Front Collision Detection System of Unmanned Ground Vehicle using 90nm CMOS

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***Abstract*— A low power, small area front collision avoidance circuit using Light Detection and Ranging technology is presented in this paper. The proposed system would help detect and avoid the objects which would otherwise collide with an autonomous vehicle. After the front sensor detects stopped or slowed down vehicles, all sensors will turn on and make decisions based on the system's algorithm calculations. The system is implemented in CMOS 90nm technology. The power consumption of the system is 1.424mW and uses a 1.2V power supply. 4ns resolution front end sensors and 1ns resolution side sensors are used to compare the target distance with a safety standard. The processing time for making decisions is 889.5ns when the car is traveling 45mph which includes the 800ns sensor detection time.**

Keywords*— *Autonomous Vehicle, CMOS, Front Collision Avoidance, 90nm IBM

I. INTRODUCTION (*HEADING 1*)

Unmanned Ground Vehicle (UGV) has become a hot research topic in recent years. With the increasing of safety constraints and complexity of the system, conventional designs using camera, radar, ultrasonic or lidar sensors are not sufficient to address the great challenges in modern autonomous vehicles [1]. For example, Traffic-Aware Cruise Control (TACC) used in Tesla's autonomous vehicles has resulted in dangerous or even fatal collisions in recent years [2]. Ultrasonic sensors can only be employed to detect short-range objects, which is not suitable for highway driving scenarios. The Frequency-Modulated Continuous-Waveform (FMCW) and Phase-Modulated Continuous-Waveform (PMCW) mm-wave radar sensors have the advantages of small size, low cost and good climate adaptability [3], but the increasing number of advanced autonomous vehicles increases the probability of interference due to limited bandwidth and methodologies [4]. Camera sensors are another popular design option as they allow for high quality in image identification but have a relatively slow processing speed. Besides, it is not capable of measuring distance and speed. Light Detection and Ranging (LIDAR) sensors are equipped with a laser and have been used over several decades. These sensors are one of the most used in autonomous vehicles today. LIDAR generates a point cloud for vehicles surrounding with high resolution [4]. However, the cost of high-quality rotational LIDAR is higher than other sensors. To improve current UGV driving safety, a real-time front collision detection system based on low-cost pulsed Time-of-Flight (TOF) flash LIDAR is introduced in this paper.

This laser detection system is similar to the graph traversal since stationary sensors provide a set of nodes around the vehicle, but the major difference compared with conventional LIDAR is that the information of the nodes is not provided to the processor since it is only needed when a collision is imminent. Hence, all the calculations are done in the hardware part for high processing speed, and the best available option or traversable node based on the road boundary information will be sent to the next stage. The resolution of the graph can be enhanced by increasing the number of stationary laser sensors. This front collision detection system can detect a stopped or slowed down vehicle within an unsafe distance on the highway and generate a safety maneuver to avoid the accident.

The hardware circuit is implemented in 90nm CMOS technology by Cadence tool. Usually, the data processing part of a sensor system is done through a powerful microprocessor. Heavy computation is required with huge data being passed into the processor. The algorithm chosen in this paper is implemented in hardware to decrease the power consumption needed for comparing the software-based computation system. Besides, the high switching speed of CMOS technology improving the response time for a life-saving system. This paper is arranged as follows. Section II discusses the theory of the front collision detection system. Section III introduces the complete hardware circuit. The simulation results are described in Section IV. Finally, Section V draws conclusions.

II. DESIGN THEORY

A. Input Signal

TOF sensors have been found to be very effective for high speed applications [5]. Typical laser drivers are capable of producing 3 to 5ns light pulses [6]. The reflected light signal is detected by a single-photon avalanche diode (SPAD), which is regarded as a digital receiver [6]. The returned analog signal is digitized by an analog comparator as shown in Fig. 3 based on its threshold voltage. The time difference, ΔT, between the time sensor starts to transmit and the time the sensor receives the pulse reflects the distance of the target, ΔR, as explained in equation (1).

$$\Delta T = \frac{2\Delta R}{c} \quad (1)$$

Where c is the speed of light, which is about 3×10^8 m/s. The input signal to the detection system in this paper is a 4ns pulse width signal with amplitudes from 400mV to 800mV, and the scaling for the input is from 0V to 1.2V in 90nm CMOS process. This paper does not include real life LIDAR signal. Instead, an expected input signal generated in MATLAB is shown in Fig. 1.

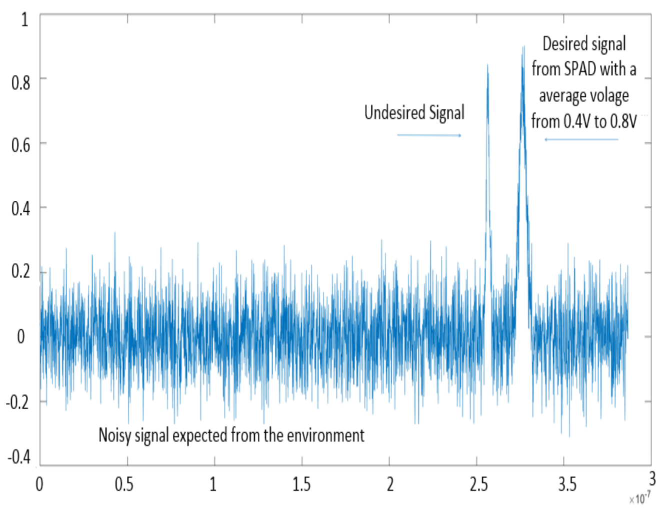

Figure. 1. Input Signal

B. Circuit Algortithm

The proposed system has eight sensors (Sensor 1 to Sensor 8) positioned around the vehicle A to detect its surroundings, and the algorithm evaluates a trajectory based on their detected signals. The positions of these eight sensors are shown in Fig. 2, which also illustrates a typical scenario that the smart car might encounter on the road. Vehicle C to F are the other cars that need to be avoided while safely maneuvering to avoid the crash with vehicle B when B is stopped or slowing down. According to the TOF information from eight sensors, the system generates a binary decision code to evaluate whether an obstacle is present at an unsafe distance and the best available option.

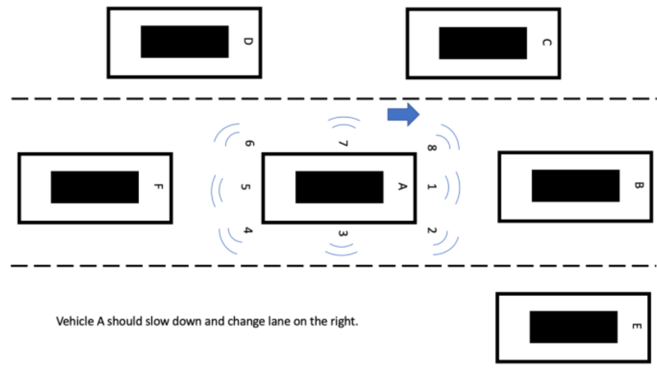

Figure. 2. Sensor Positions

The front collision detection system scans the front area through Sensor 1 to detect any possible vehicles. When front collision danger is detected, the surrounding sensors are all activated. In this case, it provides a power-saving characteristic of the system. After the surrounding sensors analyzed their scanned area, each of them provides a binary code. If the output is 'one', it means there are obstacles within its unsafe zone. If the output is 'zero', then the detected area is safe. All the values of these sensors are imported to the next stage, which analyzes the data and creates the best emergency avoidance maneuver. The final stage digital command goes to the main computer in the smart car to execute the response. A truth table that relates the readings from surrounding sensors and the final 3-bit encoded value is described in Table 1.

TABLE I Final Decision Truth Table

S1	S2	S3	S4	S5	S6	S7	S8	Output
0	X	X	X	X	X	X	X	DN
1	X	X	X	1	0	0	0	SDL
1	X	X	X	1	0	0	1	SDL
1	X	X	X	1	1	0	0	SUL
1	0	0	0	1	X	1	X	SDR
1	0	0	1	1	X	1	X	SUR
1	1	0	0	1	X	1	X	SDR
1	X	1	X	1	X	1	X	STOP
1	X	X	X	0	X	X	X	STOP

Note: S1-S8 represent sensors 1-8

In this table, 'Do Nothing' (DN) means no stopped car in front. The left side has a higher priority in this system, and the decisions are made by left side sensors without considering Sensor 3 to 5. If both Sensor 1 and Sensor 5 find targets within unsafe range, and nothing on the left side or there is a car on top left, it outputs 'Slow Down Left' (SDL), otherwise, it outputs 'Speed Up Left' (SUL) when an object detected by Sensor 6. 'Slow Sown Right' (SDR) and 'Speed Up Right' (SUR) is performed with the same idea as the left lane theory when Sensor 7 is activated but part of the right side is safe. 'STOP' command is preferred in an emergency situation if there is no vehicle behind or all vehicles around.

III. Circuit Implementation

The front collision detection system consists of eight sensor blocks and a final decision logic circuit. The front-end sensor detection system is generally designed in the same way as the other 7 sensors, as shown in Fig. 3. When examining Fig.3, it can be seen that when a lidar signal is sent out a counter (the 8-bit counter) is started. When a signal is detected the pulse detection circuit, which consists of the comparator, digital delay, and AND blocks in Fig. 3, processes the signal. This circuit generally works as follows, the comparator digitizes the received signal based off of the reference voltage, 0.4V. The signal is then determined to be a LIDAR signal based off of its pulse width, by creating a delayed version of the signal using a digital delay and comparing the digitized signal to the delayed version of itself via an AND gate (this process will be discussed in more detail in the "Pulse Detection Circuit" section). Once it is determined that the signal is a LIDAR signal, the counter is stopped, the time of flight of the lidar signal is recorded using a D flip flop. Next, the safety distance digital comparator (Comparator (digital) block) determines whether or not the path in front of the sensor is safe by comparing this recorded TOF to a timing reference, which is the safe stopping distance counter value (will be discussed in more detail in the "Safety Distance Digital Comparator" section). If it is determined there is danger (TOF is greater than safety distance counter value) a logical 1 is passed onto the next stage. All of the 8 sensor systems follow this same general logic. However, every sensor system but the front sensor system is deactivated using a clock gator, which only enables the systems when the front sensor system determines there is danger. All data from the 8 systems are passed through the decision logic circuit, which determines the appropriate action to take (will be discussed in more detail in the "Decision Logic" section). Lastly, the trigger logic circuit essentially delays the system from outputting any data until all sensors systems have accurately assessed the safety of their respective paths in order to ensure that only the correct decision is outputted. The block diagram of this system can be seen in Fig. 3.

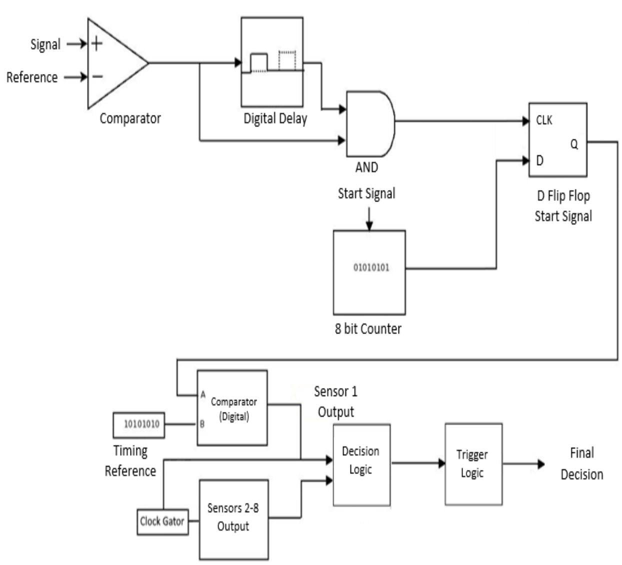

Figure 3. Top Level Block Diagram of Front Collision Detection Circuit

A. Pulse Detection Circuit

Counters are used in each sensor to measure the time difference between the TOF sensor starts and the time that the SPAD receives the pulse. The pulse detection block is explained in Fig. 4. An analog comparator and an S-R Latch is employed as the first stage for this system. This differentiator takes the input as shown in Fig. 1, and outputs a logical one whenever the input voltage is higher than its threshold 0.4V. The output of this comparator is stored and digitized in an SR latch for next stage processing. The problem for the first stage is that any voltages above the reference will be digitized to high, meaning some noise will be digitized along with the desired signal and thus stop the counter. In this case, a pulse width filter (the second stage) is proposed in this design with two D-Flip Flop (DFF) but different phase sampling clocks. This ensures that only when the pulse width is wide enough to be the desired signal, it will be recognized by the counter.

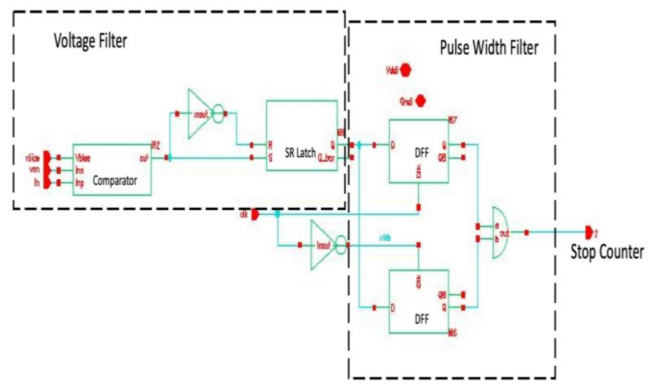

Figure. 4. LIDAR Pulse Detection System

B. Saftey Distance Digital Comparator

A digital comparator is employed to compare the counter output with a safe stopping distance digital number. Based on the national standard safe stopping distances and speeds, the vehicle speed and safety distance can be converted into a digital number for TOF information as discussed in Table 2, where a 250MHz clock frequency is used for this counter.

TABLE II Safe Stopping Distance and Binary Code

Speed (miles per hour)	Stopping Distance (m)	TOF (ns)	Counter Value
45	60	400	01100100
50	70	467	01110100
55	81	540	10000111
60	92	614	10011010
65	105	700	10101111
70	118	787	11000101

The front sensor and back sensor are the primary sensors for detecting long-range targets and avoiding collisions. The measurement requirement of these sensors is capable of counting at least 787ns. In other words, a 10 bits counter is required for a 1GHz system clock. Hence instead of counting every Nano-second, the clock is scaled down to 250MHz for long-range testing, and the counter size is decreased to 8 bits. Whereas the side sensors are used to identify vehicles in adjacent lanes, a fine resolution is needed for this short-range testing. A 16ns time threshold is set since the minimum lane requirement in the United States is 2.4 meters wide, and 1GHz clocks are used for side sensors.

To compare the counter outputs with the safety distance threshold binary code, subtractors are used as a comparator. When the counter value is greater than the threshold, it outputs low voltage. If the target is within the safety range, a high voltage of unsafety signal outputs from the digital comparator.

C. Decision Logic

As shown in Table 1, the final decision is related to all the sensors' outputs, and the decision output is concluded in the following equations. The logic circuit is implemented in Cadence as shown in Fig. 5.

$$DN = \overline{S_1} \quad (2)$$
$$SDL = S_1 \cdot S_5 \cdot \overline{S_6} \cdot \overline{S_7} \quad (3)$$
$$SUL = S_1 \cdot S_5 \cdot S_6 \cdot \overline{S_7} \cdot \overline{S_8} \quad (4)$$
$$SDR = S_1 \cdot \overline{S_3} \cdot \overline{S_4} \cdot S_5 \cdot S_7 \quad (5)$$
$$SUR = S_1 \cdot \overline{S_2} \cdot \overline{S_3} \cdot S_4 \cdot S_5 \cdot S_7 \quad (6)$$
$$STOP = S_1 \cdot (\overline{S_5} + S_3 \cdot S_7) \quad (7)$$

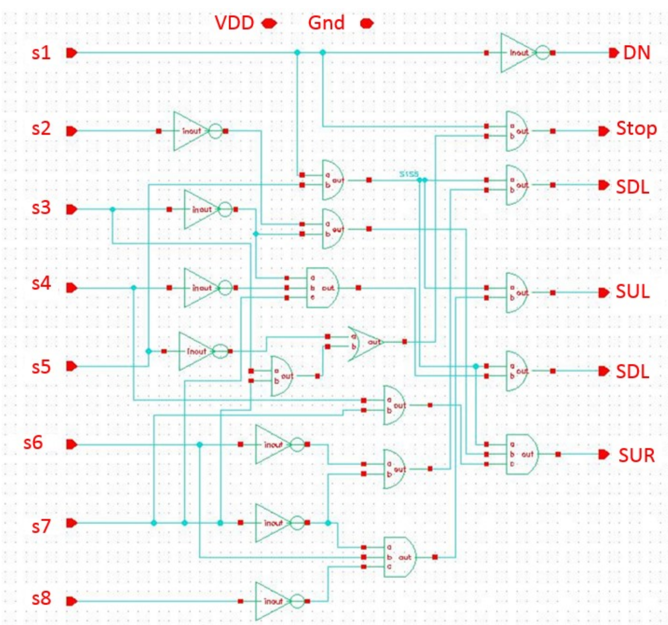

Figure 5. Decision Logic

IV. SIMULATION RESULTS

The input signals of the front end, back end, side, and corner sensors are generated in MATLAB Simulink with noise and imported to Cadence Virtuoso. A case for 'Slow Down Left' is tested and introduced in Fig. 6 for simplicity. If both front and end sensors detect target within the safety range, but there is no danger in the side lanes. The final decision from the hardware circuit is 'SDL', which follows the design truth table. The processing time for this system is 889.5ns after the sensors send out a pulse, which includes 800ns TOF long-range sensor detection for a vehicle traveling 45mph. The average power consumption is only 1.424mW during this process. An undesired noise with voltage greater than the threshold but narrow pulse width is also added in inputs, and it is filtered out by first stage filter system.

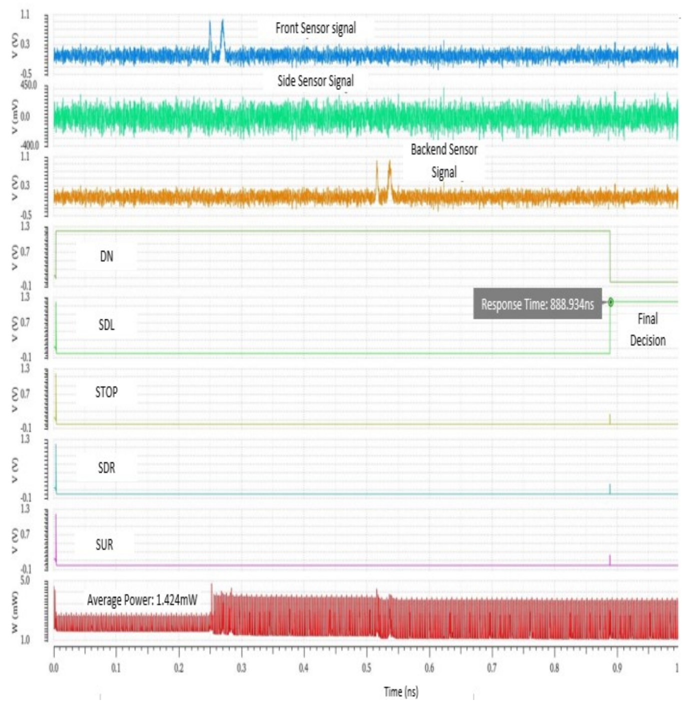

Figure 6. Simulation Result for Entire Circuit

V. CONLCULSION

Autonomous vehicles will become a very important part of transportation, as they will enhance the safety index and allow drivers to relax without dire consequences. To improve reliability, efficient sensor systems are preferred. A CMOS low power front collision detection system with LIDAR sensors is proposed in this paper to detect obstacles and make decisions in nano-seconds by employing a hardware circuit to process LiDAR signals.

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REFERENCES

[1] Yu, Huafeng, Li, Xin, Murray, Richard M., Ramesh, S., Tomlin, Claire J., Safe, Autonomous and Intelligent Vehicles. Springer International Publishing, Cham, Switzerland, 2019

[2] Poland, Kristin, McKay, Mary Pat, Bruce, Deb, Becic, Ensar, Fatal crash between a car operating with automated control systems and a tractor-semitrailer truck. Traffic Injury Prevention; Vol. 19, pS153-S156, 2018

[3] Francesco Belfiore, Antonino Calcagno, Giampiero Borgonovo, Maria Gabriella Castro, Alessandro Pisasale, Massimo Platania, Marco

Vinciguerra, Caterina Schiro’, Gesualdo Alessi, Carmelo Burgio, Salvatore Leonardi, Amedeo Michelin Salomon, Stefania Gagliano, Francesco Bartolotta, Pietro Lizzio and Salvatore Scaccianoce, A 76 to 81 GHz Packaged Transceiver for Automotive Radar with FMCW Modulator and ADC. European Radar Conference (EURAD), Electronic ISBN: 978-2-87487-049-1, 2017

[4] Kim, Geonu, Nun, Jiwoo, Lee Jungwoo, A Peer-to-Peer Interference Analysis for Automotive Chirp Sequence Radars. IEEE Transaction on Vehicular Technology, Vol 67, Issue9, 2018

[5] Li, Yan, Yu, Hang, Liu, Shaohua, Huang, Xihua, Jiang, Lai, A CMOS Time-to-Digital Converter for Real-Time Optical Time-of-Flight Sensing System. IEEE Communications Magazine, P113-P119, Aug 2018

[6] Nissinen, Jan, Kostamovaara, Juha, A high repetition rate CMOS driver for high-energy sub-ns laser pulse generation in SPAD-based time-of-flight range finding. IEEE Sensors Journal, ISSN Vol. 16, NO. 6, p1628-p1633, 2016