VOL. 11, NO. 20, OCTOBER 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

FUZZY LOGIC APPROACH FOR LINE FOLLOWING ROBOT USING AN ARRAY OF DIGITAL SENSORS

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ABSTRACT

When Lofti Zadeh introduced fuzzy logic in the 60s, it became phenomenon in the academic world. The fuzzy concept that uses reasoning rather than exact computation has been proven and successfully applied in many applications. Implementing fuzzy logic generally involves three basic procedures; (1) fuzzification, or fuzzy inference process that converts crisp sensors value into fuzzy world, (2) computation, where the fuzzy value being treated, and (3) defuzzification, where the fuzzy output is converted back into crisp values mainly for actuators. Fuzzification revolves within the context of converting sensor's data into fuzzy world. Using analog sensor for fuzzification has been long discussed by numerous literatures as the analog sensors has ranges. However, converting digital sensors into fuzzy world is much challenging than analog sensors due to logical digital output. In this paper, we explain our technique in fuzzification of an array of digital sensors with an application to a line following mobile robot. We also discuss the Pugh selection matrix in order to choose the most desired mobile robot design. Then, we apply fuzzy logic control system to the developed mobile robot. Our present results for the LFR motion control yield in much faster and efficient tracking comparable to PID and switching algorithm that uses the same platform.

Keywords: Fuzzy logic, fuzzification, line following robot, digital sensor.

INTRODUCTION

Fuzzy logic for autonomous vehicle control has gained significant popularity in the last decades due to its highly successful implementation at almost all fields. The most well-known arguments supporting fuzzy controller are the ability to cope with imprecise information in heuristic rule based knowledge and sensor measurements, the interpolative nature of the fuzzy controllers, and the flexibility in the definition of non-linear control laws [1]. Moreover, the introduction of linguistic variable instead of complex mathematical equations has increased the fuzzy system reputation.

Fuzzy inference system (FIS) is defined as a way of mapping an input space to an output space using fuzzy logic. A FIS tries to formalize the reasoning process of human language by means of fuzzy logic, which is by building fuzzy IF-THEN rules [1]. Most of fuzzy inferences are based on the analog sensors, for which the value of analog sensors will be used as the value of the universe of discourse of FIS. These values are then later used to create memberships function. A rule-based then used to yield in crisp value during defuzzification process suitable for the actuators.

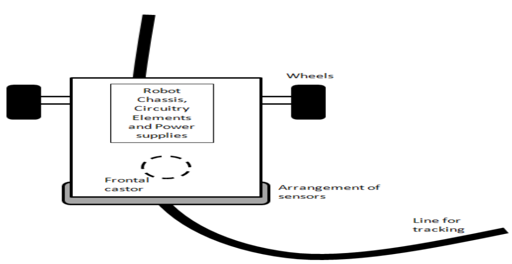

Figure-1. A typical concepts of a line tracking mobile robot.

A Line Following Robot (LFR) could be defined as a mobile robot that can follow a path [2]. The path can be visible i.e. a black line on a white surface or vice-versa, or it can be invisible like a magnetic field. Figure-1 shows a typical concept of a line following robot. This kind of robot normally is a differential drive type robot that could be consisted of two rear driving wheels, an omnidirectional caster and an array of sensors. One application of a line tracking robot is the carrier robots used in gigantic warehouse such as Kiva robots used in Amazons warehouse [3]. These robots are used in warehouse automation, where they move between shelves stations to pick and drop supplies autonomously.

A line following robot (LFR) is by far the most suitable application that helps to understand the practical application of FIS by digital sensors. To date, there are little approaches of FIS based on digital sensor for a LFR. Instead, analog sensors are used. The analog sensor values, which typically range from 0 to 5V were the values that is normally sampled for fuzzification. As it has ranges, then the universe of discourse is larger and easier to compute. In [2] for example, 8 analog sensors was used. As the line is detected, a comparator was used to convert the analog value into logic number ‘0’ or ‘1’ at some threshold voltage. Later, a switching control was used to control the robot movement. The analog sensor oriented fuzzy logic controller are well explained in [4]. This works are the most fundamental works in fuzzy logic system for a line following robot, and used to teach undergraduates students about the systems. The robot uses two proximity sensors mounted at the front of the robot, which converts the acquired voltage into fuzzy logic. Three scheme of fuzziness were introduced which were fuzzification, rule definition, and defuzzification. The researches explain

VOL. 11, NO. 20, OCTOBER 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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how the fuzzy logic control could be applied to a LFR and it was indeed very good for reference works on fuzzy logic control based on infrared distance sensors.

In this works, we used an array consisting five digital sensors that strictly outputting ‘1’ or ‘0’ with respect to line detected or not, and fed to the fuzzy logic control of the custom built line following robot. The focus is directed of the method taken to fuzzify this crisp digital input sensors. Because digital sensor does not have ranges as analog sensor, the fuzzification procedure was fairly challenging. The FIS on digital sensors were rather strenuous due to the limitation of the universe of discourse. The output from the sensors does not needed for sampling and direct digital values were used.

LFR DEVELOPMENT

In this section, we discuss the hardware development considering mechatronic system design approach that consists of three processes which are concept generation, concept screening and concept scoring. Six conceptual designs were made and concentrated. In this paper however, we do not show all the conceptual designs of LFR because they were made on hand sketch paper. The designs were then evaluated using the Pugh decision matrix [5] to systematically evaluate the alternatives based on the design specifications with a limited budget constraint. Pugh decision matrix was indeed very useful especially when the budget and costs are the limitation [5][6].

Table-1. Evaluation chart for the LFR concept design.

Criteria (weight)	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6
High efficiency (8)	+	+	+	+	0	0
High reliability (8)	+	+	-	+	0	0
Low cost (10)	0	+	0	+	0	0
Light weight (7)	0	+	0	+	0	0
Aesthetically appealing (6)	+	+	0	0	0	0
Easy to assemble (8)	0	+	+	+	+	0
Easy to dissemble (8)	0	+	+	+	+	0
Total +	3	7	3	6	2	0
Total -	0	0	1	0	0	0
Score, *J*	22	**55**	16	49	16	0

Table-1 show the Pugh evaluation matrix for all six design concepts with symbol (+) represent ‘good criteria’, (-) represent ‘bad criteria’, and 0 means neutral selection. In order to choose the desired concept, a scoring function was used. The scoring function is a weightage cost function given by Equation. (1).

$$Score, J_{\max} = \sum_{i=1}^{N} w_i G_i - \sum_{i=1}^{N} w_i B_i \quad (1)$$

where w_i are the weights of each criteria i depending on the user point of view, G_i and B_i are the good and bad of the i-th criteria respectively, and N is the total number of criteria. Since 0 is used as neutral selection, then it does not accumulated in the cost function, J. In this table, we could observe that Concept 2 has the maximum score value, therefore it was chosen for actual prototype development.

Table-2 shows the specification and the construction materials of the chosen conceptual design. Figure-2 on the other hand shows the completed hands-on design of the mobile robot platform. For this customized mobile robot, the digital sensor array used was the auto calibrating line sensor LSS05 with 10mm spacing between the sensors [7]. With this array configuration, the compatible line used in this works was a black line on a white surface with 28mm wide.

With the mobile robot structure ready, the crucial software part of the robot is then focused. It should worth be noted that the hardware design does not consider the mathematical model or the transfer function of the robot at all, which is to reflect the fuzzy logic applicability in a non-mathematical systems. In software development, Matlab is used to simulate the surface smoothness of the FIS algorithm, and later be applied to the actual microprocessor using the Arduino environment. The developed system mainly consists of (1) fuzzification of five digital inputs namely Left, M-Left, Middle, M-Right, and Right Digital Sensor, (2) decision making using rule definition of IF-ELSE statement, and (3) defuzzification to obtain the crisp value for Left and Right differential drive motor system. The fuzzification will be explained thoroughly in the subsequent section.

Table-2. Specification of the line following robot (LFR).

Controller	Arduino Duemilanove (ATmega328)
Line Sensor	Five photo-reflector (LSS05 by Cytron Technologies)
Power Supply	9V battery for controller, Fullymax Li-Po 7.4V 2200mAh 20C for motors.
Motor	Brush DC Tamiya double gearbox
Motor Driver	Flexible driver FD04A by Cytron Tech.
Built Materials	Polymethyl methacrylate (Acrylite)
Dimensions	165(L), 130(W), 120(H) [mm]
Weight	425 gram
Drive System	Two wheel differential drive
Front Wheel	Omni-directional castor [7mm(L), 30mm(D)]
Rear Wheel	Tamiya truck tire [36mm(D)]

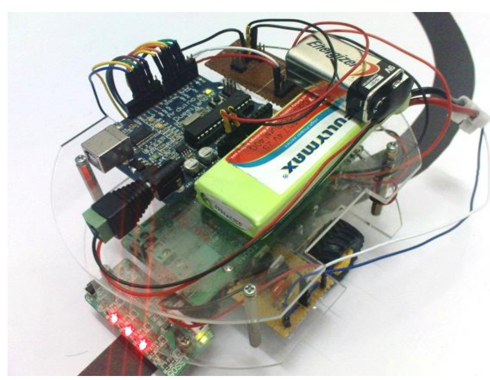

Figure-2. The developed LFR platform.

VOL. 11, NO. 20, OCTOBER 2016 ISSN 1819-6608
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FUZZY LOGIC SYSTEM

This section describes the fuzzy inference algorithm developed for our LFR robot. Figure-3 shows the diagram for the fuzzy inference system applied in the LFR. As mentioned previously, fuzzifying the digital sensor output (0 *or* 1) is an impossible work since the universe of discourse requires a range of value, for which in this case analog sensors output worked best (0 *to* 5V). Therefore, to tackle this problem, we propose to use an inferred reference database. This exhaustive reference database is built from deductive reasoning that involves logical deliberation of mobile robot movement at the time the sensors sense the line. As five sensors are used, the possible detection was 2^5 which are 32 combinations. The set point that concurs with the line width then was decided to be (01110, 01010 and 00100). The 32 combination however, includes the impossible detection i.e. 10001, 10101, etc. Therefore in such cases, the detection will be omitted. With these consideration, only 23 detection combinations left and applicable in this works as depicted in Table-3. Noted that in the arrangement of digital value, '0' means the line is not detected and vice versa for '1'. And also zeros errors for all three set point detection.

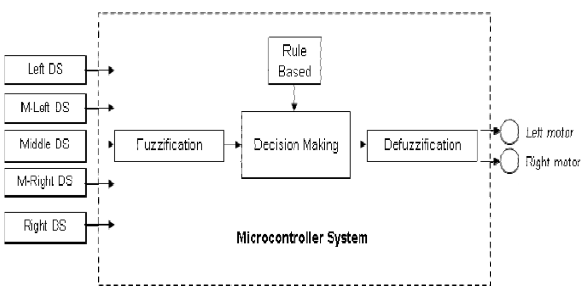

Figure-3. The fuzzy inference system of the LFR.

Parameter 'value' in Table-3 was obtained from normalization of 21 combinations (excluding the 3 set point) while parameter 'error' are obtained from the difference between value and the set point. Based on this reference database, two parameters for FIS are introduced, which are ERROR and ΔERROR. ERROR is defined as the difference of current value detected to set point, $E(t) = V(t) - SP$ while ΔERROR is the difference error value to last error value, $\Delta E(t) = E(t+1) - E(t)$. For these two parameters, the membership function is later formulated using Sugeno inferences, which are POSITIVE (P), ZERO (Z) and NEGATIVE (N). A rule based inference using the IF-ELSE statement is built in order to formulate the output membership function. A Fuzzy Associate Map (FAM) is generated using deductive reasoning approach. Nine rules were evaluated and tabulated in Table-4. The output memberships function than formulated as MOTORS, which consists of LEFT (L), FORWARD (F) and RIGHT (R) memberships. All of this membership functions are shown in Figure-4.

Table-3. Reference database based on the arrangement of digital values.

No	Arrangement Digital Values					Value	Error
1	0	0	0	0	1	0.0476	-0.4762
2	0	0	0	1	1	0.0952	-0.4286
3	0	0	0	1	0	0.1429	-0.3809
4	0	0	1	1	1	0.1905	-0.3333
5	0	0	1	0	1	0.2381	-0.2857
6	0	0	1	1	0	0.2857	-0.2381
7	0	1	1	1	1	0.3333	-0.1905
8	0	1	1	0	1	0.3810	-0.1428
9	0	1	0	1	1	0.4286	-0.0952
10	0	1	0	0	1	0.4762	-0.0476
11	0	1	0	1	0	0.5238	0.0000
12	0	1	1	1	0	0.5238	0.0000
13	0	0	1	0	0	0.5238	0.0000
14	1	0	0	1	0	0.5714	0.0476
15	1	1	0	1	0	0.6190	0.0952
16	1	0	1	1	0	0.6667	0.1429
17	1	1	1	1	0	0.7143	0.1905
18	0	1	1	0	0	0.7619	0.2381
19	1	0	1	0	0	0.8095	0.2857
20	1	1	1	0	0	0.8571	0.3333
21	0	1	0	0	0	0.9048	0.3810
22	1	1	0	0	0	0.9524	0.4286
23	1	0	0	0	0	1.0000	0.4762

In defuzzification phase, the fuzzy computations will be converted back into crisp value for actuator input, which in our case a voltage for left and right motor where the crisp value should be the motor's PWM. The weighted average membership defuzzification method [8] is used in our works with the function of $x^* = \sum_{i=1}^{n} m^i w_i \Big/ \sum_{i=1}^{n} m^i$, where x^* is the defuzzified output, m^i is the membership of the output of each rule, and w_i is the weight associated with each rule. The output surface was however, was not really smooth as expected due to non-linearity from both of input parameters. But it compensate thoroughly.

Table-4. Fuzzy rule definition using IF-THEN statement.

Rule1:	IF Error is Negative	And	Δ Error is Negative	THEN Motors is Right
Rule2:	IF Error is Negative	And	Δ Error is Zero	THEN Motors is Right
Rule3:	IF Error is Negative	And	Δ Error is Positive	THEN Motors is Right
Rule4:	IF Error is Zero	And	Δ Error is Negative	THEN Motors is Right
Rule5:	IF Error is Zero	And	Δ Error is Zero	THEN Motors is Forward
Rule6:	IF Error is Zero	And	Δ Error is Positive	THEN Motors is Left
Rule7:	IF Error is Positive	And	Δ Error is Negative	THEN Motors is Left
Rule8:	IF Error is Positive	And	Δ Error is Zero	THEN Motors is Left
Rule9:	IF Error is Positive	And	Δ Error is Positive	THEN Motors is Left

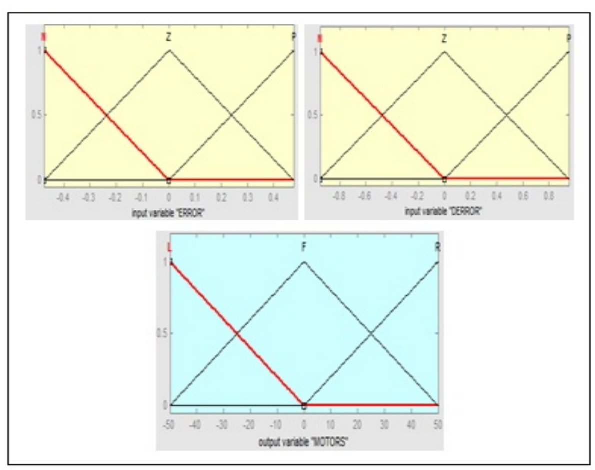

Figure-4. Membership functions for input variable (top) and output variable (bottom).

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RESULT AND ANALYSIS

The Pugh selection matrix was used in order to select the most desired conceptual design of the LFR. With the Pugh matrix suggesting the design with the highest scoring cost function *J*, we have developed the LFR as shown in Figure-2 with the most affordable cost and fairly good electronics circuits such as the LSS05 array sensors, flexible motor driver FD04A with circuit breaker for back current capability, and also multi-function Arduino controller circuits. We are also able to use the rechargeable 9V Lithium-Polymer battery that works well with Tamiya motor whilst cost effective. With the combination of these electronic packages, we can later experiments with much advance and sophisticated control designs.

Many control algorithm works well with a LFR, which mean the robot could track the line successfully and kept on the line, be it either a traditional switching method or bang-bang control, PID method, or intelligent approach methods. In this paper, the result is discussed on the speed upon the completion of tracking the line. Our fuzzification approach is proved using the speed calculation and compared with PID and traditional switching methods. This actual speed is calculated based on the time recorded to complete the oval track in one loop. The track length is 2.36m with four sharp corners. The speeds in this experiment were set to 30%, 40% and 50% of the maximum speed. These three speeds were chosen due to the fact that a much higher speed will yield in too speedy and recording the time will be troublesome. Moreover, if higher speed is used for this small low-cost double gearbox Tamiya motor, the small-sized robot cannot comprehend the speed, and it is likely to fail to track the line. Worst case it might blow the motor out.

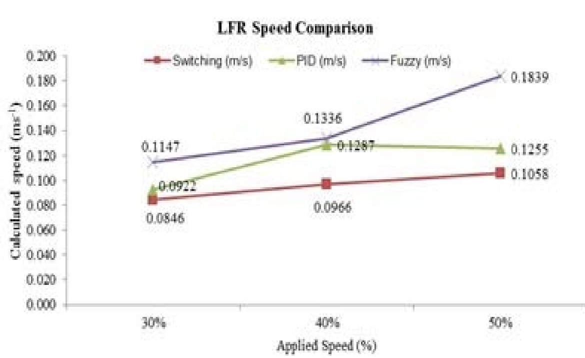

Figure-5. LFR speed comparison between three different control system.

Figure-5 shows the comparison between three control systems with the three different speeds applied. From the graph, it is shown that the calculated speed for fuzzy is higher compared to both PID and switching control method. This is possibly meant that the performance of fuzzy is better than the PID and switching. This is also implies that our fuzzification of the five digital sensors works well, and the reference database is relatively good as well. From our observation, the fuzzy movements was smoother especially in forward and on the corners, therefore the time taken to complete the full track is minimized and resulting a fairly good calculated speed. On the other hand, the speed of switching control systems maintain linearly with the three PWM. This may be due to the fact the direct control is rather effective especially when many sensors were used with the cost of lengthy programming. The PID however seems lost a bit, that might be resulting from non-optimal gains. The generic PID function [9] used in this experiments is given by Equation. (2).

$$u(t) = k_p E(t) + k_i E(\tau) d\tau + k_d \, {}^{dE}\!/_{dt} \quad (2)$$

where u(t) is the control input and E(t) is the line detection errors with reference to the inference database at sampling time, t. The applied heuristic gains are $k_p = 120$, $k_i = 1$ and $k_d = 20$ which result in the best motion in our works. In order to optimize these gains, a mathematical solution needed to be sought, thus contradict with fuzzy system where no mathematical computation is needed.

Figure-6 depicted the line following robot (LFR) motion on the described track. A simple technique was employed, where a marker was put on the LFR caster wheel and let the LFR track the line accordingly to control algorithms. As expected, by using the if-else (or bang-bang control), the LFR experience difficulties in tracking the line, swayed badly to the left and right part of the line. In order to improve this motion, a lengthy if-else condition must be made. For the PID algorithm using the gains as aforementioned, the LFR seems to follow the line nicely with little left-right sway. The fuzzy logic control (FLC) with the digital sensor fuzzification inference database describe in this paper showed better motion performance compared to the other two algorithms. It yield in less jerky motion, minimal left-right sway and at all control speed, it was faster than the other two. Thus, we could say that, the fuzzy reference database from the digital sensors works well in the line following mobile robot system.

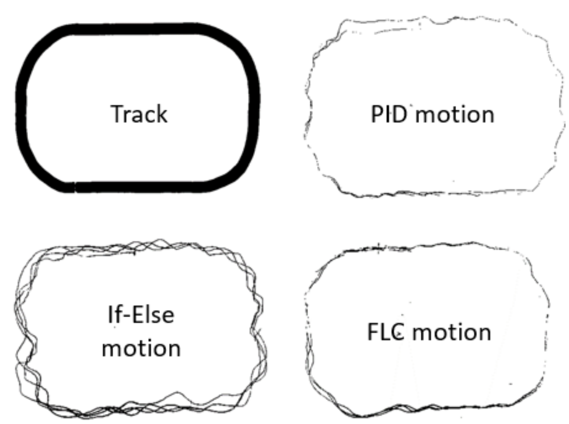

Figure-6. Recorded LFR motion on the track.

CONCLUSIONS

The mobile robot has been developed by using the mechatronic design approach where synthesis Pugh matrix was used. Among the important features was the minimum cost required to build the robot, while the circuitry was adequate enough to apply any means of control systems. The main setback in applying a fuzzy logic controller onto the robot was the universe of discourse of the fuzzy membership function. Such setback requires a span of value which is a triggering challenge in this works. Thus, the concept of digital sensor fuzzification was apprehended.

The works on fuzzification of the digital sensors is nonetheless our initial works towards a more advance and robust line following robot. The hard-built reference database was indeed our precious wealth, and very useful for our next works. We are also hoping that our reference database will be useful for other researches as well.

ACKNOWLEDGEMENTS

The author would like to acknowledge his colleagues at Universiti Malaysia Perlis (UniMAP) and also to Toyohashi University of Technology especially to the System and Control Laboratory (SYSCON) for providing materials as well as financial supports.

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