Overview of Automotive Sensors

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***Abstract*—An up-to-date review paper on automotive sensors is presented. Attention is focused on sensors used in production automotive systems. The primary sensor technologies in use today are reviewed and are classified according to their three major areas ofautomotive systems application–powertrain, chassis, and body. This subject is extensive. As described in this paper, for use in automotive systems, there are six types of rotational motion sensors, four types of pressure sensors, five types of position sensors, and three types of temperature sensors. Additionally, two types of mass air flow sensors, five types of exhaust gas oxygen sensors, one type of engine knock sensor, four types of linear acceleration sensors, four types of angular-rate sensors, four types of occupant comfort/convenience sensors, two types of near-distance obstacle detection sensors, four types of far-distance obstacle detection sensors, and and ten types of emerging, state-of the-art, sensors technologies are identified.**

***Index Terms*—Acceleration sensors, angular rate sensors, automotive body sensors, automotive chassis sensors, automotive powertrain sensors, obstacle detection sensors, position sensors, pressure sensors, review paper, rotational motion sensors, state-of-the-art sensors.**

I. Introduction

SENSORS are essential components of automotive electronic control systems. Sensors are defined as [1] "*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*." It wasn't that long ago that the primary automotive sensors were discrete devices used to measure oil pressure, fuel level, coolant temperature, etc. Starting in the late 1970s, microprocessor-based automotive engine control modules were phased in to satisfy federal emissions regulations. These systems required new sensors such as MAP (manifold absolute pressure), air temperature, and exhaust-gas stoichiometric air-fuel-ratio operating point sensors. The need for sensors is evolving and is progressively growing. For example, in engine control applications, the number of sensors used will increase from approximately ten in 1995, to more than thirty in 2010, as predicted in [2].

Automotive engineers are challenged by a multitude of stringent requirements. For example, automotive sensors typically must have combined/total error less than 3 % over their entire range of operating temperature and measurand change, including all measurement errors due to nonlinearity, hysteresis, temperature sensitivity and repeatability. Moreover, even though hundreds of thousands of the sensors may be manufactured, calibrations of each sensor must be interchangeable within ± 1 percent. Automotive environmental operating requirements are also very severe, with temperatures of -40 to $+125$ °C (engine compartment), vibration sweeps up to ± 10 g for 30 h, drops onto concrete floor (to simulate assembly mishaps), electromagnetic interference and compatibility, and so on. When purchased in high volume for automotive use, cost is also always a major concern. Mature sensors (e.g., pressure types) are currently sold in large-quantities (greater than one million units annually) at a low cost of less than $3 (US) per sensor (exact cost is dependent on application constraints and sales volume), whereas more complex sensors (e.g., exhaust gas oxygen, true mass intake air flow and angular rate) are generally several times more costly. Automotive sensors must, therefore, satisfy a difficult balance between accuracy, robustness, manufacturability, interchangeability, and low cost.

Important automotive sensor technology developments are micromachining and microelectromechanical systems (MEMS). MEMS manufacturing of automotive sensors began in 1981 with pressure sensors for engine control, continued in the early 1990s with accelerometers to detect crash events for air bag safety systems and in recent years has further developed with angular-rate inertial sensors for vehicle-stability [1] chassis systems [3]. What makes MEMS important is that it utilizes the economy of batch processing, together with miniaturization and integration of on-chip electronic intelligence [5]. Simply stated, MEMS makes high-performance sensors available for automotive applications, at the same cost as the traditional types of limited-function sensors they replace. In other words, to provide performance equal to today's MEMS sensors, but without the benefits of MEMS technology, sensors would have to be several times more expensive if they were still made by traditional electromechanical/discrete electronics approaches.

II. Objective

MEMS-based automotive sensor technology was recently reviewed by Eddy and Sparks [5]. Frank's 1997 publication [6] emphasized electronic circuits and sensor manufacture. Two classic references on automotive sensors include: Wolber's 1978 publication [7] and Heintz and Zabler's 1982 publication [8]. The objective of the present paper is to provide an up-to-date overview of current-production and emerging state-of the-art, automotive sensor technologies.

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[1]Stability systems, also called active handling systems, automatically minimize oversteer/understeer vehicle dynamics, which can occur during cornering and/or hard vehicle braking or heavy acceleration on split- μ (split coefficient of friction) road surfaces [4].

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III. Sensor Classification

As shown in Fig. 1, the three major areas of systems application for automotive sensors are powertrain, chassis, and body. In the present systems-classification scheme, anything that isn't powertrain or chassis is included as a body systems application.[2] Fig. 1 also identifies the main control functions of each area of application and the elements of the vehicle that are typically involved. The automotive industry has increasingly utilized sensors in recent years. The penetration of electronic systems and the associated need for sensors is summarized in Table I.

Powertrain applications for sensors, shown in Table I, can be thought of as the "1st Wave" of increased use of automotive sensors because they led the first widespread introduction of electronic sensors. Chassis applications for sensors are considered to be the "2nd Wave" of increased use of sensors, and body applications are called the "3rd Wave."

Automotive control functions and associated systems for powertrain, chassis and body areas of application are shown, respectively, in Figs. 2–4. These diagrams help to classify the various applications for automotive sensors. Tables II–IV provide additional detail on the types of sensors used in automotive applications.[3] In these Tables, if sensors are universally used in automotive applications, they are denoted as having a "major" production status; if the sensors are used in just a few automotive models, but not universally used, they're denoted as having "limited" production status, and some promising sensors which are getting close to production are denoted as having "R&D" status.

Table II shows that certain types of sensors predominate in powertrain application, namely rotational motion sensors,[4] pressure, and temperature. In North America, these three types of sensors rank, respectively, number one, two, and four in unit sales volume [9]. To illustrate the predominance of these sensors, there are a total of 40 different sensors listed in Table II, of which eight are pressure sensors, four are temperature sensors, and four are rotational motion sensors. Thus, 16 of 40 of the powertrain sensors in Table II belong to one of these three types of sensors. New types of recently introduced powertrain sensors, listed in Table II, include the cylinder pressure, pedal/accelerator rotary position, and oil quality sensors.

Table III shows that certain types of sensors also predominate in chassis applications, namely rotational motion and pressure (these two types were also predominate in powertrain). But, instead of temperature, inertial acceleration and angular-rate sensors round out the four types of predominant sensors. To illustrate this predominance, there are a total of 27 different sensors listed, of which four are pressure sensors, three are rotational motion sensors, five are acceleration sensors and three are angular rate sensors. Thus, 15 of 27 of the chassis sensors in Table III are one of these four types of sensors. Again, new types of sensors, currently found in chassis systems applications, include the yaw angular rate, steering wheel angular position, and strut-displacement position sensors.

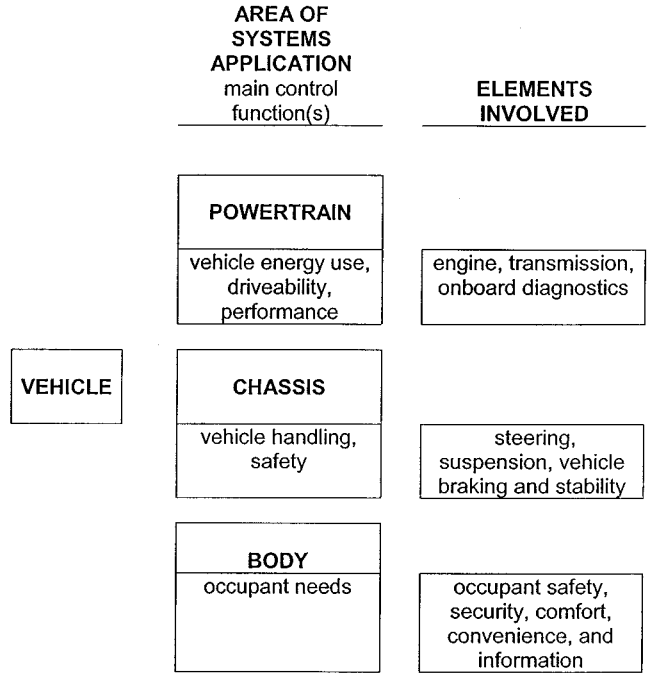

Fig. 1. Major areas of systems application for automotive sensors.

In total, there are 40 body sensors listed in Table IV. As contrasted to powertrain and chassis, Table IV shows that body sensors are very diverse and no specific types of sensors are dominant. Body sensors range from crash-sensing accelerometers, to ultrasonic near-obstacle sensors, to infrared thermal imaging, to millimeter-wave radar, to ambient-air electrochemical gas sensors. Once again, new types of sensors, currently found in body systems applications, include the ultrasonic-array reversing aid, lateral lane-departure warning, and infrared-thermal imaging night-vision sensors.

IV. Current-Product Sensor Technologies

Table II through IV list 40, 27, and 40 sensors; respectively, for powertrain, chassis and body automotive systems applications. This gives a total of 107 sensors (which still isn't all inclusive). These 107 sensors are thought to be representative of most of the major applications for sensors used in automobiles.[5] Coverage of all details, pertaining to all automotive sensors, is beyond the scope and size constraints of this paper. Attention is, therefore, focused on sensors used in automotive production systems (i.e., sensors used for instrumentation, or less significant applications, are omitted).

The approach used in this review will consist of ranking and describing sensor types, approximately in order, according to sales volume and revenue. Additionally, a given type of sensor often

[2]Body applications include occupants' safety, security, comfort and convenience functions. In the present classification, devices such as passive rf-transponder ID-tags/keys, are categorized as components of communications system, not sensors; and are therefore not be covered. Similarly, e-connected telematics devices (wireless cell phones, e-mail, internet connection, etc.) are likewise not covered.

[3]In this paper, type of sensor refers to the measurand of the sensor (i.e., the quantity measured by the sensor).

[4]Rotational sensors measure shaft rotational motion (i.e., speed), as contrasted to position sensors below that directly measure angular or linear displacements.

[5]It's noted that in Table I of Frank's publication [6], a list of automotive sensor applications was independently developed and Frank similarly obtained a total of just over 100 types of automotive sensors.

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TABLE I
DRIVING FACTORS LEADING TO INCREASED USE OF SENSORS (NORTH AMERICAN AUTOMOTIVE MARKET)

POWERTRAIN: "1st Wave," Continued Growth due to Legislation	
	Driving Factors: (*applications*)
1980s and 1990s:	driven by emissions, fuel economy, and onboard diagnostics (OBD-II) legislation, and added features:
	(*closed-loop air-fuel ratio control, catalyst deterioration, engine misfire, and O_2 sensor-degradation, diagnostic systems, cruise control, electronic transmission control*)
2000 and beyond:	driven by ultra-low emssions vehicle (ULEV) legislation, OBD-II added-feature requirements, and best-in-class driveability:
	(*fuel-injection common-rail pressure sensors, variable valve timing, optimized combustion-based engine control*)
CHASSIS: "2nd Wave," Steady Growth due to Demand for Performance	
1980s and 1990s:	driven by vehicle safety and comfort features:
	(*ABS braking, traction control, adaptive suspension, vehicle-stability, electric power steering, on-wheel tire pressure*)
2000 and beyond:	driven by safety, weight/cost reduction, multiplex compatibility, and impending legislation:
	(*vehicle/SUV anti-roll stability systems, fully active suspension, steer-by-wire, brake-by-wire, suspension-by-wire, etc.*)
BODY: "3rd Wave," Accelerating Growth due to Vehicle Personalization	
1980s and 1990s:	driven by safety legislation, security, comfort, convenience, and electronics advances:
	(*air-bag frontal-crash protection, air-bag side-crash protection, theft-deterrent systems, memory seats, navigation*)
2000 and beyond:	driven by safety, new legislation, and intelligent transportation system/electronics advances:
	(*advanced air-bags, rollover-crash curtain-bag protection, collision avoidance, intelligent/ radar cruise-control, real-time traffic and navigation*)

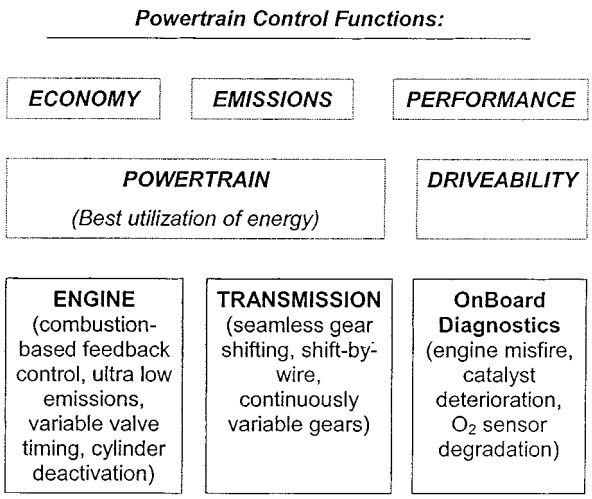

Fig. 2. Powertrain systems, control functions and applications (Simplified diagram).

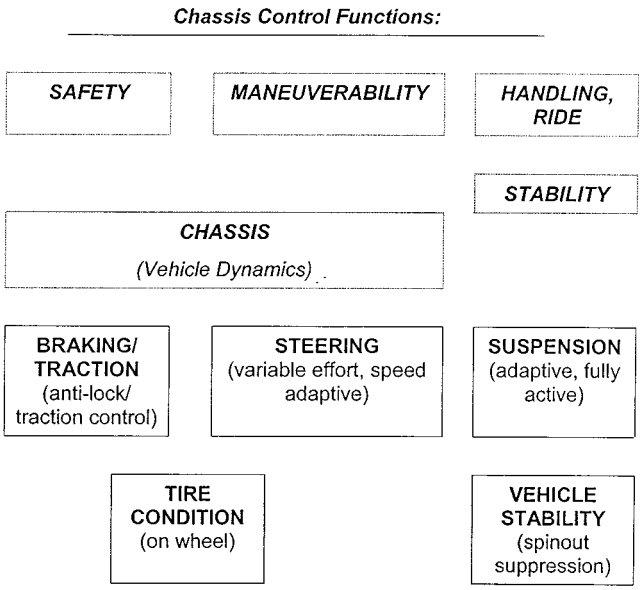

Fig. 3. Chassis systems, control functions and applications (Simplified diagram).

can be made utilizing any of several different kinds of technologies.[6] For example, rotational motion is a type of sensor which is made using any one of the following technologies/operating principles: variable reluctance, Hall effect, magnetoresistance, and so

[6]In this paper, different technologies refer to different operating principles. Discussions of sensor manufacturing technologies and/or design configurations are not addressed.

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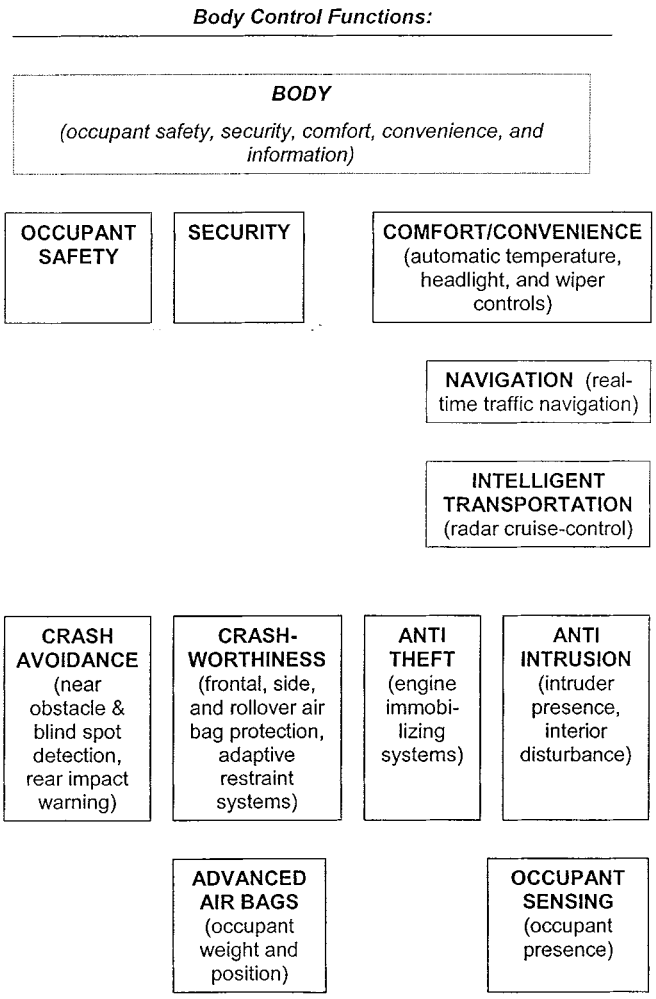

Fig. 4. Body systems, control functions and applications (Simplified diagram).

TABLE II
SENSORS USED IN POWERTRAIN APPLICATIONS

FUNCTION	POWERTRAIN SENSOR	PRODUCTION STATUS*
ENGINE CONTROL		
Cylinder	Pressure	limited
	Combustion-Gas Ion Current	limited
Manifold	Pressure	major
	Temperature	major
Turbo Boost	Pressure	limited
Engine Knock	Vibration	limited
	Combustion-Gas Ion Current	limited
Air Intake	Mass Flow & flow reversal	limited
	Volume Flow Rate	limited
Engine Torque	Magnetostrictive	R&D
	Cylinder-Firing-Induced Crankshaft Speed Modulation	R&D
Air-Fuel Ratio	Oxygen Exhaust Gas:	
	Unheated Stoichiometric	major
	Heated, Fast Light-Off	major
	Heated, Wide Range	limited
	Combustion-Gas Ion Current	R&D
Exhaust NOx Conc.	Dual-Chamber Oxygen Gas	limited
EGR	Pressure	limited
	Valve Position	limited
Crankshaft	Rotational Motion	major
Camshaft	Rotational Motion	major
Throttle, Pedal	Rotary Position	limited
Fuel Injection	Pressure	limited
ENGINE DIAGNOSTIC		
Engine Misfire	Crank Angle Running Statistics	major
	Combustion-Gas Ion Current	limited
Exhaust/Catalyst	Temperature	major
	Catalytic Activity	major
Engine Oil	Pressure	major
	Level	limited
	Quality (or contamination):	
	Predictive	major
	ac-Dielectric Constant	limited
	Cyclic Voltammogram	limited
	Thermal Conductivity	limited
Coolant System	Temperature	major
	Level	limited
Fuel Tank/System	Level	major
	Evaporative Leak Pressure	major
	Flexible Fuel Composition	limited
TRANSMISSION		
Automatic, and/or Continuously Variable	Gearshift Position	major
	Input/Output Shaft Speeds	major
	Temperature	limited
	Pressure	limited
	Torque	R&D

* Sensor production status rankings are based on the judgment of the author.

on. Because automotive applications often are specific to different sensor technologies, applications of sensors will therefore be described after all sensor technologies are first covered. References for additional information on each type of automotive sensor and for each kind of technology will also be provided.

A. Rotational Motion Sensors

Rotational motion sensors measure shaft rotational motion (they also detect reference points such as those created by the absence of one tone-wheel tooth). In North America, rotational motion sensors have the most unit sales and also the highest dollar sales (gross sales revenue), which makes them number one in the present categorization scheme. In 1999, they had slightly more than 20 percent of the gross sales revenue of all automotive sensors, with unit sales of 89 million sensors [3], [9].

1) Variable Reluctance: These sensors—also called inductive types—are electromagnetic devices which produce a pulse-train-like voltage-output signal governed by the time-varying fluctuations of magnetic flux created by rotating motion of mechanical parts. As gear teeth, slots, or magnetized poles, rotate with a shaft and pass by a sensor; flux variations are generated in the sensor's magnetic circuit (which includes a bias magnet). Via Faraday's law, the sensor generates voltage variations in its sensing coil which correspond to the derivative of magnetic flux with respect to time. Variable reluctance sensors feature low cost, small-to-moderate size, self-generated signals, and good temperature stability. On the other hand, disadvantages include loss of signal at zero speed, variable signal strength and signal phase which are dependent on shaft speed (which typically limit rotational measurement repeatability to about ± 0.1 degree), and operation generally limited to sensor air gaps no greater than about 2 mm. For additional information on this sensor, see [10] and [11, pages 194–201].

2) Wiegand Effect: Wiegand effect sensors are based on the interaction of an applied magnetic field with a sensing element that consists of a magnetic-alloy wire having a radial-gradient magnetization that varies from the wire's core to its periphery [12]. When the strength of the field in the magnetic-circuit of the sensor exceeds a threshold value, the magnetization state

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TABLE III
SENSORS USED IN CHASSIS APPLICATIONS

FUNCTION	CHASSIS SENSOR	PRODUCTION STATUS*
BRAKING		
Brake System	Pressure	major
	Fluid Level	limited
ABS Antilock Braking	Wheel Speed	major
	Pressure	major
	Lateral Acceleration	limited
Brake-By-Wire	Pedal Force/Depression Angle	R&D
STEERING		
Electric Power Steering/Steer-By-Wire	Steering Wheel Angle	limited
	Steering Wheel Torque	limited
4-Wheel Steer	Rear Wheel Steering Angle	R&D
	Steering Wheel Angle	limited
VEHICLE		
Vehicle Stability	Wheel Speed	major
	Lateral Acceleration	limited
	Yaw Angular Rate	limited
	Steering Wheel Angle	limited
Active Suspension	Strut Displacement	limited
	Chassis Height	major
	Body Acceleration:	
	Vertical	major
	Lateral	major
	Longitudinal	major
	Yaw Angular Rate	limited
	Roll Angular Rate	limited
	Strut Hydraulic Pressure	limited
	Steering Wheel Angle	limited
Tire Pressure	Wheel-to-Wheel Variance of Rolling Speed	major
	On-Wheel Sensor, Wireless	limited
Tire Temperature	On-Wheel Sensor, Wireless	limited

* Sensor production status rankings are based on the judgement of the author.

TABLE IV
SENSORS USED IN BODY APPLICATIONS

FUNCTION	BODY SENSOR	PRODUCTION STATUS*
SAFETY		
Air Bag Actuation	Crash Deceleration	major
	Vehicle Rollover (Lateral Acceleration plus Roll Rate)	R&D
	Seat-Belt-Use Buckle Status	limited
	Pressure (Side Impact)	limited
Seat Belt Locking	Vehicle Deceleration	major
	Webbing Payout Velocity	limited
Seat Occupancy	Seat Pan Bladder Pressure	R&D
	Seat Pan Load/Deflection	R&D
Occupant Presence/Pre-Crash Position	Passive Infrared Imaging	R&D
	Ultrasonic Imaging	R&D
	Machine Vision	R&D
Parking/Reversing Aid	Ultrasonic Array	major
	Wide-Beamwidth Radar	limited
Blind Spot Surveillance	Wide-Beamwidth Radar	limited
	Multi-Beam Infrared Laser Array	R&D
Lane Departure	Machine Vision	limited
Night Vision	Passive Infrared Imaging	limited
	Active near-IR Illumination	R&D
INTELLIGENT TRANSPORTATION		
Adaptive Cruise Control	Millimeter Wave Radar	limited
	Infrared Laser Radar	limited
Lateral Lane Guidance	Machine Vision	limited
	Magnetometers	R&D
Behavioral	Driver Condition/Impairment	R&D
NAVIGATION		
Absolute Position	Global Positioning	limited
Autonomous Navigation	Wheel Motion (to zero-speed)	limited
	Vehicle Yaw Rate (high resolution)	limited
COMFORT AND CONVENIENCE		
Convenience	Auto Dimming Mirror	major
	Twilight	major
	Nighttime Headlight Beams	limited
	Seat Pressure/Force Array	limited
Climate	Temperature	major
	Solar Radiation	major
	Humidity	limited
	Ambient CO, NO_x, CH_4 conc.	limited
	Rain/fog/moisture	limited
A/C Compressor Control	Pressure	major
	Temperature	major
SECURITY		
Anti Vehicle Theft	Vehicle Tilt	limited
Anti Intrusion	Vibration	limited
	Ultrasonic Interior Motion Detect	R&D

* Sensor production status rankings are based on the judgment of the author.

in the Wiegand wire element rapidly switches polarity, thereby self-generating a voltage pulse, detected by a pickup coil. Wiegand sensors feature: self-generated signal and a high-level voltage-pulse signal (at low rotation speeds). Disadvantages include spikelike-signal output and high-volume manufacturability/cost issues.

3) Hall Effect: Hall sensors produce a voltage signal that corresponds one-to-one with the fluctuations of magnetic flux created by rotating motion of mechanical parts. As tone-wheel gear teeth rotate past a Hall sensor (and its integral bias-magnet); magnetic flux variations are generated similar to those for the variable reluctance sensor, but instead of detecting the time-derivative of flux, the Hall sensor detects the flux level itself. Hall sensors are semiconductor active devices and therefore require a bias current. The Hall voltage output signal is linearly proportional to the transverse component of the flux density passing through the sensing element. In order to (a) cancel out the common-mode dc voltage component associated with the average flux level and (b) to double the output signal, pairs of Hall elements are mounted in a differential mode, side-by-side, parallel to the direction of tooth travel. For effective differential operation, spacing between sensing elements is matched to the pitch between tone-wheel teeth.

Hall sensors are made using bipolar semiconductor technology which allows their fabrication directly on the same chip along with microelectronic signal-processing circuitry. Functions such as amplification, temperature compensation, signal conditioning, etc., can be economically added. Hall sensors feature low cost, small size, operation to zero speed, excellent linearity, and rotational measurement repeatability in the neighborhood of $\pm 0.05°$. On the other hand, disadvantages include maximum operating temperature of about 175°C, air gap operation limited to no greater than about 2.5 mm, and sensitivity to external pressure acting on the sensor package. Additional information on this sensor is found in [11, pages 201–204] and [13, pages 73–148].

4) Magnetoresistor: Magnetoresistor devices exhibit a change of resistance, proportional to magnetic flux density. The resistance change is based on Lorentz force, where geometric patterns of narrow, uniformly spaced, conductive shorting stripes are deposited, perpendicular to current flow direction, on thin layers of high-carrier-mobility semiconductors (InSb or InAs). As current flows in the presence of an orthogonal external magnetic field, Hall-fields and internal shorting by

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the conductive stripes cause the conduction current to follow more tortuous (more zig-zag), higher-resistance, paths; thereby creating a resistive output signal. Magnetoresistor sensors are likewise amenable to fabrication of microelectronic signal-processing integrated circuitry directly on the same chip with the sensing element. The sensor features operation to zero speed, rotation-direction sense, excellent rotational-measurement repeatability in the neighborhood of $\pm 0.025°$, air gap operation up to 3 mm and outstanding temperature stability (maximum operating temperature of 200 °C). On the other hand, disadvantages include medium size, medium cost, and the active-device bias current requirement. Additional information on this sensor is found in [13] pages 151–171 and [15].

5) AMR Magnetoresistive: AMR *a*nisotropic *m*agneto*r*esistive sensors generate changes of resistance as an external magnetic field is rotated with respect to their magnetized thin film (typically consisting of magnetized NiFe permalloy). The sensor primarily responds to field orientation/direction, rather than field strength. Typically, four AMR sense elements, deposited on a common substrate, are connected in a Wheatstone signal-detection bridge arrangement. AMR sensors are also amenable to fabrication of integrated circuitry directly on the same chip. The sensor similarly features operation to zero speed, rotation-direction sense, excellent rotational-measurement repeatability, air gap operation up to 3 mm, and maximum operating temperature of 200 °C. Disadvantages include medium size, medium cost, and the active-device bias current requirement. Additional information on this sensor is found in [14].

6) GMR Magnetoresistive: GMR *g*iant *m*agneto*r*esistive sensors utilize ferromagnetic/nonmagnetic layered structures made up of atomically thin films, in the range of 2-to-5-nm thickness. The GMR effect is quantum mechanical in nature. The reason GMR sensors are called "giant" is because (at very low temperatures) they exhibit sensitivities to variations of applied magnetic field which are up to 20 times greater than those for AMR sensors. At room temperature, the GMR sensitivity advantage diminishes, but is still three to six times greater than that for AMR sensors. Although GMR and AMR sensors have different operating mechanisms, the two sensors function similarly; i.e., both respond primarily to field orientation/direction rather than to field strength. GMR sensors again are amenable to fabrication of integrated circuitry directly on the same chip. The sensor similarly features operation to zero speed, rotation direction sense, excellent rotational-measurement repeatability, extended air gap operation up to 3.5 mm, and a maximum operating temperature of 150°C. Disadvantages likewise include: medium size, medium cost, the active-device bias current requirement, and need for tightly controlled limits on its bias point. Additional information on this sensor is found in [13, pages 175–196] and [14].

Automotive Applications: Major uses for variable reluctance sensors include engine crankshaft and camshaft rotational control of spark timing, fuel injection timing and engine speed measurement, and for control of transmission input and output shaft speeds for electronically controlled gear shifting. Another major application for variable reluctance sensors is wheel speed, on all four wheels (for the ABS *a*ntilock *b*rake *s*ystem, traction control and vehicle stability). Wiegand effect sensors find application in aftermarket high-performance ignition systems. More stringent, OBD *onb*oard *d*iagnostic engine misfire detection requirements, newly enacted by California and federal regulators, have necessitated higher-accuracy crankshaft angular-measurements to detect the absence of individual cylinder firing torques (i.e., misfire) and this has spurred the introduction of the higher-performance magnetoresistor, AMR and GMR types of sensors. Another important application for higher-performance sensors which operate to zero speed, is the measurement of wheel rotation in vehicle navigation systems.

B. Pressure Sensors

Pressure sensors have some very diverse automotive applications. They measure pressures ranging from 10 kPa-vacuum (for OBD evaporative fuel leak detection), to 180 MPa (for diesel common-rail fuel pressure systems). This is a 18 000:1 variation in full-scale pressure range measurement requirements! Clearly, a sensor technology used in the 10-kPa application won't be robust enough for the 180-MPa fuel-pressure application. Consequently, there exist several different pressure sensor technologies. Pressure sensors have the second greatest unit sales and the sixth highest gross sales revenue, which makes them number two in the present categorization scheme.[7] In 1999, in North America, pressure sensors accounted for 9 % of all automotive sensors sales revenue, with unit sales of 78 million sensors [3], [9].

1) Piezoresistive Micromachined: Pressure sensing elements are batch fabricated, a thousand or more per wafer, using a "bond and etchback" process. Silicon diaphragms are micromachined using electrochemical etching and a silicon-to-silicon bonding process forms a vacuum reference chamber [16]. Over the past two decades, sensor die sizes have shrunk and wafer diameters have increased—both factors have helped to lower the cost of micromachined pressure sensors—see [5] page 1752. Piezoresistive strain-sense elements are implanted in appropriate areas of an etched silicon diaphragm where strains are most sensitive to applied pressure. The strain-sense elements are electrically connected into a Wheatstone bridge circuit, thereby providing a means of detecting pressure acting on the diaphragm. Modern sensors feature on-chip digital electronics which provide signal conditioning, programmable calibration of span and offset, built-in compensation for nonlinearity and temperature effects, ratiometric output signal, high accuracy over a wide temperature range and nearly identical part-to-part interchangeability.

2) Capacitive Touch-Mode Micromachined: In applications where zero-pressure range measurement is not required and where low power consumption is an advantage; capacitive "touch-mode" micromachined pressure sensors are used. In this case an extended, more flexible, silicon diaphragm is fabricated. Increasing pressure, acting on the outside surface of the flexible diaphragm, progressively deflects the diaphragm downwards, progressively flattening it against a dielectric/insulating layer

[7]Despite having unit sales nearly as great as rotational motion sensors, pressure sensor sales revenue is less than half that of rotational motion sensors. This is a tribute to the remarkable cost reductions made possible by the prevalent use of IC micromachining technology in the manufacture of pressure sensors.

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deposited above a base electrode. This geometric, progressive, flattening produces a linear increase in capacitance which is insensitive to the interfering effects of temperature [17].

3) Capacitive Ceramic-Module: In very harsh automotive applications—such as hydraulic fluids (brake, power steering, suspension, etc.)—capacitive ceramic-module configurations, also called capsules, are utilized [18]. This sensor basically consists of a diaphragm and a much thicker substrate which has a shallow cavity aligned under the diaphragm. Adjacent surfaces of the diaphragm and substrate are electroded using a guard ring geometry (which eliminates the influence of stray capacitance). The two pieces are bonded together to form a vacuum reference chamber. Increased hydraulic pressure, acting on the outside surface of the diaphragm, deflects the diaphragm closer to the underlying substrate and this produces an increase in capacitance. To insure EMI noise immunity, a high-level, binary, pulse-width-modulated output signal is provided by custom IC electronics, integrally built into the sensor package. [It's noted that this is possible with any capacitive sensor].

4) Piezoresistive Polysilicon-on-Steel: When extreme high pressure is measured—such as diesel-engine common-rail fuel pressure (up to 180-MPa)—polysilicon-on-steel sensor configurations are utilized [19]. A stainless-steel cylinder, has a closed end which is thinned down to create a stiff diaphragm. Increased hydraulic pressure, acting on the inside surface of the diaphragm, deflects the diaphragm. Polysilicon pressure-sensing elements are vapor deposited on the outside (protected side) of the steel diaphragm. Strain sensing elements are electrically connected in a Wheatstone bridge circuit, thereby providing a means of detecting pressure acting on the diaphragm.

Automotive Applications: Piezoresistive micromachined sensors are extensively used to measure engine manifold pressure (absolute and barometric), turbo-boost pressure, and evaporative fuel leak pressure. Capacitive touch-mode micromachined sensors are used to measure tire pressure inside the rotating wheel and engine oil pressure (two applications where accurate indication of the zero point isn't required). Capacitive ceramic-module sensors, are used to measure brake fluid pressure (for cruise control disengagement and ABS braking regulation), suspension hydraulic pressure, and A/C compressor pressure. Piezoresistive polysilicon-on-steel sensors are used to measure common-rail FI (fuel injection) pressure, and vehicle suspension dynamic-control hydraulic pressure.

C. Angular and Linear Position Sensors

Position sensors measure linear displacements ranging from less than one micron (a typical full-scale sensing-element movement inside a MEMS sensor) to over 200 mm (the stroke/travel of a strut in an active suspension system). This is a 200 000:1 variation in full-scale displacement range. An example of an angular-position application is the measurement over four complete revolutions, with a ± 1-degree measurement accuracy requirement, of steering-wheel angular position. Position sensors have the third greatest unit sales and the third highest gross sales revenue, which makes them number three in the present categorization scheme. In 1999, in North America, position sensors accounted for about 18 % of all automotive sensors sales revenue, with unit sales of 48-million sensors [3], [9].

1) Potentiometric: Potentiometric sensors utilize the property that the resistance of an appropriately made film, or screen-printed track, varies linearly with length. The wiper(s) can be either linearly or angularly displaced by the part whose position is to measured. The use of multiple, redundant, wipers and tracks provides improved sensor reliability [20], [21].

2) Hall Effect : In an appropriate magnetic circuit, Hall sensor voltage V_H varies as $\sin(\alpha)$; where α is the angle between flux density B acting on the sensor and bias current I applied to the sensor. Typically, two Hall sensing elements are mounted in quadrature (geometrically oriented 90° from each other). The two Hall elements each provide output signals; one varying as "$\sin(\alpha)$," and the other as "$\sin(\alpha+\pi/2) = \cos(\alpha)$". The output signal is derived from the inverse tangent of "$\sin(\alpha)/\cos(\alpha)$," the ratio of the quadrature element signals. This provides a linear indication of the angular position α of the magnet creating field B (attached to the shaft), thereby determining the angular position of the shaft [22]. Hall sensors are also used for linear position measurements, where magnet "head-on" and "slide-by" movements detect linear position—see [13, pages 99–103].

3) AMR Anisotropic Magnetoresistive: This sensor was previously described in part 5 of Section A. The sensor exhibits changes of resistance as an external magnetic field rotates with respect to its sensing-elements. Two sets of four sensing elements are typically used, each set is physically mounted (i.e., mechanically) offset from each other by a 45° angle. This 45° offset again produces a quadrature 90° *electrical* phase angle difference. The two sets of sensing elements are connected in Wheatstone bridge signal-detection IC circuits. Both bridge circuits respond to the orientation of the external magnetic field (not its field strength). In a manner akin to the Hall sensor, output signals from the two AMR-sensor bridge circuits are obtained; but in this case, the signals vary as, "$\sin(2\alpha)$" and "$\cos(2\alpha)$." From these signals, the inverse tangent of their ratio similarly produces a linear measure of the angular position, "2α," of a magnet (attached to a shaft). Here, the electrical angle goes through two cycles, as angular position of the shaft/magnet traverses one 360-degree revolution. Further information on AMR position sensors is found in [23].

4) Optical Encoder: For a steering-wheel angle sensor application, a slotted-aperture optical-encoder sensor is combined with a gear-reduction-driven potentiometric sensor [24]. The potentiometric sensor provides a continuous measurement of steering-wheel angle over a four-turn lock-to-lock turn range, but with less accuracy than the optical encoder. The encoder, with two offset bands of 90 aperture slots each, is accurate to within ± 1-degree accuracy, but it can't determine the absolute position of the steering wheel. Whenever the vehicle starts up, the sensor's encoder "learns" the true center (or zero) absolute position of the steering wheel by starting with the position indicated by the potentiometer and then refining the calibration based on a period of straight-road driving (as detected by vehicle yaw angular-rate sensors like those described below).

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5) Magnetostrictive Pulse Transit Time: Magnetostrictive-pulse transit-time sensors are used to make long, 200-mm, linear-position measurements. A donut-shaped magnet is attached to and travels with, a displacement-varying element of a suspension strut. A fixed metal rod, concentric to the center axis of a strut, serves as both a magnetostrictive medium and as an acoustic waveguide. A current pulse is applied through the entire length of the rod. When the pulse passes the magnet (attached to the strut), an acoustic pulse is created in the rod due to the interaction of the magnet's field with the applied current in the magnetostrictive rod (i.e., the direct magnetostrictive effect). An acoustic wave is launched back up the rod. When the wave reaches the top end of the rod, the magnetic permeability of the rod material is modulated by the interaction of the acoustic wave with an applied field of a bias magnet (i.e., the inverse magnetostrictive effect). This permeability change creates a voltage pulse in the sense coil circuit and the measured transit time between initiation of the current pulse and the detection of the return-wave voltage pulse, determines the magnet position (i.e., the displacement of the suspension strut) [25].

Automotive Applications: Because of their mature state of development and low cost; potentiometric sensors are extensively used to measure fuel-float level, accelerator pedal angle, and transmission gear position. Due to the harsh environment of the engine and the high number of lifetime dither cycles, noncontact Hall sensors are used to measure throttle angle, EGR valve position, and wheel-to-chassis height (via a 2-bar, linear-to-rotary displacement linkage). AMR position sensors are used in the same applications as for potentiometric and Hall sensors, however, these are sensors of choice when larger air gaps and/or higher-limit maximum operating temperatures must be accommodated. Hall sensors are also used in seat belt buckles for high-reliability detection of proper buckle engagement[8]—i.e., proper linear positions of latch and tongue parts inside the buckle [26]. Because optical sensors can be susceptible to contamination by dirt/oil, they are used in applications that provide environmentally protected mounting locations. A good example is the optical-encoder steering-wheel angle sensor used in vehicle stability enhancement systems, which is mounted on the steering column, near the IP (instrument panel). In active suspension systems, the stroke/position of a strut is accurately measured over an extended-length using magnetostrictive-pulse transit-time sensors.

D. Temperature Sensors

Temperature sensors have the fourth greatest unit sales and the seventh highest gross sales revenue, which makes them number four in the present categorization scheme. In 1999, in North America, temperature sensors accounted for about 5 % of all automotive sensors sales revenue, with unit sales of 39 million sensors [3], [9]. Temperature sensor technologies, in general use today, are listed below.

1) Silicon IC: Use of single-crystal silicon permits on-chip fabrication of IC (integrated circuit) enhancements. However, the use of IC processes also restricts the operation of silicon-based temperature sensors to an upper limit of about 150 °C. Two types of silicon sensors are in general use: (a) spreading resistance based on bulk charge conduction [13] pages 65–70 and (b) pn-junction voltage difference [27].

2) Thermistor: Ceramic-oxide compositions are manufactured to exhibit NTC or PTC (negative, or positive, temperature coefficient) resistance characteristics, where resistance of the sensors decrease, or increase, several orders of magnitude as temperature is increased [28].

3) RTD Resistive Temperature Detector: In RTD high-temperature sensors, a platinum-film sensing element is printed and then embedded inside an alumina-ceramic layered structure. The resistance of the platinum element linearly increases as temperature is increased [29].

Automotive Applications: In the temperature range of −50 to 150 °C, silicon sensors are used for measurement and control of air, gases and fluids. Thermistor-type sensors operate in various ranges between −55 to 1000 °C. Thermistors are used for engine coolant temperature measurement [28] and are also commonly used as level sensors to monitor coolant, fuel, lubricant, brake and steering fluids (where differences between the sensor's self-heating temperatures when immersed and not immersed, in a fluid provide the output signal). To measure very high temperature, over 1050 °C, as required by OBD regulations for catalyst overheat monitoring; both thermistor-type sensor and RTD-type sensors are utilized. To satisfy OBD requirements, these sensors must respond to 0-to-1000 °C step changes of temperature within 10 s.

E. Other Sensors

1) Mass Air Flow: MAF *m*ass *a*ir *f*low sensors are fourth highest in gross sales revenue. On high-performance engines, sensors based on a thermal heat-loss principle, including a hot-wire element (plus a companion compensating hot-wire element), are mounted in a bypass channel of the air intake to measure mass air flow into an engine [30]. This type of sensor measures true mass provided there's no pulsating reversal of air flow. Under certain operating conditions, pulsating reversal of air flow does occur; in which case, another configuration of the thermal flow sensor is used. This type utilizes a heat source and dual upstream and downstream thermal flow-detection elements (which are fabricated on a micromachined low-thermal-mass diaphragm) [31].

2) Exhaust Gas: EGO *e*xhaust *g*as *o*xygen sensors have the fifth greatest unit sales and the second highest gross sales revenue. Their high sales revenue reflects the higher costs of oxygen sensors which are about three times higher per sensor than, for example, rotational motion sensors. For use in closed-loop three-way catalytic-converter emissions control of engines, three types of exhaust gas oxygen sensors are currently utilized.

i) Exhaust gas-heated ZrO_2 (zirconium-dioxide) solid-electrolyte sensors electrochemically self-generate a voltage output signal which exhibits a step-like transition at the stoichiometric point (which is the

[8]This signal is an input to a system that controls the rate of inflation of air bag deployments, based upon whether or not an occupant's seat belt is buckled (together with other input signals).

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chemically correct air-to-fuel mixture ratio)–see [11, pages 208–213] and [32].

ii) Electrically heated titanium-dioxide sensors self-generate a resistive output signal which also makes a step transition at the stoichiometric ratio [33].

iii) Electrically heated, planar, low-thermal-mass, ZrO_2 sensors feature fast light off–i.e., they become operational within 5 to 10 s from the ignition-on time of engine start-up [34], [35].

For use in lean A/F *air*fuel ratio control of engine emissions, two additional types of exhaust gas sensors are utilized.

iv) Electrically heated, low-thermal-mass, planar, dual-chamber ZrO_2 sensors utilize oxygen-pump electrochemical-titration operating principles to measure A/F-ratio over a wide range [34].

v) Dual-chamber ZrO_2 sensors, similar to the wide-A/F sensor of (iv), but where the first chamber removes (pumps out) exhaust oxygen, leaving NOx (oxides of nitrogen) and the second chamber dissociates NOx into N_2 and O_2. In this sensor, the amount of electrochemical pump current in the second chamber is indicative of the exhaust-gas NOx concentration [36].

3) Engine Knock: To obtain maximum power, high-performance engines are run at their borderline limit of incipient knock. This is done using closed-loop control of spark timing based on knock sensor feedback. Cylinder-head vibrations in the frequency range of 4-to-8 kHz, excited by engine knock, are detected using broadband-resonant vibration sensors mounted on the engine cylinder-head. Vibration/knock sensors consist of piezoelectric sensing elements in spring-mass sensor packages [37].

4) Linear Acceleration: Linear-acceleration inertial sensors have the sixth greatest unit sales and the fifth highest gross sales revenue. Acceleration sensors are used as inputs for chassis applications such as: adaptive suspension, vehicle stability and ABS braking systems; as well as inputs for body-systems frontal, side and rollover crash-sensing applications. Reference [38] gives an excellent review of all types of micromachined inertial sensors, including automotive micromachined-based MEMS accelerometers. Three main types of automotive acceleration sensors employ MEMS technology, they are

i) piezoresistive MEMS sensors which incorporate silicon piezoresistors in suspension beams to detect the acceleration-induced movement of a micromachined proof mass [38, pages 1641–1642];

ii) capacitive MEMS sensors which incorporate micromachined electrodes to both sense and detect the acceleration-induced movement of a micro-beam (or plate) proof masses [38, pages 1642–1644];

iii) resonant-beam MEMS sensors which utilize the principle that a vibrating member will shift its resonant frequency proportional to the (inertial) force exerted on the member [38, page 1644] and [39].

The above MEMS types of acceleration sensors include features such as: instrumentation-grade performance at traditional-sensor low cost, robustness, electronically selectable output scales, self testability/diagnostics, on-chip signal conditioning, and multiplex/bus network connectivity. In some chassis applications, however, due to the harsh operating environment; traditional types of accelerometers continue in use today. These are capacitive-type sensors, where acceleration-induced movement of an electromachined thin-metal proof mass (packaged in a ceramic body) is sensed. The sensors feature integrally packaged custom IC circuits which provide binary, high-level, pulse-width-modulated, output signals [40].

5) Angular Rate: Angular-rate[9] inertial sensors have the seventh greatest unit sales. Angular-rate sensors are used as inputs for chassis suspension (vehicle roll and pitch) and for vehicle stability (yaw); as well as inputs for body rollover-crash-sensing (roll) and for vehicle-heading navigation applications (yaw). Similar to acceleration sensors, automotive angular-rate sensors also utilize MEMS technologies, [10] and their operation is based on detection of the effects of Coriolis forces acting on different types of vibrating mechanisms such as: rings, tines, disks, or plates.

i) The vibrating-ring type of sensor incorporates a polysilicon suspended ring, where either electrostatic and magnetic fields have both been used to excite vibrations in the ring. Either by capacitive or electromotive means (both approaches are presently employed), electrodes detect the effects of the Coriolis angular-rate force on the nodes and anti-nodes in the ring's vibration pattern with respect to the sensor's base [38, pages 1651–1652] and [41].

ii) The vibrating-tine sensor consists of a tuning-fork-like tines, supported by a cantilever-like stem. The tines are piezoelectrically driven into resonant vibration and piezoresistive sense elements in the stem detect torsional strain resulting from Coriolis angular-rate forces [42].

iii) Vibrating-plate and disk, sensors are electrostatically driven/oscillated by comb electrodes, where Coriolis-force-induced lateral displacements of the plate, or the tilt of the disk, are capacitively detected [38, pages 1648–1651] and [43], [44].

Another important automotive type of vibrating-tine angular-rate sensor is made using discrete electromechanical construction [not the MEMS construction of sensor type (ii) above]. This sensor is made from electro-formed quartz, with vibrating tines ten times larger than the MEMS type sensor (10 mm tine length versus < 1 mm in MEMS). In this sensor, drive tines are piezoelectrically excited and piezoelectric elements in a second set of pickup tines detect out-of-plane vibrations (resulting from the Coriolis force). Although larger than MEMS sensors, this type of sensor has a large share of the automotive market because of its ruggedness and high performance [45].

6) Solar, Twilight and Glare Optical Detectors: Two types of optical detectors are commonly used: (a) solar-heat-detecting

[9]The designation 'angular-rate' sensor, rather than "gyro," is appropriate because automotive sensors of this type employ vibrating mechanisms, rather than gyroscopic spinning mechanisms, to detect angular rate.

[10]A major reason why MEMS technology is extensively used for both acceleration and angular-rate inertial sensors is that these sensors can be hermetically sealed, without exposing the microelectronic circuitry to the outside environment, while still being able to detect their intended measurand (i.e., effects of inertial).

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photodiodes which respond to near infrared wavelengths and (b) twilight-detecting photodiodes which respond to visible wavelengths [46]. Solar and twilight sensors are typically mounted atop the IP in automobiles. Solar sensors provide input signals for automatic temperature control systems, whereas twilight sensors are used to automatically turn on headlights. A third application of optical detectors utilizes photosensitive microchips that detect visible-light/glare and which are used in automatic-dimming rearview mirrors [47].

7) Moisture/Rain: These sensors are usually mounted facing the windshield, behind the rearview mirror. Typically, moisture-detecting sensors emit IR (infrared) light beams through the windshield. When rain droplets impinge on the outside of the windshield, a higher refractive-index rain/liquid layer is created. Depending on design (i.e., the angle of IR beam incidence on the glass), the presence of rain on the windshield makes IR light either refract away more, or reflect back more [48]. These sensors provide feedback signals for automatic windshield wiper control.

8) Fuel Level: Although other technologies have been developed—e.g., optical, ultrasonic and capacitive—the potentiometer float-arm technology for fuel-level measurement prevails because of its low cost, high reliability and durability [49]. Thick-film resistive tracks are generally used in the potentiometer. The float is designed to traverse a path near the tank's center for all fuel levels. An appropriate functional relationship between sensor angle and fuel quantity for the particular tank shape used in each vehicle is used. A running average of fuel sensor output signals is utilized to compensate for fuel slosh created due to vehicle motion.

9) Near-Distance Obstacle Detection: Several technologies exist–namely ultrasound, microwave radar, rf capacitance and infrared multi beams; all are primarily used in reversing-aid systems ("blind spot" monitoring systems have not yet reached production status). The ultrasound technology is used in widespread production because it offers wide-area, near-distance beam coverage and is low cost [50]. On the other hand, wide-beamwidth microwave radar, although more costly, offers advantages of greater range, better accuracy and ability to operate in inclement weather. Ultrasound obstacle detection is currently in production in reversing-aid systems on (obscured-rear-vision) minivan and SUV types of vehicles. Radar types of obstacle reversing-aid detection are in production on certain commercial vehicles, partly due to legislation in some U.S. states that requires this feature for trucks. Hybrid systems, which combine ultrasound (for wide-area close-proximity obstacle detection) with wide-beamwidth radar (for extended-range, better accuracy, all-weather detection), are expected to appear soon in production [51].

10) Far-Distance Obstacle Detection: Four main technologies are used–namely millimeter-wave radar, laser radar, IR thermal imaging, and machine vision. Millimeter-wave and laser radar are used primarily in vehicle ACC *a*daptive *c*ruise *c*ontrol systems (which control both speed and vehicle-to-vehicle spacing, rather than speed alone).

i) Millimeter-wave radar operates at specified government-regulated frequencies ranging between 24.7 GHz to 77 GHz and it features the ability to accurately operate in inclement weather. Some radars use FM/CW *f*requency-*m*odulated/*c*ontinuous-*w*ave signals which allow measurement of range and range rate[11] of as many as 20 targets (including vehicles, roadway obstacles, etc.). Other automotive radars use pulsed-dopplar and/or monopulse operating principles. Most radars utilize some form of beam scanning, with 10-Hz repetition (update) sweep rates, to resolve, for example, whether targets are in the same roadway lane, an adjacent lane, or an oncoming lane. Some radars utilize all-electronic (no moving parts) beam scanning [52], [53]. Other radars utilize mechanically driven beam scanning [54]. Heavy-truck radars often use nonscanning, single-lane coverage, fixed beams [55].

ii) Laser radar, or lidar (acronym derived from: *l*ight + ra*dar*), emits narrow, pulsed, IR beams at wavelengths in the vicinity of 850 nm. Short-duration 25-ns pulses are emitted sequentially over wide range of beam-scan (both horizontal and vertical) directions. Transit times of individual pulses determine distances to reflecting targets. Beam scanning on automotive lidars is generally accomplished using electromechanically driven mirror-scan mechanisms [56], [57]. Laser radar performance is diminished by inclement weather and/or dirty lenses (actually, this limitation is promoted as a safety benefit because it limits the use of ACC in poor weather when driver visibility is also limited). On the other hand, laser radar features high accuracy, wide angular coverage and precise target location.[12] [13]

iii) Passive IR, nonradiating, thermal imaging, night vision is available on production automobiles [61]. Development of two-dimensional, micromachined, IR bolometric focal-plane arrays [62] was the key technical breakthrough most responsible for night vision becoming low cost enough for automotive application. For automotive night vision, a typical focal-plane array consists of 240 lines, each 320 pixels wide, giving a total of 76 800 pixel image elements. When infrared thermal energy (from pedestrians, deer, other cars, etc.) is incident on the array, each pixels alters its capacitance, which is electronically monitored and input to a heads-up, real-time, small video display of a virtual image viewed by the driver above the hood of the vehicle [61].

iv) Machine vision is used to monitor a vehicle's position relative to roadway lane markings. When, for example, a truck begins to stray outside its lane (possibly indicating a drowsy driver problem), an audible lane-departure "rumble strip" sound is sent to the speaker on whichever side of the roadway the truck is departing [63]. The

[11]Range is derived from the transit time of the FM/CW return signal and range rate is derived from the doppler frequency shift of the return signal.

[12]To take advantage of the respective advantages of millimeter-wave radar and laser radar, these systems have been combined into one hybrid system, which features premium performance derived from the best of both radar systems [58].

[13]To suppress mutual interference either among radar or laser beams, radiated by multiple vehicles on the highway; spread-spectrum phase-modulated signal-coding techniques are used [59], [60].

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vision sensor consists of a) a digital camera, with typically 100 000 pixels and 120-dB dynamic range, mounted on the windshield inside the truck cab; and b) advanced image-recognition software that incorporate lane-recognition/vehicle trajectory algorithms.

11) Additional Production Sensors: Additional automotive sensors are in volume production, but are not covered in the above paper. These sensors include

i) short-circuit-ring position sensor used in electronically controlled diesel injection pumps;
ii) finger-type angular-position and angular-speed sensor;
iii) oil level/quality sensor using heated wires to detect change in heat conductivity due to oil aging.

V. Emerging Sensor Technologies

Emerging, state-of the-art, sensor technologies are defined here as those which are currently in the R&D stage of development, or those which have been newly introduced and which are expected to have a significant impact on automotive systems development.

A. Engine Combustion Sensors

1) Spark Plug Ion-Current (Using Either dc or ac Applied gap Voltage): Detects misfire and detonation/knock; and also indicates in-cylinder peak pressure and air-fuel ratio [64], [65].

2) Fiber-Optic Diaphragm-Reflection: Detects in-cylinder pressure waveform [66], [67].

3) Piezoresistive Silicon-Carbide-On-Insulator: Detects in-cylinder pressure waveform [68].

B. Oil Quality/Deterioration Sensing

1) Stress-Based Predictive Method: Cumulative stress on oil is calculated from combined effects of engine revolutions and oil temperature [69].

2) Multisensor: Detects oil dielectric constant and oil level (capacitively), plus oil temperature [70].

C. Engine/Transmission/Steering Torque Sensors

1) Twist-Angle Torsion-Bar: Twist angle due to applied torque is detected potentiometrically (using sliding contacts [71], [72]); and also via the following noncontact methods

i) optically, using variable apertures [73];
ii) optically, using displaceable bar codes [74];
iii) magnetically, using displaceable air gaps [75];
iv) electrically, using eddy current with variable shaded poles [76].

2) Non-Torsion-Shaft Magnetoelastic Detection: In one sensor, ac-excitation is used to detect changes in shaft permeability [77]. In the other type, permanently magnetized shafts or sleeves self-generate a dc-magnetic flux signal [78], [79]. Both sensors operate without contacting the rotating shaft.

3) Engine-Crankshaft Speed Variation Due to Cylinder-Firings: Math algorithms are used to derive the engine torque from measurements of engine-flywheel speed modulation due to individual cylinder firings—high-resolution rotational motion sensors are utilized [80].

D. Multi-Axis Micromachined Inertial Sensors

1) Two-Axis Accelerometer/Tilt: Single-chip micromachined two-axis (x-y, lateral-longitudinal, vehicle axes) dual-function, sensors are used for vehicle-security systems (e.g., towaway tilt detection) [81], [82].

2) Combined Angular-Rate/Acceleration: Micromachined combined-function sensors are fabricated on the same substrate, providing in one package dual independent measurements of lateral vehicle acceleration and yaw angular rate for use in chassis systems for input to vehicle stability systems and for body systems for rollover-crash-sensing [83]. This sensor is in major production in Europe.

VI. Summary

A comprehensive review of current-production and emerging state-of the-art automotive sensor technologies is made. This paper covers nearly 50 different types of automotive sensors—all of which currently find widespread application, or are expected to have a significant future impact on automotive systems development. For automotive powertrain applications, the predominant sensors in use today are rotational motion, pressure and temperature. For chassis applications, predominant sensors include inertial acceleration and inertial angular rate sensors. As opposed to powertrain and chassis, body systems applications sensors are more diverse and no single sensor types dominate. Ten types of emerging, state-of the-art, sensors technologies are also identified.

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References

[1] H. Norton, "Transducer fundamentals," in *Handbook of Transducers*. Englewood Cliffs, NJ: Prentice Hall, 1989, ch. 2.
[2] M. Barron and W. Powers, "The role of electronic controls for future automotive mechatronic systems," *IEEE/ASME Trans. Mechatronics*, vol. 1, pp. 80–88, Mar. 1996.
[3] R. Grace, "Application opportunities of MEMS/MST in the automotive market," in *Proc. Vehicle Displays Microsens. '99*, Ann Arbor, MI, Sept. 22–23, 1999, pp. 25–31.
[4] D. Hoffman and M. Rizzo, "Chevrolet C5 corvette vehicle dynamic control system," in *SAE Int. Congr. Expo.*, Detroit, MI, Feb. 23, 1998, Paper 980 233.
[5] D. Eddy and D. Sparks, "Application of MEMS technology in automotive sensors and actuators," *Proc. IEEE*, vol. 86, pp. 1747–1755, Aug. 1998.
[6] R. Frank, "Future sensing in vehicle applications," in *Sensors and Transducers*. ser. Publication PT-68, R. Jurgen, Ed. Warrendale, PA: SAE, 1997, pp. 499–512.
[7] W. Wolber, "A worldwide overview of automotive engine control sensor technology," in *SAE Congr. Expo.*, Detroit, MI, Feb. 27, 1978, Paper 780 207.
[8] F. Heintz and E. Zabler, "Problems in the application of sensors in motor vehicles," *Sens. Actuators*, vol. 3, pp. 327–341, 1982/1983.
[9] "North American Automotive Sensor Market," Frost and Sullivan, Mountain View, CA, 1999.
[10] A. Pawlak, J. Adams, and T. Shirai, "Novel variable reluctance sensors," in *SAE Int. Congr. Expo.*, Detroit, MI, Feb. 25, 1991, Paper 910 902.
[11] W. Ribbens, "Engine crankshaft angular position sensor," in *Understanding Automotive Electronics*, 5th ed. Woburn, MA: Newnes Butterworth-Heinemann, 1998, pp. 194–201.
[12] D. Dlugos, "Wiegand effect sensors theory and applications," *SENSORS Mag.*, pp. 32–34, May 1998.

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[13] "Silicon Temperature Sensors," in *Semiconductor Sensors*, 1999-04-01 ed: Infineon Technologies, 1999, pp. 65–70.
[14] M. Caruso, T. Bratland, C. Smith, and R. Schneider, "A new perspective on magnetic field sensing," *SENSORS Mag.*, pp. 34–45, Dec. 1998.
[15] D. Partin, T. Schroeder, J. Heremans, B. Lequesne, and C. Thrush, "Indium antimonide magnetoresistors for automotive applications," in *Proc.,Vehicle Displays Microsens.'99*, Ann Arbor, MI, Sept. 22–23, 1999, pp. 183–188.
[16] J. Schuster and W. Czarnocki, "Automotive pressure sensors: Evolution of a micromachined sensor application," in *SAE Int. Truck Bus Mtg.*, Cleveland, OH, Nov. 17, 1997, Paper 973 238.
[17] W. Baney, D. Chilcott, X. Huang, S. Long, J. Siekkinen, and S. Staller, "A comparison between micromachined piezoresistive and capacitive pressure sensors," in *SAE Int. Truck Bus Mtg.*, Cleveland, OH, Nov. 17, 1997, Paper 973 241.
[18] A. Sabetti, R. Bishop, T. Charboneau, and T. Wiecek, "Automotive pressure transducer for underhood applications," in *SAE Int. Congr. Expo.*, Detroit, MI, Feb. 29, 1988, Paper 880 413.
[19] M. Dunbar and K. Sager, "A novel, media-compatible pressure sensor for automotive applications," *Sensors Mag.*, pp. 28–34, Jan. 2000.
[20] G. Kanelas and D. Alman, "New sensors help put pedal to the metal," *SENSORS Mag.*, pp. 66–69, May 1999.
[21] R. Frodl and D. Schoedlbauer, "Modern concepts for low cost, high performance position sensors," in *SAE Int. Congr. Expo.*, Detroit, MI, Feb. 23, 1998, Paper 980 172.
[22] A. Woerth, H. Winner, and Robert Bosch, "Apparatus for Determining Rotational Position of a Rotatable Element Without Contacting It," U.S. Patent 5 880 586, Mar. 9, 1999.
[23] K. Dietmayer, "New concepts for contactless angle measurement in automotive applications," in *SAE Int. Congr. Expo.*, Detroit, MI, Mar. 1, 1999, Paper 1999-01-1040.
[24] A. Madni and R. Wells, "An advanced steering wheel sensor," *SENSORS Mag.*, pp. 28–40, Feb. 2000.
[25] D. Nyce, "Magnetostrictive linear position sensors," *SENSORS Mag.*, pp. 38–46, Nov. 1999.
[26] L. Brown, R. Ellis, and TRW, "Seat Belt Buckle With Hall Effect Locking Indicator," U.S. Patent 5 898 366, Apr. 27, 1999.
[27] K. Lacanette, "Using IC temperature sensors to protect electronic systems," *SENSORS Mag.*, pp. 28–34, Jan. 1997.
[28] J. Carter, "Thermistor control of engine coolant systems," *SENSORS Mag.*, pp. 65–68, Sept. 1996.
[29] N. Kato, N. Ikoma, and S. Nishikawa, "Exhaust gas temperature sensor for OBD-II catalyst monitoring," in *SAE Int. Congr. Expo.*, Detroit, MI, Feb. 26, 1996, Paper 960 333.
[30] N. Arai, Y. Sekine, Y. Nishimura, T. Osawa, and M. Tsutsui, "Advanced design for a bypass type of hot-wire air flow sensor," in *SAE Int. Congr. Expo.*, Detroit, MI, Feb. 26, 1990, Paper 900 259.
[31] U. Konzelmann, H. Hecht, and M. Lembke, "Breakthrough in reverse flow detection—A new mass air flow meter using micro silicon technology," in *SAE Int. Congr. Expo.*, Detroit, MI, Feb. 27, 1995, Paper 950 433.
[32] W. J. Fleming, "Zirconia oxygen sensor—An equivalent circuit model," in *SAE Int. Congr. Expo.*, Detroit, MI, Feb. 25, 1980, Paper 800 020.
[33] A. Takami, T. Matsuura, T. Sekiya, T. Okawa, and Y. Watanabe, "Progress in lead tolerant titania exhaust gas oxygen sensors," in *SAE Int. Congr. Expo.*, Detroit, MI, Feb. 25, 1985, Paper 850 381.
[34] H. Neumann, G. Hotzel, and G. Lindemann, "Advanced planar oxygen sensors for future emission control strategies," in *SAE Int. Congr. Expo.*, Detroit, MI, Feb. 24, 1997, Paper 970 459.
[35] J. Yoo, J. Bonadies, E. Detwiler, M. Ober, and D. Reed, "A study of a fast light-off planar oxygen sensor application for exhaust emissions reduction," in *SAE Int. Congr. Expo.*, Detroit, MI, Mar. 6, 2000, Paper 2000-01-0888.
[36] H. Inagaki, T. Oshima, S. Miyata, and N. Kondo, "NOx meter utilizing ZrO_2 pumping cell," in *SAE Int. Congr. Expo.*, Detroit, MI, Feb. 23, 1998, Paper 980 266.
[37] S. Dues, J. Adams, and G. Shinkle, "Combustion knock sensing: Sensor selection and application issues," in *SAE Int. Congr. Expo.*, Detroit, MI, Feb. 26, 1990, Paper 900 488.
[38] N. Yazdi, F. Ayazi, and K. Najafi, "Micromachined inertial sensors," *Proc. IEEE*, vol. 86, pp. 1640–1659, Aug. 1998.
[39] T. Kvisteroy, H. Jakobsen, and SensoNor asa, "Force Sensor Device (Accelerometer)," U.S. Patent 5 834 646, Nov. 10, 1998.
[40] E. Reidemeister and L. Johnston, "Capacitive acceleration sensor for vehicle applications," in *SAE Int. Congr. Expo.*, Detroit, MI, Feb. 27, 1995, Paper 942 260.
[41] I. Hopkin, C. Fell, K. Townsend, T. Mason, and British Aerospace, plc., "Vibrating Structure Gyroscope," U.S. Patent 5 932 804, Aug. 3, 1999.
[42] R. Voss, K. Bauer, W. Ficker, T. Glesissner, W. Kupke, M. Rose, S. Sasson, J. Schalk, H. Seidel, and E. Stenzel, "Silicon angular rate sensor for automotive applications with piezoelectric drive and piezoresistive read-out," in *Proc. 1997 Int. Conf. Solid-State Sens. Actuators (Transducers '97)*, Chicago, IL, June 16–19, 1997, pp. 879–882.
[43] M. Lutz, W. Golderer, J. Gerstenmeier, J. Marek, B. Maihofer, and D. Schubert, "A precision yaw rate sensor in silicon micromachining," in *SAE Int. Congr. Expo.*, Detroit, MI, Feb. 23, 1998, Paper 980 267.
[44] D. Teegarden, G. Lorenz, and R. Neul, "How to model and simulate microgyroscope systems," *IEEE Spectrum*, pp. 67–75, July 1998.
[45] A. Madni and R. Geddes, "A micromachined quartz angular rate sensor for automotive and advanced inertial applications," *Sensors Mag.*, pp. 26–34, Aug. 1999.
[46] W. Butler, "Integrated optical sensing of changing environmental illumination," *SENSORS Mag.*, pp. 24–36, June 1999.
[47] N. Martin, "Mirror, mirror. What's in the rear?," *AI Autom. Ind.*, pp. 81–83, June 1993.
[48] J. Britt, "An optical rain sensor," *SENSORS Mag.*, pp. 69–72, Oct. 1997.
[49] G. Nagy Jr., "Fuel level sensor design from a system perspective," in *SAE Int. Congr. Expo.*, Detroit, MI, Feb. 24, 1997, Paper 971 072.
[50] D. McNamara, B. Tucker, and R. Kwiecinski, "Automotive obstacle detection systems: A survey of design requirements & vehicle integration issues," in *Proc. Int. Congress Transportation Electron. (Convergence '98)*, Dearborn, MI, Oct. 19–21, 1998, SAE Paper 98C021, pp. 159–166.
[51] T. Murphy, "Rear vision made simple," *Ward's Auto World*, pp. 57–58, Jan. 2000.
[52] W. Prestl, T. Sauer, J. Steinle, and O. Tschernoster, "The BMW active cruise control ACC," in *SAE Int. Congr. Expo.*, Detroit, MI, Mar. 6, 2000, Paper 2000-01-0344.
[53] S. W. Redfern, "A millimeter-wave forward looking radar sensor for automotive applications," in *Proc. Int. Congress on Transportation Electronics (Convergence '98)*, Dearborn, MI, Oct. 19–21, 1998, SAE Paper 98C040, pp. 279–285.
[54] G. Widmann, M. Daniels, L. Hamilton, L. Humm, B. Riley, J. Schiffmann, D. Schnelker, and W. Wishon, "Comparison of lidar-based and radar-based adaptive cruise control systems," in *SAE Int. Congr. Expo.*, Detroit, MI, Mar. 6, 2000, Paper 2000-01-0345.
[55] J. Woll, "Radar-Based adaptive cruise control for trucks," *Auto. Eng. Int. (SAE)*, pp. 130–132, Nov. 1998.
[56] S. Tanaka, T. Nalagawa, M. Akasu, Y. Fukushima, and W. Bracken, "Development of a compact scan laser radar," in *SAE Int. Congr. Expo.*, Detroit, MI, Mar. 1, 1999, Paper 1999-01-1044.
[57] T. Matsui, "Development of laser radar cruise control system," in *Proc. Int. Congress Transportation Electron. (Convergence '98)*, Dearborn, MI, Oct. 19–21, 1998, SAE Paper 98C003, pp. 19–25.
[58] D. Kurylko, "Venture (automotive distance control systems GmbH) to develop distance sensor," *Autom. News*, p. 30G, Nov. 1996.
[59] J. C. Reed and Delco Electronics Corp., "Continuous Wave Wideband Precision Ranging Radar," U.S. Patent 5 731 781, Mar. 24, 1998.
[60] J. Paranto, D. Liskow, M. Minden, and Hughes Electronics, "Random Pulse Burst Range-Resolved Doppler Laser Radar," U.S. Patent 5 621 514, Apr. 15, 1997.
[61] N. Padgett, "Night vision comes to cadillac," *AI Automotive Industries*, p. 98, Sept. 1998.
[62] B. Cole, R. Higashi, and R. Wood, "Monolithic two-dimensional arrays of micromachined microstructures for infrared applications," *Proc. IEEE*, vol. 86, pp. 1679–1686, Aug. 1998.
[63] J. Broge, "Heavy-duty truck safety systems," *Auto. Eng. Int. (SAE)*, pp. 101–105, May 2000.
[64] H. Wilstermann, A. Greiner, P. Hohner, R. Kemmler, R. Maly, and J. Schenk, "Ignition system integrated AC ion current sensing for robust and reliable online engine control," in *SAE Int. Congr. Expo.*, Detroit, MI, Mar. 6, 2000, Paper 2000-01-0553.
[65] M. Hellring, T. Munther, T. Rognvaldsson, N. Wickstrom, C. Carlsson, M. Larsson, and J. Nytomt, "Robust AFR (air-fuel ratio) estimation using ion current and neural networks," in *SAE Int. Congr. Expo.*, Detroit, MI, Mar. 1, 1999, Paper 1999-01-1161.
[66] M. Fitzpatrick, R. Pechstedt, and Y. Lu, "A new design of optical in-cylinder pressure sensor for automotive applications," in *SAE Int. Congr. Expo.*, Detroit, MI, Mar. 6, 2000, Paper 2000-01-0539.
[67] T. Poorman, S. Kalashnikov, M. Wlodarczyk, A. Daire, W. Goeke, R. Kropp, and P. Kamat, "Multi-channel and portable fiber optic combustion pressure sensor system," in *SAE Int. Congr. Expo.*, Detroit, MI, Feb. 27, 1995, Paper 952 084.

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[68] R. Muller, M. Hart, A. Truscott, A. Noble, G. Krotz, M. Eickhoff, C. Cavalloni, and M. Gnielka, "Combustion pressure based engine management system," in *SAE Int. Congr. Expo.*, Detroit, MI, Mar. 6, 2000, Paper 2000-01-0928.
[69] S. E. Schwartz and D. J. Smolenski, "Development of an automatic engine oil-change indicator system," in *SAE Int. Congr. Expo.*, Detroit, MI, Feb. 23, 1987, Paper 870 403.
[70] E. Irion, K. Land, T. Gurtler, and M. Klein, "Oil-quality prediction and oil-level detection with the TEMIC QLT-sensor," in *SAE Int. Congr. Expo.*, Detroit, MI, Feb. 24, 1997, Paper 970 847.
[71] H. Ng, L. Rupert, M. Devsam, and Methode Electronics, "Torque and Position Sensor," U.S. Patent 5 837 908, Nov. 17, 1998.
[72] K. Jost, "BI technologies torque/position sensor for electric steering," *Auto. Eng. Int. (SAE)*, p. 74, June 2000.
[73] S. Horton and Lucas Industries, "Optical Displacement Sensor and Torque Sensor Employing Relatively Movable Slit Patterns," U.S. Patent 5 841 132, Nov. 24, 1998.
[74] K. Eisenhauer, J. Andrew, J. Baxter, D. Boyton, S. Robinson, and F. Heitger, "Opto-electronic torque, absolute angle and rate sensor for electric steering applications," in *SAE Int. Congr. Expo.*, Detroit, MI, Mar. 1, 1999, Paper 1999-01-1035.
[75] M. Hidenobu, N. Daido, I. Makoto, N. Kyotani, and Koyo Seiko, "Torque Sensor," U.S. Patent 4 907 460, Mar. 13, 1990.
[76] K. Chikaraishi, K. Satoh, and NSK, "Torque Sensor," U.S. Patent 5 796 014, Aug. 18, 1998.
[77] J. Jeremiasson and C. Wallin, "Balancing of individual cylinders in a V8 diesel engine based on crankshaft torque measurement," in *SAE Int. Congr. Expo.*, Detroit, MI, Feb. 23, 1998, Paper 981 063.
[78] I. J. Garshelis and C. A. Jones, "A torque transducer based on local bands of naturally stabilized remanent circumferential magnetization," *J. Appl. Physics*, vol. 85, pp. 5468–5470, Apr. 1999.
[79] S. Bitar, J. Probst, and I. Garshelis, "Development of a magnetoelastic torque sensor for formula 1 and CHAMP car racing applications," in *SAE Int. Congr. Expo.*, Detroit, MI, Mar. 6, 2000, Paper 2000-01-0085.
[80] N. Cavina, F. Ponti, and G. Rizzoni, "Fast algorithm for on-board torque estimation," in *SAE Int. Congr. Expo.*, Detroit, MI, Mar. 1, 1999, Paper 1999-01-0541.
[81] M. Judy and Analog Devices, "Apparatus and Method for Multi-Axis Capacitive Sensing," U.S. Patent 5 939 633, Aug. 17, 1999.
[82] H. Weinberg and C. Lemaire, "Using the ADXL202 accelerometer as a multifunction sensor (tilt, vibration and shock) in car alarms," in *Techn. Note, Rev. A, Analog Devices* Norwood, MA, 1998, p. 4.
[83] K. Funk, F. Laermer, B. Elsner, W. Frey, and Robert Bosch, "Acceleration Sensing Device," U.S. Patent 5 996 409, Dec. 7, 1999.

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