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

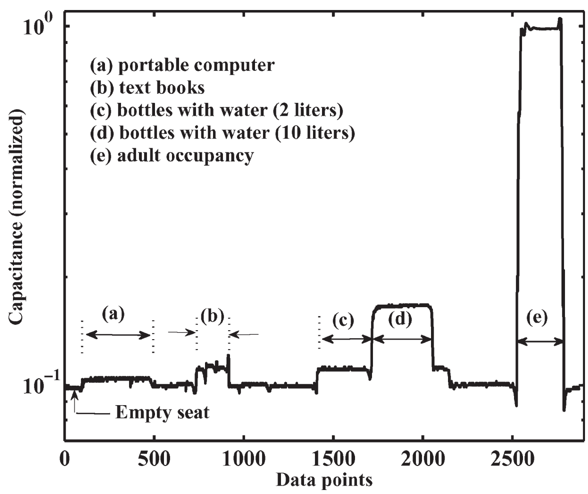

Fig. 11. Capacitance values measured between transmitter segment T_3 and receiver R for various scenarios. A capacitance measurement is also taken and shown for an AO. The results show that the change in capacitance for cases (a), (b), and (c) are very low in comparison with the change in capacitance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

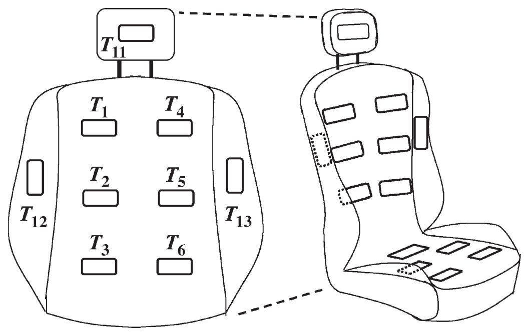

Fig. 12. Pictorial view of an automobile seat equipped with proposed capacitive sensing electrodes. Two additional electrodes T_{12} and T_{13} are introduced in the backrest area of the seat. This provides collateral information that is particularly useful for controlling the firing of window curtain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

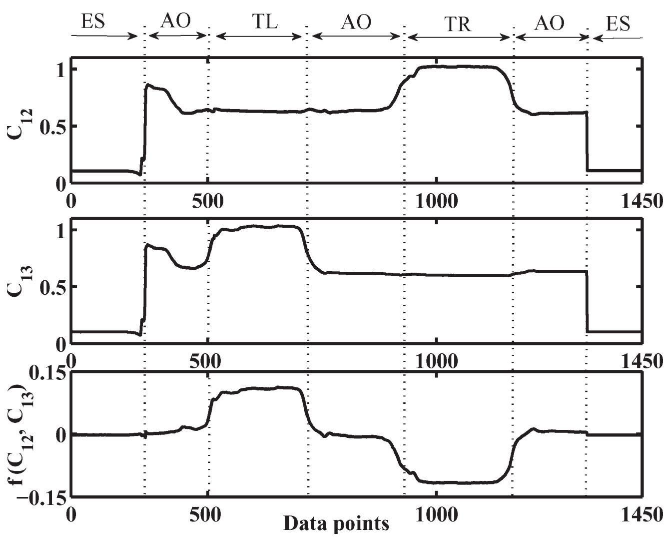

Fig. 13. Change in capacitances were recorded and plotted for ES, AO, TL, AO, TR, AO, and ES in order. C_{12} and C_{13} are the capacitances between receiver R and transmitter T_{12} and T_{13}, respectively. A function $f(C_{12}, C_{13}) = (C_{13} - C_{12})/(C_{13} + C_{12})$ is computed and plotted.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