

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  $B_2, \dots, B_{11}$  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  $90^\circ$  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  $100\text{-}\mu\text{m}$ -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

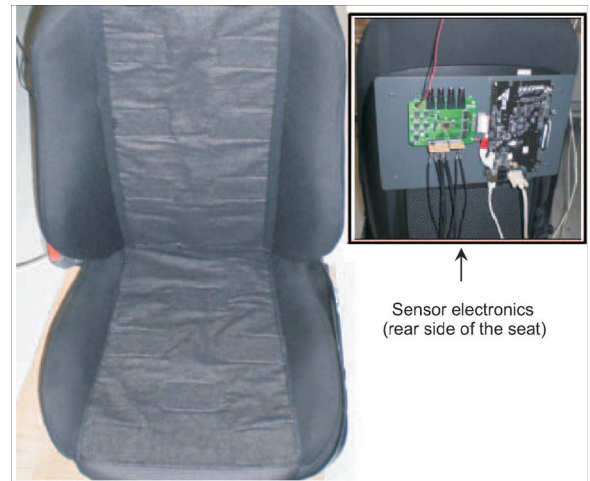


Fig. 9. Automobile seat equipped with prototype capacitive sensing system. Electrodes are stitched to a cotton cloth material and placed in the seat. Associated sensor electronics is fitted in the rear of the seat.

in  $0.25\text{-}\mu\text{m}$  CMOS technology [18], [19]. The principle of operation of the sensor IC is explained in Section II-A.

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  $\mu\text{CLinux}$  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  $18\text{ }\mu\text{s}$ . Thus, a system with 11 electrodes takes roughly  $198\text{ }\mu\text{s}$  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  $\mu\text{CLinux}$  Board, and it can

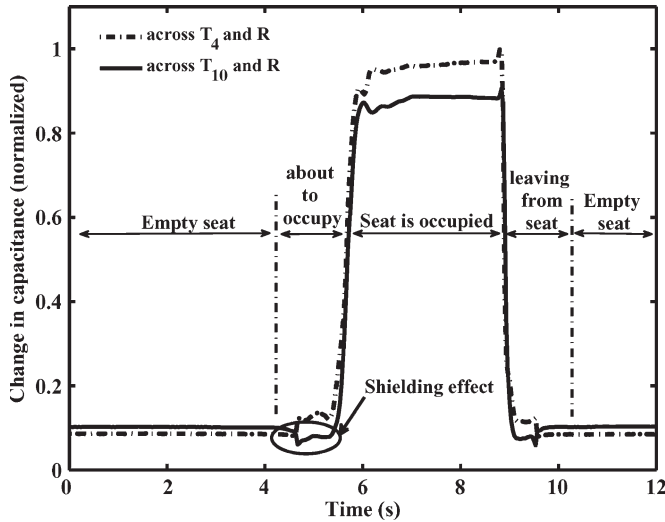


Fig. 10. Typical change in capacitance values observed with the prototype. Capacitance values were recorded between each transmitter and receiver for conditions such as when the seat is empty, when it is about to be occupied by an adult passenger, when it is occupied, and when the occupant is leaving 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  $\mu$ s 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	

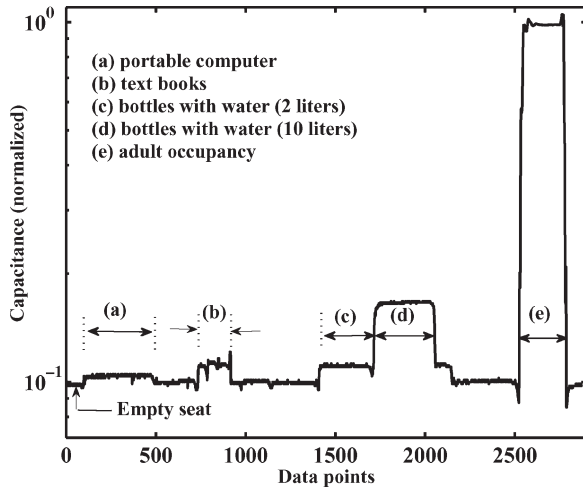


Fig. 11. Capacitance values measured between transmitter segment  $T_3$  and receiver  $R$  for various scenarios. A capacitance measurement is also taken and shown for an AO. The results show that the change in capacitance for cases (a), (b), and (c) are very low in comparison with the change in capacitance 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

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

$T_1$  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.

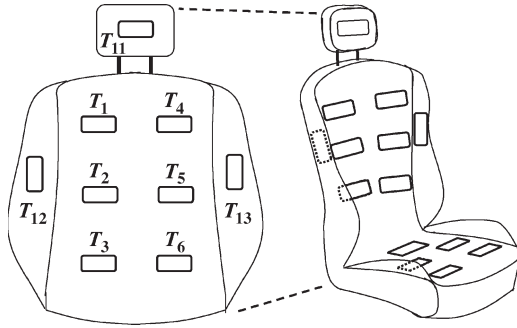


Fig. 12. Pictorial view of an automobile seat equipped with proposed capacitive sensing electrodes. Two additional electrodes  $T_{12}$  and  $T_{13}$  are introduced in the backrest area of the seat. This provides collateral information that is particularly useful for controlling the firing of window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

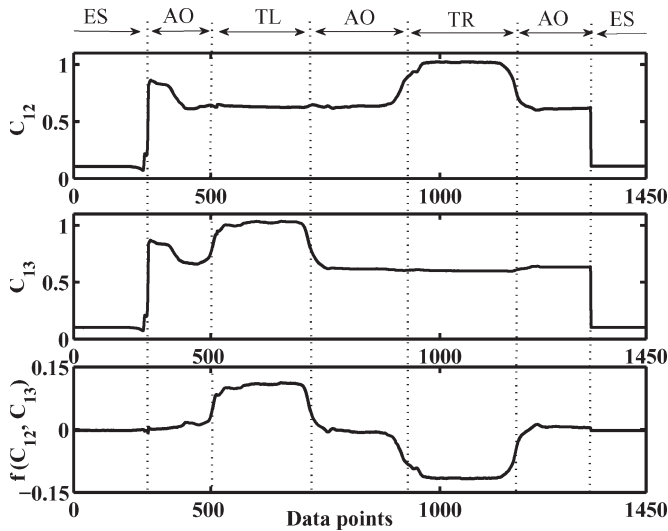


Fig. 13. Change in capacitances were recorded and plotted for ES, AO, TL, AO, TR, AO, and ES in order.  $C_{12}$  and  $C_{13}$  are the capacitances between receiver  $R$  and transmitter  $T_{12}$  and  $T_{13}$ , respectively. A function  $f(C_{12}, C_{13}) = (C_{13} - C_{12})/(C_{13} + C_{12})$  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  $\mu$ s 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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