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Real-time Density-Based Dynamic Traffic Light Controller Using FPGA

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***Abstract*—This paper presents a real-time density-based dynamic Traffic Light Controller(TLC) system using a Field Programmable Gate Array(FPGA) with Verilog hardware description language (VHDL). Here, real-time traffic density is detected using an array of IR sensors placed on each road of a four-way junction. Continuous monitoring of these sensors provides real-time vehicle density to ensure proper signal switching. Features e.g, minimum smart delay feature, making way for emergency vehicles, traffic violation detector, and priority sequencing have been incorporated to reflect real-life scenarios. Real-time implementation of the model has also been verified using a micro-controller. The study also proposes an RNN-based approach to synchronize multiple junctions and optimizes average traffic flow time between them. It has a superior performance compared to existing systems in terms of average waiting time and traffic light switching time. This system can serve as a pivotal step-stone in building an automated traffic system for modern cities.**

***Index Terms*—Traffic Light Controller(TLC), Verilog, FPGA, Finite State Machine (FSM), Real-time, Density Sensor**

I. Introduction

With growing number of vehicles in urban cities, traffic congestion and transportation delay are becoming more prominent issues. Traditional traffic control systems suffer from two major drawbacks [1] [2]. Firstly, the switching between traffic lights based on fixed time delays provides equal amount of time for both high and low traffic density roads. Secondly, they do not have any provisions for emergency vehicles. Real-time density-based dynamic traffic light controller (RTDD-TLC) has drawn a lot of attention to overcome this deficiencies.

FPGA based intelligent TLC has been previously investigated to model an efficient traffic flow system. Singh *et al.* designed a 24-hour traditional delay-based traffic light controller in which a different delay for traffic lights is applied for each time zone [3]. Another approach uses a fixed time scheme during peak hours and a sensor-based algorithm during off-peak hours [4]. The performance of three state encoding schemes have also been tested in Verilog using Mealy Type Finite State Machines [5]. A different dynamic TLC has also been proposed where the density of traffic is measured based on the number of active sensors [6]. Priority sequence-based approach has also been developed by changing the stop times for each road manually [7]. A 24 hour TLC for a junction has been realized in Verilog HDL where main roads are controlled with fixed time while the narrow roads are controlled based on sensors [8]. Alternate approaches in this field include state charts [9], PicoBlaze processor [10] and fuzzy control [11] which are more efficient for complex control systems and mixed-flow networks [12]. TLCs based on micro-controllers are also common in literature [13], [14].

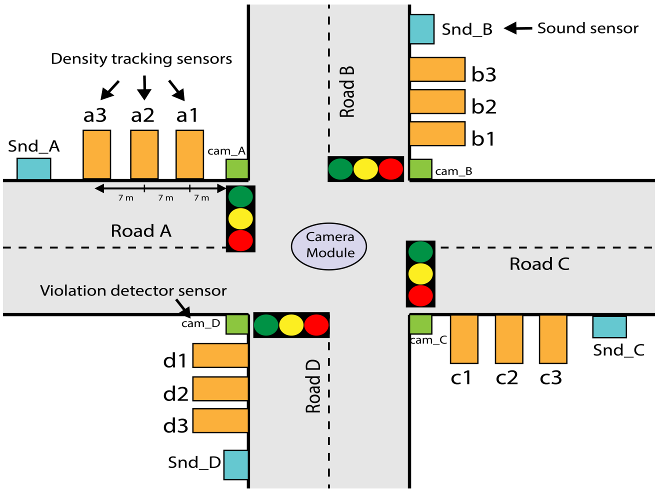

Fig. 1: Overview of the complete traffic system structure of a four-way junction with 5 sensors on each road along with a camera module

In this context, a novel real-time density-based dynamic TLC system is proposed in this study. Rather than using a fixed delay for a signal as in [3], [4], [15], the proposed system continuously checks for sensor outputs to address real-time vehicle density. This system also includes a set of unique features for practical purposes along with a proposed LSTM-based RNN architecture to minimize traffic flow time between adjacent junctions.

II. Methodology

A. System Structure Overview

The proposed traffic system is based on a four-way junction as shown in Fig. 1. Each road accommodates three IR sensors (e.g., a1, a2 and a3 on road A) to detect passing by vehicles and track their density on that particular road. They are placed after certain intervals from the stoppage line as per requirement. There is also a sound sensor (e.g., Snd_A) on each road which detects the sound of any emergency vehicle and passes that information along. Moreover, there is also one IR sensor (e.g., cam_A) on each road to detect vehicles for traffic rule violation. The number of sensors can vary depending on desired criteria e.g, needed accuracy and cost.

B. System Algorithm

The automated traffic control system proposed in this study has a total number of 27 states as demonstrated by the finite state machine (FSM) of Fig. 2 with all possible transitions. The

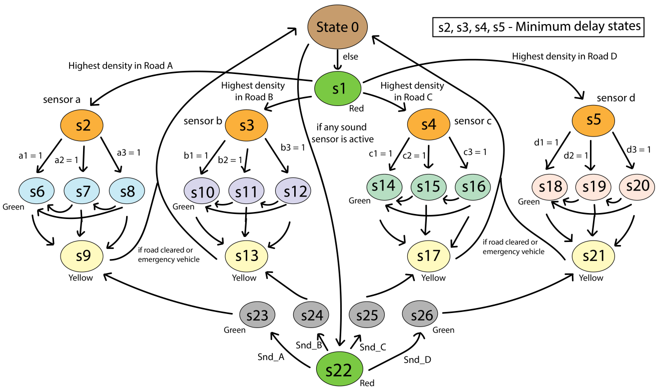

Fig. 2: State diagram of the proposed traffic light controller system showcasing all the states and their triggering conditions

system starts or resets from the s0 state. After that, depending on the density tracking sensors and sound sensors, the system moves to s22 in case of emergency otherwise it moves to state s1. From s1, the system moves to one of the s2, s3, s4, s5 states depending on the density of vehicles on road A, B, C, or D, respectively.If the system moves to s2, then it can move to three different states (s6, s7, or s8) depending on the output of the density tracking sensors. In these states, only road A will have a green signal and the rest will have red. Other states have been assign for road B, C and D using the same algorithm. The combination of these three different states for a single road realizes the density of the vehicles in addition to their presence.

The unique features of the proposed system are listed below.

1) Real-time density feature: This intelligent traffic system is integrated with a real-time density-based system. Suppose at any moment, road A has a green signal but traffic density in road C is greater than road A. This TLC will be able to realize this and give a green signal to road C after turning road A's signal to yellow and then red thereby ensuring proper management of traffic flow for all the roads.

2) Minimum smart delay feature: Although the density tracking sensors are continuously detecting vehicle density on the roads, it is not wise to make instantaneous changes based on sensor outputs. Hence, whenever a particular road gets a green signal because of the highest vehicle density, it is held at green for a certain amount of time. After that, the traffic signal may be shifted depending on vehicle density tracking sensor outputs. That is achieved in this proposed system where s2, s3, s4 and s5 states represent minimum delay states.

3) Allowing emergency vehicles to pass: For emergency vehicles, the system goes to s22 state and check for the road that has the emergency vehicle. Depending on the output of the sound sensors, the system moves to s23, s24, s25 ,or s26 state. The corresponding state remains active as long as the emergency vehicle is there.

4) Camera module to detect traffic violation: Our system has a total of four rule violation detector IR sensors. These sensors are placed in front of the stoppage line of each road. The sensor produces a low signal during a red light if all the vehicles are behind the designated line. In case of any rule violation, the sensor gets activated and turns on the camera module which then captures the image of the vehicle and sends it to the traffic road authority for further action.

5) Priority Condition: In case of equal traffic congestion or emergency vehicle on multiple roads, the priority would be: $RoadA > RoadB > RoadC > RoadD$. This list can be updated manually to accommodate specific needs.

III. Results and Discussions

A. Timing diagrams for different case studies

In order to verify the system, timing simulation is performed using Quartus II software with ALTERA FLEX 10K chip. In simulation results, road_A, road_B, road_C and road_D represent the output traffic lights on the four roads, respectively. For these variables, a value of 100, 010 and 001 represent red, yellow and green signals, respectively. Camera is another output variable which is set to 1 whenever there is any traffic rule violation and 0 otherwise. For simulation purposes, a pulse signal of period 1 ns has been used as clock signal.

Referring to Fig. 3(a), case study 1 focuses on the real-time density tracking feature. As vehicle density on road C is greater than the other roads, road C is given a green signal until its density remains highest. After that, the system follows the priority condition. Fig. 3(b) and 3(c) represent case study 2 and 3 by focusing on the emergency condition (by going to state 22) and traffic rule violations (by turning on camera module), respectively. Fig. 3(d) shows case study 4 which demonstrates the minimum smart delay feature. Initially, a green signal is given on road A. Road C achieves a greater vehicle density after a short time but the green signal on road A is carried on for extra 5 clock cycles (manually set and can be changed) due to the smart delay feature. Finally Fig. 3(e) demonstrates case study 5 which focuses on a real-time complex practical situation.

B. Real-time implementation and verification

An identical system using a micro-controller is designed in Proteus to emulate and verify the Verilog-based proposed system. An intersection has been modeled with similar features using Arduino ATMega 2560R3 micro-controller. The schematic model is presented in Fig. 3(f), which represents and verifies the case study 5 results obtained in 3(e).

C. System performance evaluation

1) Average waiting time: The average waiting time of a vehicle refers to the time it has to wait due to a red signal on that particular road. A comparative analysis is performed here with a fixed-cycle conventional traffic light controller system as in [15] using the same parameters for all the cases as shown in Fig. 4(a). An example of the calculation method is shown in Table 1 for case study 4. Fig. 4(a) demonstrates that the proposed real-time density based dynamic TLC system performs significantly better compared to conventional TLC which is a direct consequence of taking the current vehicle density into account for switching the signals. Our system becomes more efficient whenever the traffic pattern is complex as suggested by the results of case studies 4 and 5.

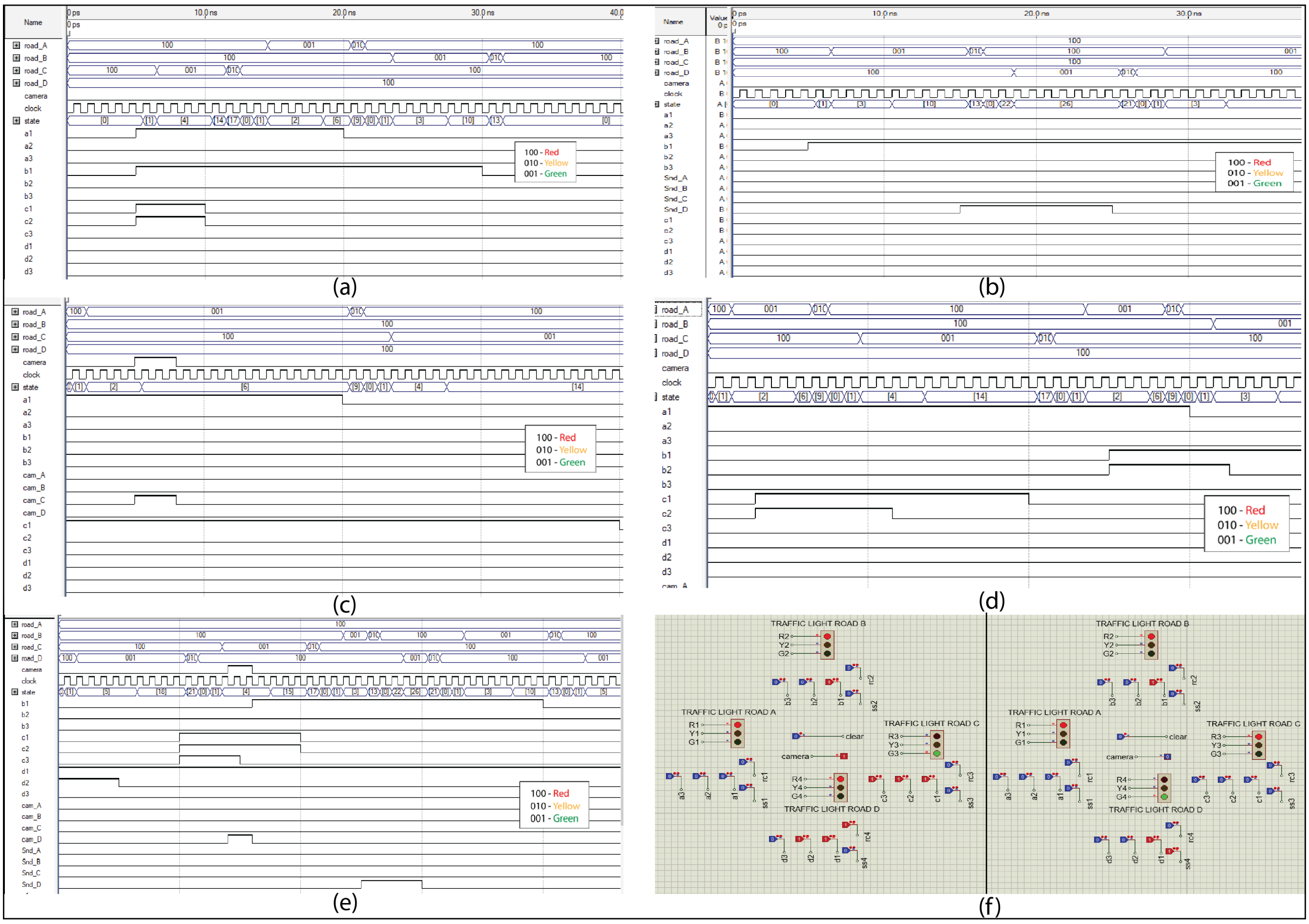

Fig. 3: Timing diagrams for (a) Case study 1: representing real-time density feature; (b) Case study 2: representing emergency condition; (c) Case study 3: representing camera module to detect traffic rule violation; (d) Case study 4: representing minimum smart delay system; (e) Case study 5: representing a complex practical situation; (f) Verification of case study 5 by implementing the model using microcontroller on Proteus

TABLE I: Waiting time of vehicles for case study 4

	Waiting time (in clock cycles)	
Vehicle list	**Proposed TLC system**	**Conventional TLC system**
1st vehicle on road A	0	0
2nd vehicle on road A	17	0
1st vehicle on road B	6	25
2nd vehicle on road B	11	30
1st vehicle on road C	6	17
2nd vehicle on road C	11	22

2) Average traffic light switching time: Fig. 4(b) shows the average traffic light switching time for both systems with a fixed (10) no of cycles for the conventional one. Due to its dynamic behavior, the proposed TLC system generally results in a less average switching time whenever the traffic is random. For case study 3, sensors are artificially kept high for a long time to observe the camera module which resulted in a high switching time.

IV. Integration of Neural Networks

To ensure overall traffic system efficiency, it is imperative to synchronize multiple junctions in a nearby area. To achieve this, we hereby propose an LSTM-based recurrent neural network architecture (illustrated in Fig. 5) in which all the outputs of sensors and traffic lights of the TLCs are given. With the historical and current TLC data, it will be possible to obtain the traffic flow distribution at the next time unit. The optimal objective of the network will be to minimize the average traffic flow time between adjacent junctions.

V. Humanitarian Impact

In the US, recent research from transport data company INRIX found the total cost of lost productivity caused by congestion to be 87 billion in 2018 [16]. Coming to lost hours, one of the most congested cities of the US, Boston saw an average loss of 164 hours in 2018 due to traffic congestion which led to 4.1 billion dollars worth of economic loss. Traffic rule violation, reckless driving, mismanagement, etc. are the leading cause behind accidents which leads to 1.3 milion deaths every year [17]. The United Nations General Assembly has set an ambitious target of halving the global number of deaths and injuries from road traffic crashes by 2030. Our automated traffic flow control can help in achieving this goal. The proposed system makes moving on roads time-efficient and economically favourable which is a fundamental step for future smart cities.

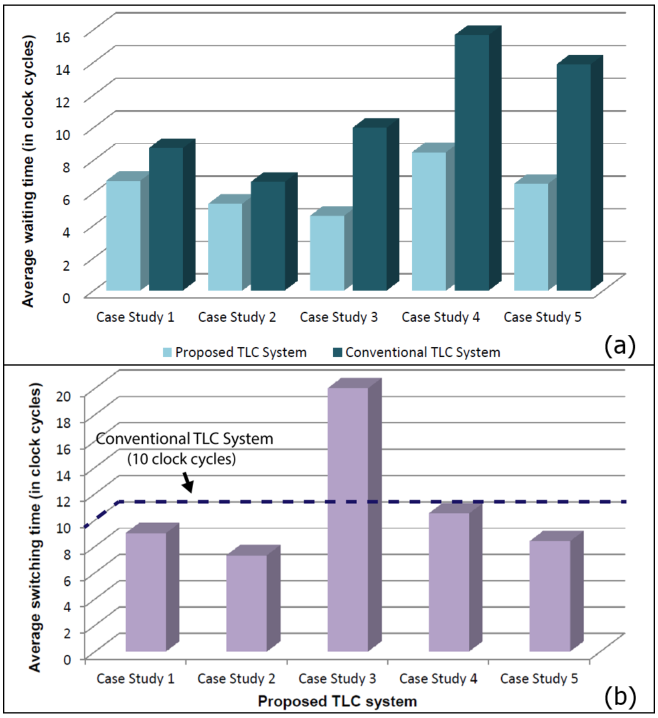

Fig. 4: Comparison of (a) average waiting time and (b) average traffic light switching time for the 5 case studies between conventional and proposed TLC systems

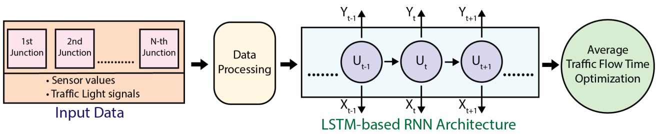

Fig. 5: Proposed LSTM-based RNN architecture to ensure minimum average traffic flow time between adjacent junctions

VI. Conclusion

In summary, we have designed and implemented a real-time density-based dynamic TLC system of a four road junction using Verilog with ALTERA FLEX 10K chip. The proposed system not only provides a modernized solution to the existing analog TLC system but also incorporates unique features to enhance the practical implementation of this system. The ability to make real-time decisions based on vehicle density on different roads while identifying emergency vehicles and traffic rule violation, will certainly contribute to reduce heavy traffic congestion by a large margin. Our system performs better in terms of average waiting and traffic light switching time compared to the conventional pre-timed TLC. Smooth traffic flow between adjacent junctions is also achieved with the combination of neural networks. Implementing this real-time automated system in large metropolitan city junctions can prove to be quite resourceful.

Data Availability

For further research in this area, the source code and simulation files can be accessed upon request via email.

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