FIGURE 4: (a) mBot V1.1 bluetooth module. (b) Features of mCore board

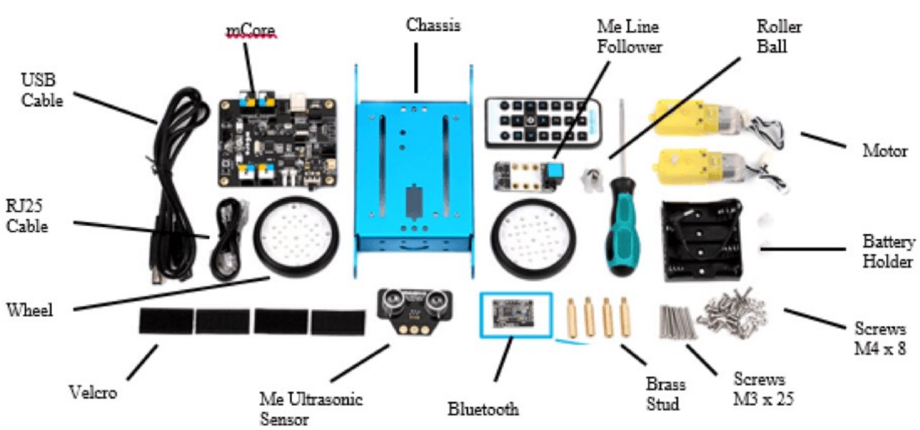


FIGURE 5: Part list of mBot V1.1 bluetooth module

Figure 5 above shows the part list of mBot V1.1 bluetooth module. It consists of USB cable, mCore, chassis, Me Line Follower sensor, roller ball, 2 motors, battery holder, screws M4x8, screws M3x25, brass stud, bluetooth, Me Ultrasonic sensor, velcro, wheels and RJ25 cable.

Significantly in this project, Mbot is given a command to move towards the target and then, the ultrasonic sensor is applied to detect and avoid obstacles along the way. The experiment is to be conducted on uneven terrain based on obstacle avoidance method. Uneven terrain presents many challenges for example, dead end path, sudden obstacles appearance and other. Therefore, the FLC algorithm will be implemented to the MBot to solve the problems as the controller can deal with high uncertainty present in an uneven terrain.

ALGORITHM OF FUZZY LOGIC CONTROLLER FOR MOBILE ROBOT NAVIGATION

Fuzzy logic control systems have four main stages, which are fuzzification, fuzzy rules, inference system, and defuzzification. Figure 6 below shows the block diagram of the development of mobile robot system based on fuzzy logic controller. The Me Ultrasonic sensor that we used will measures the distances between the mobile robot and the target. The signals that have been received by the sensor will be send to the microcontroller system. Then, the microcontroller system will implement the fuzzy logic control algorithm and send the signals to the motors of the mobile robot.

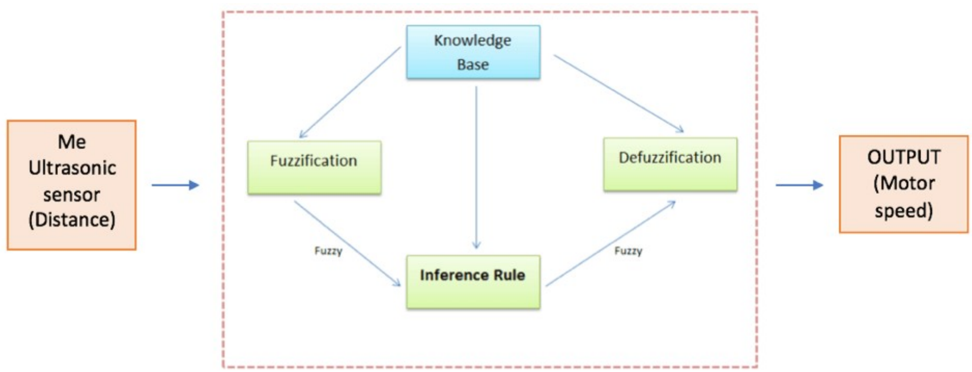


FIGURE 6: Block diagram of the mobile robot system

1. Fuzzification

Fuzzification is the process of mapping crisp inputs to fuzzy membership functions (Ibrahim & Alshanableh, 2011). Figure 7 and 8 below shows input and output crisp variables of the system. For this paper, we synthesize a fuzzy controller that uses one input and one output. The input is the distance between the front side distance of the robot and target. The range input space was partitioned based on a relevant maximum ultrasonic sensor measurement of 420cm, i.e. the universe of discourse for range spans the interval [10cm, 420cm]. The linguistic variables used for the distance between the robot and obstacles are: N: Near [10cm,35cm], S: Safe [30cm, 65cm] and F: Far [60cm,420cm]. The membership function is illustrated in the Figure 7 below. The intervals are divided according to our observation during experiments and the capability of MBot to detect the obstacles based on collected data.

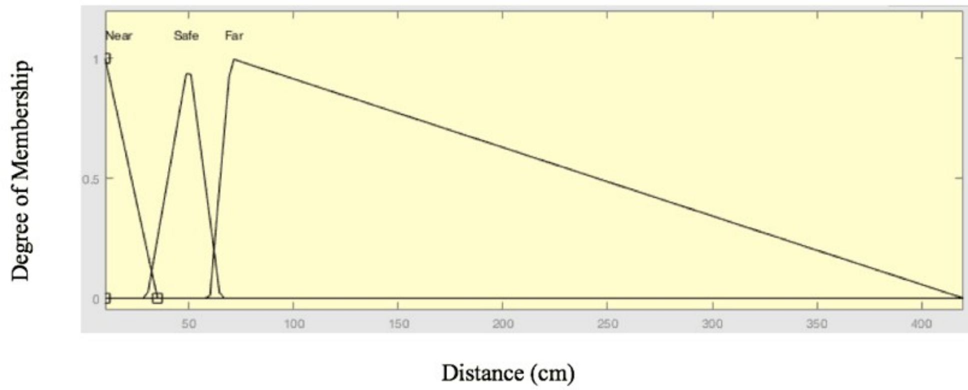


FIGURE 7: Front distance between MBot and target

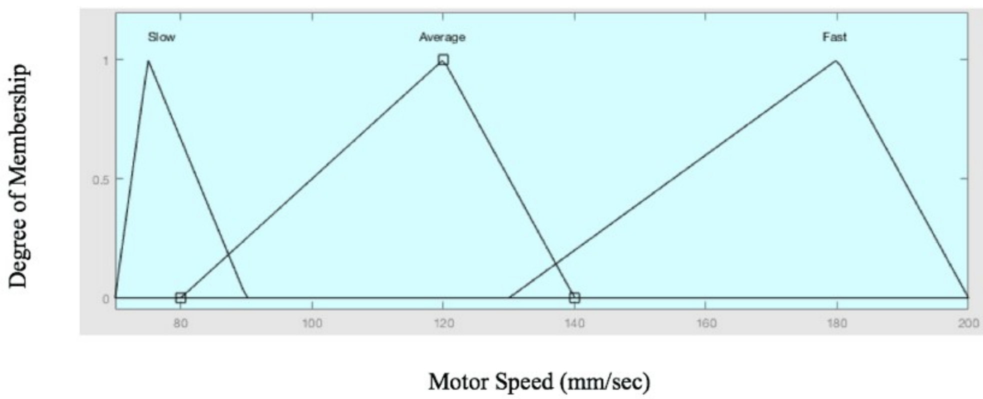


FIGURE 8: Speed of the motors

The output for this project is the speed of the motors moved towards the target. The range output space was partitioned based on a relevant maximum speed for the mBot which is 200mm/sec. The linguistic variables used are: S: Slow [70mm/sec, 90mm/sec], A: Average [80mm/sec, 140mm/sec] and F: Fast [130mm/sec, 200mm/sec] and the interval from 70mm/sec-200mm/sec. Figure 7 above illustrated the membership function of the motor speed. The intervals are divided according to our observation during experiments and the capability of MBot to move towards the target.

2. Fuzzy rules and inference system

After defining the membership functions of the input and output of the system, we will generate the fuzzy rules to relate the output actions of the controller to the sensors inputs. Based on the membership function selected, a rule-base was designed to effect move speed of the motors towards the target. A total of 3 rules were formulated.

- **IF**: Distance is Near (N) **THEN**: Speed is Slow (S).
- **IF**: Distance is Safe (S) **THEN**: Speed is Average (A).
- **IF**: Distance is Far (F) **THEN**: Speed is Fast (F).

Rule I describe the situation where the obstacles are not presented along the way of the mobile robot (Mbot) so Mbot will continue to go at full speed until membership of far becomes smaller than the medium. Rule II will be fired if Mbot encounter obstacles at medium distance and speed will be reduced a little. Rule III is fired if Mbot is too closed to the obstacles and speed is reduced to the very low and then when the requirements are meet, Mbot will turn away from the obstacles at a moderate speed.

The fuzzy rules are usually in the form of IF-THEN statements as shown above. However, the rules also can be shown in the table format as shown in Table 1 below.

Table 1: The list of the fuzzy rules for the motors of the mobile robot

Input	Output
Near (N)	**Slow (S)**
Safe (S)	**Average (A)**
Far (F)	**Fast (F)**

3. Defuzzification

The last stage of fuzzy controller is the defuzzification. Defuzzification is the stage where a crisp output is generated based on the inputs and the rule base. There are several methods available to obtain a crisp output from a fuzzy system. For this paper, we used centroid calculation method. The centroid method is one of the commonly used defuzzification methods (Ibrahim & Alshanableh, 2011). Here, a weighted average of all the active rules determines an output by summing all of the output variables over their relative membership values (Ibrahim & Alshanableh, 2011). Expressed mathematically, if the membership functions are μ_i and the outputs are μ_i, then the crisp centroid output u is defined as

$$u = \frac{\sum_{i=1}^{u} u_i \mu_i}{\sum_{i=1}^{n} \mu_i} \tag{7}$$

EXPERIMENTAL RESULTS

The experiment part of this paper is divided into two scenarios. In the first scenario, the mobile robot navigates in an uneven terrain without using fuzzy logic controller whereas in the second scenario, the mobile robot navigates with the uses of FLC. For this experiment, we created one controlled environment that is similar to the unstructured environment. As shown in Figure 9, we created the environment by using layers of fabrics to represent uneven terrain of the environment. Figure 9 below shows the place where the experiments were conducted.

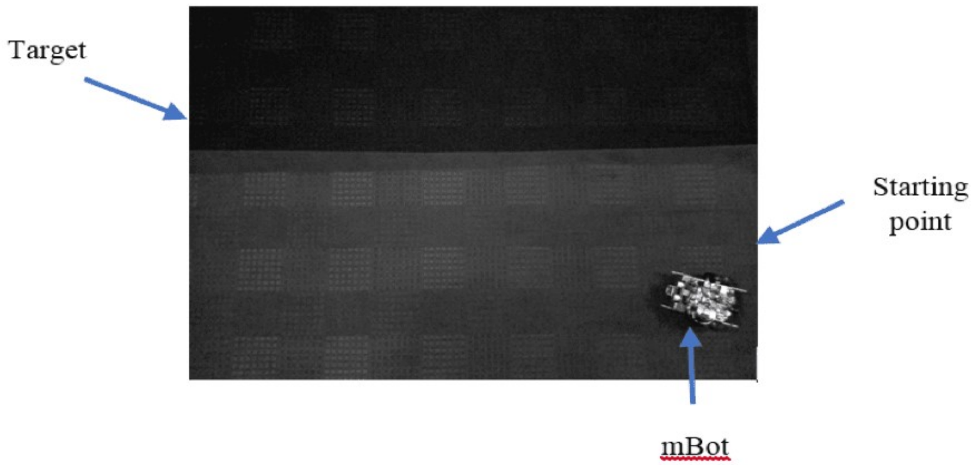
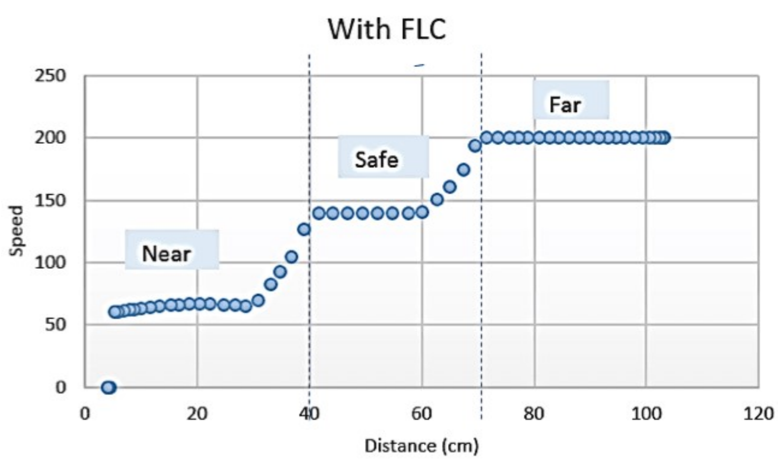
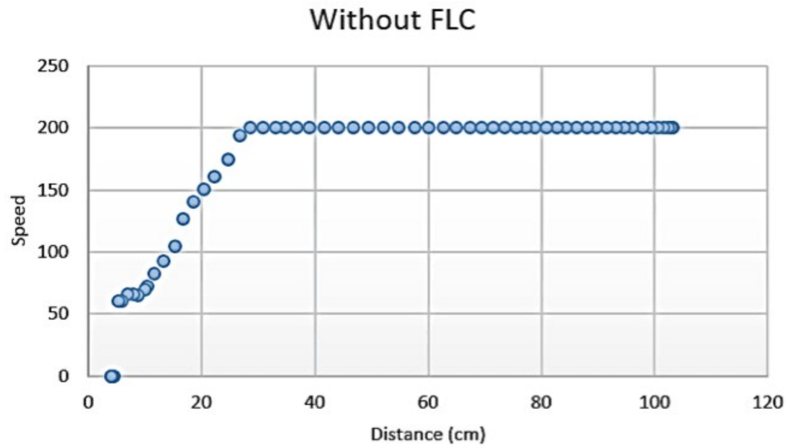


FIGURE 9: Experiment setup in Uneven Terrain

Let us assume that the robot intends to navigate from the starting point to the target as shown in Figure 9 above. The distance between the two points are approximately 2 meters. In all scenarios, the robot moves from the starting point towards the target. Figure 10a and Figure 10b below illustrates the effect on the navigation of mobile robot in two situations; with FLC and without FLC.



(a)



(b)

FIGURE 10: (a) with FLC. (b) without FLC.

We have compared the navigation of mobile robot with FLC and without FLC. As we can see in the figures above, the movement of the mobile robot in uneven terrain by using FLC is smoother than without using FLC. The mobile robot will stop smoothly when the distance detected was near. However, the decision of the output still depends on the hardware sensitivities which are the distance of the target detected by the sensor and the speed of the motors. The minimum distance of the target detected by the sensor is 2cm while the minimum speed of the motors is 40mm/sec. In addition, we also have recorded the time elapsed for the mobile robot to move from the starting point towards the target. The time elapsed for the mobile robot to move from the starting point towards the target by using FLC is faster than not using FLC.

Table 2: Time elapsed for the robot to move from starting point to end point

	With FLC	**Without FLC**
Time elapsed	5 seconds	10 seconds

As a result, from the data collected it is proven that the control of the speed of the motors by using FLC is better than conventional system in an uneven terrain.

CONCLUSION

In this paper, we presented the implementation of FLC to the real time control of mobile robot navigation in uneven terrain. We have performed one experiment using mBot V1.1 robot kit on the controlled environment that we created which is similar to the real-time unstructured environment. According to the experimental results, we can conclude that the implementation of FLC in mobile robot navigation generates smooth motion and reducing the navigation time in unstructured environment.

Besides that, it is also proven that the FLC system can be implemented into the MBot where the speed of the motors garadually decreases ad MBot begins to move towards the target. For future work, we plan to add more sensors to the robot and variables which is not only focus on the motion of mobile robot towards the target and also extend the controller by using Type-2 fuzzy logic controller.

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