Designing of a Fuzzy Logic based Traffic Controller System using VHDL

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Abstract: This paper proposes a novel traffic controller hardware, which can be emulated the human knowledge as fuzzy logic rules, and its application as the controller for dynamic traffic load control system. The structure of this proposed hardware is derived based on expert system in the form of fuzzy IF-THEN rules. The initial setting of its parameters can be intuitively chosen from expert's experience. The developed traffic controller module uses knowledge based fuzzy rules and parameters. Knowledge based feature makes the developed hardware design more simple and efficient, especially when compared with traditional trial and error based method. Smart and flexible functionality of the Fuzzy Traffic Controller (FTC) system can effectively minimize traffic jam occurrences at interchange on road area. The FTC is targeted for the Field-Programmable Gate Arrays (FPGA) platform. To develop the system, the behaviour level of the FTC algorithm has been described in VHDL under MAX+PLUS II environment. Simulations have been carried out to verify the correct functionality of the FTC chip. Finite State Machine (FSM) is used to ensure precise traffic flow operation. The FPGA Express, (Synthesis tool) has been used to get gate-level schematic of the FTC chip. Finally, the design codes of the FTC have been downloaded into FPGA Educational board (Altera FLEX10K). Performance comparison of the developed expert FTC chip with other conventional controller for controlling traffic light is evaluated.

Key words: Expert Fuzzy system, Traffic controller, VHDL, Synthesis, FPGA.

INTRODUCTION

Fuzzy systems are being used successfully in an increasing number of application areas; they use linguistic rules to describe the systems. These rule-based systems are more suitable for solving the complex system problems mathematically. One of the most important considerations for designing any fuzzy system, the generation of the fuzzy rules as well as the membership functions are applied for each fuzzy set. In most existing applications, the fuzzy rules are generated by expert system in the area, especially for control problems with only a few inputs. With an increasing number of variables, the possible number of rules for the system increases exponentially, which makes it difficult for experts to define a complete rule set for good system performance. An automated way to design fuzzy systems is called evolving fuzzy system (Yuhui, S., 1999) that comprises Neuro-Fuzzy system, genetic fuzzy system and fuzzy expert system in general. Most fuzzy logic systems encoded human reasoning into a program to make decisions or control a system. Fuzzy logic comprises fuzzy sets, which are a way of representing nonstatistical uncertainty and approximate reasoning. Fuzzy systems have demonstrated their ability for classification, modelling (Plamen, A., 2002) or control (Driankov, D., 1993) in a huge number of applications. Fuzzy Logic Controllers (FLCs) have been used successfully in numerous control systems. The most common implementations of FLCs rely on microprocessors or micro controller.

Traditional traffic controllers are bottleneck and inefficient in handling dynamic traffic load, and this is evident in virtually all the cities across the globe. In a conventional Traffic Light Controller (TLC), the traffic lights change at constant cycle time (Aleksandar, B., 2001; Cheng, P., 2001; Caig, R., 1998; Nainar, 1996; James, F., 1998; Pitu Mirchandani, 2001; Ralf Niemann, 1998; Richard P. Zanardo, 1999), which is clearly not the optimal solution. It would be more feasible and sensible to pass more cars at the green interval if there are fewer cars waiting behind the red lights or vice versa. This paper introduces fuzzy expert system theory in TLC system to provide an intelligent green interval response based on dynamic traffic load inputs. The primary contribution from the success of this work is the development and realization of fuzzy logic algorithm.
based on hardware module. So this evolutionary scheme will overcome the inefficiency of conventional traffic controllers that has a preset cycle time regardless of dynamic traffic load. The rest of the paper is organised as follows.

In Section 2, we illustrate the basic concepts of the FTC algorithm that gives an insight of fuzzy logic theory, the techniques of fuzzification, inference rule and defuzzification methods. Section 3 describes the traffic controller design and provides a detailed discussion on the requirements of the traffic controller design, features, and enhancement of the FTC as the final integration product with fuzzy logic algorithm. Section 4 describes VHDL simulation results and provides with in depth behavioural and functional characteristics of the FTC design. Section 5 presents implementation in FPGA. Comparison between conventional and developed FTC chip is described in Section 6. Finally, the paper is concluded in Section 7.

2. Basic Concepts of FTC:

Knowledge based fuzzy expert system for the FTC have been discussed in which the membership function, shapes and types and the fuzzy rule set, including the number of rules, are evolved in this section. The FLC algorithm involves knowledge based technique for gathering and processing information with the methods of approximate reasoning. The Fuzzy control system can mimic human decision making processes as well as allow imprecise information and uncertain environments. To design the FTC hardware chip, firstly, we determine the number of fuzzy partition for the input and output linguistic variables. The number of fuzzy set partition is large enough to provide an adequate approximation and yet be small enough to save memory space. This number has an essential effect on how fine a control can be obtained. Next, we adopt the membership function for the fuzzy variables. The most common type of membership functions are triangular, trapezoidal, and bell-shaped function. The fuzzy control rules are derived based on combination of expert knowledge and control process model. Learning based rules can be proposed for future improvement of the system.

Fuzzy set theory provides a basic mathematical formalism to deal with different types of uncertainty within a single conceptual framework using three steps described in sub sections 2.1, 2.2, and 2.3. It formalizes qualitative concepts that have no precise boundaries, extending the rigid 0 or 1 statement of conventional logic to comprise the intermediate value. The intermediate value allows us to represent the linguistic variables such as false or true as numerical values. The subjective vagueness of concept such as “high traffic volume” or “low traffic volume difference”, as well as derivation of the decision on the basis of such linguistic variables become accessible to us through the tool of fuzzy logic as demonstrated in this work. Most of our linguistic information is usually defined as fuzzy term to develop the system. It is more convenient and efficient to communicate our knowledge in fuzzy terms compared to precise definition of crisp term that may result in inefficient and inconvenient procedure. Many systems are too complex to describe in crisp value such as a complex chemical process. With this concept, many fuzzy logic controllers have been designed in various daily applications such as bullet train controller, washing machine, temperature control, and video camera etc.

2.1 Fuzzification:

The Fuzzification as well as the deterministic uncertainty is concerned with the degree of events occurs rather than the likelihood of their occurrence. The non-linear mapping of input state into control value is known as fuzzification process. It is a conversion of real world signal into a fuzzy value for subsequent fuzzy logic calculation. Fig. 1 dictates the fuzzy membership function of Traffic_vol (unit in number of vehicles) used in the FTC controller in this paper.

The x-axis is the input value that relates to an assigned set (Low, Medium, and High) with the trapezoidal or triangular shape of membership function. The trapezoidal or triangle shape has introduced fuzziness to the input (Traffic_vol), which may involve two fuzzy sets with different degree of membership function. The input of traffic volume represents the range of universal of discourse from 0 to 100. The definition of membership is based on the expert knowledge. For an example, when the traffic volume is considered medium, then the number of vehicle is from 10 to 30. Next the traffic volume is considered high, when the number of vehicle is above 30. Fig. 2 explained how membership function can be applied to determine the traffic_vol (unit in no. of vehicles) using the concept of the fuzzy set theory from Fig.1.

Assume that the system detected (–8) for the traffic volume differences between the traffic lanes (waiting lane and passing lane) as FTC input. Note that this ‘small’ traffic volume differences may belong to two sets of membership class namely ZERO and N_LOW. The traffic volume (–8) has membership degree of 0.4 to ZERO set, while membership degree of 0.8 to N_LOW (negative low) fuzzy set. The mathematical statements in Fig. 3 show the fuzzy logics are represented in the overall membership function using simple linear
equations. For example, $N_{\text{high\_vol\_diff}} = \min(1, -1/5*X - 5)$ represents the membership function of negative high ($N_{\text{high}}$), which is the leftmost trapezoidal shape. When the input is more than –30, traffic_vol_diff is belongs to $N_{\text{high}}$ with absolute membership degree of 1. If the input is between –30 and –25, traffic_vol_diff will have a membership degree represented by negative slope of $(-1/5*X - 5)$. Therefore, the overall statement will return the minimum value between 1 and $(-1/5*X - 5)$ that represents the trapezoidal shape. Similarly, the triangular shape can be represented by a minimum function that returns value of two intercepting straight line at predefine input of x as given by others mathematical statement in Fig. 3.

In essence, the membership function has been described by “min” function, where the matching degree of input is simply an operation that returns the mapping function between input and fuzzy value. Fuzzy set operator is used primarily for defining the fuzzy linguistic rule or inference engine. There are two operators, namely “min”, and “max” operator. The “min” operator means the intersection of two variables while “max” operator means union of them. The “min” operator is implemented by “AND” and the “max” operator is implemented by “OR”. These operators are used throughout the fuzzification and defuzzification process as
well. The min operator used in defining the membership function is coincided and has similar meaning in inference engine. The usage of “AND” or “OR” operator is usually depend on knowledge based input. A fuzzy rule is operated using a series of “if-then” statements. The inference engine determines the matching degree of the current fuzzy input (class) with respect to each rule. Table 1 dictates the fuzzy rule set for the FTC.

These fuzzy rules are usually derived from expert system to achieve optimum results. In general, the rules are developed based on the following steps:

- Provide a description of the typical operating methods used by the operator.
- Define the performance indices of the system (safety, reduce traffic congestion, consistency and accuracy).
- Define a model for predicting.
- Convert expert human operating method into control rules.

2.2 Inference Mechanism:

The inference mechanism (if part) decides which rules are to be fired according to the input strength. At final stage (then part), the fired rules are combined to form the fuzzy control action. In the averaging method, it is possible to avoid choosing the specific rules to be fired and the output of each rule with different strength are taken into consideration. Therefore, the reasoning mechanism consists of the matching degree of fuzzy input to each rule and averaging of the weight from each rule. Examples of linguistic rules are:

- If the traffic volume is high and difference is positive low, then the green interval is high.
- If the traffic volume is medium and difference is positive medium, then the green interval is positive medium.
- If the traffic volume is low and difference is positive high, then the green interval is positive high.
- If the traffic volume is medium and difference is zero, then the green interval is medium.

The operation on traffic volume and traffic differences give the output of high, medium, and low from the respective linguistic rules shown in Table 1.

<table>
<thead>
<tr>
<th>TRAFFIC VOLUME</th>
<th>TRAFFI_VOL _DIFF = ACTIVE_LANE TRAFFIC –AVERAGE WAITING TRAFFIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGH</td>
<td>P_HIGH P_MEDIUM P_LOW ZERO N_LOW N_MEDIUM N_HIGH</td>
</tr>
<tr>
<td>MEDIUM</td>
<td>P_HIGH MEDIUM MEDIUM MEDIUM MEDIUM MEDIUM MEDIUM N_HIGH</td>
</tr>
<tr>
<td>LOW</td>
<td>P_HIGH LOW LOW LOW LOW LOW LOW N_HIGH</td>
</tr>
</tbody>
</table>

Fig. 4 to Fig. 7 describes a fuzzy expert system method to design the FTC chip based on these rules using specific input values of traffic volume and the volume differences. Note that the traffic volume and volume differences belongs to two fuzzy sets with different degree of membership function as explained earlier. From Fig.4, traffic volume membership function, the input of 26 vehicles volume has 0.75 degree of membership to medium class and 0.35 degree of membership to high class. Similarly, Fig.5 showed the traffic volume differences input of –8 that give 0.80 degree of membership function to N_low fuzzy set and 0.40 to zero fuzzy set. Fig. 6 describes the operation of fuzzy logic on rules. If the traffic volume is medium and difference is zero, then the green interval is medium. In Fig. 7, if the traffic volume is high and difference is N_Low, then the green high interval will yield the truncating result at 0.35. Based on the defined fuzzy rules and the operation of traffic volume (high and medium classes) with traffic differences (zero and negative low classes), will produce more set of fuzzy rules. Therefore, the complexity or number of green interval returns from the operation followed by the available defined fuzzy rules that specify the interaction among the available value of traffic volume and the traffic differences. Each of the individual green interval output from the fuzzy rules will then go through defuzzification process to produce the final output. Thus, the derivation of the fuzzy rules in this work is purely heuristic in nature and relies on the qualitative knowledge of process behaviour. Fuzzy control rules have the form of fuzzy conditional statements that related to the linguistic rules rather than numerical in nature.

2.3 Defuzzification:

Defuzzification is a mapping from a space of fuzzy control action defined over an output universe of discourse into a space of non-fuzzy control action. The defuzzifier also performs an output denormalization if normalization is performed in fuzzification module. The proposed fuzzy controller in this work uses the concept of Tsukamoto Defuzzification Model (Clarence W. De Silva, 2002), which is, weighted average method compared to other methods. This model aggregates each rule’s output by the method of weighted average and
thus simplifies the process of defuzzification. In this model, the consequent of each fuzzy if-then rule have been averaged out to get the mean of all rules by the following Eq. 1.

\[
\text{Green\_Cycle} = 0.25 \times (\text{rule\_high} + \text{rule\_N\_high} + \text{rule\_P\_high})
\]
The average method has been used to simplify the calculation of green cycle as demonstrated in Fig.8.

3. Development of FTC Algorithm:

The FTC algorithm is designed at four traffic flow (A, B, C, and D) at 4-way intersections in different locations as shown in Fig. 9. The coordination of traffic flow can be executed in an orderly fashion. Ideally, there are 4 traffic volume variable as the inputs that approach the 4-way junction.

There are some general objectives in placing a traffic signal and must be made in order to balance among these objectives:

- Moving traffic in an orderly fashion,
- Minimizing delay to vehicles and pedestrians,
- Reducing crash-producing conflicts, and
- Maximizing capacity for each intersection approach.

The traffic model is developed based on a fuzzy control scheme for regulating the traffic flow on a 4-way traffic intersection. The FTC comprising of 21 fuzzy rules is used to adjust the green phase with input of queue length (waiting at the intersection) to the number of vehicles that passed through East-West (EW) and North-South (NS) direction. Fig.9 illustrates the states of major traffic flow and assumption of the active input variables used for each of them. The four input variable are VOULME_NS, VOLUME_ES, VOLUME_SW, and VOLUME_EW. Assuming that VOLUME_NS gives the average of traffic flow between north and south direction, and VOLUME_EW gives the average traffic volume between eastsouth, and west-north. Similarly, VOLUME_EW and VOLUME_SW are considered for other fashion. Based on the 4-way junction and major traffic flow indicated above, there are a total of 10 different traffic states after simplification. These are YELLOW_NS(YELLOW_SN), YELLOW_EW(YELLOW_WE), RED_NS(RED_SN), RED_EW(RED_WE), GREEN_SW(GREEN_NE), GREEN_NS(GREEN_SN), GREEN_SE(GREEN_NW), GREEN_ES(GREEN_WN), GREEN_EN(GREEN_WS), and GREEN_EW(GREEN_WE). There are several modes of operation in the system, which are normal mode, emergency mode, pedestrian mode, alternate counter clockwise traffic flow direction, and yellow light extension mode etc. Both of the clockwise (CW) and counter clockwise (CCW) operation modes use fuzzy controller to calculate the green cycle time during the 4 major traffic flows at the traffic network described earlier. Fig.10 describes the FSM, which has been used to implement the FTC algorithm.

4. VHDL Simulation Results:

The following VHDL simulation diagrams from Fig.11 to 13 illustrate the functionality of the FSM controller. The overall FTC has been tested and demonstrated with various traffic scenarios and load conditions. Fig.11 illustrates the simulation result of the traffic light controller module with integrated fuzzy controller and emergency control. Once the “start” pulse goes active, the traffic controller is transit to State 1, but in next instance when Emergency4 signal goes high then the traffic controller switched to State A followed by the next triggering clock (1). Once the Emergency4 is active low, the traffic immediately switched to State B. Notice that “clr” signal is used to indicate the clearance of traffic at intersection during the state transition. During simulation, “clr” input is varies to validate the response of traffic controller. The “clr” signal remains high when no traffic detected at the intersection. When all the traffic RED lights are turned on (State 3, State 6, State 9, and State C), the system will not transit to next state if the “clr” signal remains low. Under normal traffic condition, the intersection however should be clear of traffic and any one of the lanes can be allowed green light. The “clr” bit become extremely important (as safety feature) to detect any violation during the change of traffic light and yet be able to prevent accident by holding on to RED light. Besides, the yellow light cycle time is observed to be dependent on vehicle speed. When speedy condition is not detected, the yellow duration is default at 10 clock cycles. Referring to Fig.10, with the above state transition concept, the controller module will invoke fuzzy controller and produce green cycle at State 1, State 4, and State 7 and State A. During these states, the “green cycle” will only show the same cycle count as “fuzzy count” as indicated in region (3) of Fig.11. Fig.12 indicates the complete functional diagram of the twelve states transitions followed by the FSM diagram. Fig.13 demonstrates the simulation of FLC behaviour with respect to the dynamic change of traffic condition at the intersection.

The controller is able to switch immediately from high fuzzy count of Hex 32 to as low as Hex 0F when it detects a sudden and significant accumulation of vehicle at waiting lane while passing lane only received
Fig. 8: Defuzzification.

Fig. 9: Major a) Traffic Flow-A, b) Traffic Flow-B, c) Traffic Flow-C, & d) Traffic Flow D.

Fig. 10: FTC State Diagram.
few incoming vehicles count. The developed VHDL codes of the FTC have been compiled under MAX+PLUS II CAD environment. Proper stimuli as input were fed into the generated Test bench and corresponding output simulation waveforms were examined to verify the correct functionality of the FTC.

Fig.14 shows the Register Transfer Level (RTL) view of the FTC.
Fig. 13: Traffic Light Controller Module Simulation.

Fig. 14: RTL view of the FTC modules.
The main modules of the FTC consist of TRAFFICLIGHTCONTROLLER, PULSECONVERTER, EMERGENCYCONTROLLER, FUZZYCONTROLLER with operating CLOCKDIVIDER. The FTC has a total of 42 inputs and 17 outputs. The fuzzy controller is the central of intelligent, knowledge base processor that read two inputs namely traffic volume and volume difference from traffic light controller. The TLC has used for calculating green cycle that feedback from fuzzy controller block to determine the traffic light interval. EMERGENCYCONTROLLER and PULSECONVERTER are activated hand in hand time when there is an emergency signal detected. The purpose of EMERGENCYCONTROLLER is to ensure that the system responses to the valid emergency input. The TRAFFICLIGHTCONTROLLER module as the heart of FTC receives emergency and clear input signal from PULSECONVERTER. FUZZYCONTROLLER is responsible for the green phase calculation using fuzzy logic. Traffic volume and differences in traffic volume between the passing (active) lane versus waiting lanes is calculated in the TRAFFICLIGHTCONTROLLER and fed into FUZZYCONTROLLER module.

5. FPGA Implementation:

Synthesis is the process of generating logic circuit that meets the desired functional behavioral of VHDL codes or any compatible design entry methods under CAD environment. The FPGA Express, RTL synthesis tool, compiled the VHDL codes to generate the netlist file that have been downloaded into the FPGA board. The FPGA Express provides comprehensive visual feedback on the HDL design through RTL schematic and finally gate-level schematic. The FTC is designed to optimize the usage of chip area rather than device speed, since the gate delay will not critically impact on the controller performance. Investigations were based on synthesis time, synthesis quality, (logic area, delay, speed) and integration with specific FPGA technology. Table 2 indicates the various aspects of FTC controller logic cells after optimisation of the generated logic cells for FTC chip of VLSI implementation. It is observed from Table 2, the complexity of logic increases in FUZZYCONTROLLER and TRAFFICLIGHTCONTROLLER modules. However, FUZZYCONTROLLER module occupied the highest logic area due to complexity in the fuzzy algorithm, which involved intensive and repeated logic calculation.

<table>
<thead>
<tr>
<th>Modules</th>
<th>Input Pin</th>
<th>Output Pin</th>
<th>Logic Cells</th>
<th>Logic Cells Utilized</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLOCKDIVIDER</td>
<td>1</td>
<td>1</td>
<td>31</td>
<td>2%</td>
</tr>
<tr>
<td>EMERGENCYCONTROLLER</td>
<td>5</td>
<td>4</td>
<td>12</td>
<td>1%</td>
</tr>
<tr>
<td>FUZZYCONTROLLER</td>
<td>16</td>
<td>8</td>
<td>525</td>
<td>45%</td>
</tr>
<tr>
<td>PULSECONVERTER</td>
<td>5</td>
<td>8</td>
<td>80</td>
<td>6%</td>
</tr>
<tr>
<td>TRAFFICLIGHTCONTROLLER</td>
<td>55</td>
<td>33</td>
<td>464</td>
<td>40%</td>
</tr>
<tr>
<td>TOTAL (FTC)</td>
<td>42</td>
<td>17</td>
<td>1116</td>
<td>94%</td>
</tr>
</tbody>
</table>

6. Comparison between Conventional and Developed FTC Chip:

In developing technologies and improved socio-economic conditions, the numbers of vehicle around the world continue to increase. The numbers of vehicle in rural areas and surrounding highways running through our rural areas continue to increase and the existing road conditions, in many instances, are not adequate enough to handle this increased traffic. This has increased the level of congestion on our rural highways. These, along with ever changing weather patterns, have increased the number of accidents and traffic related fatalities and are continuing threat to travel safety and security (Nikunja K. Swain, 2006). Research is being conducted both in academia and industry to address these challenges effectively through the application of novel technologies such as Fuzzy Logic. In dynamic traffic control [7], the Genetic Fuzzy Logic Control (GFLC) can he identified more effective and efficient encoding methods in selecting the logic rules, tuning the membership functions, or both deserve to be explored to further improve the control performance. It also deserves to examine if the learning results of GFLC, the composition of logic rules, and the shapes of tuned membership functions are interpretable or not. If so, the GFLC can be used to explain an expert’s judgment and decision; otherwise it works just like a black box. Based on the literature survey, the following proposed FTC hardware can be solved the different problem issues in dynamic control system to perform better efficiency in the traffic control by minimizing traffic jam occurrences at interchange on road area. The developed FTC chip is cheaper and faster for implementation that can be used to replace the conventional Proportional Integral Derivative (PID) or multivariable controller chip in control system. The FTC chip also allows the use of cheaper sensor and enables new functionalities in conventional hardware control system. Because the fuzzy logic processing does not required very precise sensor input. Beside it, the inaccurate information can be handled very easily by fuzzy algorithm. Therefore, it decrease the production cost dramatically and increase its production value.
7. Conclusion:

The FTC chip has been designed using fuzzy expert system, which is based on knowledge based algorithm in this paper. To design the different hardware modules of the FTC chip, the VHDL codes has been converted into architectural gate-level netlist by FPGA Express tool. Finally, the netlist has been downloaded into FPGA board to verify the functionality of the FTC chip. We have also optimised the design codes for minimising the gate area, timing delay and speed performance etc during logic synthesis phase.

This research work has overcome the weakness of the conventional traffic controllers with the capability of providing varying green cycle interval based on dynamic traffic load changes at every lane in a 4-way junction control. Further improvement of fuzzy rule in FTC chip can be automated using genetic learning with little change to the construction of the fuzzy rule generation architecture. Another future improvement opportunity is the integration of neural network or Genetic Algorithm (Amaual, J.F.M., 2002) with fuzzy logic controller. However, this concept and its efficiency compared to existing FTC design is something yet to be validated.

REFERENCES


