DESIGN AND IMPLEMENTATION OF DSP-BASED INTELLIGENT CONTROLLER FOR AUTOMOBILE BRAKING SYSTEM

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***Abstract*:** An intelligent braking system has great potential applications especially, in developed countries where research on smart vehicle and intelligent highways are receiving ample attention. The system when integrated with other subsystems like automatic traction control, intelligent throttle, and auto cruise systems, etc will result in smart vehicle maneuver. The driver at the end of the day will become the passenger, safety accorded the highest priority and the journey optimized in term of time duration, cost, efficiency and comfortability. The impact of such design and development will cater for the need of contemporary society that aspires to a quality drive as well as to accommodate the advancement of technology especially in the area of smart sensors and actuators. The emergence of digital signal processor enhances the capacity and features of universal microcontroller. This paper introduces the use of TI DSP, TMS320LF2407 as an engine of the system. The overall system is designed so that the value of inter-vehicle distance from infrared laser sensor and speed of follower car from speedometer are fed into the DSP for processing, resulting in the DSP issuing commands to the actuator to function appropriately.

***Key words*:** Smart Vehicle, Digital Signal Processor, Fuzzy Controller, and Infra Red Laser Sensor

1. INTRODUCTION

Intelligent braking system has found a lot of potential applications in countries like the United States, Japan, Germany, France etc. Research work on smart vehicle dates back to early 1970's. Despite this, it was not until early 1990's, that some of the research products become common place on the roadways after the research on smart vehicles received tremendous support from governments and private firms. A comprehensive, long-term project called Intelligent Vehicle Highway System (IVHS), also known as Intelligent Transportation System (ITS) was later formed and aimed to achieve certain research targets.

The intelligent braking system when integrated with other subsystems like automatic traction control, intelligent throttle, auto cruise systems, etc will eventually result in a smart vehicle. The driver at the end of the day will become the passenger, safety is accorded the highest priority and the journey will be optimized in term of time duration, cost, efficiency and comfortability. Yet, the need for the driver to have control over certain functions may become indispensable. This comes from the fact that the full-integrated system does not still completely converge to a stable system and also to alleviate certain problems of liability to a certain extent whenever accident occurs. It seems more natural to allow the driver to gradually transfer control of one function at a time to the automated system until the complete system deployment totally unfolds.

In the design of intelligent braking system, the driver is allowed to overtake the handling of the brake pedal from the controller during certain circumstances. For example, when an animal is about to cross the road in front of the moving vehicle. This is due to the lack of capability of machines to classify and predict certain actions. Machines, on the other hand, have great information processing power and its ability to withstand the aging has always put it ahead of human. With the advancement of microcontroller technology, the emergence of the digital signal processor has paved the way to many successful achievements specifically in industrial control. This paper discusses the hardware implementation for the intelligent braking system using digital signal processor (DSP) as the heart of the system as well as the communication link between sensor, actuator and other peripheral devices. To achieve this, infrared laser sensor will input the value of inter-vehicle distance into the DSP for signal processing, which later commands the actuator with appropriate signaling.

2. SENSOR

The choice of sensors to measure the inter-vehicle distance has been discussed thoroughly in [1]. Besides the capability of infrared laser sensor to measure the long distance range (at least 100 meter), the response time, cost efficiency and size have been put into consideration for this application. There are several ways to configure and position the sensor so as to have the best measurement [1,2]. For the implementation of the system in this research, the vehicle will be equipped with four-beam infrared laser sensor as illustrated in Fig. 1.

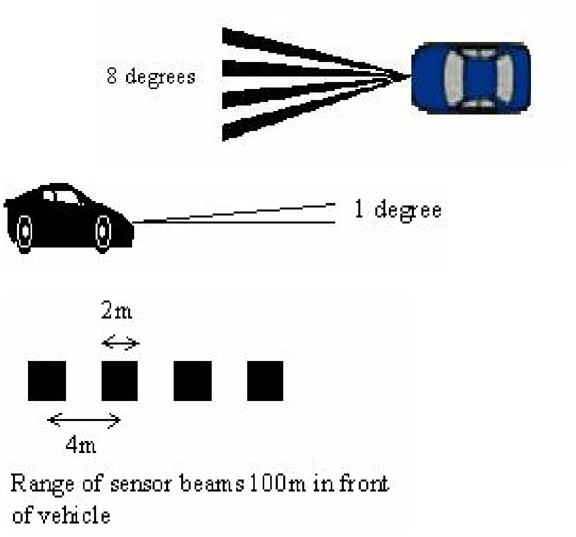

Fig. 1: Sensor Positioning and Characteristic

This configuration will enable the detection of preceding vehicle on bends. The tightest relevant radius on the highway (especially in the highway exit) is assumed to be 500 meters. In this case, the horizontal aperture angle must be at least 8^0 for an inter-vehicle distance of 75 meters. The vertical aperture is fixed to be 1^0 and is positioned in such a way to avoid false reading due to the road conditions. To obtain this configuration, the four-beam infrared laser sensor is arranged next to each other in one lateral plane. The outputs of this sensor are then connected to an integrator before being fed into the embedded DSP through P2 (expansion analog connector). Each beam of the sensors delivers a signal every 100 ms. Thus, at every clock at least four sets of readings are received. For this research work, only part of highways, which are straight in nature have been studied. For that reason only the reading from the two beams in the middle were focused on. The other two readings can be utilized, when they are to detect the inter-vehicle distance while negotiating a corner. As such, another sensor is needed to monitor the steering angle so as to determine the degree of the road curvature and decide which laser sensor readings are to be used. In general, these basic distance readings suffer from serious degradation to a certain extent, that is, there could be great differences in the measured values as compared to the ideal value used in the simulation study. In practice, the signals received may be reflected from traffic signs, guideposts, or crash barriers. For this reason, a special corrective measure can be introduced to preprocess this signal before being sent to the DSP. On the other hand, using data extrapolation from look-up table or knowledge-based system can be another approach to solve this problem. Alternatively, each vehicle can be equipped with a special tag that can reflect unique signal to be sensed by the detector of the sensor.

3. ACTUATOR

The actuator of the system is part of a module called Auxiliary Hydraulic Module (AHM). As shown in Fig. 2, AHM consists of hydraulic pump, valves and actuator. The function of the module is to provide input force to the vacuum booster through an actuator and brake pedal. Output signal from the DSP controller is in the form of pulse width modulation (PWM) and is amplified using a power amplifier. AHM later processes this signal and generates the necessary pressure against the brake pedal. PWM is a square wave signal of fixed frequency but varied duty cycle. It is possible to control the output force and the brake pedal by varying the duty cycle. If the hydraulic pump draws off a constant amount of fluid through the valves while the valves are opened, no pressure is developed but once it closes completely, an abrupt rise of pressure is attained. By switching the valves at high frequency (typically 100 Hz), coupled with varying duty cycle, the pressure inside the cylinder of the actuator can be controlled. Eventually, this pressure pushes the piston of the actuator and applies appropriate force to the brake pedal. At the maximum value of duty cycle, which implies the valve is opened for most of the time, no force is applied to the brake. The mapping from the duty cycle to the brake line pressure has been discussed by Reza, et al.[4]. The result suggests that the brake model can be approximated by the first order system.

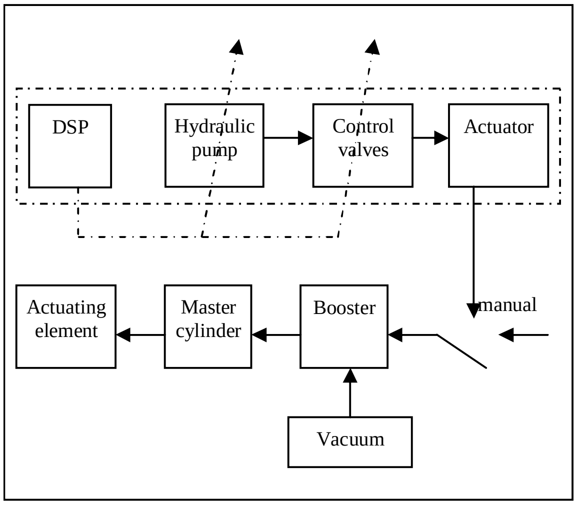

Fig. 2: Block Diagram of Auxiliary Hydraulic Module

4. CONTROLLER

Successful longitudinal control of vehicles in ITS applications is highly dependent on adequate control of vehicle subsystems. In particularly, Brake system is highly nonlinear and possesses wide range of uncertainties. The observed nonlinearities and uncertainties in the brake system are a combination of friction, dead zones and hysteresis [4,9]. In designing the brake control strategy, the main objective is to cancel the nonlinearities of the system so as to make the brake system behaves as uniformly as possible throughout the operating range of the system. Several control strategies have been developed to deal with the brake dynamics, which first need to be modeled. Three-state model strategy has been proposed [10] whilst a nonlinear first order model for the brake dynamics was developed [11,12]. In the former paper, the author employs sliding control technique, which is a kind of robust design technique usually used to compensate for the nonlinearities. The later uses a controller that employs feedback linearization to cancel the nonlinearities and a modified proportional integral (PI) compensator to achieve the desired control action. Both approaches involve rigorous mathematical formulation and impose many constraints. Due to the severe constraints inherent in vehicles dynamics, sometimes the global results are not very much relevant to the real applications. In this paper, the brake control strategy is in the form of fuzzy inference system (FIS) with the model employed being based on the condition that as the front vehicle decelerates rapidly and the engine torque alone may not achieve the vehicle following condition unless with the use of brake. With that assumption made, the dynamic of the vehicles in this situation can be formalized as,

$$\begin{aligned} \dot{x}_l &= v_l \\ \dot{x}_f &= v \\ \dot{v}_f &= \frac{1}{m}\left(-cT_b - f_o - c_1 v_f - c_2 v_f^2\right) \end{aligned} \tag{1}$$

where T_b is the braking torque, m is vehicle mass, f_o, $c_1 v_f$, $c_2 v_f{}^2$ represent the static friction force, rolling friction force and air resistance force respectively. The control objective is to have the following vehicle speed to track the front vehicle speed as,

$$v_f \approx v_l \tag{2}$$

The best set of the FIS is then loaded into DSP to perform the input-output data mapping so as to study and evaluate the performance of this control strategy.

The technology of DSP features the cross-link between microprocessor and microcontroller technology. In most of the specific driven applications, real time operation, compact and small-scale circuitry coupled with high processing speed are always required. By having Harvard type architecture, the DSP is able to have a parallel processing by maintaining two separate bus structures namely program and data buses, and the special instruction set which allows the processor to go for full speed execution [5,6]. The TMS320LF2407 is a fixed-point processor optimized for control applications. In this research work, this processor has been chosen to be the processor for the braking system. While some of its features are not comparable to the features found in other type of processors, they are adequate enough to run the application excellently for this research work. For instant, a typical universal microprocessor has faster clock speed compared to DSP. However, when it comes to the signal processing tasks, the DSP supersedes the universal microprocessor in the two to three order of speed [13]. Even though a very fast speed universal microprocessor with certain signal processing functions programmed on it can be easily found in the market nowadays, the price is impractical for the braking application. In fact with the USD$11.75 [14] TMS320LF2407 30 MHz processor, the problem can be handled relatively better as compared to USD$94.70 [15] Intel Celeron 566 MHz processor. A dedicated fuzzy chip on the other hand is limited in its usage in the sense that the chip is tailored for fuzzy algorithm without having necessary circuitry for signal processing. Among features that TMS320LF2407 possesses are integrated on chip ADC module, PWM module, memory expansion capability, relatively high speed (30 MHz) and several logging port options [7,8], which are needed for system under study. The system employs TSK fuzzy inference system as a kernel to the controller. It takes two inputs from the sensors namely the inter-vehicle distance and following vehicle speed, whereas the PWM output signal is generated from already fine-tuned thirty set of rules to operate the actuator. The tuning process is done using Matlab software through the adaptive neuro fuzzy approach with back propagation algorithm. The Matlab generated inference system forms the basis of the file, which would be downloaded into the DSP. This allows the off-line batch updating for the inference system if the input output data pairs are available. Fig. 3 shows a brief system architecture where one of the dual event managers is utilized. The general-purpose timer triggers the fetching of data from analog expansion port (P2) and activates the interrupt service routine every 100 ms. The on-chip PWM module outputs the scaled signal and sent this to the power amplifier to finally drive the actuator. The cost of additional circuit such as the integrator is worth it so as to secure the accuracy of sensor reading. The 10 bits ADC can have a resolution of up to 0.146 meter compare to the use of on chip counter, which is capable of having a resolution of 5 meters [1].

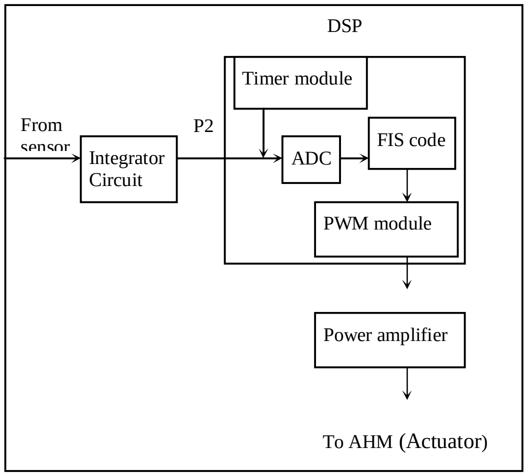

Fig. 3: A Brief System Architecture

5. HARDWARE SETUP AND RESULTS

Fig. 4 shows a layout of TMS320LF2407 DSP used in the research study and the complete module is depicted in Fig. 5. JTAG-compliant scan base emulation set is used as an interfacing between the host computer and the processor and allows the processor to be debugged in real time mode. Fig. 6 shows the complete set of devices used for the implementation of this system. The integrated development environment (IDE) called Code Composer for the DSP, as seen in the screen of the computer in the figure, is a useful tool to develop the code for the processor. The program code of fuzzy algorithm is developed in C and the complete program flowchart is shown in Fig. 7. The code complies the ANSI C specification and can easily be altered based on the fuzzy inference system developed in Matlab software.

The maximum time marked for 400 samples of set data to be read from the host computer and processed in the processor is 27 sec. This corresponds to about 67.5 msecs for each data to be inferred. It is important that this process consumes less time than the scanning time of the sensor reading, which is 100 msecs for each reading. This further confirms the feasibility of the fuzzy code to be run on the DSP

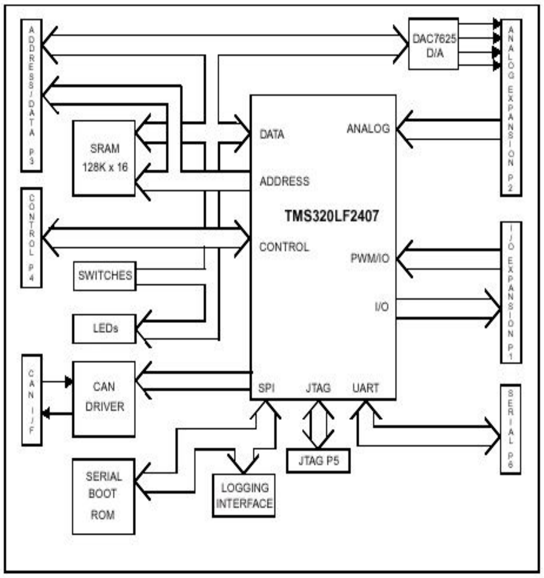

Fig. 4: TMS320LF2407 EVM Layout

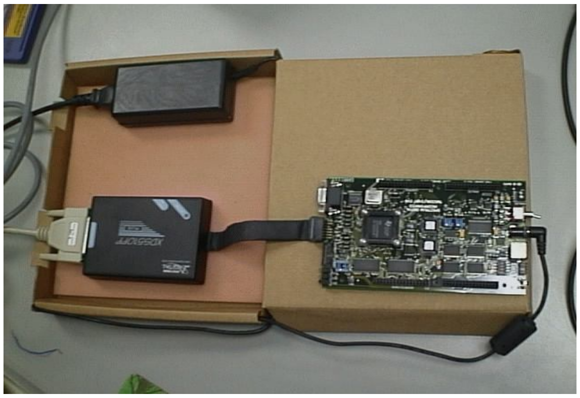

Fig. 5: The EVM Board and JTAG-Compliant Scan Base Emulation Set

Fig. 6: The DSP Setup

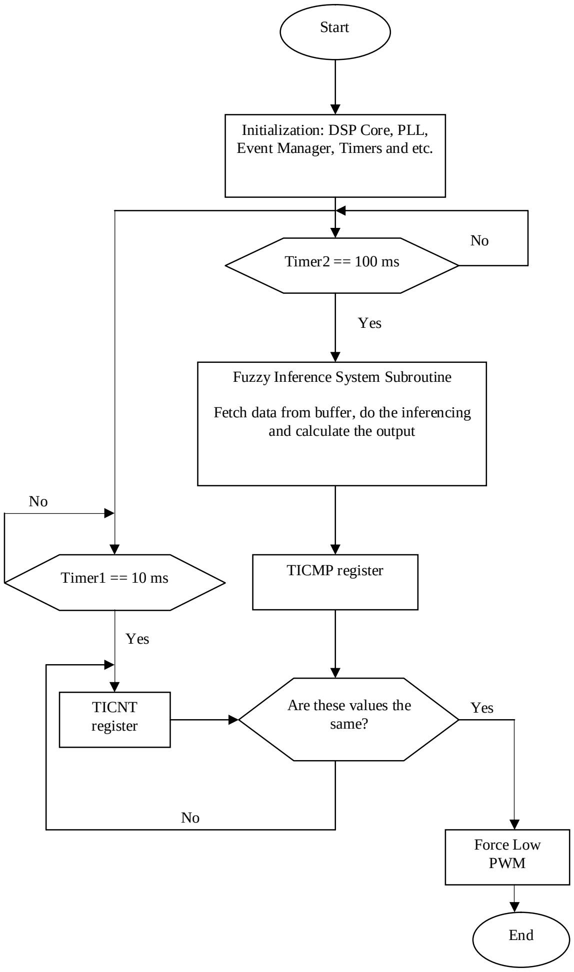

Fig. 7: Software Implementation of Brake Controller

A series of plots (Fig.9-11) are generated for some of the simulation cases using Matlab. They are used as a benchmark to measure the reliability of the DSP. This is done through comparing them with the plots generated using the hardware (DSP) shown in Fig. 12-15 in the Appendix. For each case of hardware tests, the plots generated are the two inputs to the DSP, namely the distance error and the distance error rate of change. Meanwhile the last plot in each case shows the brake command, which is actually the output from the DSP. The observed result shows that the DSP can accurately track the simulation result, which is done using Matlab software. Table 1 depicts the entire initial values used to distinguish all the cases under study.

Table 1: Initial Values for Different Simulation Cases

Initial value	*Case 1*	*Case 2*	*Case 3*	*Case 4*
Velocity of following vehicle	30 m/s	30 m/s	30 m/s	30 m/s
Velocity of front vehicle	25 m/s	25 m/s	25 m/s	20 m/s
Initial inter-vehicle distance	90 m	50 m	120 m	90 m
Offset	36 m	36 m	36 m	36 m
Free time	1.8 s	1.8 s	1.8 s	1.8 s

5.1 Comments on Case 1

Following the well-known 3-second method, the safe distance of the following vehicle from the front vehicle is set based on their velocities. Case 1 in Table 1 shows the parameters that are used to initialize the simulation of the system. The offset is a constant that needs to be added to have the optimum safe distance value. With the front vehicle moving at 25m/s and then suddenly stops at 0 m/s, it is shown in Fig. 8(a) and 8(b), that the following vehicle is capable of stopping safely before collision. Figure 8(c) illustrates the brake force applied whenever the braking action of the vehicle takes place. It can be seen that at the very beginning of the simulation, a relatively low force is applied. This is to adjust the safe distance value formulated in supervisory controller. The force later reduces to zero and it is not until the collision has occurred that the braking force is activated again to make sure the following vehicle stops safely

5.2 Comments on Case 2

For case 2, the initial condition for inter-vehicle distance is set to be close to the value of 50 m. For this set of simulations, it is clear that this distance is crucial in terms of the velocities that both vehicles display. The brake is applied from the first second of the simulation and finally reduced to zero as shown in Fig. 9(c). At the tenth second of the simulation, when the current distance is about 53 m, the applied brake force is high to ensure the following vehicle can avoid the collision. Even though the brake force manages to stop the vehicle, its application is quite sudden and this can jerk the passengers of that vehicle. However, under real circumstances, this will hardly happen, as the vehicle will be always maintained at an appropriate distance right from the beginning.

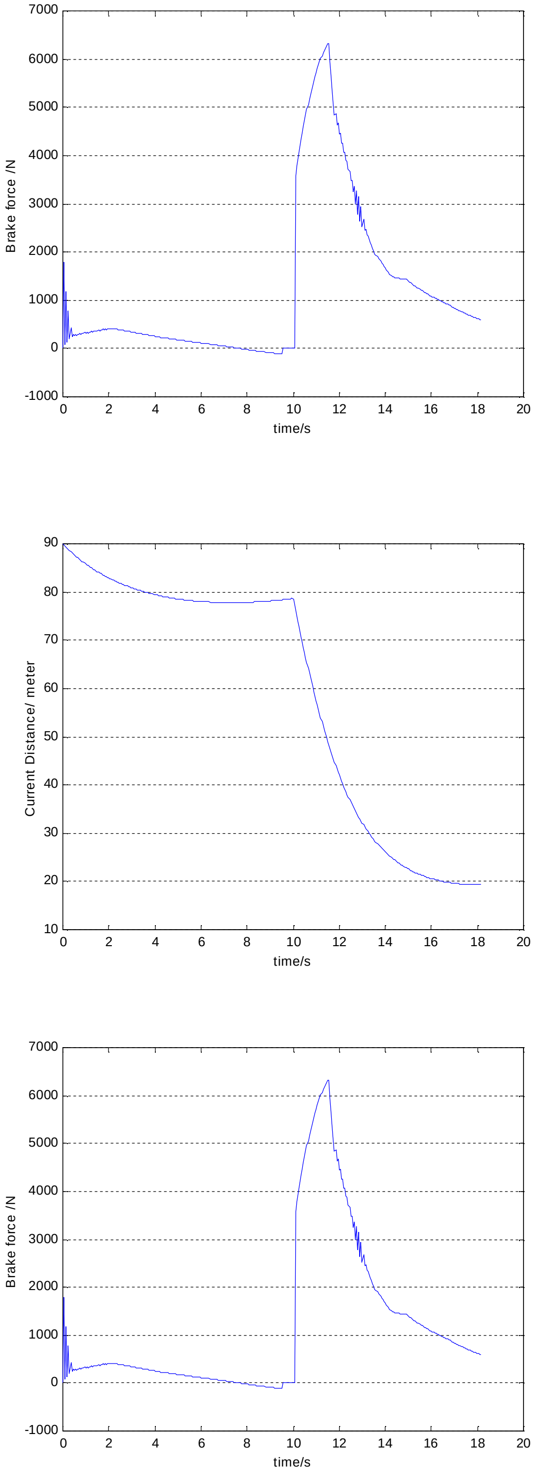

Fig. 8: Plots for Case 1: (a) Velocity Profiles (solid – front car). (dash – following car), (b) The Inter-vehicle Distance and (c) Brake Force

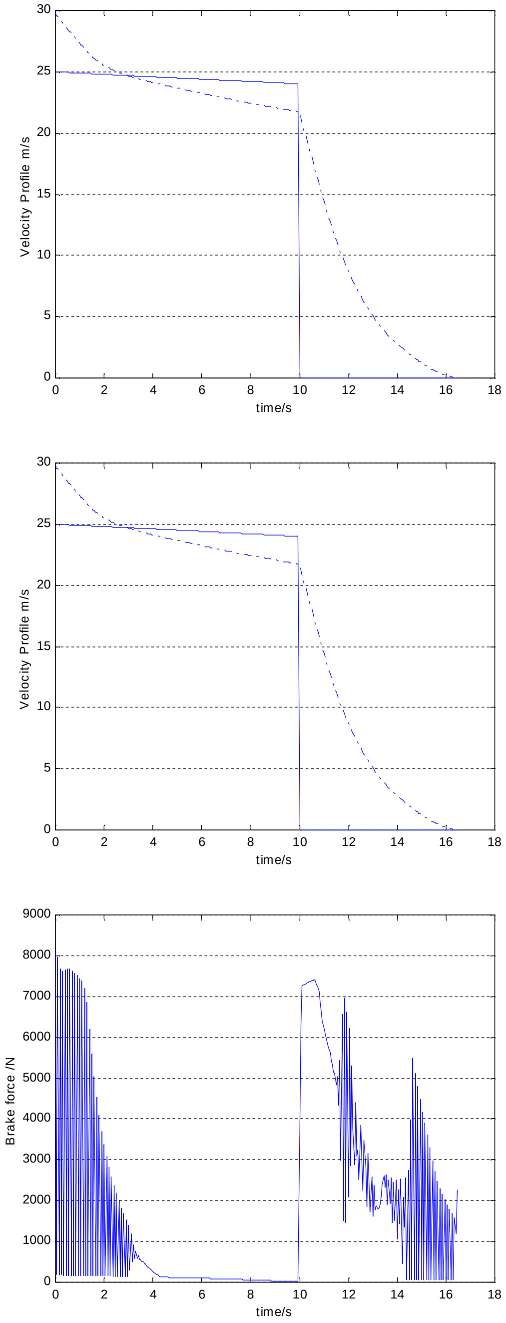

Fig. 9: Plots for Case 2: (a) Velocity Profiles (solid – front car). (dash – following car), (b) The Inter-vehicle Distance and (c) Brake Force

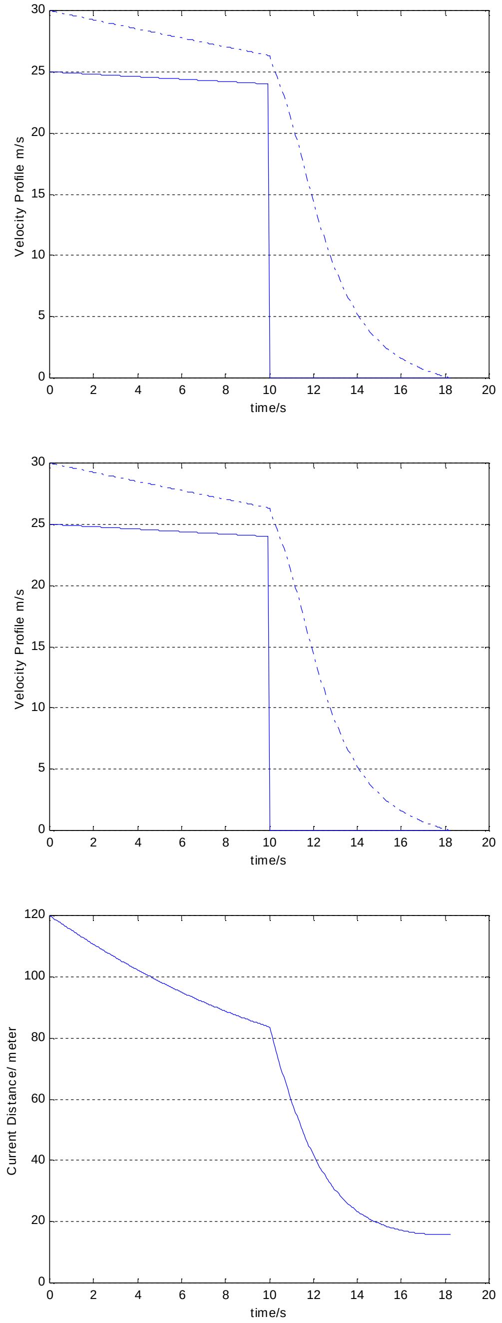

Fig. 10: Plots for Case 3: (a) Velocity Profiles (solid – front car). (dash – following car), (b) The Inter-vehicle Distance and (c) Brake Force

5.3 Comments on Case 3

The offset value is set to be 36 m and is automatically added to the safe distance expression. This value was found to be the best constant value so as to increase the reliability of the safe distance formulation. For case 3, whose initial values are shown in Table 1, the inter-vehicle distance is set to be 120 m. The following vehicle applies no brake force until the front vehicle stops abruptly. It stops at the distance of 17 m from the front vehicle in a very smooth action. This is shown in Fig. 10(b).

5.4 Comments on Case 4

The different between initial values for case 4 in Table 1 and those in case 1 is the slower velocity of the front vehicle, which is now 20 m/s. As expected and shown in Fig. 11(c), the brake force is applied from the beginning until the tenth second of the simulation. Due to the closer inter-vehicle distance at that time, faster response of brake system can be noted so as to avoid the collision.

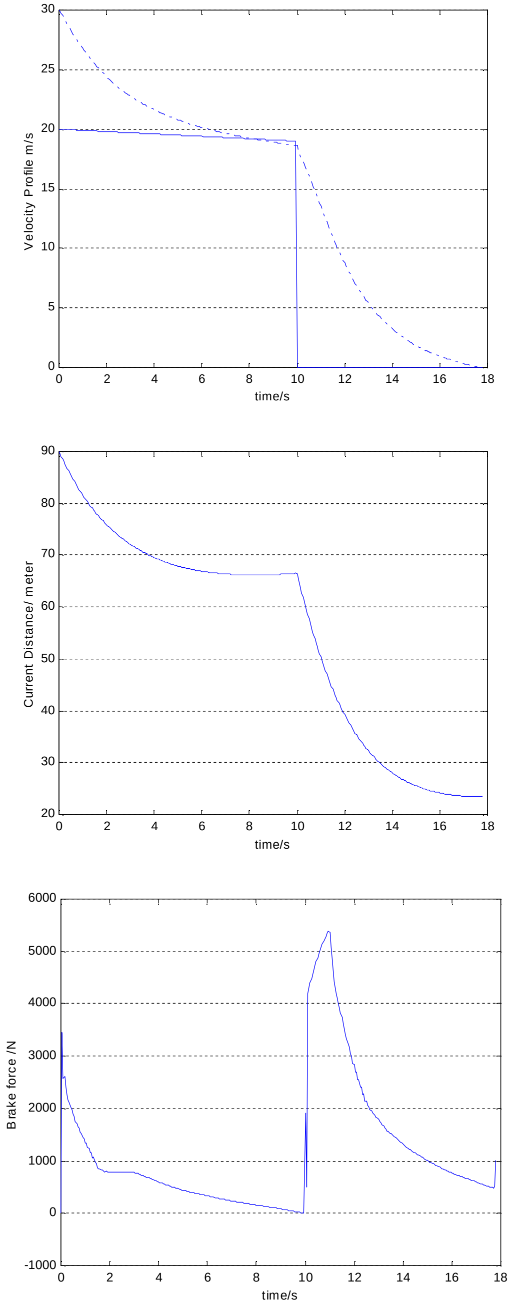

Fig. 11: Plots for Case 4: (a) Velocity Profiles (solid – front car). (dash – following car), (b) The Inter-vehicle Distance and (c) Brake Force

6. CONCLUSION

The use of fuzzy logic algorithm in DSP is a fairly new development in automotive application. TMS320LF2407 is a type of processor, which can provide high computation power in signal processing tasks especially when the process heavily involves multiplication and summation operations. When this processor is programmed using fuzzy algorithm, the issue of memory space cannot be avoided. However, with the 192 KWords of total zero wait state external memory interface, the problem is alleviated. In the field of braking system, the notation brake-by-wire implies electronically controlled braking system. The technique of using laser sensor for effective measurement of inter-vehicle distance via integration procedure has been suggested for optimal performance of the braking system. For the actuator of the system, a module called Auxiliary Hydraulic Module is fixed before the brake pedal so as to apply controllable force upon the pedal. The results of the simulation studies have shown the effectiveness of off line neuro-fuzzy control to achieve a near-human behavior in controlling the braking system. The downloaded fuzzy algorithm in the processor memory bank works efficiently and only consumes less than half of the program memory space. It is also recorded that the speed of the fuzzy inference process is within the time of scanning the input signal obtained from the host computer. This demonstrates the feasibility and practicability of the code to be used in the real time controller.

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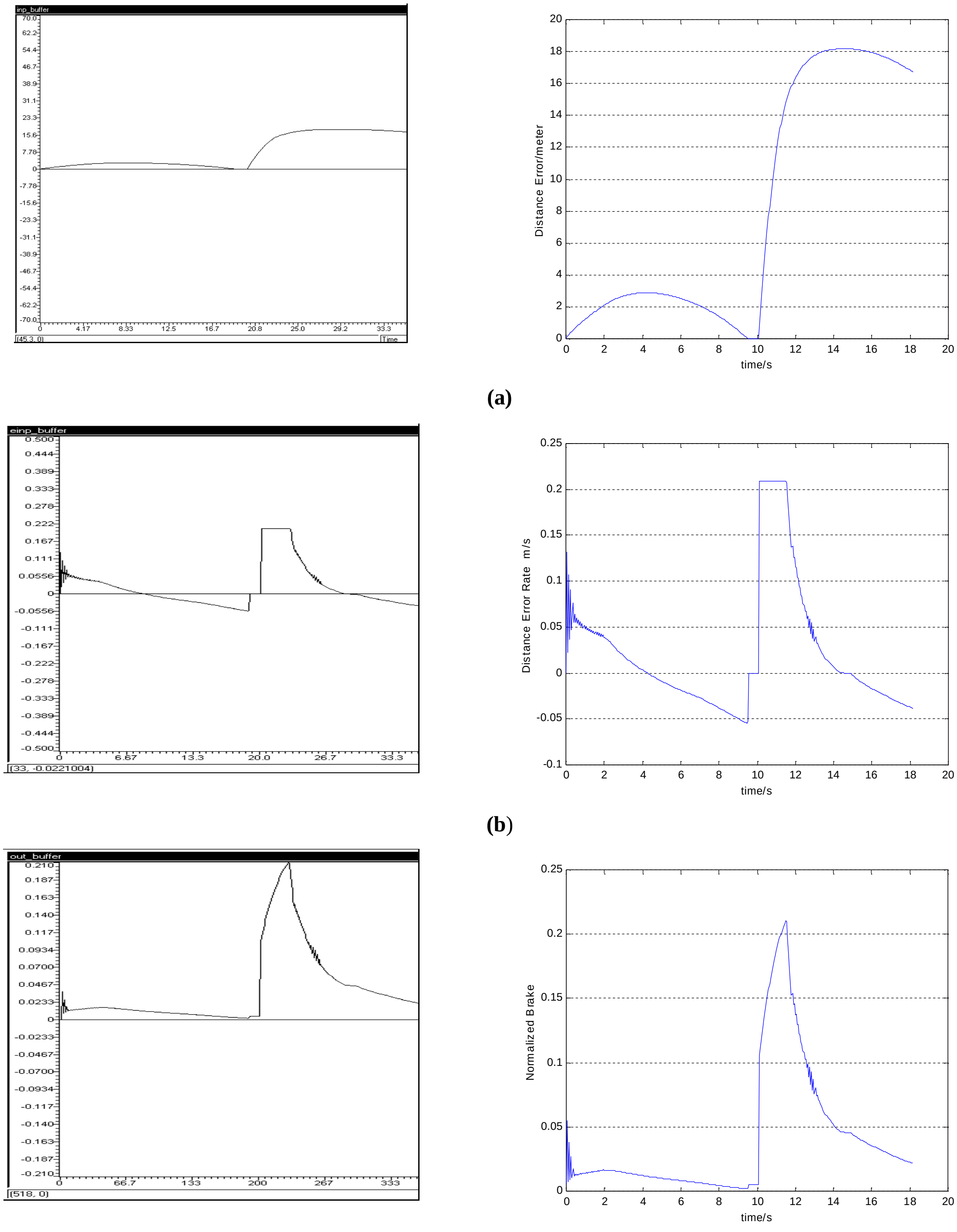
APPENDIX

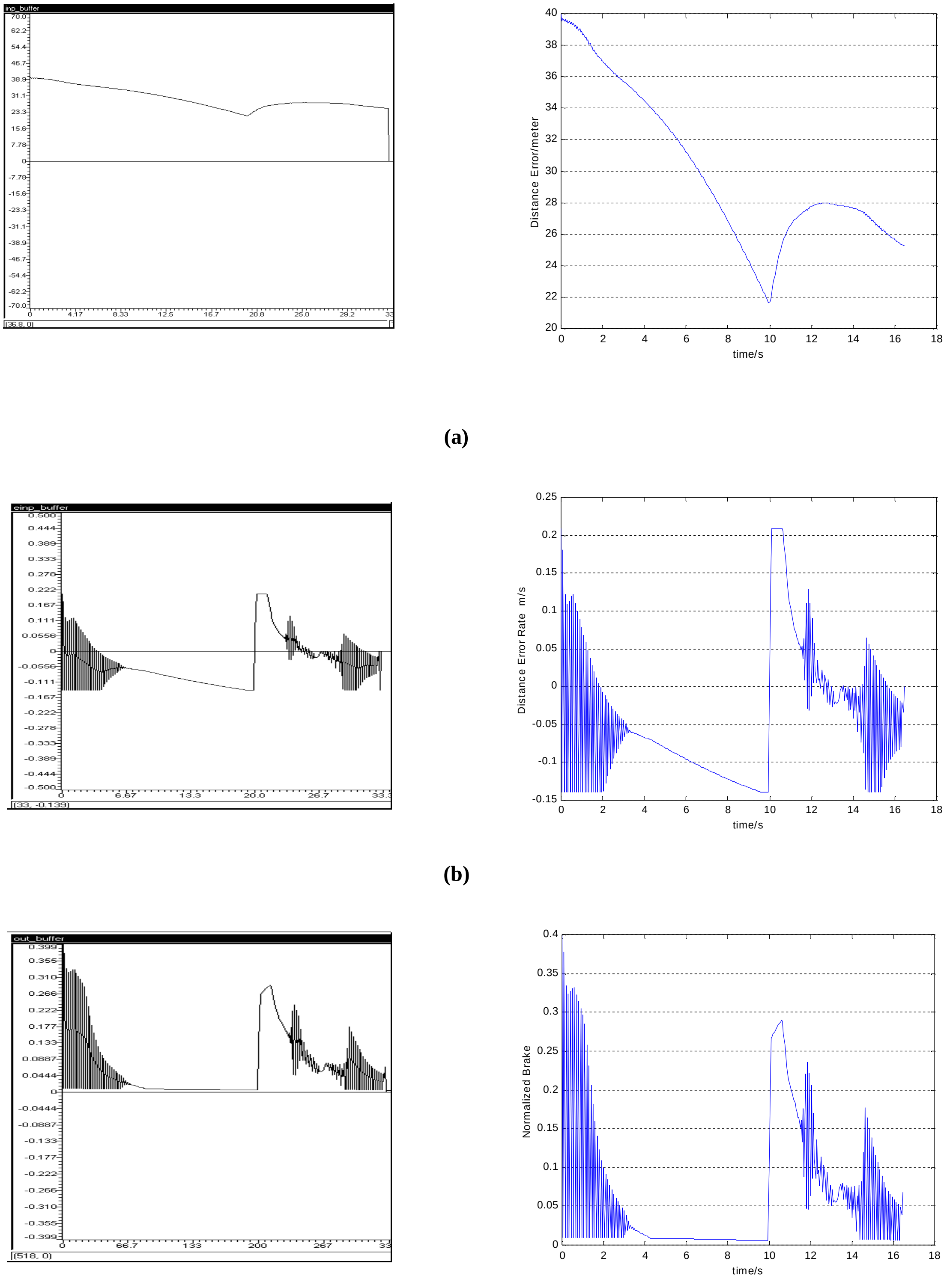


(a)

(b)

(c)

Fig.. 12: (a): Plot of Distance Error vs. Time for Case 1 **(b)**: Plot of Distance Error Rate of Change vs. Time for Case 1 **(c)**: Plot of Normalized Brake Output vs. Time for Case1



(a)

(b)

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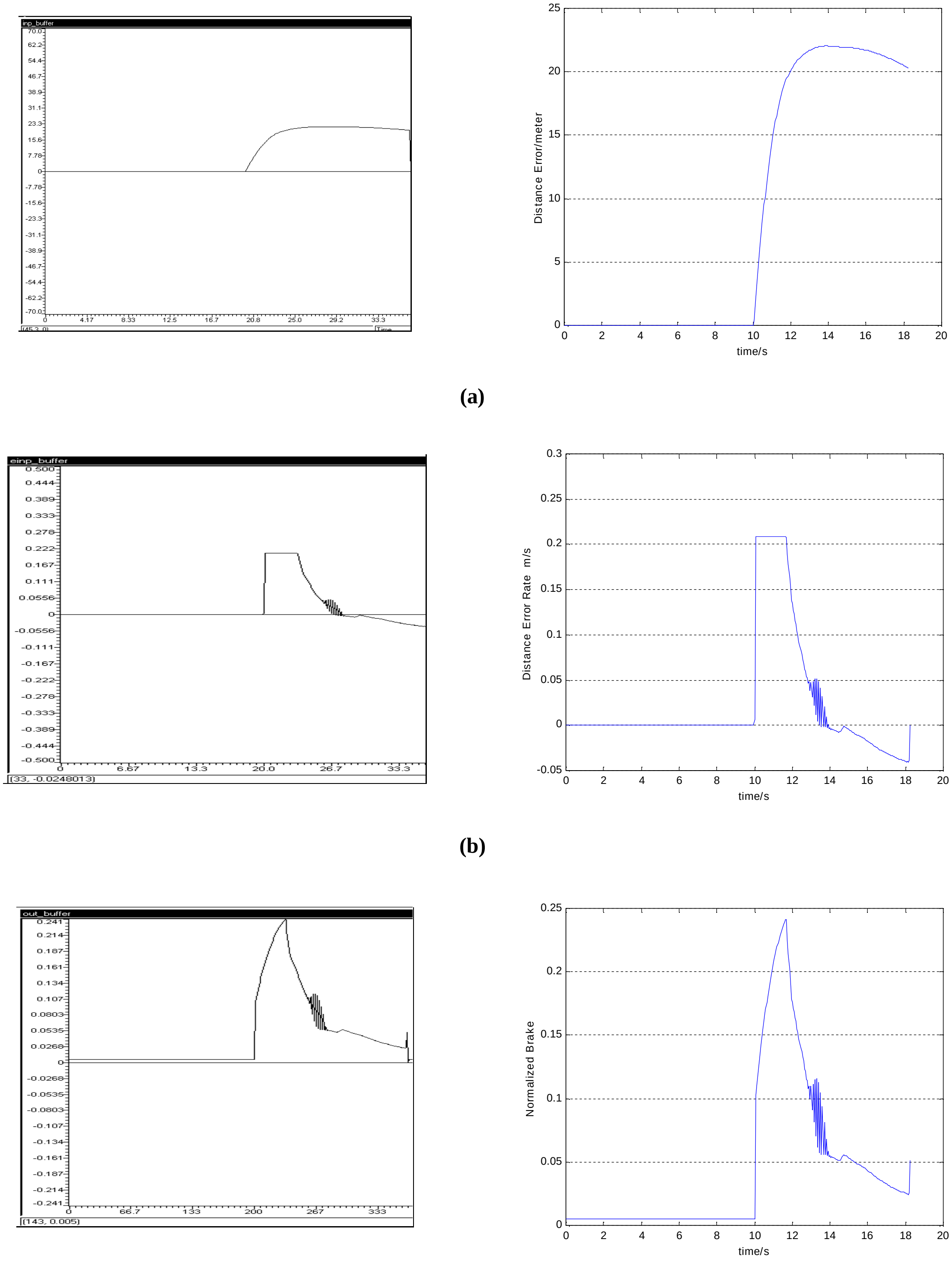
Fig. 13(a): Plot of Distance Error vs. Time for Case 2 **(b)**: Plot of Distance Error Rate of Change vs. Time for Case 2 **(c)**: Plot of Normalized Brake Output vs. Time for Case 2

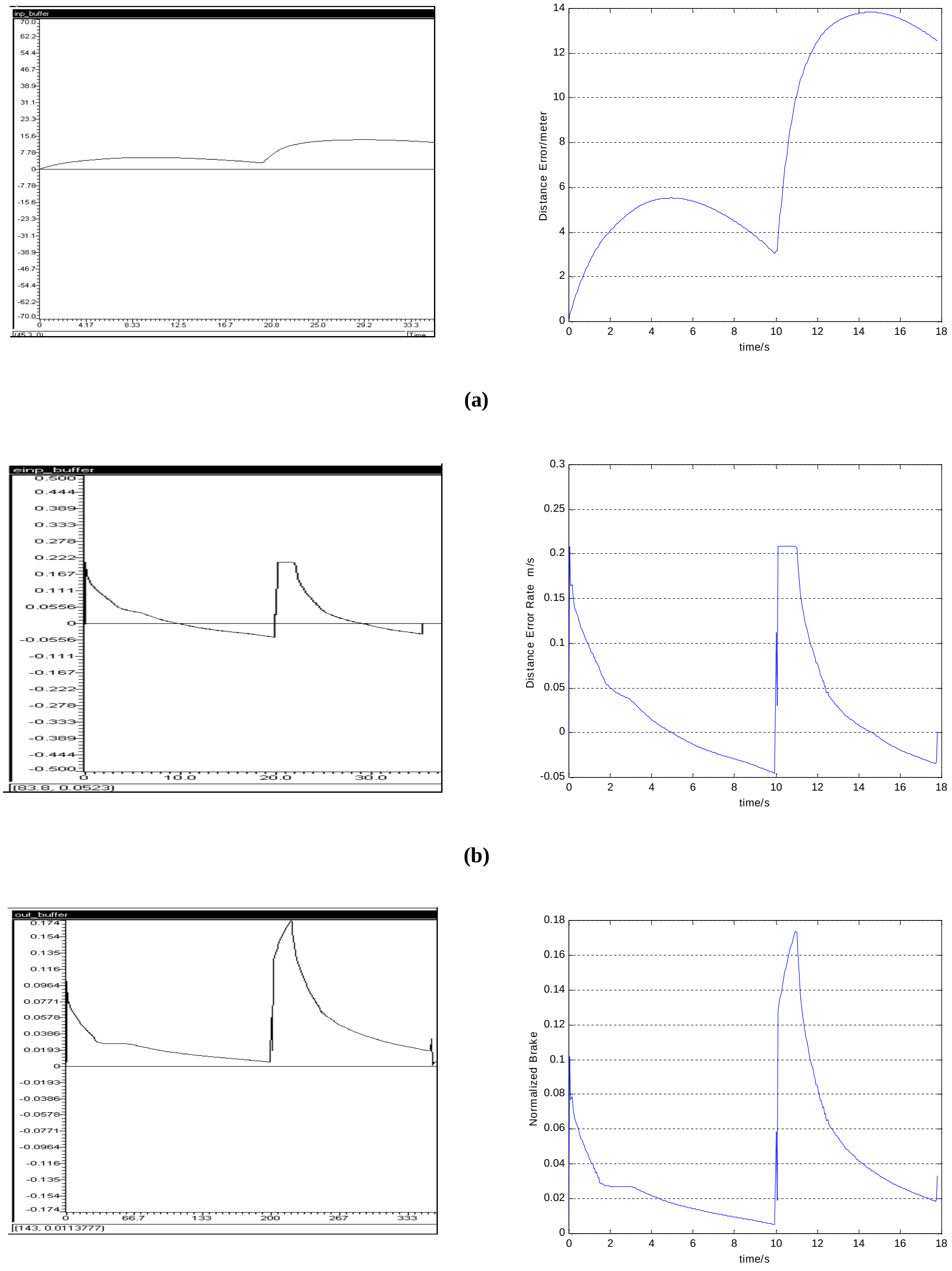


(a)

(b)

(c)

Fig. 14(a): Plot of Distance Error vs. Time for Case 3 **(b)**: Plot of Distance Error Rate of Change vs. Time for Case 3 **(c)**: Plot of Normalized Brake Output vs. Time for Case 3



(a)

(b)

(c)

Fig. 15(a): Plot of Distance Error vs. Time for Case 4 **(b)**: Plot of Distance Error Rate of Change vs. Time for Case 4**(c)**: Plot of Normalized Brake Output vs. Time for Case 4

BIOGRAPHIES

Momoh Jimoh E. Salami received his B.Sc. degree from University of Ife, Nigeria in June 1977, postgraduate diploma from Philips International Institute for Technological Studies, Eindhoven, Netherland in Dec. 1979 and PhD from University of Calgary, Canada in June 1985. He has wide teaching experience in many high academic institutions in various countries. He joined IIUM in Sept. 1996 and is currently the Head of Department of Mechatronics Engineering. He has authored or co-authored more than 50 publications including textbook, journals and conference papers. His research interests include intelligent system design and digital signal and image processing. Dr. Momoh is a senior member of IEEE.

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