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

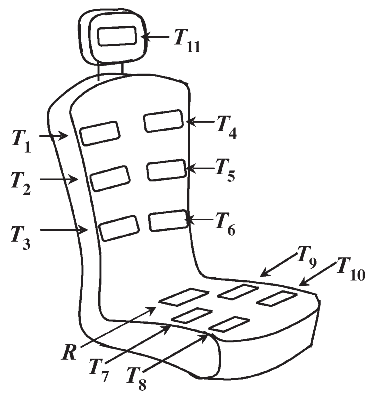

Fig. 1. Automobile seat equipped with the proposed structure of capacitive sensing electrodes. Electrode R in the sitting area is the common receiver, while electrodes $T_1, T_2, \ldots, T_{11}$ are transmitters.

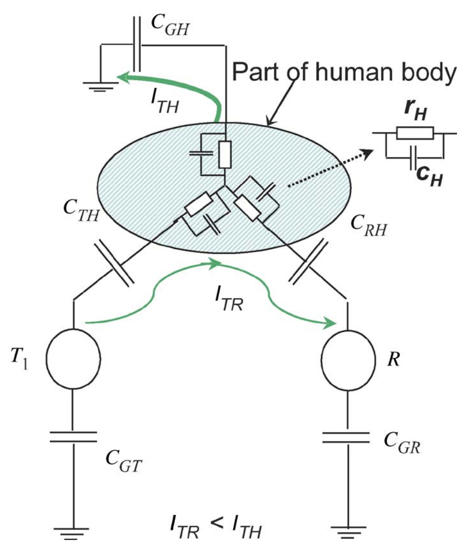

Fig. 2. Equivalent circuit showing the shielding effect by a human body. In shielding mode, current I_{TH} increases as the human body enters the vicinity of the sensor. Hence, the signal received by R is reduced.

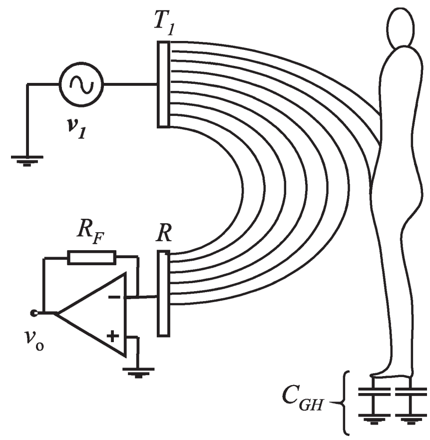

Fig. 3. Pictorial representation of the shielding of electric field lines due to the presence of a human in the far sensor vicinity. For clarity, the electric field lines from transmitter to ground are not shown. Similarly, the distributed capacitances between the human body and ground are represented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

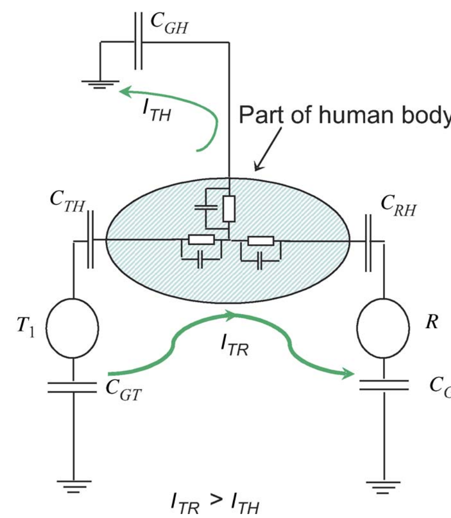

Fig. 4. Capacitances C_{TH} and C_{RH} are larger than C_{GH} when the human body is very close to the sensor vicinity. Under this condition, the coupling effect is more dominant than the shielding effect.

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

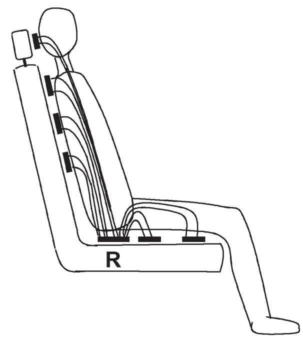

Fig. 5. Pictorial representation of electric field pattern of the proposed method during AO. An adult occupant, when normally seated, makes good capacitive coupling with R and all transmitters.

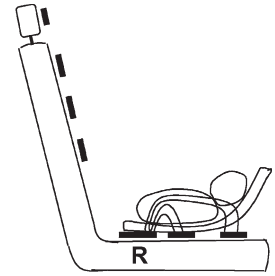

Fig. 6. Electric field line pattern of the sensor system in the presence of an infant in a rear-facing infant seat.

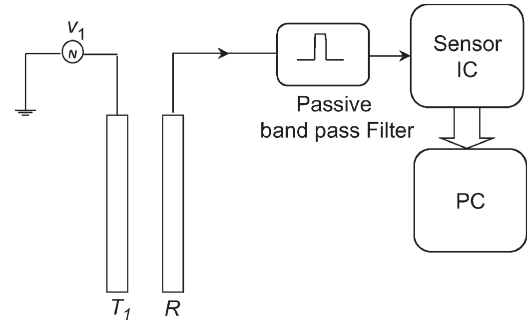

Fig. 7. Block diagram representation of the capacitance measurement system. The receiver signal is bandpass filtered and fed to the sensor IC. Output of the sensor IC is read and displayed by a PC. For brevity, only one transmitter–receiver pair is shown.

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)

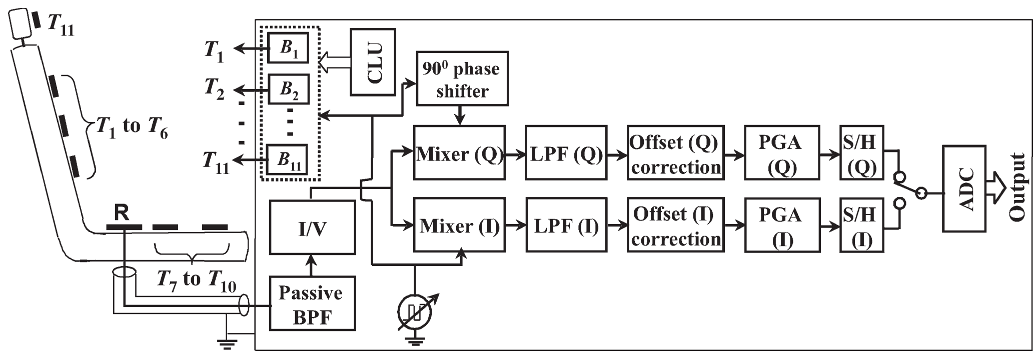

Fig. 8. Carrier-frequency-based measurement system using I/Q demodulation technique [18] with an array of transmitter electrodes and a common receiver electrode for the proposed seat occupancy sensing system. The buffer units $B_1 - B_{11}$ drive the transmitter segments. These buffers are enabled and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

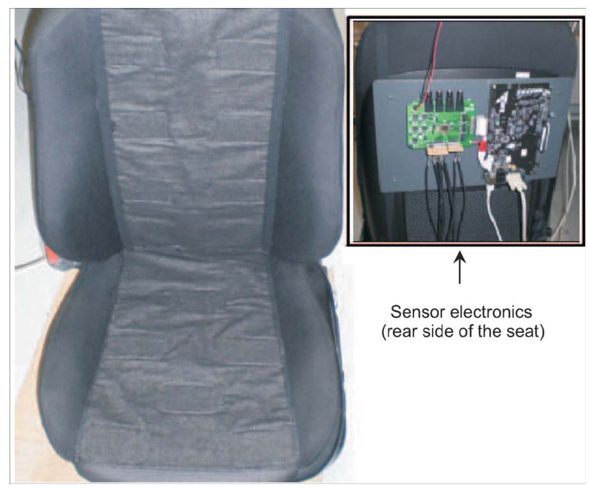

Fig. 9. Automobile seat equipped with prototype capacitive sensing system. Electrodes are stitched to a cotton cloth material and placed in the seat. Associated sensor electronics is fitted in the rear of the seat.

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

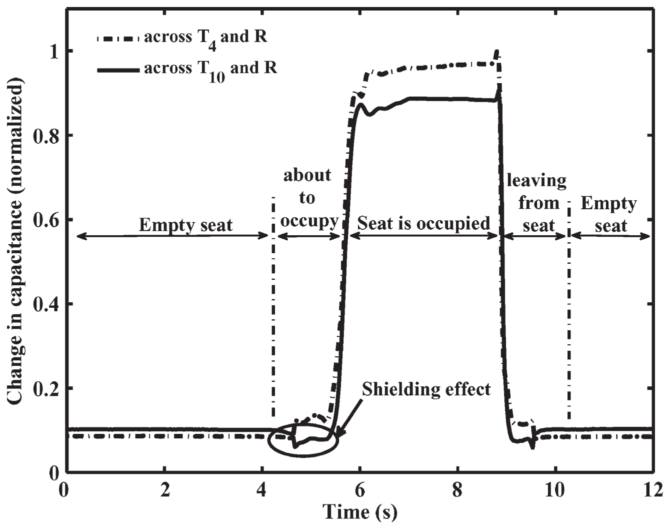

Fig. 10. Typical change in capacitance values observed with the prototype. Capacitance values were recorded between each transmitter and receiver for conditions such as when the seat is empty, when it is about to be occupied by an adult passenger, when it is occupied, and when the occupant is leaving the seat. Capacitances recorded between T_4 and R, as well as T_{10} and R, are shown here. As expected, capacitance values increase, due to coupling, when occupied by an adult. Shielding effect is also visible in the data from electrode T_{10} when the passenger is near and about to occupy the seat.

run in parallel to the data acquisition. Hence, the measurement time of the overall system can be equal to the measurement time of the sensor IC. Thus, the system takes up to 200 μs to complete a full set of measurements. Fig. 9 shows a photograph of the automobile seat equipped with sensor electrodes along with required sensor electronics. Shielded cables were used for the electrical connections from the receiver and transmitter to the sensor IC board. A virtual instrument has been developed in the LabVIEW environment to read the capacitance values, process the data, and give a display about the position and type of the seat occupant.

The developed system has been tested for different conditions of occupancy. Readings were recorded for the capacitance between each transmitter electrode and the receiver. The typical changes in capacitances recorded between T_4 and R, as well as T_{10} and R, when the seat is empty, when it is about to be occupied by an adult passenger, when it is occupied, when the passenger is leaving the seat, and when it is empty again are shown in Fig. 10. Electrode T_4 is situated in the backrest area while T_{10} is placed in the sitting area of the seat. As expected, capacitance values were increased, due to the coupling effect, when the seat was occupied by an adult. Shielding effect was observed in the data from electrode T_{10} when the passenger was near and about to occupy the seat. The measured values of capacitances for ES, AO, FB, Turned Right (TR), Turned Left (TL), and Legs Up (LU) conditions were tabulated and given in Table I. Readings are normalized using the maximum value observed for the condition AO. A large amount of change in capacitance was observed between ES and AO conditions. As expected, the capacitances measured across T_1, T_4, T_{11}, and R were decreased when the occupant was in an FB position. T_1 and T_4 are in the top row of the backrest area, and T_{11} is in the head position of the seat. When the occupant was in position TR, the coupling with electrodes in the left column of the backrest area of the seat got reduced. Hence, the capacitances between T_4, T_5, T_6, and R were much lower than those for the condition AO. Similarly, the coupling with electrodes in the right column increased, and a corresponding increase in measured values from T_2 and T_3 were observed. In position TR, the shoulder and head portions of the occupant were moved forward. This was observed as a corresponding reduction in capacitance from the reading of T_1. Similar effects were observed when the occupant was in condition TL. The characteristics were similar, except for the fact that the right and left columns of electrodes have an opposite effect as compared with the case TR. It is an out-of-position condition if the occupant keeps the legs in upward direction while sitting. In such a condition, coupling with the outermost electrodes from the sitting area of the seat alone will be reduced. As expected, readings from T_8 and T_{10} were low while all other readings were less affected. Tests were also carried out, placing a portable computer, textbooks (3.5 kg), plastic boxes, water bottles, leather bags, etc., in the seat. The capacitance change observed for each case were recorded, and the important situations along with the readings for an AO are shown in Fig. 11. It can be seen from Fig. 11 that the changes in capacitance values observed in the presence of a portable computer, textbooks, water bottles, etc., in the seat are not significant compared to the corresponding values during an AO. This indicates that, in most practical cases, the system can successfully distinguish an AO from the presence of other materials as previously seen and avoids the misuse of air bags.

Tests were also carried out to validate the performance of the developed system for various practical situations. Important test results are tabulated and given in Table II. For all the mentioned test cases in Table II, capacitance readings between T_3 and R are used. The reading obtained for a normal AO is taken as unity. The first test was to study the effect of the passenger wearing a wet cloth, for example, due to sweat. In order to test this condition, the sitting and backrest areas of the seat were covered with a wet cotton blanket of nearly 2-mm thickness, and then, an adult passenger occupied the seat. The capacitance values observed in this condition were 1.07 times more than its corresponding values for a normal AO. Thus, a passenger wearing thick wet clothes will be seen by the system as a human with a slightly enlarged size (1.07 times in this test case). However, the system can still successfully perform occupancy detection and classification as this condition is equivalent to a person with a bigger body size occupying the seat. The effect of wearing a thick pullover garment (as a sweater) was also tested. Two layers of pullovers, each with a thickness of 4 mm, were used. As expected, the capacitance readings decreased because of the presence of the pullover material with low relative permittivity between the electrodes and the human body. The use of special seat covers made of wooden or cotton material is common to improve the sitting comfort. The capacitance measured with the presence of such a cover was nearly 0.04 per unit higher than an ES condition. The aforementioned test cases, namely, wearing a wet cloth and a pullover garment and placing a seat cover, nearly equally alter the capacitances between every transmitter and receiver and hence effectively allows the correction for such environmental effects. The capacitance reading was 0.16 per unit higher than an empty condition when a

TABLE I
RESULTS (NORMALIZED) OBTAINED WITH THE PROTOTYPE SYSTEM. CAPACITANCE VALUES BETWEEN EACH TRANSMITTER AND THE COMMON RECEIVER FOR ES, AO, FB, TR, TL, AND LU CONDITIONS WERE RECORDED. THE VALUE OF CAPACITANCE MEASURED BETWEEN T_4 AND R FOR THE CONDITION AO WAS 24.90 pF

Occupant status	Back rest area of seat						Sitting area of seat				Head
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}
ES	0.132	0.106	0.106	0.125	0.126	0.136	0.145	0.144	0.144	0.157	0.036
AO	0.867	0.517	0.698	1.000	0.687	0.884	0.445	0.909	0.603	0.893	0.171
FB	*0.225*	0.842	0.875	*0.256*	0.996	1.125	0.658	1.564	1.042	1.363	*0.158*
TR	*0.362*	*1.482*	*1.262*	*0.237*	*0.245*	*0.389*	0.782	1.193	1.358	1.583	0.185
TL	*0.224*	*0.222*	*0.298*	*0.297*	*1.170*	*1.450*	0.675	1.645	1.235	1.601	0.173
LU	1.051	0.720	0.820	1.496	0.986	1.122	0.678	*0.115*	0.815	*0.124*	0.190

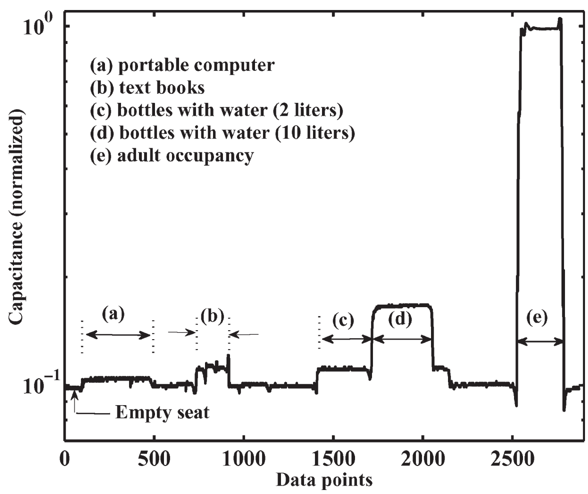

Fig. 11. Capacitance values measured between transmitter segment T_3 and receiver R for various scenarios. A capacitance measurement is also taken and shown for an AO. The results show that the change in capacitance for cases (a), (b), and (c) are very low in comparison with the change in capacitance observed for an AO. In case (d), 20 beer bottles each filled with 500 mL of water were placed in a basket, and the noticed change in capacitance was nearly 5.5 times lower than AO as the volume taken by the basket is a mix of water, glass, and air.

TABLE II
CAPACITANCE (NORMALIZED TO READING FOR AO) MEASURED BETWEEN TRANSMITTER T_3 AND RECEIVER R FROM THE PROTOTYPE FOR DIFFERENT CONDITIONS

Seat scenario	Capacitance
adult occupancy	1.00
adult on a wet blanket (2 mm thick)	1.07
adult with pull over (8 mm thick)	0.82
seat cover (10 mm thick)	0.04
infant seat (70 mm thick)	0.16
infant (10 kg) in an infant seat	0.27

commercially available baby seat with a thickness of 70 mm was placed on the seat. Then, a baby weighting 10 kg was allowed to sit on the baby seat, and an increase of 0.27 per unit was observed in the capacitance readings. These measurement results indicate promising occupancy detection capabilities of the developed sensing system.

Results obtained for different child seat conditions are presented in Table III. Capacitance values were recorded for Vacant Infant seat (VI), Forward-Facing baby (FF), Rearward-Facing baby (RF), Vacant Booster seat (VB), Booster seat with Baby (BB), booster Cushion with Baby (CB), and ten Beer bottles in a vacant booster cushion seat (BE) conditions. A baby-shaped dummy filled with water weighting 10 kg was used for the investigations. In Table III, $T_{(1,4)}$ indicates the average value $(T_1 + T_4)/2$ of the readings obtained from electrodes T_1 and T_4. Similarly, $T_{(2,5)} = (T_2 + T_5)/2$, $T_{(3,6)} = (T_3 + T_6)/2$, $T_{(7,9)} = (T_7 + T_9)/2$ and $T_{(8,10)} = (T_8 + T_{10})/2$. As can be seen from Table III, for the conditions FF and RF, the capacitance values were increased for the electrodes from the backrest area as compared with the condition VI. This is because of the presence of the baby in the sensing volume and, hence, the increase in capacitive coupling between R and the transmitter electrodes in the backrest of the seat. During condition FF, the head and shoulder portions of the baby rest in between the receiver R and the transmitter electrodes in the backrest area. However, during condition RF, the same sensing volume will be occupied by the legs of the baby. Thus, during condition FF, higher capacitance values compared to those of condition RF were noticed for the electrodes in the backrest area. For conditions FF and RF, due to the shielding effect, the measured capacitance values for electrodes in the sitting area were lower than for condition VI. In the sitting area, the receiver and transmitter electrodes are in the same plane and, due to the presence of infant seats, there is more than 5 cm of vertical distance between the baby and the electrode plane. Thus, the child actually acts as a shield for the electrodes in the sitting area. Similarly, for conditions BB and CB, the electrodes in the sitting area are in shielding mode. Thus, for conditions BB and CB, the capacitance values observed for the transmitter electrodes in the sitting area were lower than the corresponding values obtained for condition VB. Also, for conditions BB and CB, due to the dominant coupling effect, the capacitance values read from electrodes in the backrest area were larger than the corresponding values obtained for condition VB. Readings obtained for ten filled beer bottles kept in the booster cushion seat are also given in Table III. As can be seen in Table III, the electrodes in the sitting area are in shielding mode, while those in the backrest area are in coupling mode. However, the shielding and coupling effects observed for this condition are significantly lower than those for conditions BB and CB, which permits one to distinguish between child occupancy and beer bottles placed in a booster seat or cushion.

TABLE III
CAPACITANCE VALUES OBSERVED FOR VI, FF, RF, VB, BB, CB, AND BE ARE PRESENTED

Test case	Back rest area			Sitting area	
	$T_{(1,4)}$	$T_{(2,5)}$	$T_{(3,6)}$	$T_{(7,9)}$	$T_{(8,10)}$
VI	0.118	0.104	0.123	0.175	0.136
FF	0.151	0.146	0.182	0.109	0.079
RF	0.139	0.131	0.164	0.073	0.094
VB	0.117	0.102	0.148	0.159	0.113
BB	0.162	0.148	0.260	0.101	0.080
CB	0.210	0.178	0.348	0.078	0.091
BE	0.153	0.144	0.158	0.124	0.108

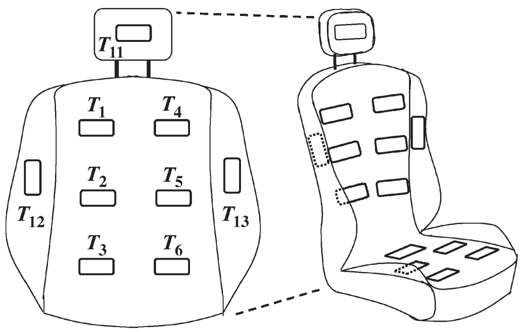

Fig. 12. Pictorial view of an automobile seat equipped with proposed capacitive sensing electrodes. Two additional electrodes T_{12} and T_{13} are introduced in the backrest area of the seat. This provides collateral information that is particularly useful for controlling the firing of window curtain air bags. Typical change in capacitances recorded from the prototype for a test case is shown in Fig. 13.

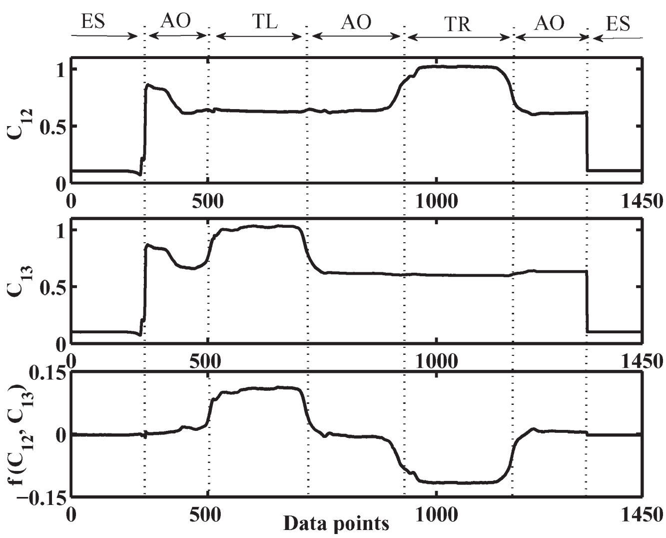

Fig. 13. Change in capacitances were recorded and plotted for ES, AO, TL, AO, TR, AO, and ES in order. C_{12} and C_{13} are the capacitances between receiver R and transmitter T_{12} and T_{13}, respectively. A function $f(C_{12}, C_{13}) = (C_{13} - C_{12})/(C_{13} + C_{12})$ is computed and plotted. The polarity and magnitude of $f(C_{12}, C_{13})$ give an indication of the degree of TL or TR status of the passenger.

The shoulder and head positions of the occupant in the backrest area of the seat are very important as far as the operation of window curtain air bags is concerned. It will be dangerous to deploy window curtain air bags when the passenger is very close to it. In such a condition, the deployment force should be controlled and kept low to avoid possible harmful effects. Thus, the current posture of the passenger, particularly the highly TR and TL conditions, is valuable to meet this demand. The TR and TL conditions can reliably be sensed by introducing two new transmitting electrodes T_{12} and T_{13} as shown in Fig. 12 in the right and left side extensions (wings) of the backrest area of the seat. Let C_{12} and C_{13} be the capacitances between receiver R and transmitters T_{12} and T_{13}, respectively. Whenever the occupant is in position TL or TR, according to the degree of inclination, the occupant's body will get close to the corresponding transmitter segment, and hence, the associated capacitance C_{12} or C_{13} will be increased. This feature has been incorporated in the prototype system and tested. Fig. 13 shows typical variations in capacitances observed during a test cycle for the conditions of ES, AO, TL, AO, TR, AO, and ES in order. A function $f(C_{12}, C_{13}) = (C_{13} - C_{12})/(C_{13} + C_{12})$ is computed and plotted. The polarity and magnitude of $f(C_{12}, C_{13})$ give an indication of the degree of status TL or TR of the passenger. In such an electrode system, the number of transmitting electrodes in the backrest area can be minimized by replacing T_1 and T_4 by an electrode of the same size in the middle of the current positions of T_1 and T_4. The same procedure can be applied to the electrodes T_2 and T_5, as well as T_3 and T_6. In the modified system, the backrest area will only have a single column (instead of two) of three electrodes along with the side electrodes T_{12} and T_{13}.

IV. Conclusion

A simple and cost-effective seat occupancy detection scheme suitable for smart air-bag systems has been developed based on a capacitive sensing principle. The system successfully senses the presence of an occupant. It also detects out-of-position condition of a seat occupant. In the proposed system, the whole measurement is made by using a single receiving electrode and, hence, provides a less-complex measurement method for the occupant sensing system. A prototype has been developed, and its performance for various possible conditions of seat occupancy has been evaluated, proving the practicality of the proposed scheme. The developed system takes up to 200 μs to complete a full set of measurements and, hence, guarantees a dynamic operation of the air-bag system. The measurement principle is based on a carrier-frequency method and uses a lock-in-amplifier technique to obtain the final capacitance values. This technique provides a precise measurement of capacitances and, hence, gives details about the occupancy, even in the presence of external electromagnetic interference.

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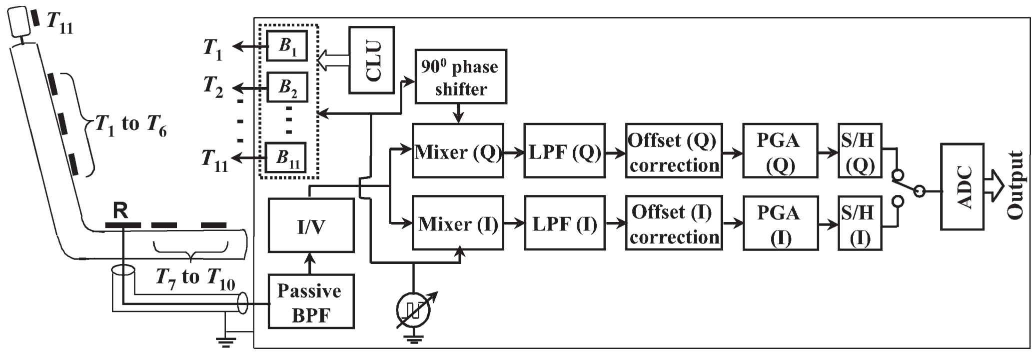

Fig. 8. Carrier-frequency-based measurement system using I/Q demodulation technique [18] with an array of transmitter electrodes and a common receiver electrode for the proposed seat occupancy sensing system. The buffer units $B_1 - B_{11}$ drive the transmitter segments. These buffers are enabled and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

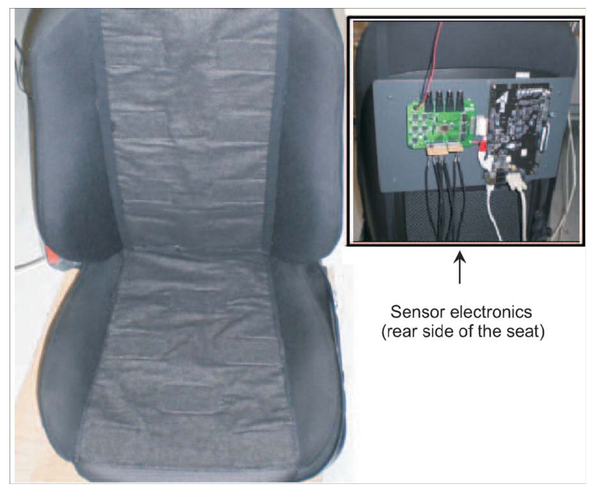

Fig. 9. Automobile seat equipped with prototype capacitive sensing system. Electrodes are stitched to a cotton cloth material and placed in the seat. Associated sensor electronics is fitted in the rear of the seat.

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

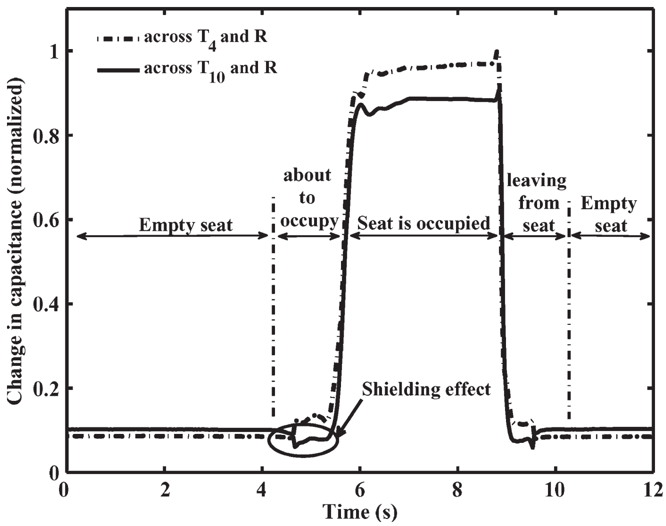

Fig. 10. Typical change in capacitance values observed with the prototype. Capacitance values were recorded between each transmitter and receiver for conditions such as when the seat is empty, when it is about to be occupied by an adult passenger, when it is occupied, and when the occupant is leaving the seat. Capacitances recorded between T_4 and R, as well as T_{10} and R, are shown here. As expected, capacitance values increase, due to coupling, when occupied by an adult. Shielding effect is also visible in the data from electrode T_{10} when the passenger is near and about to occupy the seat.

run in parallel to the data acquisition. Hence, the measurement time of the overall system can be equal to the measurement time of the sensor IC. Thus, the system takes up to 200 μs to complete a full set of measurements. Fig. 9 shows a photograph of the automobile seat equipped with sensor electrodes along with required sensor electronics. Shielded cables were used for the electrical connections from the receiver and transmitter to the sensor IC board. A virtual instrument has been developed in the LabVIEW environment to read the capacitance values, process the data, and give a display about the position and type of the seat occupant.

The developed system has been tested for different conditions of occupancy. Readings were recorded for the capacitance between each transmitter electrode and the receiver. The typical changes in capacitances recorded between T_4 and R, as well as T_{10} and R, when the seat is empty, when it is about to be occupied by an adult passenger, when it is occupied, when the passenger is leaving the seat, and when it is empty again are shown in Fig. 10. Electrode T_4 is situated in the backrest area while T_{10} is placed in the sitting area of the seat. As expected, capacitance values were increased, due to the coupling effect, when the seat was occupied by an adult. Shielding effect was observed in the data from electrode T_{10} when the passenger was near and about to occupy the seat. The measured values of capacitances for ES, AO, FB, Turned Right (TR), Turned Left (TL), and Legs Up (LU) conditions were tabulated and given in Table I. Readings are normalized using the maximum value observed for the condition AO. A large amount of change in capacitance was observed between ES and AO conditions. As expected, the capacitances measured across T_1, T_4, T_{11}, and R were decreased when the occupant was in an FB position. T_1 and T_4 are in the top row of the backrest area, and T_{11} is in the head position of the seat. When the occupant was in position TR, the coupling with electrodes in the left column of the backrest area of the seat got reduced. Hence, the capacitances between T_4, T_5, T_6, and R were much lower than those for the condition AO. Similarly, the coupling with electrodes in the right column increased, and a corresponding increase in measured values from T_2 and T_3 were observed. In position TR, the shoulder and head portions of the occupant were moved forward. This was observed as a corresponding reduction in capacitance from the reading of T_1. Similar effects were observed when the occupant was in condition TL. The characteristics were similar, except for the fact that the right and left columns of electrodes have an opposite effect as compared with the case TR. It is an out-of-position condition if the occupant keeps the legs in upward direction while sitting. In such a condition, coupling with the outermost electrodes from the sitting area of the seat alone will be reduced. As expected, readings from T_8 and T_{10} were low while all other readings were less affected. Tests were also carried out, placing a portable computer, textbooks (3.5 kg), plastic boxes, water bottles, leather bags, etc., in the seat. The capacitance change observed for each case were recorded, and the important situations along with the readings for an AO are shown in Fig. 11. It can be seen from Fig. 11 that the changes in capacitance values observed in the presence of a portable computer, textbooks, water bottles, etc., in the seat are not significant compared to the corresponding values during an AO. This indicates that, in most practical cases, the system can successfully distinguish an AO from the presence of other materials as previously seen and avoids the misuse of air bags.

Tests were also carried out to validate the performance of the developed system for various practical situations. Important test results are tabulated and given in Table II. For all the mentioned test cases in Table II, capacitance readings between T_3 and R are used. The reading obtained for a normal AO is taken as unity. The first test was to study the effect of the passenger wearing a wet cloth, for example, due to sweat. In order to test this condition, the sitting and backrest areas of the seat were covered with a wet cotton blanket of nearly 2-mm thickness, and then, an adult passenger occupied the seat. The capacitance values observed in this condition were 1.07 times more than its corresponding values for a normal AO. Thus, a passenger wearing thick wet clothes will be seen by the system as a human with a slightly enlarged size (1.07 times in this test case). However, the system can still successfully perform occupancy detection and classification as this condition is equivalent to a person with a bigger body size occupying the seat. The effect of wearing a thick pullover garment (as a sweater) was also tested. Two layers of pullovers, each with a thickness of 4 mm, were used. As expected, the capacitance readings decreased because of the presence of the pullover material with low relative permittivity between the electrodes and the human body. The use of special seat covers made of wooden or cotton material is common to improve the sitting comfort. The capacitance measured with the presence of such a cover was nearly 0.04 per unit higher than an ES condition. The aforementioned test cases, namely, wearing a wet cloth and a pullover garment and placing a seat cover, nearly equally alter the capacitances between every transmitter and receiver and hence effectively allows the correction for such environmental effects. The capacitance reading was 0.16 per unit higher than an empty condition when a

TABLE I
RESULTS (NORMALIZED) OBTAINED WITH THE PROTOTYPE SYSTEM. CAPACITANCE VALUES BETWEEN EACH TRANSMITTER AND THE COMMON RECEIVER FOR ES, AO, FB, TR, TL, AND LU CONDITIONS WERE RECORDED. THE VALUE OF CAPACITANCE MEASURED BETWEEN T_4 AND R FOR THE CONDITION AO WAS 24.90 pF

Occupant status	Back rest area of seat						Sitting area of seat				Head
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}
ES	0.132	0.106	0.106	0.125	0.126	0.136	0.145	0.144	0.144	0.157	0.036
AO	0.867	0.517	0.698	1.000	0.687	0.884	0.445	0.909	0.603	0.893	0.171
FB	*0.225*	0.842	0.875	*0.256*	0.996	1.125	0.658	1.564	1.042	1.363	*0.158*
TR	*0.362*	*1.482*	*1.262*	*0.237*	*0.245*	*0.389*	0.782	1.193	1.358	1.583	0.185
TL	*0.224*	*0.222*	*0.298*	*0.297*	*1.170*	*1.450*	0.675	1.645	1.235	1.601	0.173
LU	1.051	0.720	0.820	1.496	0.986	1.122	0.678	*0.115*	0.815	*0.124*	0.190

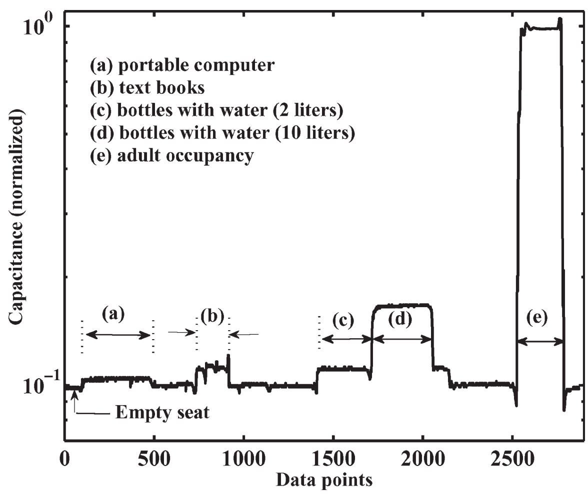

Fig. 11. Capacitance values measured between transmitter segment T_3 and receiver R for various scenarios. A capacitance measurement is also taken and shown for an AO. The results show that the change in capacitance for cases (a), (b), and (c) are very low in comparison with the change in capacitance observed for an AO. In case (d), 20 beer bottles each filled with 500 mL of water were placed in a basket, and the noticed change in capacitance was nearly 5.5 times lower than AO as the volume taken by the basket is a mix of water, glass, and air.

TABLE II
CAPACITANCE (NORMALIZED TO READING FOR AO) MEASURED BETWEEN TRANSMITTER T_3 AND RECEIVER R FROM THE PROTOTYPE FOR DIFFERENT CONDITIONS

Seat scenario	Capacitance
adult occupancy	1.00
adult on a wet blanket (2 mm thick)	1.07
adult with pull over (8 mm thick)	0.82
seat cover (10 mm thick)	0.04
infant seat (70 mm thick)	0.16
infant (10 kg) in an infant seat	0.27

commercially available baby seat with a thickness of 70 mm was placed on the seat. Then, a baby weighting 10 kg was allowed to sit on the baby seat, and an increase of 0.27 per unit was observed in the capacitance readings. These measurement results indicate promising occupancy detection capabilities of the developed sensing system.

Results obtained for different child seat conditions are presented in Table III. Capacitance values were recorded for Vacant Infant seat (VI), Forward-Facing baby (FF), Rearward-Facing baby (RF), Vacant Booster seat (VB), Booster seat with Baby (BB), booster Cushion with Baby (CB), and ten Beer bottles in a vacant booster cushion seat (BE) conditions. A baby-shaped dummy filled with water weighting 10 kg was used for the investigations. In Table III, $T_{(1,4)}$ indicates the average value $(T_1 + T_4)/2$ of the readings obtained from electrodes T_1 and T_4. Similarly, $T_{(2,5)} = (T_2 + T_5)/2$, $T_{(3,6)} = (T_3 + T_6)/2$, $T_{(7,9)} = (T_7 + T_9)/2$ and $T_{(8,10)} = (T_8 + T_{10})/2$. As can be seen from Table III, for the conditions FF and RF, the capacitance values were increased for the electrodes from the backrest area as compared with the condition VI. This is because of the presence of the baby in the sensing volume and, hence, the increase in capacitive coupling between R and the transmitter electrodes in the backrest of the seat. During condition FF, the head and shoulder portions of the baby rest in between the receiver R and the transmitter electrodes in the backrest area. However, during condition RF, the same sensing volume will be occupied by the legs of the baby. Thus, during condition FF, higher capacitance values compared to those of condition RF were noticed for the electrodes in the backrest area. For conditions FF and RF, due to the shielding effect, the measured capacitance values for electrodes in the sitting area were lower than for condition VI. In the sitting area, the receiver and transmitter electrodes are in the same plane and, due to the presence of infant seats, there is more than 5 cm of vertical distance between the baby and the electrode plane. Thus, the child actually acts as a shield for the electrodes in the sitting area. Similarly, for conditions BB and CB, the electrodes in the sitting area are in shielding mode. Thus, for conditions BB and CB, the capacitance values observed for the transmitter electrodes in the sitting area were lower than the corresponding values obtained for condition VB. Also, for conditions BB and CB, due to the dominant coupling effect, the capacitance values read from electrodes in the backrest area were larger than the corresponding values obtained for condition VB. Readings obtained for ten filled beer bottles kept in the booster cushion seat are also given in Table III. As can be seen in Table III, the electrodes in the sitting area are in shielding mode, while those in the backrest area are in coupling mode. However, the shielding and coupling effects observed for this condition are significantly lower than those for conditions BB and CB, which permits one to distinguish between child occupancy and beer bottles placed in a booster seat or cushion.

TABLE III
CAPACITANCE VALUES OBSERVED FOR VI, FF, RF, VB, BB, CB, AND BE ARE PRESENTED

Test case	Back rest area			Sitting area	
	$T_{(1,4)}$	$T_{(2,5)}$	$T_{(3,6)}$	$T_{(7,9)}$	$T_{(8,10)}$
VI	0.118	0.104	0.123	0.175	0.136
FF	0.151	0.146	0.182	0.109	0.079
RF	0.139	0.131	0.164	0.073	0.094
VB	0.117	0.102	0.148	0.159	0.113
BB	0.162	0.148	0.260	0.101	0.080
CB	0.210	0.178	0.348	0.078	0.091
BE	0.153	0.144	0.158	0.124	0.108

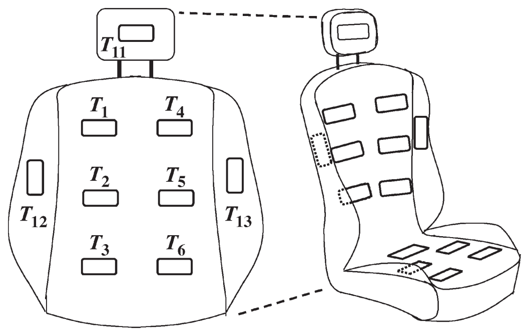

Fig. 12. Pictorial view of an automobile seat equipped with proposed capacitive sensing electrodes. Two additional electrodes T_{12} and T_{13} are introduced in the backrest area of the seat. This provides collateral information that is particularly useful for controlling the firing of window curtain air bags. Typical change in capacitances recorded from the prototype for a test case is shown in Fig. 13.

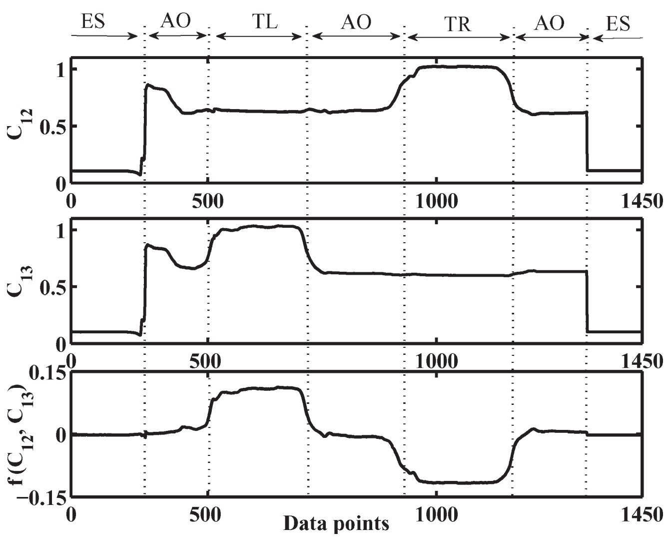

Fig. 13. Change in capacitances were recorded and plotted for ES, AO, TL, AO, TR, AO, and ES in order. C_{12} and C_{13} are the capacitances between receiver R and transmitter T_{12} and T_{13}, respectively. A function $f(C_{12}, C_{13}) = (C_{13} - C_{12})/(C_{13} + C_{12})$ is computed and plotted. The polarity and magnitude of $f(C_{12}, C_{13})$ give an indication of the degree of TL or TR status of the passenger.

The shoulder and head positions of the occupant in the backrest area of the seat are very important as far as the operation of window curtain air bags is concerned. It will be dangerous to deploy window curtain air bags when the passenger is very close to it. In such a condition, the deployment force should be controlled and kept low to avoid possible harmful effects. Thus, the current posture of the passenger, particularly the highly TR and TL conditions, is valuable to meet this demand. The TR and TL conditions can reliably be sensed by introducing two new transmitting electrodes T_{12} and T_{13} as shown in Fig. 12 in the right and left side extensions (wings) of the backrest area of the seat. Let C_{12} and C_{13} be the capacitances between receiver R and transmitters T_{12} and T_{13}, respectively. Whenever the occupant is in position TL or TR, according to the degree of inclination, the occupant's body will get close to the corresponding transmitter segment, and hence, the associated capacitance C_{12} or C_{13} will be increased. This feature has been incorporated in the prototype system and tested. Fig. 13 shows typical variations in capacitances observed during a test cycle for the conditions of ES, AO, TL, AO, TR, AO, and ES in order. A function $f(C_{12}, C_{13}) = (C_{13} - C_{12})/(C_{13} + C_{12})$ is computed and plotted. The polarity and magnitude of $f(C_{12}, C_{13})$ give an indication of the degree of status TL or TR of the passenger. In such an electrode system, the number of transmitting electrodes in the backrest area can be minimized by replacing T_1 and T_4 by an electrode of the same size in the middle of the current positions of T_1 and T_4. The same procedure can be applied to the electrodes T_2 and T_5, as well as T_3 and T_6. In the modified system, the backrest area will only have a single column (instead of two) of three electrodes along with the side electrodes T_{12} and T_{13}.

IV. Conclusion

A simple and cost-effective seat occupancy detection scheme suitable for smart air-bag systems has been developed based on a capacitive sensing principle. The system successfully senses the presence of an occupant. It also detects out-of-position condition of a seat occupant. In the proposed system, the whole measurement is made by using a single receiving electrode and, hence, provides a less-complex measurement method for the occupant sensing system. A prototype has been developed, and its performance for various possible conditions of seat occupancy has been evaluated, proving the practicality of the proposed scheme. The developed system takes up to 200 μs to complete a full set of measurements and, hence, guarantees a dynamic operation of the air-bag system. The measurement principle is based on a carrier-frequency method and uses a lock-in-amplifier technique to obtain the final capacitance values. This technique provides a precise measurement of capacitances and, hence, gives details about the occupancy, even in the presence of external electromagnetic interference.

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