A New Decision Making Algorithm for Airbag Control

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Abstract— Recently, airbag systems have been introduced to supplement the seat belt system primarily to reduce head injuries. Most of the present airbag systems use distributed mechanical sensors, which are costly, not easy to calibrate, and not effective to trigger the airbag on time for different types of crashes. An electronic sensor is more effective in the sense that the signal from the accelerometer can be digitized and analyzed to study the behavior of the signal for different types of crashes. Unfortunately, most of the algorithms which are used for electronic sensors still have some problems. They either fail to trigger the airbag on time for several types of high speed crashes such as pole and angle crashes, or if they do trigger at these crashes they also trigger at low speed barrier crashes.

A new algorithm for an electronic sensor is presented in this paper. This algorithm has been developed by analyzing a large volume of data obtained from actual crash testing experiments. The algorithm works for all types of crashes. The algorithm has been tested by applying it on real crash testing data. A hardware circuit has also been proposed in the paper, which can be used to implement the algorithm for real-time operations.

I. INTRODUCTION

AIRBAG systems are used in many current vehicle restraint systems to supplement seat belt systems primarily to reduce head injuries. Recent studies show that the airbag reduces head and chest injuries significantly [1]–[3].

Two types of crashes are widely investigated in the literature [7]–[12]. One of these crashes is called the *barrier-crash* and the other one is called the *pole-crash*. A crash is called a *barrier-crash* when a car hits a very hard stationary barrier such as a concrete wall. If the car hits the barrier perpendicularly, we say that it is a *frontal barrier-crash* or 90° *barrier-crash*; otherwise, the crash is called an *angular barrier-crash*. A crash is called a *pole-crash* when a car hits a pole or a small tree.

Normally the airbag is deployed if the collision force is equivalent to a frontal collision with a stationary barrier (90° barrier-crash) at a speed of 14 mi/h or higher [6]. The greater the collision impact the earlier the airbag should be deployed. Because, the airbag has to be deployed before an occupant moves forward five inches relative to the car [4]. Normally it takes 30 milliseconds for an airbag to be deployed after it gets a trigger signal from the airbag sensor. Thus, an airbag sensor is to be designed in such a way that it can send a trigger pulse to the airbag deployment circuit 30 ms before the time when

the occupant's head moves forward five inches with respect to the car. This triggering point is often called the 5-30 ms point [9]. For a barrier-crash at 30 mi/h the 5-30 ms point comes within 26 ms after the crash occurred.

An airbag can be used only once. Since replacing a used airbag costs at least $500 [6], it's obviously critical for the airbag to inflate only when absolutely necessary. Thus, the airbag should not be deployed when a car moves through a very rough or bumpy road, or when it hits a small traffic sign pole, e.g., stop or yield sign pole.

Most of the present airbag systems use distributed mechanical sensors. All the mechanical sensors work almost on the same principle. In a typical mechanical sensor a stainless steel ball is held by a magnet at one end of a closed cylinder. The crash impact overcomes the precisely calibrated magnetic bias and the ball moves through the cylinder to close electrical contacts and complete the airbag triggering circuit [4]–[5]. Mechanical sensors can be designed to take the above mentioned specifications into consideration, but the necessary calibration for the sensors is not that simple.

Very little work is available in the literature on electronic sensors for airbag systems and their algorithms for airbag deployment. The algorithms for electronic sensors are based on a single-point electronic accelerometer placed in the passenger compartment. This accelerometer is expected to overcome the limitations of the current distributed mechanical sensors which are costly and ineffective in triggering the airbag on time for different types of crashes. An electronic sensor is more effective, because the accelerometer signal can easily be digitized and analyzed in order to study the characteristics of different types of crashes. However, the current algorithms which are based on a single-point accelerometer still have a number of problems, such as: sometimes they don't trigger the airbag on time for several pole and angle crashes, or if they do trigger at these crashes they also trigger at low speed barrier crashes [9], [11], [12].

This paper presents a new algorithm for airbag control. The algorithm has been developed by analyzing a large volume of data obtained from actual crash testing experiments. Those data were collected for a period of 200 milliseconds from an accelerometer located on the vehicle. The accelerometer data contains vital information of a crash. In order to develop the algorithm, first we analyzed the unfiltered accelerometer signal in time domain, and then we studied the frequency response of the signal and analyzed its components. After that we studied the filtered accelerometer signal in time domain, and finally we developed an algorithm based on our observation. A hardware

circuit is also proposed in the paper which can be used to implement our algorithm for real-time operation.

The rest of the paper is organized as follows: some basic crash sensing parameters are discussed in Section II, Section III describes the accelerometer signal and its components, the airbag control algorithm is presented in Section IV, Section V shows the test results, and finally Section VI presents the conclusions.

II. SOME BASIC CRASH SENSING PARAMETERS

There are many parameters which can be used to determine the severity of a crash. Some of these parameters are: the change in vehicle velocity over a period of time, the change in vehicle energy over a period of time, the jerk (derivative of the acceleration) over a period of time, etc. Some of these parameters are good to determine the severity of one type of crash, and other parameters are good for other types of crashes. For example, the change in vehicle velocity is a good parameter to make a decision whether or not the airbag is to be fired during a frontal barrier crash. However, the change in vehicle velocity alone is not a good parameter for pole and angular barrier crashes.

In order to develop our algorithm, we first investigated a number of basic parameters to determine the severity of a crash. These basic parameters are:

- The accelerometer signal, $s(t)$, itself.
- The change in vehicle velocity, $\Delta v = \int s(t)\,dt$
- The absolute value of $s(t)$, i.e., $|s(t)|$
- The integral of the absolute value of $s(t)$, i.e., $\int |s(t)|\,dt$
- The derivative of $s(t)$, i.e., $ds(t)/dt$
- The integral of the absolute value of the derivative, i.e., $|\int |ds(t)/dt|\,dt$
- Number of oscillation per unit time in $s(t)$.

We consider these parameters as the basic parameters because any other parameter which is a monotonously increasing function of these parameters will not discriminate between different types of crashes if the basic parameters did not. This will save us time by not looking at many parameters such as the energy in the signal, $E = \int s(t)^2\,dt$, which is the integral of a monotonously increasing function of $|s(t)|$.

An important parameter that discriminates between all types of crashes is the change in vehicle energy (note that the vehicle energy is not the same as the energy in the signal) which can be computed as follows

$$\Delta E = \int m.s(t).v(t)\,dt \qquad (1)$$

where, $v(t) = \int s(t)\,dt + v_0$, m is the mass of the vehicle, and v_0 is the initial velocity (crash speed) of the vehicle. If we assume m to be equal to 1, then the above parameter is the change in energy per unit mass. However, there are several problems in using the change in vehicle energy. Firstly, this parameter requires us to keep an eye on the vehicle velocity, v_0, at the beginning of the crash. Secondly, the parameter ΔE changes significantly for the same change in car velocity, Δv, at different crash speed (v_0). For example, if a car hits a very hard stationary barrier at a speed of 14 mi/h, then the severity
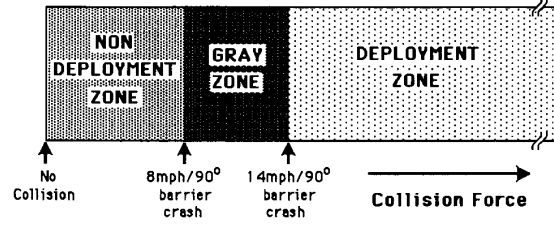

Fig. 1. Different zones of a collision. The collision force is expressed in terms of the vehicle speed for a 90° barrier crash.

of this crash to the occupant is the same as that of the crash where the car hits a similar stationary car at a speed of 28 mi/h. Because, for the former crash the car velocity will change from 14 mi/h to 0, and for the later crash the velocity will change from 28 mi/h to 14 mi/h. Thus, as far as the movement (with respect to the vehicle) of an occupant's head is concerned, it is the same in both the cases. Hence, the severity of both the crashes is the same. But the value of ΔE for the former crash is much less than the later crash. Hence, we should avoid any parameter which depends on the change in vehicle energy, rather than the change in vehicle speed.

As mentioned earlier that an airbag must be deployed if the collision force is equivalent to a frontal collision with a stationary barrier (90° barrier-crash) at a speed of 14 mi/h or higher. On the other hand an airbag must not be deployed if the collision force is equivalent to a 90° barrier-crash at a speed of 8 mi/h or less. If the collision force is equivalent to a 90° barrier-crash at a speed of v (where, 8 mi/h $< v <$ 14 mi/h), then we say that the crash occurred in the gray zone. If a crash occurs in the gray zone, then there is no requirement as far as the triggering of the airbag is concerned. This means that a deployment or a nondeployment of the airbag is equally acceptable if a crash occurs in the gray zone. Fig. 1 shows the different zones of a collision. For a pole crash the gray zone is in the range 11 mi/h $< v <$ 17 mi/h, where v is the crash speed. This means that the collision force of a 17 mi/h/pole crash is equivalent to that of a 14 mi/h/90° barrier crash. Similarly, a 11 mi/h/pole crash is equivalent to an 8 mi/h/90° barrier crash.

A. Change in Vehicle Velocity (ΔV)

From the time domain analysis of the unfiltered accelerometer signal we found that only the change in vehicle velocity is a good parameter to determine whether or not the airbag should be fired in case of a frontal barrier crash (90° barrier crash). But, this parameter is not good for making any decision during a pole or angular crash. Fig. 2 shows the change in vehicle velocity curves for six different crashes: two 8 mi/h/90° barrier crashes (see curves C1 and C2), two 14 mi/h/90° barrier crashes (see curves C3 and C4), and two 19 mi/h/pole crashes (see curves C5 and C6). Out of these six crashes the airbag must not be deployed for the two 8 mi/h/90° barrier crashes, because these two crashes occur in the nondeployment zone. The movement of the dummy in every crash test was recorded using a high-speed camera. By monitoring the dummy movement it was found that the 5 -
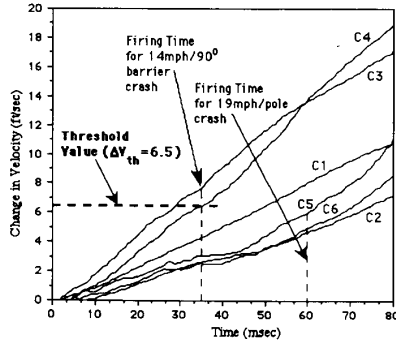
Fig. 2. Change in vehicle velocity versus time after the crash. (C1, C2: 8 mi/h/90° barrier crash; C3, C4: 14 mi/h/90° barrier crash; and C5, C6: 19 mi/h/pole crash.).

30 ms point for each of the two 14 mi/h/90° barrier crashes (curves C3 and C4) occurs approximately 35 ms after the beginning of the crash. Thus, for the crashes C3 and C4 (see Fig. 2) the airbag must be triggered within 35 ms after the crash occurred. From the dummy movement it was found that for the 19 mi/h/pole crashes the 5-30 ms point occurs approximately 60 ms after the beginning of the crash. Hence, for each of the two 19 mi/h/pole crashes (curves C5 and C6) the airbag must be triggered within 60 ms after the crash.

If the change in vehicle velocity, ΔV, is selected as a parameter for triggering the airbag, then we must determine a threshold value of ΔV which can be used to make a decision whether or not the crash occurred in the deployment zone. Such a threshold value can easily be determined for barrier crashes only. For example, by looking at Fig. 2 one can easily select a threshold value of $\Delta V_{th} = 6.5$ to trigger the airbag for a 14 mi/h/90° barrier crash, which is the lowest speed barrier crash that requires an airbag deployment. If $\Delta V \geq \Delta V_{th}$ within 35 ms after the crash occurred, then it is sure that the crash occurred in the deployment zone and therefore, the airbag must be triggered. But it is not possible to select a threshold value of ΔV which can be used to trigger the airbag for 19 mi/h/pole crash (see Fig. 2). Because, if such a threshold value is selected to trigger the airbag within 60 ms after the occurrence of a 19 mi/h/pole crash, then that threshold value will also trigger the airbag for an 8 mi/h/90° barrier crash. Thus, the parameter ΔV can not be used to discriminate a 19 mi/h/pole crash from an 8 mi/h/90° barrier crash until it is too late to trigger the airbag for a 19 mi/h/pole crash. Therefore, only ΔV alone is not enough to make a decision whether or not the airbag is to be triggered for all types of crashes. However, the parameter ΔV can be used in the airbag control algorithm as follows:

```
If  ΔV ≥ ΔVth within 35 ms after the crash
    Then crash occurred in the develop-
         ment zone no matter what the
         type of the crash is;
    Else further parameter testing is
         necessary to determine whether
         or not it is a pole or an
         angular barrier crash.
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In order to select a good parameter for discriminating pole crashes against frontal barrier crashes (90° barrier crashes) we need to clearly understand the differences between barrier and pole crashes. During a frontal barrier crash the entire bumper of the vehicle is affected. But during a pole crash only a part of the bumper is affected. Thus, the vehicle starts losing energy at a higher rate for a barrier crash than for a pole crash. As a result, for a frontal barrier crash the vehicle velocity decreases rapidly than for a pole crash of equivalent collision force. A pole crash, which requires airbag deployment, normally breaks a part of the bumper. The pole then cuts through the bumper and hits other distributed solid objects (motor, radiator, etc.) in the vehicle. When the pole hits a solid object the magnitude of the vehicle deceleration increases, i.e., the vehicle slows down rapidly. After that if the pole breaks the solid object, then the vehicle deceleration will decrease, i.e., the vehicle will not slow down as rapidly as it was. If the pole hits another solid object, then the magnitude of the vehicle deceleration will increase again. From the above discussion it is clear that the accelerometer signal of a pole crash (which requires airbag deployment) will have more swings than a frontal barrier crash which does not require airbag deployment. We kept this fact in mind in order to determine a parameter which will allow us to trigger the airbag at the appropriate time for a pole crash. The above fact led us to investigate the accelerometer signal in detail.

III. THE ACCELEROMETER SIGNAL AND ITS COMPONENTS

There is no doubt that during a crash the accelerometer signal, $s(t)$, contains vital information about the crash. It can be assumed that the signal $s(t)$ contains two components: the vehicle acceleration component and the noise component. Thus, we can write

$$s(t) = a(t) + n(t) \tag{2}$$

where $a(t)$ is the vehicle acceleration component and $n(t)$ is the noise component. The vehicle acceleration component, $a(t)$, is a negative number during a crash. The component $a(t)$ contains the important information about the crash. The noise component depends on several factors, such as: the location of the accelerometer, the vibration and deformation of the vehicle during a crash. For example, if the accelerometer is placed at the front of the vehicle, then the noise component is higher than if it is placed in the passenger component. Normally the accelerometer signal contains too much noise if it is located in a soft part of the vehicle, or in that part of the vehicle which is vulnerable to a crash. In order to design a good electronic crash sensor it is desirable to place the accelerometer at the least noisy location in the vehicle, so that the vehicle acceleration component, $a(t)$, can easily be separated from the accelerometer signal, $s(t)$.

Some authors modeled $a(t)$ by a haversine pulse which is a low frequency component (0–10 Hz) [7], [10]. Thus, they filtered the signal $s(t)$ using a low-pass filter of cutoff frequency 10 Hz to investigate several parameters such as the first derivative of $a(t)$ (Jerk) [8], the energy in $a(t)$ and the energy in the noise component $n(t)$ [10].
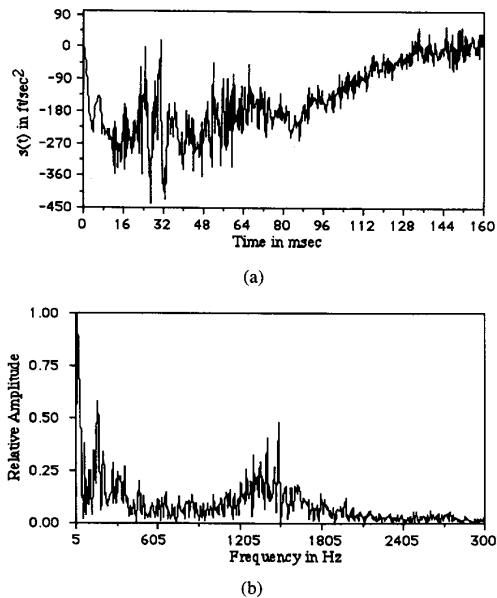
Fig. 3. (a) Accelerometer signal $s(t)$ collected from an accelerometer located at the rocker near the driver's door. (b) Frequency response of $s(t)$.
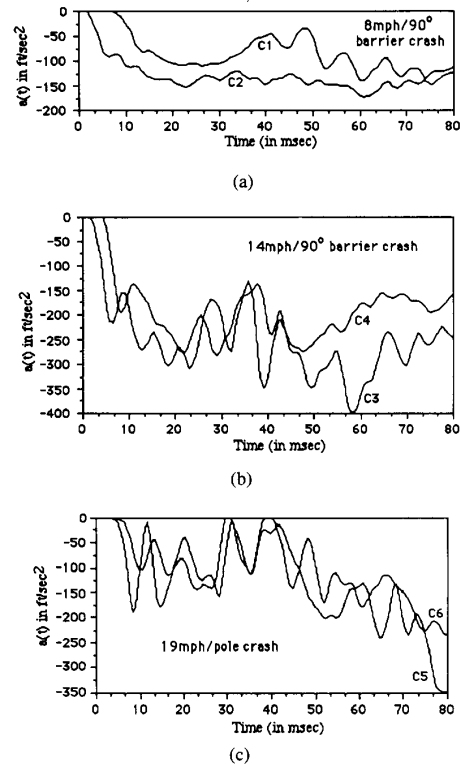

Fig. 4. The vehicle acceleration component $a(t)$ of different crashes. (a) 8 mi/h/90° barrier crashes (C1, C2), (b) 14 mi/h/90° barrier crashes (C3, C4), and (c) 19 mi/h/pole crashes (C5, C6).

We believe that filtering the signal down to 10 Hz will not only eliminate or average some of the important information in the signal $s(t)$, but also will incur a long time delay in the filtered signal which could be longer than the firing time.

It is important to study the whole slowing components which contain pulses at moderate frequency due to several distributed solid objects in the car (bumper, motor, radiator, etc.). These pulses are very important to measure the intensity of a crash. A higher speed crash causes a higher frequency and amplitude pulses than a lower speed crash.

To analyze the slowing component $a(t)$ we took several accelerometer readings for the same crash at different locations in the vehicle. We found that different accelerometer locations yield to different signals. There are three reasons for that. Firstly, the accelerometer measures the slowing of that part of the vehicle where it is located. For example, an accelerometer placed in the front of the vehicle will give higher values than an accelerometer placed in the passenger compartment or at the end of the vehicle. Because, as the front part of the vehicle breaks down by absorbing most of the vehicle energy, the other parts of the vehicle still keeps moving. Secondly, each part of the vehicle vibrates at a different frequency, and there are several locations which oscillate at low frequencies, and this oscillation component may overlap with the slowing component $a(t)$. Thirdly, the way the accelerometer is mounted in the vehicle: this means that if the accelerometer is loosely fixed in the vehicle, it will shake and vibrate at a frequency which could overlap with the slowing component $a(t)$. After analyzing a large set of crash testing data we found that the best location of an accelerometer is at the rocker near the driver's or passenger's door. Fig. 3(a) shows the signal $s(t)$ collected from an accelerometer which was located at the rocker near the driver's door, and Fig. 3(b) shows its frequency response. From the frequency response it is clear that the noise

component is widely separated from the signal component. Most of the signal components are within 0–500 Hz, and the noise is very dominant within the frequency range 900–1800 Hz. Thus, the vehicle acceleration component $a(t)$ can easily be separated from the noise component $n(t)$ using a low-pass filter of appropriate cutoff frequency. Earlier in this paper we analyzed six crashes (see Fig. 2) to determine the change in vehicle velocity during the crash. We are going to further analyze the same six crashes. Fig. 4 shows the component $a(t)$ of these six crashes, obtained by filtering them using a low-pass filter of cutoff frequency 500 Hz. As mentioned earlier, it was difficult for us to discriminate a 19 mi/h/pole crash from an 8 mi/h/90° barrier crash by monitoring only the change in vehicle velocity ΔV (see Fig. 2). But Fig. 4 shows that the $a(t)$ component of a 19 mi/h/pole crash has more swings than an 8 mi/h/90° barrier crash, as it was expected from our previous discussion in Section III. The fact that a pole crash which requires an airbag deployment has more swings in the signal $a(t)$ than a 90° barrier crash which does not require airbag deployment can be used to determine whether or not a pole crash occurred in the deployment zone.

IV. THE AIRBAG CONTROL PARAMETERS AND THE ALGORITHM

We have already mentioned that ΔV, the change in vehicle velocity, is a good parameter for frontal barrier crashes. A second parameter is introduced in this section which can
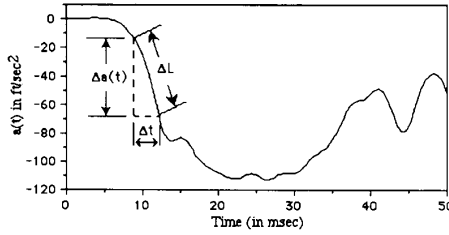
Fig. 5.   Differential length ΔL of curve $a(t)$.

Fig. 6.   The length of $a(t)$ curve for four crashes. C1, C2: 8 mi/h/90° barrier crash. C5, C6: 19 mi/h/pole crash.

be used to discriminate a deployment pole crash from a nondeployment barrier crash. An airbag control algorithm is then developed in this section based on the two parameters discussed in the paper.

The second parameter which is introduced in this section gives a quantitative measure of the swinging effect of the filtered accelerometer signal. Fig. 4 shows that for a 19 mi/h/pole crash, the amplitude of the swings of $a(t)$ is higher than that of an 8 mi/h/90° barrier crash. Thus, we wanted to determine the second parameter in such a way that it will be a monotonously increasing function of the number of swings and the total amplitude of the swings. It is obvious that the value of such a parameter will be higher for a 19 mi/h/pole crash than for an 8 mi/h/90° barrier crash. We chose the length of the $a(t)$ curve as our second parameter, because this quantity increases with the number of swings and the swing amplitudes. The differential length ΔL of the $a(t)$ curve between times t and $t + \Delta T$, as shown in Fig. 5, can be determined as

$$\Delta L = \sqrt{[\Delta a(t)]^2 + (\Delta t)^2}$$
$$= \left(\sqrt{\left(\frac{\Delta a(t)}{\Delta t} \right)^2 + 1} \right) \Delta t. \qquad (3)$$

Hence, the length of the curve $a(t)$ from time 0 to t can be determined as

$$L = \int_0^t \left(\sqrt{\left(\frac{da(t)}{dt} \right)^2 + 1} \right) dt. \qquad (4)$$

Fig. 6 shows the length of the $a(t)$ curve versus time for four crashes: two 19 mi/h/pole crashes (curves C5 and C6) and two 8 mi/h/90° barrier crashes (curves C1 and C2). From this figure it is seen that at the firing point of the 19 mi/h/pole crash there is a large gap between the curves of 19 mi/h/pole crashes and the curves of 8 mi/h/90°barrier crashes. Thus, it is very easy to discriminate 19 mi/h/pole crashes from the 8 mi/h/90° barrier crashes using our second parameter, which is the length of the acceleration curve (L).

The physical meaning of L is that it gives a quantitative measure of the swinging effect of the filtered accelerometer signal. The value of L increases with the number and amplitude of swings in the accelerometer signal. The accelerometer signal of a deployment pole crash has more high amplitude swings than a nondeployment barrier crash. This fact made the parameter L useful for developing our airbag control algorithm.
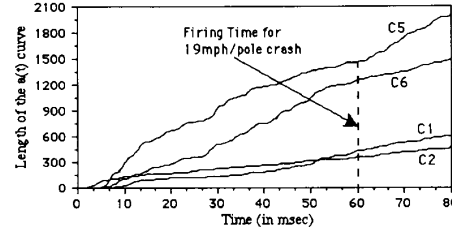
A. Development of the Airbag Control Algorithm

Now we are ready to develop an algorithm for the airbag control. Both the above mentioned parameters must be used in the algorithm. One parameter without the other will not be a good choice. Because, we have already seen that only ΔV, the change in vehicle velocity, can't be used to trigger the airbag for a pole crash. Similarly only the length of the $a(t)$ curve, L, may not be a good choice. Because, the value of L may be large when driving through a rough or bumpy road. However, the change in velocity over a period of T_1 (the firing time for the minimum speed frontal barrier crash which requires an airbag deployment) will be much less when driving through a rough or bumpy road. Hence, even though L may be large, the very small value of ΔV will indicate that it is not a crash. We need to select a threshold value of ΔV, say ΔV_1, which will discriminate a crash (deployment or nondeployment crash) from driving through a rough or bumpy road and from other types of slowing conditions of the vehicle, such as braking the vehicle. Such a threshold value can easily be determined for a particular vehicle by knowing how fast the vehicle can be braked. Assume that a vehicle moving at 60 mi/h can be completely stopped within 3 s (which is a very optimistic assumption) by applying brakes. The average change in vehicle velocity over a period of T_1 =35 ms for such a braking condition will be

$$\Delta V = \frac{60\,\text{mi/h}}{3\,\text{s}} \times \frac{1760 \times 3\,\text{ft/mi}}{1000\,\text{ms/s}} \times 35\,\text{ms}$$
$$= 3696\,\text{ft/h}$$
$$= 1.027\,\text{ft/s}$$

which is a very small number. Note that for an 8 mi/h/90° barrier crash the change in vehicle velocity over a period of 35 ms is between 2–4 ft/s. Thus, even for the nondeployment barrier crash, the change in vehicle velocity over a period of 35 ms is 2–4 times higher than that for the very optimistic braking condition, explained before. Hence, a value of ΔV_1 (threshold value of ΔV) can easily be selected for a given type of vehicle to discriminate a crash (deployment or nondeployment crash) from other types of slowing conditions of a vehicle. Thus, if the value of ΔV over a period of T_1 is less than ΔV_1, then the airbag must not be fired no matter what the value of L (the length of $a(t)$ curve) is. If ΔV (over a period of T_1) is greater than ΔV_1, then it is understood that some kind of crash has been detected. But whether or not the airbag is to be fired will depend on the results of further testing. Once a crash

has been detected, another threshold value of ΔV, say ΔV_2, is necessary to determine whether or not it is a deployment barrier crash. For the crashes shown in Fig. 2, a value of 6.5 ft/s can be used for ΔV_2 to detect a deployment frontal barrier crash. Similarly a threshold value of L, say L_{th}, is necessary to determine whether or not it is a deployment pole crash. Let T_2 be the firing time for the minimum speed deployment pole crash. The value of L must then be computed over a period of T_2. For the crashes shown in Fig. 6, a value of 1200 can be used for L (see Fig. 6) to detect a deployment pole crash.

B. Computation of ΔV and L

Since the firing time for the lowest speed barrier crash which requires an airbag deployment is T_1, the value of ΔV must be computed over a period of T_1. At any given time the value of ΔV can be computed using the accelerometer signal of the most recent T_1 time. A sliding window of length T_1 can be used for computing ΔV. At any given time, whatever part of $a(t)$ is available within the window, only that part can be used to determine ΔV. Every time a new sample comes in, the window is moved by one sample. This means that the least recent sample is moved out of the window when a new sample moves into the window. Every time the window is moved, the value of ΔV is recomputed. Similarly another sliding window of length T_2 can be used to determine the value of L.

Based on the above discussion we present the following algorithm for airbag control.

ALGORITHM

Initialization

1. Use a window, say Window 1, of length T_1. Where T_1 is the firing time of the minimum speed frontal barrier crash which requires an airbag deployment.
2. Use another window, say Window 2, of length T_2. Where T_2 is the firing time of the minimum speed pole crash which requires an airbag deployment.
3. Initialize the contents of both windows to 0.

Normal Mode

4. Get a new sample from the accelerometer and slide Window 1 and Window 2 by one sample.
5. Determine ΔV within Window 1.
6. Determine L within Window 2.
7. If $\Delta V > \Delta V_1$
   Then go to step 8 (STAND BY MODE). This means that a crash has been detected.
   Otherwise go to step 4.

Stand By Mode

8. Get a new sample from the accelerometer and slide Window 1 and Window 2.
9. Determine ΔV within Window 1.
10. Determine L within Window 2.
11. If $\Delta V < \Delta V_1$
    Then go to step 4 (return to NORMAL MODE). This means that the crash does not require an airbag deployment.
12. If $\Delta V \geq \Delta V_2$ or $L \geq L_{th}$
    Then go to step 14 (FIRE).
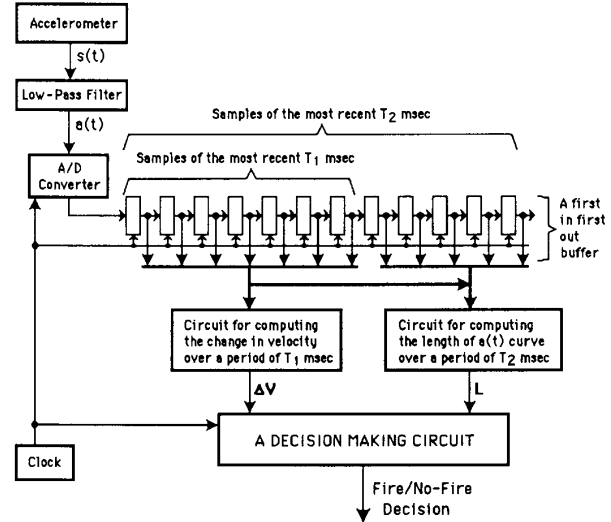13. Go to step 8 (stay in STAND BY MODE)

Fig. 7. A proposed hardware to implement the airbag control algorithm.

Fire Mode

14. **Fire the airbag.**

Fig. 7 shows a proposed hardware which can be used to control the airbag. The accelerometer signal $s(t)$ is filtered by a low-pass filter to get the vehicle acceleration component $a(t)$. The $a(t)$ component is then converted to digital output using an A/D converter.

The digital outputs are then stored into a first in first out (FIFO) buffer. The size of the FIFO buffer is equal to T_2. This means that this buffer will keep the $a(t)$ signals of the most recent T_2 time. As a new sample comes into the buffer, the least recent sample is moved out of the buffer. The $a(t)$ signals of the most recent T_1 $(T_1 < T_2)$ time are then fed into a circuit which computes the change in vehicle velocity, ΔV. Note that the change in vehicle velocity, ΔV, over a period of T_1 can be computed by integrating either $s(t)$ or $a(t)$ signal. Because, the integral over the noise component will be approximately zero. This means that

$$\Delta V = \int_0^{T_1} s(t)\,dt$$
$$= \int_0^{T_1} a(t)\,dt + \int_0^{T_1} n(t)\,dt = \int_0^{T_1} a(t)\,dt. \quad (5)$$

The $a(t)$ signals of the entire buffer are fed into another circuit which computes the length of the $a(t)$ curve. The circuits for computing ΔV and L can be designed using systolic architecture to achieve the real-time speed. The outputs of these two circuits are fed into a third circuit which will make a decision whether or not the airbag is to be fired. This decision making circuit can be implemented as a synchronous sequential machine with only three states: NORMAL, STAND-BY and FIRE. The state diagram of this sequential machine is shown in Fig. 8.
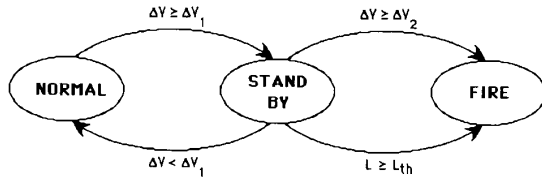
Fig. 8. State diagram of the decision making circuit.

V. Test Results and Discussions

The algorithm is tested by applying it on many crash testing data, and the results are presented in this section. The test results are very close to the requirement, and in no case the airbag failed to fire if it was required to fire. The test results are also discussed in this section. Finally some suggestions are presented which explains what changes can be made in the structure of a vehicle in order to have more accurate firing time from the algorithm.

A. Test Results

We have tested our algorithm by applying it on many sets of crash testing data from two types of vehicles. Since we didn't have sufficient crash testing data from other types of vehicles and every crash testing is very expensive, we could not apply our algorithm on any other types of vehicles. However, we believe that the findings of our research will help other researchers to develop better airbag control algorithm. From now on we will indicate one type of vehicles as Type-I vehicles, and the other type of vehicles as Type-II vehicles. The test results for the Type-I and Type-II vehicles are presented in Tables I and II, respectively. The crash testing data for each type of vehicles were divided into two groups. One group of data was used to determine the threshold values ΔV_1, ΔV_2, and L_{th}, and the other group of data was used to test the algorithm. The different threshold values for the Type-I vehicles are: $\Delta V_1 = 1.03$ ft/s, $\Delta V_2 = 6$ ft/s, and $L_{th} = 950$, and those for the Type-II vehicles are: $\Delta V_1 = 1.03$ ft/s, $\Delta V_2 = 9.5$ ft/s, and $L_{th} = 1200$.

B. Discussion of the Results

From Table I it is seen that the algorithm satisfied the required firing condition for all the crash modes presented in this table. The required firing condition was determined by monitoring the movement of the dummy during a crash. For two of the three 19 mi/h/pole crashes the algorithm fired the airbag significantly earlier than the requirement. Early firing is acceptable as long as the algorithm does not fire in the nondeployment zone of a crash. If we don't use the parameter L to determine whether or not the airbag is to be fired, then the firing doesn't occur in time for the 19 mi/h/pole crashes. For these crashes the firing is delayed by at least 20 ms.

Test results of a number of crashes of Type-II vehicles are presented in Table II. In addition to frontal barrier crashes and pole crashes, the algorithm was also tested on three other types of crashes: an angular (30°) barrier crash, a bumper override crash and a car to car frontal crash with 50% overlap on the left side. If the frontal body of a vehicle hits an object before its bumper, then that crash is called a bumper override crash.

TABLE I
COMPARISON OF THE TEST RESULTS VERSUS
THE REQUIREMENT FOR TYPE-I VEHICLES

Crash Mode	Required Firing Time in msec	Firing Time from the Algorithm in msec
8mph/90° barrier	No Fire	No Fire
8mph/90° barrier	No Fire	No Fire
19mph/pole	57	31
19mph/pole	63	49
19mph/pole	59	57
14mph/90° barrier	44	40
14mph/90° barrier	32	30
31mph/90° barrier	22	22
31mph/90° barrier	22	22

TABLE II
COMPARISON OF THE TEST RESULTS VERSUS
THE REQUIREMENT FOR TYPE-II VEHICLES

Crash Mode	Required Firing Time in msec	Firing Time from the Algorithm in msec
14mph/90° barrier	35	31
17mph/pole	56	55
31mph/pole	32	26
22mph/30° barrier on the left side of the vehicle	52	53
31mph/bumper override	47	33
31mph/car to car on the left side	60	40

For example, if a car crashes with a large truck, then it is a bumper override crash. Table II shows that the algorithm satisfied the required firing condition for almost all the crash modes of Type-II vehicles presented in this table. However, only for one crash mode the firing time of the algorithm is off by only 1 ms from the required timing. Even for the Type II vehicles if we don't use the parameter L in the algorithm then firings for the pole crashes are also delayed. The delays for the 17 mi/h and 31 mi/h pole crashes are 25 and 6 ms, respectively.

From both Tables I and II it is observed that for the 90° barrier crashes the firing time from the algorithm matches very closely to that of the requirement. However, for other types of crashes sometimes the algorithm fires significantly earlier than the requirement. Early firing is acceptable if the crash occurs in the deployment zone. But if the early firing condition is present in an algorithm, then most of the time that algorithm might trigger the airbag for gray zone crashes. As it was mentioned earlier, a deployment or a nondeployment of the airbag is equally acceptable for gray zone crashes. However, since an airbag can be used only once and the replacement of an airbag is expensive, it would be desirable to minimize the number of firings for gray zone crashes.

C. Frontal Barrier Crashes versus other Crashes

The frontal (90°) barrier crashes are very easy to detect, because during such a crash the entire bumper is pushed toward the vehicle, and as a result the crash force is uniformly

distributed over the entire bumper. When the bumper hits the body of the vehicle, the crash force is uniformly distributed over the entire frontal part of the vehicle. Thus, the vehicle decelerates very rapidly, and thereby it is relatively easier for the algorithm to detect this crash and determine whether or not the crash occurred in the deployment zone.

For other types of crashes only a part of the bumper is hit. Thus, if the bumper is not strong enough then a part of it (the part which is hit by the object) breaks down and the vehicle keeps on moving until it hits the object. Hence, for this type of crash the vehicle does not decelerate as fast as it does for a frontal barrier crash of an equivalent collision force, until the object hits a very hard part of the vehicle. This is the reason why the change in vehicle velocity during the first few tens of milliseconds for a minimum speed pole crash which requires an airbag deployment is almost similar to that of a maximum speed frontal (90°) barrier crash which does not require the deployment of the airbag. For a pole and other types of nonfrontal barrier crashes, the vehicle starts decelerating at a high rate once a hard part of its body is hit by the object. But that time is too late to trigger the airbag. This is the reason why the change in vehicle velocity during the first few tens of milliseconds can not be used for all types of crashes to determine whether or not the crash occurred in the deployment zone.

D. Suggestions for Changing the Structure of a Vehicle

From the previous discussion it is clear that the breakage of the front bumper makes it difficult (if not impossible) to determine whether or not a pole or nonfrontal barrier crash occurred in the deployment zone. The crash sensing technique can be improved if a hard bumper instead of a soft bumper is used in a vehicle, so that the bumper is not easily breakable. If a hard bumper is used in a vehicle then the shock absorber which is used between the bumper and the body of the vehicle will absorb most of the energy and will break down before the bumper breaks down. If the bumper does not break down then the collision force will be distributed over the entire bumper, and the vehicle will decelerate at a higher rate for this case than for the case where the bumper breaks down very easily. Thus, the use of a hard front bumper will let us have an early indication (from the knowledge of ΔV), whether an airbag is to be fired for a pole or other nonfrontal barrier crashes.

VI. CONCLUSIONS

A new airbag control algorithm is presented in this paper. This algorithm uses two different parameters to predict the severity of the crash. The first parameter is the change in vehicle velocity, and the second parameter is the length of the filtered accelerometer signal, $a(t)$, curve. The first parameter is used to determine whether or not a frontal-barrier crash

occurred in the deployment zone. The second parameter is used to determine whether or not the airbag is to be fired for a pole or other nonfrontal barrier crashes. We tested our algorithm by applying it on a number of crash testing data. Our algorithm fired the airbag for all the cases where the deployment of the airbag is necessary. In most of the cases our algorithm fired the airbag earlier than the requirement, except in one case where the firing occurred only 1 ms after the requirement. Since every crash testing is very expensive, we could not apply our algorithm to many types of vehicles. However, our study will help other researchers in designing their airbag control algorithm by incorporating the facts which we presented in this paper. We have also given some suggestions regarding how to design the front bumper, so that even a better algorithm can be developed for the airbag control.

REFERENCES

[1] G. S. Nusholtz and R. Molinaro, "Force deflection curves for air bag response," *Experimental Techniques*, pp. 33–35, Mar./Apr. 1991.
[2] G. S. Nusholtz, J. Wu, and P. Kaiker, "Passenger air-bag study using geometric analysis of rigid-body motion," *Experimental Mechanics*, pp. 264–270, Sept. 1991.
[3] A. Mani and P. Krishnaswamy, "Advances in crash simulation technology," *Automotive Engineering*, pp. 20–23, Feb. 1991.
[4] "How an air bag knows when to deploy," *Automotive News*, pp. E28, Sept. 26, 1988.
[5] H. Shinto, K. Ogata, F. Teraoka, and M. Fukabori, "Simulation and testing of an all-mechanical air bag system," *Automotive Engineering*, pp. 29–31, June 1991.
[6] D. Chaikin, "Airbags," *Popular Mechanics*, p. 81, June 1991.
[7] J. L. Allen, "Power-rate crash sensing for safety device actuation," SAE 920478, pp. 55–60.
[8] T. Gioutsos, "A predictive based algorithm for actuation of airbag," SAE 920479, pp. 61–66.
[9] D. S. Breed and V. Castelli, "Trends in sensing frontal impacts," SAE 890750, pp. 37–49.
[10] R. W. Diller, "Electronic sensing of automobile crash for airbag deployment," SAE 910276, pp. 65–67.
[11] D. S. Breed and V. Castelli, "Problems in design and engineering of airbag systems," SAE 880724, pp. 1–30.
[12] D. S. Breed, V. Castelli, and F. Shakoohi, "Are barrier crashes sufficient for evaluating airbag sensor performance?," SAE 900548, pp. 165–171.

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