Seat Occupancy Detection Based on Capacitive Sensing

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***Abstract*—This paper presents a simple yet efficient seat occupancy detection scheme based on a capacitive sensing principle. Parameters such as the presence, position, and type of the occupant of the seat are essential for successful air-bag control in vehicles. Without this information, during a collision, the air bag may be inflated to an empty seat (ES), wasting it and, hence, leading to allied repair and reinstallation. Also, if deployed, it can cause fatal injuries to infants in rear-facing infant seats. The proposed capacitive sensor system detects the presence of an occupant and provides information about the occupant's position. A prototype occupancy detection system has been developed, and the feasibility of the new method has been validated through practical tests. The developed system takes 200 μs to complete a measurement and, hence, promises real-time operation of the air-bag system. The presented method employs a carrier-frequency method and lock-in-amplifier technique to measure the capacitances. Thus, the influence of external electromagnetic fields on the final result is kept low.**

***Index Terms*—Capacitive sensor, carrier-frequency-based measurement, electric field sensing, seat occupancy detection.**

I. Introduction

AIR-BAG systems in vehicles play a crucial role in passenger safety. Air bags save thousands of lives each year, according to the National Highway Traffic Safety Administration, Washington, DC [1]. A typical airbag safety system consists of a set of crash sensors, a control unit, igniters, and air bags. The air-bag control unit, for its efficient operation, requires information about the presence, position, and type of the occupant of the seat. In the absence of this information, during an accident, the air bag may be inflated to an unoccupied seat, wasting it and, hence, leading to associated costly repairs. If the air bag is deployed to a seat that is occupied by an infant in a rear-facing infant seat, it can cause fatal injuries [1]. Automobile manufacturers are currently developing smart air-bag systems [2] that may be able to optimize deployment force based on parameters such as severity of crash and occupant type, size, and position. It is important for a sensing system to provide data on the aforementioned parameters at a sufficiently high rate to enable the air-bag control unit to take decisions dynamically.

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Efforts for sensing the presence of an occupant using pressure sensors [3]–[5] and occupant classification using stereovision [6] and optical sensors [7], [8] have been reported. The optical and weight-based systems are ill suited for dynamic observations. Forces during an incident can hardly be used to obtain information about occupancy. Optical sensors provide rather low sampling rates and require complex signal processing to cope with rapidly changing illumination levels, large data sets, etc. Capacitive sensors offer advantages in such situations. The relationship between the capacitances between the human body and nearby electrical wirings in a building has been studied in [9]. Detailed theoretical and practical aspects of electric field imaging have been reported in [10]. Seat occupancy detection based on electric field sensing has been presented in [10]–[12], which provides a comparatively low measurement rate. A capacitive sensing system with a low electric field radiation has been proposed [13]. An electric field sensor for human proximity sensing to be attached on the air bag inflator cover has been developed [14].

We propose a new seat-occupant sensing system based on a capacitive principle. It uses a single receiving electrode and multiple transmitting electrodes [15]. The proposed system provides information about the presence, type (distinguishes between adult and child occupants), and position of an occupant. The developed system typically takes 200 μs to complete a full set of measurements and, hence, enables the air-bag control unit to react in real time during an accident. The measurement principle employed is based on a carrier-frequency method [16] and uses a lock-in-amplifier technique. This technique promises a precise measurement of capacitance even in the presence of external electromagnetic interferences. As the system uses a single receiving electrode, the calibration of the system is much simpler in comparison to systems with multiple receiving electrodes. The principle behind human proximity sensing, the technique employed for capacitance measurement, details of the prototype occupancy sensing system developed, and test results are described in the following sections.

II. Capacitive Sensing for Seat Occupancy Detection

The sensor electrode arrangement of the proposed seat occupancy detection scheme is shown in Fig. 1. There are 11 transmitting electrodes $T_1, T_2, \ldots, T_{11}$ and a common receiving electrode R. The system makes use of the change in capacitance between the receiver R and each transmitting electrode to obtain parameters related to the occupant. The receiver

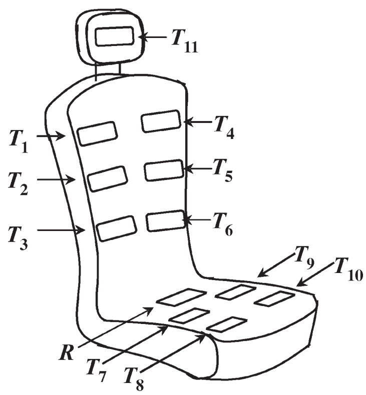

Fig. 1. Automobile seat equipped with the proposed structure of capacitive sensing electrodes. Electrode R in the sitting area is the common receiver, while electrodes $T_1, T_2, \ldots, T_{11}$ are transmitters.

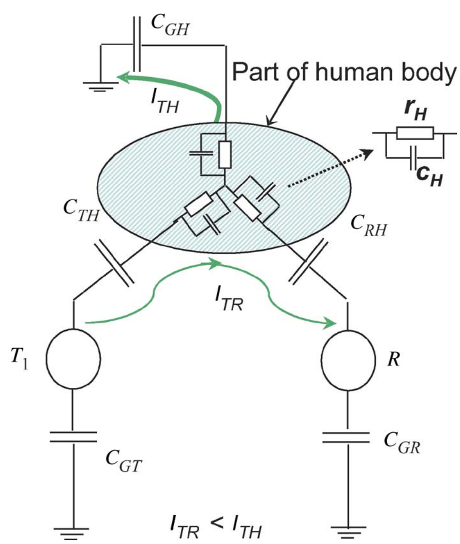

Fig. 2. Equivalent circuit showing the shielding effect by a human body. In shielding mode, current I_{TH} increases as the human body enters the vicinity of the sensor. Hence, the signal received by R is reduced.

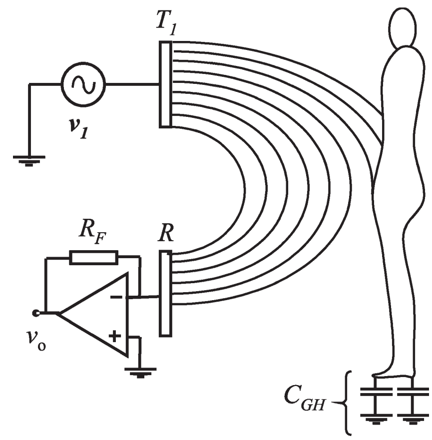

Fig. 3. Pictorial representation of the shielding of electric field lines due to the presence of a human in the far sensor vicinity. For clarity, the electric field lines from transmitter to ground are not shown. Similarly, the distributed capacitances between the human body and ground are represented by a lumped capacitance C_{GH}.

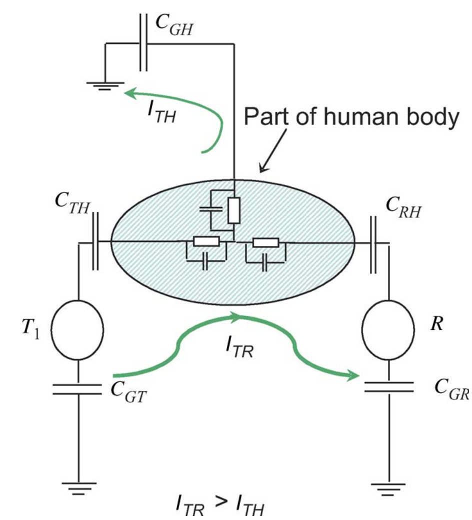

Fig. 4. Capacitances C_{TH} and C_{RH} are larger than C_{GH} when the human body is very close to the sensor vicinity. Under this condition, the coupling effect is more dominant than the shielding effect.

electrode R is placed in the sitting area of the seat, as shown in Fig. 1. A conducting sheet is placed below the receiver and kept at circuit ground potential. An insulating layer is provided between the conductive sheet and the receiver electrode R. The conducting sheet shields the electric field lines that will otherwise reach R mainly through the seat material and structure, thus resulting in a large offset capacitance. An electrical equivalent circuit of the sensor system with a human body in the vicinity of the sensor electrodes is shown in Fig. 2. For simplicity, only one transmitter T_1 and the receiver R are used to explain the principle of operation. There are capacitances C_{TH} between the transmitter T_1 and the human body, C_{RH} between the receiver and the human body, and C_{GH} between the human body and ground. There are also capacitances C_{GT} and C_{GR} from the transmitter and receiver to ground, respectively. The part of the human body that is in the sensor vicinity is represented in the equivalent circuit with a parallel combination of a resistance r_H and a capacitance c_H [11], as shown in Fig. 2.

Let us consider that the transmitter is kept at an electric potential and the receiver is at circuit ground potential. Then, there will be electric field lines emanating from the transmitter to the receiver. Consider, as shown in Fig. 3, that only a small portion of the sensing volume is now occupied by the human body. In such a case, the human body shields some of the electric field lines as shown in Fig. 3. Consequently, the signal received by R and, hence, the output signal v_0 will be reduced compared to a vacant condition. In this mode, the capacitances C_{TH} and C_{RH} will be low in value as compared with C_{GH}. Thus, as in Fig. 2, a significant part of the transmitted current I_{TH} will flow to the ground through the human body. Consequently, the displacement current I_{TR} that flows between the transmitter and receiver will be reduced. The receiver signal will gradually be reduced as the human body enters more into sensor vicinity. This continues as long as C_{TH} and C_{RH} are lower in value than C_{GH}. This is called the shielding mode of operation. On the other hand, when the human body comes very close or is between the transmitter and receiver (refer to Fig. 4), C_{TH} and C_{RH} become much larger than C_{GH}, and hence, I_{TH} will be much lower compared with I_{TR}. Thus, the I_{TR} from

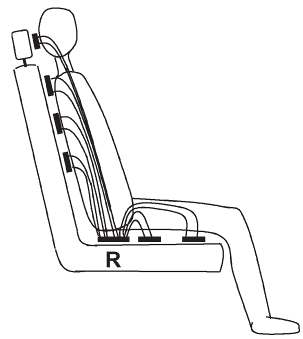

Fig. 5. Pictorial representation of electric field pattern of the proposed method during AO. An adult occupant, when normally seated, makes good capacitive coupling with R and all transmitters.

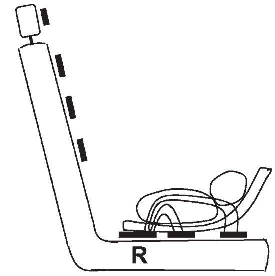

Fig. 6. Electric field line pattern of the sensor system in the presence of an infant in a rear-facing infant seat.

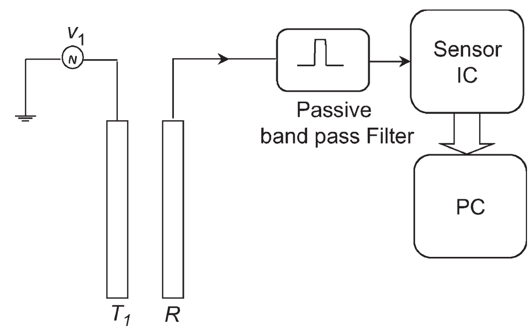

Fig. 7. Block diagram representation of the capacitance measurement system. The receiver signal is bandpass filtered and fed to the sensor IC. Output of the sensor IC is read and displayed by a PC. For brevity, only one transmitter–receiver pair is shown.

the transmitter to the receiver electrode increases in comparison with its value during the shielding mode. This is referred to as the coupling mode of operation, and it is shown using an equivalent circuit in Fig. 4.

When a person sits in a seat equipped with sensor electrodes, as shown in Fig. 1, any one of the aforementioned modes can occur depending on the occupant's position. If the occupant is far from the transmitter–receiver pair, the dominant mode of operation will be shielding and will change to coupling mode once the occupant comes very close to the sensor electrodes. As long as a person normally sits in the seat, the capacitance between the occupant's body and the receiver is stable, and the capacitance between the body and the transmitter gradually increases as the occupant gets closer to the transmitter. Thus, in this condition, the system is in the coupling mode of operation as far as the receiver and transmitting electrodes in the backrest area of the seat are concerned. When a passenger is about to occupy the seat, the electrodes in the sitting area of the seat will be in the shielding mode of operation but will change to coupling mode once the seat is occupied by the passenger. These are the properties exploited in the proposed method to sense human proximity in an automobile seat. A pictorial representation of the pattern of electric field lines between the transmitters and the receiver in the presence of an adult human body are shown in Fig. 5. A transmitter electrode is placed at the backrest head position. The receiver gets a signal from this electrode if the occupant sits normally as shown in Fig. 5. If the person sits in a forward bend (FB) position, the reception from the head position electrode as well as from the other electrodes in the top row of the backrest area will be reduced. Similarly, if the occupant turns left or right, then the corresponding capacitance values will be changed.

In the case of infant seat occupancy, the capacitive coupling with the backrest portion of the seat will be much lower than that for an adult occupancy (AO). Fig. 6 shows the electric field line pattern for such a case. The capacitances between the electrodes in the sitting area and receiver are important for sensing infant seat occupancy as they are in close proximity with the child compared to the electrodes in the backrest area of the seat. In the case of a rearward-facing child, due to the nonuniform volume distribution of the child body (the volume of the leg portions is lower than the volume of the head and shoulder portions), the capacitive coupling with the backrest portion of the seat will be lower than that for a forward-facing child occupancy. Hence, for a rearward-facing child occupancy, the receiver gets lower signal levels from the transmitters placed in the backrest area of the seat compared to a forward-facing child occupancy. This information can be used as an indication for rearward-facing child occupancy. The conductance between the transmitter and receiver can also be measured along with capacitance. This will provide additional information that is useful to distinguish between the human body and other objects such as textbooks, a laptop, food, etc., that may be placed on the seat.

A. *Principle of Capacitance Measurement*

Fig. 7 shows a block diagram representation of the capacitance measurement system with a transmitter–receiver pair. A rectangular excitation is applied to the transmitter. A passive bandpass filter that follows the receiver attenuates unwanted out-of-band frequency components that may be present in the receiver signal [17]. A sensor integrated circuit (IC), based on a carrier-frequency measurement principle [13], [18], measures the capacitance between each transmitter and the common receiver. The capacitance values provided by the sensor IC are read, processed, and displayed in a personal computer (PC).

A functional block diagram of the capacitance measurement system based on the carrier-frequency principle is shown in Fig. 8. As explained in the previous section, the sensor consists of a set of transmitter electrodes and a common receiver electrode. Transmitter electrodes $T_1, T_2, \ldots, T_{11}$ are electrically connected to the buffer units $B_1, B_2, \ldots, B_{11}$ in order. When a measurement cycle is initiated, the control and logic unit (CLU)

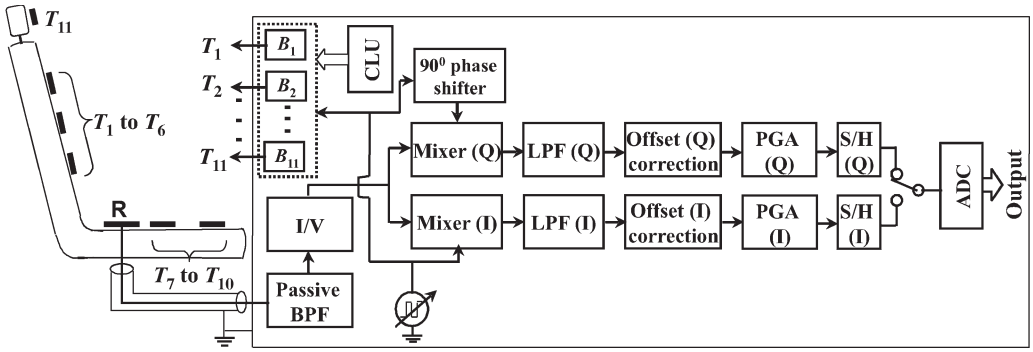

Fig. 8. Carrier-frequency-based measurement system using I/Q demodulation technique [18] with an array of transmitter electrodes and a common receiver electrode for the proposed seat occupancy sensing system. The buffer units $B_1 - B_{11}$ drive the transmitter segments. These buffers are enabled and disabled by the CLU in the sensor IC according to a user-defined sequence.

in the sensor IC is programmed to enable the buffer unit B_1 alone first to excite T_1 with the carrier signal. During this period, all other transmitter electrodes are at ground potential. Once the sensor IC completes the measurement between T_1 and R, buffers $B_2, \ldots, B_{11}$ will be enabled in a similar fashion in an ascending order, and corresponding measurements will be made by the IC. This way, the carrier signal is applied to each transmitting electrode in a sequential manner. As shown in Fig. 8, when a transmitter electrode is excited, the displacement current that flows from the transmitter to the receiver enters into a current-to-voltage converter. The output of the current-to-voltage converter is mixed with the carrier signal for the in-phase (I) channel. A 90° phase-shifted carrier is used for the quadrature phase (Q) channel. The outputs from the I and Q channel mixers are low-pass filtered, and the offsets in both the channels are removed before feeding it into corresponding programmable gain amplifiers (PGAs). Second-order RC low-pass filters with a 3-dB cutoff frequency of typically 150 kHz (depends on factors such as temperature and process variations) are used for low-pass filtering. The outputs from the I and Q channel PGAs are fed to a successive-approximation-register-type analog-to-digital converter, which provides the digital output. The output of the I channel is proportional to the conductance between the corresponding transmitter and receiver electrodes while the Q channel provides an output which is proportional to the capacitance between the electrodes [13], [18], [19]. The capacitance values are used to obtain the presence, position, and type of the occupant while the dielectric properties of objects present between the transmitter and receiver can be obtained using the conductance and capacitance values. Electromagnetic compatibility features of this measurement technique have been presented in [13].

III. Experimental Setup and Results

A prototype capacitive sensing system has been developed and installed on an automobile seat. Transmitting electrodes, 10 cm in length and 5 cm in width, were fabricated by using 100-μm-thick copper plates. The receiver electrode was made identical to the transmitter segment. Transmitter and receiver electrodes were stitched to a cotton cloth material and placed on the sitting and backrest areas of the seat as shown in Fig. 9. A prototype capacitance measurement system has been developed by using a capacitance-to-digital converter IC implemented in 0.25-μm CMOS technology [18], [19]. The principle of operation of the sensor IC is explained in Section II-A.

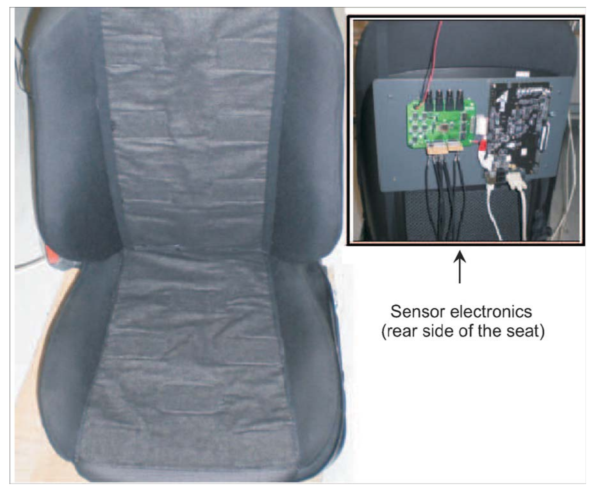

Fig. 9. Automobile seat equipped with prototype capacitive sensing system. Electrodes are stitched to a cotton cloth material and placed in the seat. Associated sensor electronics is fitted in the rear of the seat.

The frequency of the carrier signal used in the prototype system is 5 MHz. For carrier frequencies above 10 MHz, we observed a number of resonance conditions. For carrier frequencies in the range of several kilohertz, the analog low-pass filtering is not efficient due to the comparatively large bandwidth of the low-pass filter of the mixers. The measurement system consists of the sensor IC and a μCLinux Board with a digital signal processor (DSP). A Blackfin processor is used to define initialization parameters for the sensor IC to acquire data from the sensor IC and the data transmission to the host computer. The measured data are then processed in the host computer. Communication between the DSP board and the host computer is accomplished via an Ethernet connection and a transmission control protocol/IP protocol stack. The time required to measure the capacitance between a transmitter and receiver R is about 18 μs. Thus, a system with 11 electrodes takes roughly 198 μs to complete the measurement process. The time required for final decision making depends on the performance of the microprocessor and the complexity of the classification algorithm. For the developed prototype, a simple classification based on predefined threshold levels is used. This algorithm can be implemented in the μCLinux Board, and it can