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PREFERENCE AND PLACEMENT OF VEHICLE CRASH SENSORS

Md. Syedul Amin, Salwa Sheikh Nasir, Mamun Bin Ibne Reaz, Mohd. Alauddin Mohd. Ali, Tae-Gyu Chang

Subject review
Crash detection sensors play a vital role in vehicular safety applications. One of the major applications of these sensing systems is the use in occupant restraint systems. Besides, sensors are extensively used in the accident mitigation and advanced vehicle control system. Crash sensors have advanced significantly in the last few decades. Yet, existing demands and challenges bring new innovations and improvements in their functions. This paper reviews the sensor technologies and placement of sensors for accident detections with an emphasis on the rollover crash detection. The paper also suggests sensor selection for particular crash detection depending on the performance of the sensors. The demand for the sensors for a responsive driving environment and safe vehicle system shall remain a challenging and active area for years to come. Thus, this review shall work as a guideline for the researchers who wish to study on the crash detection and sensor selection.

Keywords: *accelerometer, angular rate sensor, crash, GPS, sensor*

Izbor i postavljanje senzora za otkrivanje sudara vozila

Pregledni članak
Senzori za detekciju sudara su od bitne važnosti u aplikacijama za sigurnost vozila. Jedna od najvažnijih primjena tih mjernih sustava je u sustavima za vezanje vozača u vozilu. Uz to, senzori se uveliko koriste za ublažavanje udesa i u razvijenom sustavu upravljanja vozilom. Senzori za otkrivanje sudara su se u zadnjih nekoliko desetljeća značajno razvili. Ipak, postojeći zahtjevi i izazovi dovode do novih inovacija i poboljšanja njihovih funkcija. U ovom se radu daje pregled senzorskih tehnologija i postavljanja senzora za otkrivanje udesa s naglaskom na otkrivanje sudara prevrtanjem vozila. Daje se i prijedlog za izbor senzora za otkrivanje pojedinog sudara ovisno o radnim karakteristikama senzora. Potražnja za odgovarajućim senzorima u sigurnom sustavu vozila ostaje izazov i aktivno područje rada u nadolazećim godinama. Zato ovaj pregled treba koristiti kao putokaz istraživačima koji se žele baviti detekcijom sudara i izborom senzora.

Ključne riječi: *mjerač ubrzanja, senzor kutne brzine, sudar, GPS, senzor*

1 Introduction

The development of a transportation system has been the generative power for us to have the highest civilization above creatures in the earth. But it can also bring disaster and kill us through accidents. Every minute, on average, at least one person dies in a vehicle crash [1]. Automobile accidents also injure at least ten million people every year globally [2]. In 2012, 34 080 people died and 2,35 million were injured or disabled in vehicle traffic crashes only in the USA. Besides, road crashes cost $230,6 billion property loss per year in the USA and $518 billion globally, costing individual countries from 1 ÷ 2 % of their annual GDP [3].

The effort on decreasing the number of accidents and their consequences in road transportation has been growing stronger and stronger in recent years [4]. Crash detection is a helpful concept in preventing accidents, collisions and minimizing human injury [5]. The National Highway Traffic Safety and Administration (NHTSA) and other road related safety authorities have called for the mandatory consideration of crash detection systems in a vehicle [6].

Vehicle safety system comprises active and passive safety system [7]. The pre-emptive measures are taken in active safety system to reduce the possibility of crashes. Reactive measures are taken to reduce severity of injuries in passive safety system and the crash is detected by crash detection system. The scope of this paper is kept to passive safety system as the active safety system focuses on reducing the possibility of crashes. For the successful deployment of a passive safety system, time is a crucial factor. The earliest the correct crash can be detected, the quickest measures can be taken for the deployment of passive safety systems [5]. Besides the safety system, the crash detection can also immediately activate the rescue services which can save a lot of human lives [8, 9].

The objective of the present paper is to provide an up-to-date overview of emerging state-of the-art automotive sensor technologies related to crash detection. Pre-crash detection system provides the early warning and also reduces the false alarm rate of the restraint system. Coverage of all details pertaining to pre-crash detection is beyond the scope of this paper. Attention is focused on the sensors used in crash detection that trigger the passive safety applications.

2 Sensors for crash detection

Sensors are defined as "devices that transform (or transduce) physical quantities such as pressure or acceleration (called measurands) into output signals (usually electrical) that serve as inputs for control systems" [10]. The requirements of automotive sensors are sprouting which demands a difficult balance between accuracy, robustness, manufacturability, interchangeability, and low cost. The development of automotive sensors started with the mechanical sensors and is presently continuing with the Micro-Electro-Mechanical Systems (MEMS) sensors. Out of all the automotive sensors, crash sensors provide key vehicle dynamic parameters that allow the sensing algorithm to estimate current and future states related to crash [11, 12]. Among them, the dominant types can be categorized into two main groups: mechanical and electronic [13]. A pen picture on conventional sensor would provide a better understanding of the present day sensors.

Traditionally, mechanical, magneto-mechanical or electro-mechanical sensors were used to detect vehicle crashes. Although the sensors are constructed differently, they are generally grouped as the mechanical type because they all rely on mechanical movements of a sensing mass inside the sensor to function as a crash sensors [13]. A collision propels the sensing mass forward proportional to the intensity of the impact as illustrated in Fig. 1 [13]. Since the sensing mass in a mechanical sensor needs to move a certain distance before the sensor is triggered, the sensor often serves somehow as an integrator of the crash pulse and is partially immune against a false signal like acceleration spike. These crash sensors were commonly seen in a majority of passenger vehicles produced in the late 1980s and early 1990s.

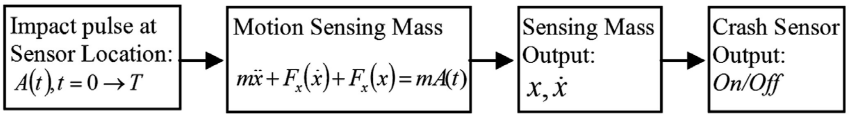

Figure 1 Schematic diagram of mechanical crash sensors [13]

Electronic sensors consist of a transducer to generate a crash signal, a circuitry to process the generated signal and a means to send out a triggering signal. They take advantage of the versatility of signal-processing techniques and the flexibility in integrating electronic units [13]. Although the transducer signal is not theoretically restricted to acceleration pulses only, the use of accelerometer dominates in vehicular applications [14]. A flow chart of the functioning principles of an electronic sensor is shown in Fig. 2 [13].

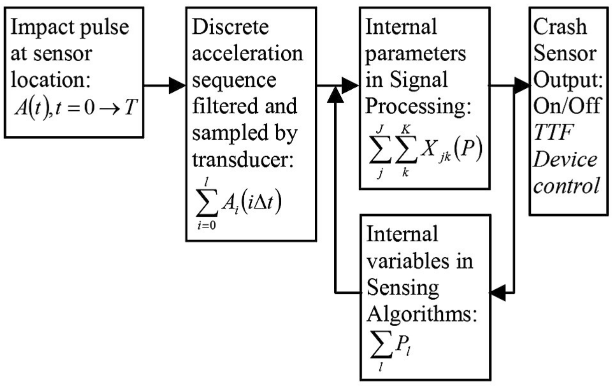

Figure 2 Schematic diagram of electronic crash sensor [13]

MEMS sensors are widely used in present days. MEMS started its journey in automotive sector in 1981. MEMS replaced the traditional limited-function sensors with their high-performance and low cost. The economy of batch processing, together with miniaturization and integration of on-chip electronic intelligence of MEMS have contributed to the improved performance, reliability and lower-cost sensors [15, 16]. Various types of MEMS sensors are used for crash detection. The widely used crash sensors are the accelerometers and angular rate sensors [17]. The other important crash sensors are pressure sensor, shock sensor, tilt sensor, wheel speed sensor, etc. Besides, various other sensors like Global Positioning System (GPS), laser scanner, acoustic sensor, radar, etc. are used to augment the performance of the main crash detection sensors. However, focus is given on the main sensors as discussed below.

2.1 Acceleration sensors

Accelerometers are the stars of the MEMS and are widely used in vehicle frontal, side, and rollover crash sensing [17, 18]. An accelerometer generally consists of a proof mass suspended by compliant beams anchored to a fixed frame. It senses the sudden changes in acceleration using the physical mechanisms underlying MEMS based on piezoresistive, ferroelectric, capacitive, piezoelectric, electromagnetic, tunnelling or optical technology [19].

Piezoresistive sensor incorporates suspended piezoresistor beams to detect the acceleration-induced movement [20, 21]. Their temperature tolerance, frequency range, readout circuitry and low packaged weight made them popular in high shock applications [19].

Capacitive sensor incorporates micromachined electrodes to sense and detect the acceleration related movement of a micro-beam proof mass [20]. High sensitivity, good DC response and noise performance, low drift, low temperature sensitivity, low-power dissipation, and a simple structure made them very attractive for numerous automotive related applications [22]. Due to the high impedance of sense node, capacitive accelerometers can be susceptible to Electromagnetic Interference (EMI) [23].

Tunnelling device accelerometers have wide bandwidth and high sensitivity but suffer from larger low-frequency noise levels. The drift of the tunnelling barrier usually does not have a large impact on the performance of the sensor since these sensors are operated in a closed-loop mode with small operating current level [24, 25].

Resonant-beam MEMS sensor utilizes the principle of vibrating member that shifts its resonant frequency that is proportional to the force exerted on the member [20]. The main advantage of resonant sensors is their direct output and small bandwidth.

Many researchers have fabricated arrays of accelerometer switches for use as a threshold. The main advantages of these devices are the simple low-power interface circuitry and the digital output [26].

2.2 Angular Rate Sensor (ARS)

A critical and widely used sensor for rollover crash detection system is the ARS or gyroscope. Besides rollover crash detection, they can also provide heading information for inertial navigation purpose [27]. They directly measure the changing rate of angular positions based on the Coriolis effect acting on various types of vibrating mechanisms [17, 28]. Initially, mechanical yaw rate sensors were used based on a piezoelectrically actuated and sensed vibrating steel cylinder as the sensing element [29, 30]. Present day ARS utilize the benefit of MEMS technologies [30 ÷ 32].

Piezoelectric crystal vibrating structures, variations of micromachined structures and ceramic/metallic-alloy vibrating structures are the most popular technologies for automotive ARS [33 ÷ 40]. The ceramic type sensor has been extensively used in rollover applications. However, a mechanical shock and vibration isolation structure are usually needed to improve gravity (g) immunity of the sensor [35]. Accuracy and stability of the quartz-tuning-fork-type sensors together with immunity to linear accelerations made them popular in vehicle dynamic control and crash sensing. The oscillating-rotor sensors are also widely used in rollover crash detection with features of low cost and small size [38].

In some sensors, at times, ARS and accelerometer are combined together in MEMS technology [11]. Although packed in one package, they provide dual independent measurements of lateral vehicle acceleration and yaw angular rate for use in chassis systems for input to vehicle stability systems and body systems in rollover crash sensing [38]. This sensor is widely used in European vehicles.

2.3 Pressure sensor

Since 1996, pressure sensors have been widely used to detect side crashes. They provide a signal that is robust against interferences and proportional to the severity of the crash which helps to inflate the airbag accordingly [40]. The crash detection is based on measuring the increased pressure inside the door cavity due to the deformation of the door during an impact. The change of pressure for a short period of time can be calculated using the adiabatic Eq. (1) [40].

$$\Delta V = V_0 \frac{1}{k} . \frac{\Delta P}{P_0} = \text{const.} \frac{\Delta P}{\Delta P_0}, \tag{1}$$

where the change in the volume of the cavity is represented by ΔV, increase in pressure by ΔP and ambient pressure by P_0. Thus, the signal $\Delta P/P_0$ is proportional to the change in volume and directly correlates to the crash intensity.

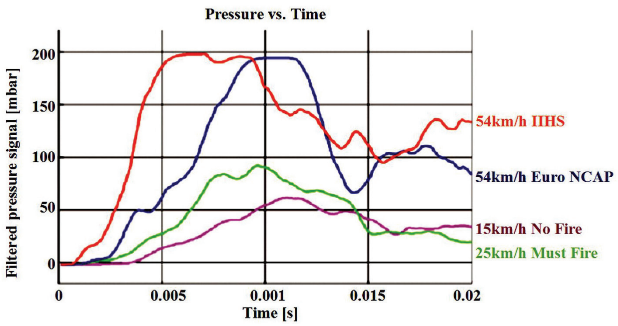

Figure 3 Side crash pressure signal waveforms with various intensities [40]

A sample signal waveforms for different side crash conditions are shown in Fig. 3 from where it is evident that a pressure sensor can distinguish between deployment-relevant crashes and non-deployment related crashes within only a few ms [40].

In a high side impact, the doors are typically deformed quickly. With a delay in transferring the accelerations to the rest of the body, delays the signal from the accelerometer. Moreover, pressure sensor provides a normalized differential pressure signal independent of ambient pressure and temperature [40]. As such, crash algorithms do not need to reflect ambient conditions.

2.4 Miscellaneous crash detection sensors

GPS, wheel speed and piezoelectric shock sensors are also used in combination with the accelerometer, ARS and pressure sensors to augment the performance and reliability of the crash detection system. Various researchers utilized the GPS to detect crash. Both side slip and absolute velocity are necessary in determining the vehicle's behaviour in crash situations [41]. GPS with a frequency range of 1 Hz to 100 Hz in combination with the inertial sensors is utilized to correctly estimate the sideslip and roll angle [41 ÷ 46]. Although they provide accurate estimation, they are generally expensive to deploy in most production vehicles. Various researchers utilized the vehicle wheel speed sensors to augment the crash detection. Combining with the acceleration sensor, it provides more reliable crash detection and thereby reduces false alarm rate [17, 47].

3 Types of crashes

Knowledge on different types of vehicle crash is required for selecting the correct sensor. Vehicle crash can be categorized mainly in four types: front, side, rear and rollover crash [48]. Out of these crashes, rollovers are the most frequent and fatal crashes with respect to serious head and neck injuries [49 ÷ 51]. Fig. 4 shows the statistics of various types of crashes. Each crash type has its own unique set of sensing requirements and restraint countermeasure deployment strategy as discussed below [52].

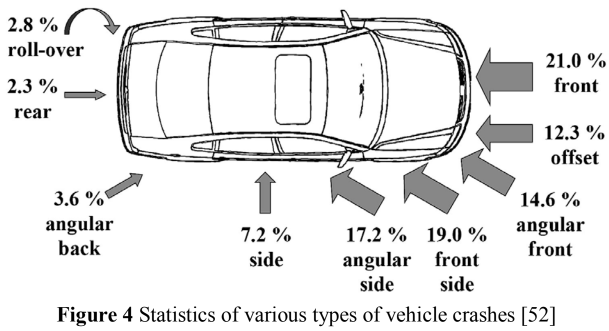

Figure 4 Statistics of various types of vehicle crashes [52]

Frontal or head-on crash occurs when two vehicles strike each other at the front. It is the most common crash where the airbag is deployed as passive restraint system [53]. Most modern vehicles use micromachined, accelerometer-based sensors for front crash [48, 54]. A combination of electrical accelerometer and mechanical acceleration switch is also utilized to detect front crash [55]. Piezoelectric shock sensors can also provide significant front crash data [56].

A rear-impact crash occurs when one vehicle strikes another vehicle from behind. The restraint system for rear crash is limited with the seat belt pretension system. Rear detection system normally uses accelerometer sensors [48].

Side-impact crashes are considered to be very serious crashes since there is less protection [57]. This crash occurs when one vehicle strikes the side of another vehicle. For most conventional vehicle structures, acceleration-based sensors are used to sense and discriminate side crash [48]. In recent days, the focus is shifted to the pressure based detection system by combining pressure sensors with acceleration sensors which can fire the safety system in time [40, 58].

In roll-over crash, a vehicle rotates laterally or longitudinally at least 90 degrees with complex vehicle motion which can include trip, climb-over, fall-over and other events [35]. During the past decades, there has been a steady increase in studies addressing rollover crashes [59]. Information about roll angle of the vehicle body is important in predicting and sensing rollovers. As such ARS is a vital sensor for rollover sensing [60, 61]. As many rollover events may be initiated by side impacts, immunity to linear accelerations is very important for a rollover sensing system.

Several sensors for detecting vehicle rollover were tested by various researchers [62, 63]. Lateral acceleration data can be used to accurately estimate low roll angles on smooth roads but is less accurate at measuring relatively large angles on uneven terrain. However, a sensor set of lateral acceleration and roll rate sensor is a good combination. Accelerometers are relatively inexpensive in comparison to other roll measuring sensors but suffer from inaccuracy [64]. Rate sensors are also relatively inexpensive depending on the levels of accuracy. However, they are intrinsically prone to unacceptable errors when exposed to linear accelerations. Considering these facts, MEMS ARS based on Coriolis effects have higher immunity to linear accelerations. Lateral velocity, side slip angle and tire slip angle are also required to determine the vehicle rollover events. These measurements are often determined through the use of multiple sensors working together [65, 66].

4 Sensor selection criteria

The basic requirements of crash sensors or sensing systems are to sense crash severity and to trigger timely deployment of restraint devices. When a crash sensor is selected for a vehicle platform, the corresponding sensitivities are chosen so that the sensor can satisfy the performance requirements in various crashes [13].

4.1 ARS

Sensing range, offset errors, scale factor, errors bandwidth, noise, *g*-sensitivity, self-diagnosis are the key parameters that need to be determined and evaluated [67] for ARS. The criteria are discussed below. The same criteria are applicable for other crash sensors.

Higher sensing range reduces resolution in a given dynamic range. As the rollover sensing system reaches the decision before the peak roll rate, a sensing range ±200 to 300 degrees/second is sufficient.

A nominal offset is the design target. Offset error, specially the dynamic offset errors, limits the measurement accuracy and causes the sensor to saturate asymmetrically which limits the sensing range.

Combined with ARS output dynamic range and offset errors, scale factor or sensitivity may cause the ARS to saturate asymmetrically. Thus, a larger nominal scale factor is desirable for higher sensing accuracy.

When the ARS input frequency rises more than the bandwidth limit, the signal rate attenuates. Moreover, sensor noise levels also increase with larger bandwidth and reduce the sensor accuracy and resolution. Root mean square (RMS) noises are critical for rollover applications due to the utilization in digital and analogue filters.

ARS needs to be immune to linear accelerations as it may produce false angular rate for its *g*-sensitivity. It needs to be considered with broad amplitude and spectrum waveforms in all the orthogonal directions. Self-diagnosis is also important as sensor failure can result in a system anomaly [17].

4.2 Accelerometers

Frequency response, maximum operation range, sensitivity, resolution, offset, full-scale nonlinearity, shock survival and off-axis sensitivity are the criteria of accelerometer selection [20, 25]. The specifications of accelerometer for crash sensing are given in Tab. 1. While considering all the criteria may increase the reliability of the measurement, they may also negatively impact the cost of the system.

Table 1 Typical specifications of accelerometer for crash sensing

Parameter	Value
Range	±50*g*
Frequency Range	DC-400 Hz
Resolution	<0,1*g*
Off-axis Sensitivity	<5 %
Nonlinearity	<2 %
Max. shock 1ms	>2000*g*
Temperature Range	−40 °C to 85 °C
Bandwidth	1 kHz

5 Placements of sensors

The detection of a crash depends primarily on the type of crash pulses. The location of sensor installation affects the crash pulses [13]. The traditional strategy of multiple sensors placement has moved towards the concept of single-point sensing to reduce the costs of wiring [13, 48, 68]. Today's crash sensors need to be integrated with various sensing technologies into a complete and integrated system [13]. Modern vehicles generally include five acceleration crash sensors placed at right-front and left-front, at right-side and left-side, central sensor mounted in the passenger compartment. As three-row-seat vans and Sport Utility Vehicles (SUV) have longer lateral-coverage, these vehicles require two additional side satellite crash sensors, mounted in their rear-quarter panels [17]. The placement of sensors in terms of crash type is discussed in subsequent paragraphs.

Crash sensors mounted in the central passenger compartment are normally used to sense and discern frontal impacts [48, 54]. Typically, the passenger compartment location provides timely discrimination of frontal impact events. Sometimes, an auxiliary sensor in the front crush zone is used to improve sensing performance for these vehicles [48]. Fig. 5 shows the importance of locating a satellite sensor in the crush zone of the vehicle. Using single point sensors, with the option of adding the auxiliary front sensor, is the most effective method for triggering passive safety system.

Rear impact sensors are normally located in the central passenger compartment, often utilizing the frontal sensing element while processing opposite polarity signal [48].

Pressure sensor provides the independence of the sensor signal from the exact mounting point of the sensor inside of the door [40, 48]. Fig. 6 shows the simultaneously recorded pressure waveform for three different mounting locations inside the door, which illustrates the independence of mounting location. To augment the system performance, additional satellite accelerometers are also placed in the door frames [69].

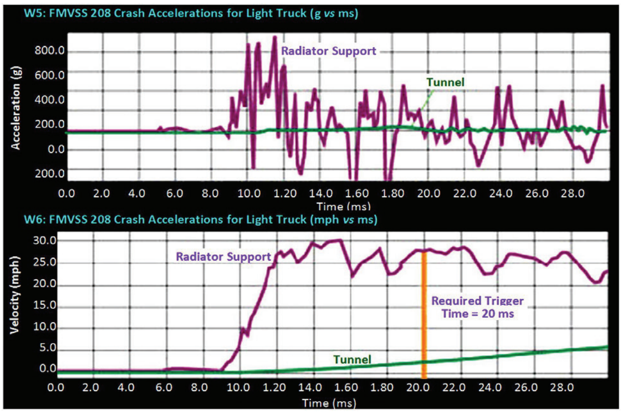

Figure 5 Acceleration and velocity crash data or a light truck in a 30 mph frontal impact barrier test [48]

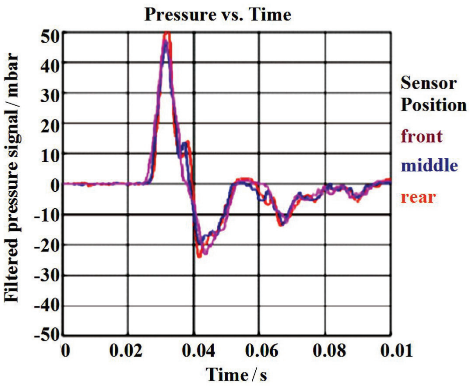

Figure 6 Side impact pressure signal waveforms with various intensities [40]

Rollover sensors can be either stand-alone modules or integrated into the single point sensor. If used as a stand-alone module, the rollover sensor typically uses a discrete signal or serial data interface to output the imminent rollover decision to the single point sensor which, in turn, controls and diagnoses the restraint countermeasures [48].

6 Discussions

Crash detection plays a key role in vehicular safety applications. Front, rear, side and rollover are the main vehicle crashes where the highest fatality occurs in rollover crashes. Sensors are the most essential parts in a crash detection system. With continued progression of research in sensing system, the conventional mechanical sensors are overridden by MEMS based sensors which are robust, reliable, compact and accurate. The major sensors for crash detection are accelerometer, ARS, pressure and tilt sensors. Besides, GPS and shock sensor are utilized to augment the sensing reliability. The variation of the crash dynamics demands different types of sensors as shown in Tab. 2 with their placement locations.

The crash pulses provided by the sensors are affected by the sensor locations. Although the concept of single point sensing system replaced the traditional strategy of multiple sensor placement, in recent years researchers have found that multiple sensors placed in different vehicle location act better within an integrated system [13, 48, 68, 70]. Sensors placed at the central compartment in combination with satellite sensors placed at the front location is the most effective method for both front and rear crash sensing [17, 48, 54]. Pressure sensors placed inside the door cavity with additional satellite accelerometer sensors work best for side crash sensing [42, 48]. For rollover crash detection, sensors can work either standalone or can be integrated into the single point sensors [40]. As such, sensors placed in various places in an integrated system would work more effectively for all kind of crashes.

Table 2 Crash types and various sensor placements

Crash Type	Sensor	Placement
Front	Accelerometer, shock sensor	Central compartment and satellite sensor in front
Rear	Accelerometer	Central compartment
Side	Accelerometer, pressure sensor	Central compartment and door cavity
Rollover	Accelerometer, Angular rate sensor, tilt sensor, GPS	Central compartment and satellite sensor in front

Table 3 MEMS based accelerometer sensor's advantages and disadvantages

Mechanism	Advantages	Disadvantages	Suitability
Capacitive	High sensitivity, good DC response, better noise performance, low temperature sensitivity,	susceptible to EMI due to high impedance	Less suitable
Piezoresistive	Upper frequency range, high temperature range, low output impedance	-	Most suitable
Tunneling	Highly sensitive to displacement, larger low-frequency noise levels, low operating current level, less drift	-	Suitable
Resonant-beam	Low cost	Small band-width	Not suitable
Digital	Low power interface	Expensive	Suitable

The MEMS based crash sensors dominate in recent days. They have diverse physical mechanisms for sensing with various advantages and disadvantages for different crashes. Tab. 3 summarizes the various MEMS acceleration sensors. It is evident that piezoresistive and tunnelling device accelerometers are preferred for crash detection due to their upper frequency range, high temperature range and low output impedance voltage for readout circuitry whereas resonant accelerometers are unsuitable due to small bandwidths [19]. Silicon capacitive accelerometers are less suitable than piezoresistive accelerometers as they are susceptible to EMI due to high impedance [23]. Digital accelerometers are suitable due to their low power interface circuitry with higher cost [26, 71]. The specifications mentioned in Tab. 1 need to be considered for sensor selection.

The ARS is the main sensor for rollover crash detection which directly measures the changing rate of angular positions based on the Coriolis effect [33 ÷ 37]. From Tab. 4 it is evident that quartz-tuning-fork and oscillating-rotor ARS are the most suitable for rollover sensing whereas ceramic sensor is suitable with modification and combined angular-rate/acceleration sensor is suitable at the cost of high expense [33 ÷ 37, 39]. Besides the underlying physical mechanism, sensing range, offset errors, scale factor, errors bandwidth, noise, *g*-sensitivity, self-diagnosis etc. are the key parameters that need to be considered for sensor selection.

Table 4 Advantages and disadvantages of MEMS based ARS

Mechanism	Advantages	Disadvantages	Suitability
Ceramic	Vibration isolation structure	Mechanical shock and vibration isolation required for *g* immunity	Suitable with modification for rollover
Quartz-tuning-fork	Accurate and stable, higher resonant frequency, immune to linear acceleration	-	Suitable for rollover and vehicle dynamics sensing
Oscillating-rotor	low cost, small size	-	Widely used for rollover detection
Combined ARS/Accelerometer	Single package dual output	Higher cost	Widely used in European vehicle

Pressure sensors are the most suitable for side crash sensing with the criteria given below [40]. The performance can be further augmented by combining pressure sensors with acceleration sensors.

- Quick response compared to accelerometer sensor.
- Independence of sensor placement along the door.
- Better recognition of side impacts than with purely using accelerometers.
- A direct link to the risk of injury and the crash intensity with the physical measurement principle.

With sufficient filtering and averaging over time, inclinometer or tilt sensors can provide useful roll angle data to augment rollover crash sensing [28]. Sensor scale factors (sensitivity), noises and offsets (output with 0*g* input) over temperature are the key technical parameters for selection of these sensors [28]. Besides the tilt sensors, GPS can also provide estimation of sideslip for rollover sensing [41 ÷ 46]. Wheel speed sensor and piezoelectric shock sensor can further improve the crash sensing [17, 47].

7 Conclusions

Vehicular safety systems have been an active research topic. In particular, occupant restraint systems are mandated by the government and continuously pursued by industry. A crash sensing system is the most critical part of a restraint system that monitors and controls the use of restraint systems. The application of crash sensing demands a combination of expertise from various disciplines, especially with the evolving trend of utilizing electronics in sensing devices. Through the discussions of various crash sensors, the characteristics of various sensors are analysed and the potential complications of sensor selection and placement requirements are presented. Finally, suggestions are made on the selection and placement of sensors for various types of accidents. With more advanced technologies, the safety concerns intensified instead of diminishing. The demand for a safe driving environment and safe vehicles will further promote the requirements of vehicular crash sensors. As such, crash sensing shall remain a challenging and interesting area for years to come.

8 References

[1] Jones, W. D. Keeping Cars from Crashing. // IEEE Spectrum. 38, 9(2001), pp. 40-45.
[2] Sun, Z.; Bebis, G.; Miller, R. Monocular Precrash Vehicle Detection: Features and Classifiers. // IEEE Transactions on Image Processing. 15, 7(2006), pp. 2019-2034.
[3] Annual Global Road Crash Statistics. URL: http://www.asirt.org/KnowBeforeYouGo/RoadSafetyFacts/RoadCrashStatistics/tabid/213/Default.aspx (08.10.2013).
[4] Zimmerman, E.; Muntean, V.; Melz, T.; Seipel, B.; Koch, T. Novel Pre-Crash-Actuator-System Based on SMA for Enhancing Side Impact Safety Advanced Microsystems for Automotive Applications. Berlin Heidelberg: Springer, 2009.
[5] Hannan, M. A.; Hussain, A.; Samad, S. A. System Interface for an Integrated Intelligent Safety System (ISS) for Vehicle Applications. // Sensors, 10, 2(2010), pp. 1141-1153.
[6] NHTSA. Federal Motor Vehicle Safety Standards; Side Impact Protection. URL: https://www.federalregister.gov/articles/2012/11/28/2012-28810/federal-motor-vehicle-safety-standards-side-impact-protection. (25.08.2013).
[7] Rieger, G.; Scheef, J.; Becker, H.; Stanzel, M.; Zobel, R. Active Safety Systems Change Accident Environment of Vehicles Significantly-a Challenge for Vehicle Design. // Proceeding of 19th ESV Conference / Washington D.C., 2005, pp. 1-11. Paper No: 05-0053.
[8] Drawil, N. M.; Basir, O. Inter vehicle-Communication-Assisted Localization. // IEEE Transactions on Intelligent Transportation Systems. 11, 3(2010), pp. 678-691.
[9] Amin, M. S.; Reaz, M. B. I.; Jalil, J. Accident Detection and Reporting System Using GPS, GPRS and GSM Technology. // Proceedings of International Conference on Informatics, Electronics & Vision / Dhaka, Bangladesh, 2012, pp. 640-643.
[10] Norton, H. N. Handbook of Transducers. Prentice Hall, 1989.
[11] Fleming, W. J. Overview of Automotive Sensors. // Sensors Journal IEEE. 1, 4(2001), pp. 296-308.
[12] Schiffmann, J. K.; Wallner, E. J.; Gidwani, S. B. Vehicle Rollover Sensing, Google Patents, 1999.

[13] Chan, C. Y. On the Detection of Vehicular Crashes-System Characteristics and Architecture. // IEEE Transactions on Vehicular Technology. 51, 1(2002), pp. 180-193.
[14] Sherman, S. J.; Brokaw, A. P.; Tsang, R. W. K.; Core, T. Monolithic Accelerometer, Google Patents, 1994.
[15] Maluf, N.; Williams, K. Introduction to Micro-electromechanical Systems Engineering. Artech House Publishers, 2004.
[16] Meyer, G. Advanced Microsystems for Automotive Applications. Berlin Heidelberg: Springer, 2012.
[17] Fleming, W. J. New Automotive Sensors—a Review. // Sensors Journal IEEE. 8, 11(2008), pp. 1900-1921.
[18] Johnson, J. D.; Zarabadi, S. R.; Christenson, J. C.; Noll, T. A. Single Crystal Silicon Low-G Acceleration Sensor. SAE Technical Paper, 2002.
[19] Vijila, G.; Vijayakumar, S.; Alagappan, M.; Anju, G. Design and Analysis of 3D Capacitive Accelerometer for Automotive Applications. // The COMSOL Conference 2011 / Bangalore, India, 2011, pp. 1-6.
[20] Yazdi, N.; Ayazi, F.; Najafi, K. Micromachined Inertial Sensors. // Proceedings of the IEEE. 86, 8(1998), pp. 1640-1659.
[21] Dong, P.; Li, X.; Wang, Y.; Feng, S.; Li, S. An Axial-Beam Piezoresistive Accelerometer for High-Performance Crash Detection of Automotive Industry. // 5th IEEE Conference on Sensors /Daegu, South Korea, 2006, pp. 1481-1484.
[22] Sherman, S. J.; Tsang, W. K.; Core, T. A.; Payne, R. S.; Quinn, D. E.; Chau, K. H. L.; Farash, J. A.; Baum, S. K. A Low Cost Monolithic Accelerometer; Product/Technology Update. // International Electron Devices Meeting Technical Digest / San Francisco, USA 1992, pp. 501-504.
[23] Zhao, W.; Xu, L. Design of a Capacitive SoiMicromachined Accelerometer. // Sensor & Transducers. 103, 4(2009), pp. 52-64.
[24] Yeh, C.; Najafi, K. A Low-Voltage Tunneling-Based Silicon Microaccelerometer. // IEEE Transactions on Electron Devices. 44, 11(1997), pp. 1875-1882.
[25] Ibrahim, H. LQR Optimial Control for Micromachined Tunneling Accelerometer. // Proceedings of the 9th WSEAS international conference on Signal processing, robotics and automation / Cambridge, UK, 2010, pp. 20-22.
[26] Selvakumar, A.; Yazdi, N.; Najafi, K. Low Power, Wide Range Threshold Acceleration Sensing System. // 9th Annual International Workshop on MEMS / San Diego, USA, 1996, pp. 186-191.
[27] Söderkvist, J. Micromachined Gyroscopes. // Sensors and Actuators A: Physical. 43, 1(1994), pp. 65-71.
[28] Schubert, P. J.; Nichols, D.; Wallner, E. J.; Kong, H.; Schiffmann, J. K. Electronics and Algorithms for Rollover Sensing. // Progress in Technology. 101(2004), pp. 145-159.
[29] Reppich, A.; Willig, R. Yaw Rate Sensor for Vehicle Dynamics Control System. SAE, 1995.
[30] Lutz, M.; Golderer, W.; Gerstenmeier, J.; Marek, J.; Maihofer, B.; Mahler, S.; Munzel, H.; Bischof, U. A Precision Yaw Rate Sensor in Silicon Micromachining. // International Conference on Transducers / Chicago, USA 1997, pp. 847-850.
[31] Thomae, A.; Schellin, R.; Lang, M.; Bauer, W.; Mohaupt J.; Bischopink, G.; Tanten, L.; Baumann, H.; Emmerich, H.; Pintér, S.; Marek, J.; Funk, K.; Lorenz, G.; Neul, R. A Low Cost Angular Rate Sensor in Si-Surface Micromachining Technology for Automotive Application. SAE Technical Paper, 1999.
[32] Neul, R.; Gomez, U.; Kehr, K.; Bauer, W.; Classen, J.; Doring, C.; Esch, E.; Gotz, S.; Hauer, J.; Kuhlmann, B.; Lang, C.; Veith, M.; Willig, R. Micromachined Gyros for Automotive Applications. // Sensors 2005 IEEE / California, USA, 2005, pp. 527-530.
[33] Yukawa, J.; Nozoe, T.; Ohgoshi, H.; Murakami, M. Angular Rate Sensor for Dynamic Chassis Control. // SAE Technical Paper, 1998.
[34] Ichinose, T.; Terada, J. Angular Rate Sensor for Automotive Application. // SAE Technical Paper, 1995.
[35] Kong, H.; Wallner, E. Automotive Rollover Angular Rate Sensors and Evaluation. // SAE transactions, 108, 6; PART 1(1999), pp. 686-693.
[36] Gomez, U. M.; Kuhlmann, B.; Classen, J.; Bauer, W. New Surface Micromachined Angular Rate Sensor for Vehicle Stabilizing Systems in Automotive Applications. // The 13th International Conference on Solid-State Sensors, Actuators and Microsystems / USA, 2005, pp. 184-187.
[37] Schubert, R.; Richter, E.; Mattern, N.; Lindner, P.; Wanielik, G., Advanced Microsystems for Automotive Applications. Springer, 2010.
[38] Neul, R.; Gomez, U.; Kehr, K.; Bauer, W.; Classen, J.; Doring, C.; Esch, E.; Gotz, S.; Hauer, J.; Kuhlmann, B.; Lang, C.; Veith, M.; Willig, R. Micromachined Angular Rate Sensors for Automotive Applications. // Sensors Journal IEEE. 7, 2(2007), pp. 302-309.
[39] Funk, K.; Laermer, F.; Elsner, B.; Frey, W. Acceleration Sensing Device. Google Patents, 1999.
[40] Adam, B.; Brandt, T.; Henn, R.; Reiss, S. A New Micromechanical Pressure Sensor for Automotive Airbag Applications. // Advanced Microsystems for Automotive Applications / Springer, 2008. pp. 259-284.
[41] Bevly, D. M.; Sheridan, R.; Gerdes, J. C. Integrating INS Sensors with GPS Velocity Measurements for Continuous Estimation of Vehicle Sideslip and Tire Cornering Stiffness. // Proceedings of the 2001 American Control Conference / Virginia, USA, 2001, pp. 25-30.
[42] Ryu, J.; Rossetter, E. J.; Gerdes, J. C. Vehicle Sideslip and Roll Parameter Estimation Using GPS. // 6th International Symposium of Advanced Vehicle Control / Hiroshima, Japan, 2002, pp. 373–380.
[43] Ryu, J.; Gerdes, J. C. Integrating Inertial Sensors with GPS for Vehicle Dynamics Control. // Journal of Dynamic Systems, Measurementand Control. 126, 2(2004), pp. 243 - 254.
[44] Leung, K. T.; Whidborne, J. F.; Purdy, D.; Barber, P. Road Vehicle State Estimation Using Low-Cost GPS/INS. // Mechanical Systems and Signal Processing. 25, 6(2011), pp. 1988-2004.
[45] Anderson, R.; Bevly, D. M. Estimation of Tire Cornering Stiffness Using GPS to Improve Model Based Estimation of Vehicle States. // IEEE Intelligent Vehicles Symposium, / Las Vegas, USA, 2005, pp. 801-806.
[46] Rock, K. L.; Beiker, S. A.; Laws, S.; Gerdes, J. C. Validating GPS Based Measurements for Vehicle Control. // International Mechanical Engineering Congress and Exposition / ASME International Mechanical Engineering Congress and Exposition IMECE /Florida, USA, 2005, pp. 583–592.
[47] Gerstenmaier, J.; Leiber, H. Safety Equipment for a Motor Vehicle. Google Patents, 1994.
[48] Kosiak, W. K.; Rohr, S. Future Trends in Restraint Systems Electronics, SAE Brazil, 1999.
[49] Bedewi, P. G.; Godrick, D. A.; Digges, K. H.; Bahouth, G. T. An Investigation of Occupant Injury in Rollover: Analysis of Injury Severity and Source by Rollover Attributes.//Progress in Technology, 101(2004), pp. 437-451.
[50] Hernandez, W. Improving the Response of a Rollover Sensor Placed in a Car under Performance Tests by Using aRls Lattice Algorithm. // Sensors. 5, 12(2005), pp. 613-632.
[51] Digges, K. H. Summary Report of Rollover Crashes. // FHWA/NHTSA National Crash Analysis Center, The

George Washington University/National Crash Analysis Center, 2002, pp. 1-32.

[52] Furstenberg, K.; Baraud, P.; Caporaletti, G.; Citelli, S. et al., Development of a Pre-Crash Sensorial System-the Chameleon Project. // VDI Berichte. 1653(2001), pp. 289-310.

[53] Ching-Yao, C. Trends in Crash Detection and Occupant Restraint Technology. // Proceedings of the IEEE, 95, 2(2007), pp. 388-396.

[54] Chou, C. C.; Le, J.; Chen, P.; Bauch, D. Development of CAE Simulated Crash Pulses for Airbag Sensor Algorithm/Calibration in Frontal Impacts. // 17th International Technical Conference on the Enhanced safety of Vehicles / Amsterdam, Netherlands, 2001, pp. 1-12. Paper No. 301.

[55] Matsunaga, T.; Esashi, M. Acceleration Switch with Extended Holding Time Using Squeeze Film Effect for Side Airbag Systems. // Sensors and Actuators A: Physical. 100, 1(2002), pp. 10-17.

[56] Kithil, P.; Novak, J. Crash Sensing Using Piezoelectric Sensors on Vehicle Windshields // Proceedings of the 6th International Symposium on Sophisticated Car Occupant Safety Systems. / Karlsruhe, Germany, 2002, pp. 371-376.

[57] Tandler, J.; Preis, C.; Willersinn, D.; Grinberg, M. Side Pre-Crash Sensing System Specification. // IEEE Intelligent Vehicles Symposium / Tokyo, Japan, 2006, pp. 377-382.

[58] Winkler, G.; Stierle, T.; Malbouef, T. Combining Acceleration and Dynamic-Pressure Sensing for Side-Impact Restraint Activation. // Proceedings of the 6th International Symposium and Exhibition on Sophisticated Car Occupant Safety Systems / Germany, 2002, pp. 14.1-14.10.

[59] Parenteau, C.; Thomas, P.; Lenard, J. US and UK Field Rollover Characteristics. // Progress in Technology, 101(2004), pp. 34-40.

[60] Hac, A.; Nichols, D.; Sygnarowicz, D. Estimation of Vehicle Roll Angle and Side Slip for Crash Sensing. // SAE Technical Paper, 2010, pp. 01-05.

[61] Berg, A.; Rücker, P.; Kröninger, M. A Realistic Crash Test Setup to Assess the Real World Performance of Advanced Rollover Sensing Systems. // The 20th International Technical Conference on Enhanced Safety of Vehicle / Lyon, France, 2007, pp. 1-9. Paper No. 07-0362.

[62] Hac, A.; Brown, T. D.; Martens, J. Detection of Vehicle Rollover. SAE Technical Paper, 2004.

[63] Schneider, S. P. Cost Effective Rollover Mitigation Strategy. Virginia Polytechnic Institute and State University, 2010.

[64] Schubert, P. J.; Cluff, C. A. Adaptive Rollover Detection Apparatus and Method. Google Patent, 2005.

[65] Willig, R.; Mörbe, M. New Generation of Inertial Sensor Cluster for Esp-and Future Vehicle Stabilizing Systems in Automotive Applications. // Advanced Microsystems for Automotive Applications. 2003, pp. 113-125.

[66] Beiker, S. A.; Gaubatz, K. H.; Gerdes, J. C.; Rock, K. L. GPS Augmented Vehicle Dynamics Control. // SAE Technical Paper, 2006.

[67] Kong, H.; Betts, A. Cancellation of Unknown Angular Rate Effects in Linear G Sensitivity Testing for Angular Rate Sensors. // SAE transactions, 109, 6(2000), pp. 36-40.

[68] Kelley, J. P. Sensing Considerations and Trade-offs for Single Point Sensing. SAE, 1993.

[69] Seidel, H. Safety Relevant Microsystems for Automotive Applications. // Proceedings of the 1998 International Symposium on Micromechatronics and Human Science / Nagoya, Japan, 1998, pp. 23-28.

[70] Ching-Yao, C.; Shokoohi, F. Sensing Problems in Automotive Occupant Restraint Systems. // Proceedings of the Intelligent Vehicles Symposium / Detroit, USA, 1995, pp. 60-65.

[71] Noetzel, J.; Tonnesen, T.; Benecke, W.; Binder, J.; Mader, G. Quasianalog Accelerometer Using Microswitch Array. // Sensors and Actuators A: Physical. 54, 1(1996), pp. 574-578.

Authors' addresses

Md. Syedul Amin, PhD Student
Department of Electrical, Electronic and Systems Engineering
Universiti Kebangsaan Malaysia
43600 UKM, Bangi, Selangor, Malaysia
E-mail: syedul8585@yahoo.com;

Salwa Sheikh Nasir, MSc Student
Department of Electrical, Electronic and Systems Engineering
Universiti Kebangsaan Malaysia
43600 UKM, Bangi, Selangor, Malaysia
E-mail: sitinurulsalwa@yahoo.com

Mamun Bin Ibne Reaz, PhD, Professor
Department of Electrical, Electronic and Systems Engineering
Universiti Kebangsaan Malaysia
43600 UKM, Bangi, Selangor, Malaysia
E-mail: mamun.reaz@gmail.com

Mohd. Alauddin Mohd. Ali, PhD, Professor
Department of Electrical, Electronic and Systems Engineering
Universiti Kebangsaan Malaysia
43600 UKM, Bangi, Selangor, Malaysia
E-mail: mama@eng.ukm.my

Tae-Gyu Chang, PhD, Professor
School of Electrical & Electronics Engineering
Chung-Ang University
Seoul 156-756, Korea
E-mail: tgchang@cau.ac.kr