ADVANCED OCCUPANT DETECTION SYSTEM: DETECTION OF HUMAN VITAL SIGNS BY SEAT-EMBEDDED FERROELECTRIC FILM SENSORS AND BY VIBRATION ANALYSIS

Pierre Orlewski
CRP Gabriel Lippmann
Laurent Federspiel
IEE SA
Luxemburg
Mark Cuddihy
Manoharprasad Rao
Ford Motor Company,
Stephen Fuks
IEE Sensing Inc.
USA
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ABSTRACT

The concepts of human seat occupancy detection and driver's drowsiness monitoring require a sophisticated, sensing technology capable of capturing human vital signs in a reliable manner. The concept discussed in this paper may help enable the development of future systems capable of detecting an occupant in a seat.

The present study explores the feasibility of detecting humans based on a polymer sensor fitted into the seat cushion and capable of capturing human vital signs. A bulk, polypropylene ferroelectric film has been charged and polarized in a strong external electric field prior to the sensor assembly. The resulting 323 sq cm sensors displayed a high piezoelectric d33 coefficient of approximately 200 pC/N, considerably higher than vibration sensors made of PVDF or PVDF-TR piezoelectric films. This type of electroresponsive polymer has been used for medical respiration, heartbeat and epileptic seizure monitors.

We employed dedicated, microprocessor-based electronics including charge and variable gain amplifiers and 4th-order anti-aliasing filter for data collection. Three different types of algorithms have been fitted or developed and tested: i) a commercial medical monitor with estimation of respiratory and heart beat rates, ii) a signal extraction, filtering and matching wavelet-based algorithm for vital sign detection and (iii) a frequency domain, 2nd-order classifier for humans/objects, using knowledge-based discrimination.

Experimental data involved a minimum of 20 human subjects ranging from a 5-month old infant in a child restraint to a 95^{th}%ile male, both in fully static (sleeping like) and non-static scenarios. Recordings using test loads and a pack of water bottles were also collected as the counterpart to the passengers.

Human-specific presence detection and discrimination from objects by detection of vital signs was achieved within a relatively short detection time in this conceptual study. Infants and small children were placed in dedicated child restraint seats (CRS) and not moved during the data collection, thus simulating sleeping children. All subjects were detected typically within a 20 seconds sampling interval. In a few cases and with additional time, their respective signals could be extracted from collected data as confirmed by a medical monitor used in parallel.

INTRODUCTION

The concept of human seat occupancy detection requires a sophisticated, sensing technology. Any proposed solution should be capable of quickly and reliably capturing and analyzing data to identity characteristics of the human body (such as vibration frequency eigen-values) and human vital signs (such as respiration rate and/or heart beat). The constraint of seat-specific detection rather than entire vehicle interior monitoring implies the use of seat-embedded sensors. This brings additional functional restrictions of sensor size and materials as directly impacting the seating comfort, seat designs and seat manufacturing process. For all those reasons, the use of thin, electromechanical polymer was the approach investigated in this study.

SENSOR TECHNOLOGY

Over the past decade a lot of research has been carried out on multilayer electret films extruded from various polymer materials like polyethylene (PE), polystyrene (PS), polyurethane (PU), and polyethylene terephtalate (PET). Those successfully brought to the large scale commercial applications included polytetrafluoro-ethylene (PTFE), polyvinylidene fluoride (PVDF) and its copolymer (PVDF-TR) and more recently a porous, monolayer polypropylene (PP) film [1,2,3]. Even employed in relatively slim thickness of 90µm, the latter displays excellent sensitivity in the 130 - 200 pC/N range and at vibration frequencies spanning from 1 to 150 KHz. Those principal characteristics, together with the simplicity of the sensor setup, as well as its cost effectiveness, made this intrinsically sensing material attractive for slim acoustic and photoacoustic transducers [4], paramedical, patient in bed monitoring [5], vital sign monitoring including both, respiration rate and heart activity [6] and recently for the wireless ballistographic chair [7]. Detectors built with such a ferroelectric material are transient state sensors reacting only on transient compression or release and are insensitive to the constant force or load applied to its surface.

INITIAL PROOF OF CONCEPT

In the early part of our study we employed an A4-size electromechanical sensor including a 90µm polypropylene EMFi film (Emfit Ltd.) and two bottom and top PET layers, both covered with ca. 6 µm screen-printed silver paste. All three layers have been assembled using double-sided bonding spacer (3M) exclusively applied to the contour of vibration sensitive PP layers. It allowed a stable electrical contact between the sensing layer and the conductive electrode paste and finally a direct charge change measurement instead of a capacitive measurement, which is generally noisier. An additional silver and dielectric double-layer was printed on top of one PET film to protect the sensor from external electromagnetic disturbances (shielding). The sensor was simply deployed on horizontal portion of the vehicle rear bench. It was interfaced to the DAS1000 data logger via original electronics used for a para-medical bed exit and seizure monitor supplied from Emfit Ltd (Finland). Initial testing included a sample of 3 adult male passengers covering the range from 50th- 95th percentile and a variety of objects up to the weight of approximately 15kg, supposed to be transported on the rear bench seat. Our attention was initially focused on two major questions: (1) Would it be possible to extract human vital signals captured by the sensor exclusively fitted to the seating portion of the vehicle bench seat (no backrest sensor present), while the vehicle is operating at low vibration noise conditions (parked with engine on or cruising on smooth paved roads)? (2) Would it be possible to use this information for a robust discrimination of human passengers from transported cargo? Collected vibration time-domain data has been denoised by using classical Coiflet's wavelets [8] with universal thresholding method as proposed by Donoho and Johnstone [9].

Each human test subject was monitored for 60 seconds of steady seating at a sampling frequency of 1 kHz. A reduced sample of 32 seconds was used for analysis in order to avoid the bias from initial and continuing compression of seat materials. As shown on Figure 1 below, we were able to extract a quite regular and reliable vital sign signal especially from steady vehicle with engine on. Signal periodicity coincides well with the typical human respiration rate and a higher frequency component, probably in relation to the heart beat, is clearly perceptible on the top of every peak.

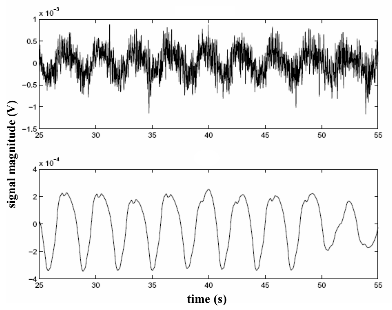

Figure 1. Vital signals from 50%ile male passenger in steady vehicle with engine on: raw signal (upper) and extracted human respiration after wavelet denoising (bottom).

A similar approach, except with 2 (backrest and seat cushion) ferroelectric EMFi sensors fitted to an office chair, and a wavelet analysis has been adopted in the past by Postolache et al. [6] for a remarkably good separation of respiration signal embedded in the heart rate ballistocardiogram (BCG).

Test conditions and sampling

For the setup of a discrimination algorithm, a larger data set has been collected consisting of a 5 x 32 data series recorded in a non-moving vehicle with the engine ON and OFF. The test series included 4 objects (5, 10, 15kg load stamps and a 9L 6x1.5L water pack), 3 adult males and 1 empty seat, every sequence being repeated twice. The second set of data was collected while the vehicle was cruising. It totaled 5x16 data series (incl. 2 repetitions) from 4 objects, 3 humans and 1 empty seat. The third set of data (2x48) has been collected in similar conditions as previously described but with intentionally aged sensors. Finally, 40 data series were collected while the vehicle was traveling at 70 km/h on very smooth paved road and at 50 km/h on a paved but non-smooth road. From the total number of 371 useable vibration profiles (out of the first 376 recordings, 5 were damaged), 144 profiles were used in algorithm setup and discrimination training while the remaining 227 were used in further testing.

Discrimination Algorithm

A three-step discrimination algorithm was established. In the first step a data sequence of an arbitrarily selected 50th percentile male test subject was collected in a steady vehicle with engine on. After extracting a 32.7sec window and performing wavelet decomposition, the noise was removed from the signal using universal hard thresholding. A representative *physiological pattern* was manually picked up from the cleaned signal. In the second, still off-line stage, all 144 test sequences were employed in a setup of the *training database* (Fig.2). The following wavelet-based signal denoising and reconstruction, autocorrelation, correlation with physiological pattern and FFT analysis, resulted in 5 primary signal characteristics (max DSP frequency, max DSP value, max FFT frequency, max FFT value and max correlation with physiological pattern). These physical signal parameters were then converted to a set of classification features among which, the barycentres (centers of mass) of the Human and non-Human (cargo or empty seat) clusters were the most prominent classifiers.

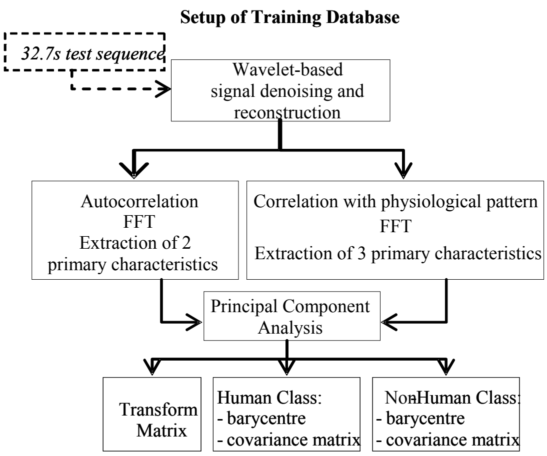

Figure 2. Off line setup of Training Database.

In the on-line phase, every incoming, “unknown” vibration sequence from the 227 testing data sets was submitted to exactly the same wavelet denoising procedure as previously employed with the training sequences.

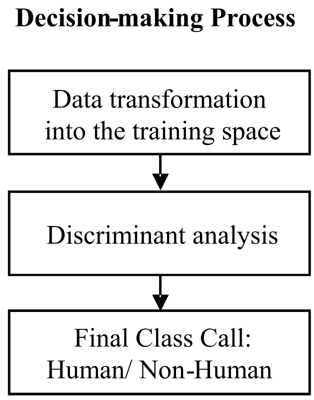

Figure 3. On-line decision-making process.

After data transformation into the training space, the final (Human or non-Human) discrimination call (Fig. 3) was issued from Discriminant Analysis (DA). The prevalent discriminators in the DA were the respective distances to the human and non-human class barycentres and the likeness to the canonical *physiological pattern*. The overall human / cargo (or empty seat) discrimination performance during this part of the study reached 93.5% of correct decisions. As expected, most of the errors (false positives) came from driving scenarios, while non- detection (false negatives) errors resulted exclusively from testing with parked vehicle (Tab.1). This result was obtained without any *a priori* knowledge about the state of vehicle (stationary or moving). In real life, this information may be retrieved from the vehicle CAN bus which would improve the performance. In the present study, use of this information improved the final discrimination, with up to 98.8% of the decisions correctly classified.

Table 1.
Confusion matrix of the final discrimination: FN–false negatives, FP–false positives.

	Steady vehicle with engine ON	Cruising vehicle
FN	5	0
FP	0	17
Total	224	112

In this conceptual study, extraction of the vital signs from the electromechanical film sensor fitted into the vehicle seat cushion was achieved, even in presence of relatively large vibration noise background generated by a moving vehicle. It was realized that with currently available sensor technology, one needs to address also other human body characteristics for the robust discrimination over the large number of passengers and objects potentially carried in the rear seats and to cover real-world driving scenarios (e.g., road quality, vehicle velocity and acceleration, types of chassis)

DETECTION TRIALS OF TODDLERS AND INFANTS

One of the sensors employed in the previous study was fitted into the rear bench seat with thick foam trim. We used both the original electronic interface for paramedic vital sign monitoring (from Emfit Ltd., Finland) and its modified version with reduced amplification gain. The principal point of interest was the feasibility of vital sign capture and detection of infants installed in a CRS. All tests were made with a rearward-facing class 1 child restraint seat and with a forward facing seat (Fig. 4). Two infants (4 and 5 months old) and two toddlers (22 and 24 months old) were involved in detection trials in a parked vehicle with the engine off. These tests were conducted during the winter period, with the children warmly dressed. The thick clothes constituted an additional damping factor of the vital signals supposed to propagate through the base of the CRS. As at this stage we were exclusively interested in vital signs, all of children were encouraged to stay motionless, simulating a sleeping child scenario.

Figure 4. Detection trials with child restraint seats (from left to right 4 month old infant in rearward-facing seat and 22 month old toddler in a forward-facing seat)

All tests were repeated at least 5 times with both types of electronic interface. With the original Emfit interface setting, typically 20 seconds were required to detect vital signs within preset signal robustness and quality requirements. Even with the inevitable high frequency movements of the children, the software was able to yield realistic, average heat beat rates of approximately 115 beats / min and 90 beats / min respectively for the infants and for toddlers. Trials with modified electronics and modified amplification gains and filtering parameters accelerated the detection of vital signs down to approximately 15 sec (toddlers) and 10 sec (infants) but computed heart rates were unrealistically low.

This assessment demonstrated the conceptual feasibility of detection of infants with a very sensitive vibration sensor installed in the car seat, with both ballistocardiograph and respiration signals of acceptable quality. The “child detected” decision exclusively relied on vital signals and did not account for other captured signals, generated by small body movements of the children. Additionally, in order to detect a child with this conceptual approach, a sensor-CRS contact surface is necessary and complete absorption of vibrations within a physiological frequency range from 0.1 to 2.0 Hz by the CRS cannot occur.

TOWARDS A VERSATILE INTELLIGENT PEOPLE DETECTOR IN THE VEHICLE SEATS

Although conceptual feasibility was shown in laboratory testing, the robustness of in-vehicle occupant detection by vital signals will be limited in the real-world driving due to the vibration noise. Therefore, human vital signs cannot be the exclusive detection target and must by accompanied by another “human factor”, well distinguishable from the surrounding vibration background of a moving vehicle. Such a physical entity, moderately influenced by chassis vibrations, is apparent mass resonance frequency of the human body, which significantly differs from empty seat and seat cargo resonance frequencies (Fig. 5 and Fig. 6).

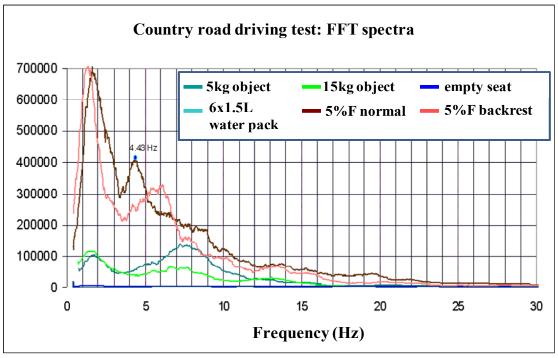

Figure 5. Frequency spectrum of 5^{th}%ile female and of seat cargoes up to 15 kg during 50 km/h cruising on smooth road.

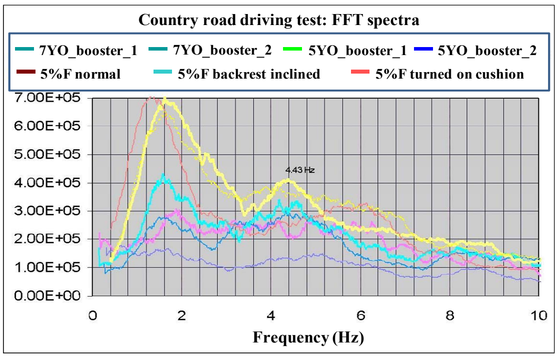

Figure 6. Frequency spectrum of 5th%ile female (various seating postures) and of 5&7 YO children seated on booster seats during 50 km/h cruising on smooth road.

In the test cases using human occupants, a 5th percentile female adopting different seating postures and 5 and 7 year old children in booster seats, the human mass resonance peaks at approximately 4.43Hz and is perceptible and in agreement with data found in the literature [10,11]. In contrast, the resonance frequency of unanimated seat cargo peaks at higher frequencies, starting from 7-8Hz on and thus allows for the human /non-human seat occupancy discrimination.

Dual mode discrimination strategy and new algorithm setup

After basic detection assessments were conducted both in parked and in moving vehicles, the focus was shifted to the dual mode detection scenario. The magnitude of the vehicle chassis vibrations was selected as the trigger between vital signals and apparent mass vibration characteristics in the dedicated algorithm (Fig. 7). For study, the vehicle vibration noise level was assumed to be known, which in practice is achievable in the vehicle either by retrieving this information from the CAN bus or by installing a dedicated, vertical accelerometer.

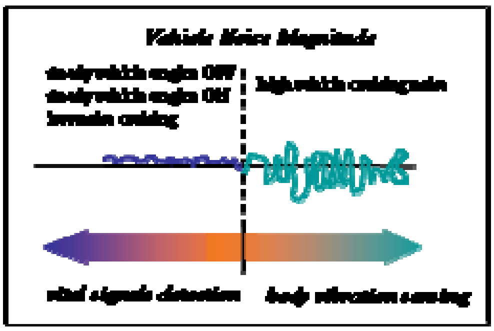

Figure 7. Dual mode discrimination strategy triggered by vehicle's noise magnitude.

The sensors (Fig.8) were modified and their sensitive surface was reduced to ca. 323 cm^2 in order to fit 3 places of a sedan rear bench seat.

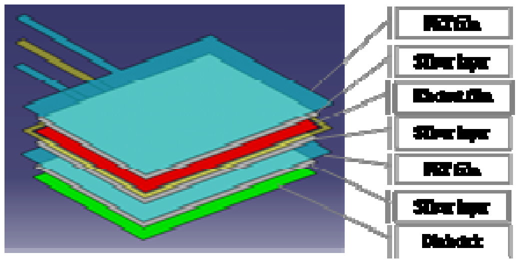

Figure 8. Electromechanical sensor setup with 90µm porous polypropylene ferroelectric film (length: 214 mm, width: 152 mm, thickness: 370 µm).

All three sensors fitted into the rear bench were quasi-simultaneously controlled by an electronics module specially developed for this purpose. It included (Fig.9) a 12 bit Field Programmable Gate Array microprocessor (µC), a 3-channel multiplexer (MUX), a 12 bit ADC converter, charge- and variable gain amplifiers and a 4th-order antialiasing filter. All data was stored on the laptop PC hosting the graphical user interface. The discrimination software operated alternatively in the real-time and in the off-line mode.

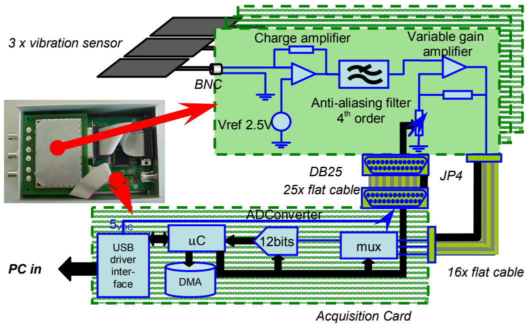

Figure 9. Block diagram of acquisition electronic interface.

A new, dedicated algorithm was developed, different from the computation-intensive algorithm with wavelet filtering used in the initial proof of concept. It involved several discrete discrimination features computed both from the time domain and frequency domain spectra, depending on the vehicle noise magnitude (a major feature trigger) and specifically addressing vital signs and/or vibration properties of the human beings. Current front outboard seat belt reminder systems emit their warning within 30-60 seconds. For this reason, we limited a spectral window to only 8 seconds in order to be able to collect and average the discrimination status over at least 3 samples.

During the algorithm setup (training) and validation, data was collected with both a parked vehicle (engine on and off) and with a vehicle moving with three different velocities (50, 70 and 90 kph) on three types of roads (smooth paved, rough paved and gravel roads). The human test subjects (collected with 2 to 5 repetitions) were: 95th and 50th percentile adult males, 5th percentile female, 3 and 6 year old children sitting on booster seats. A few tests also involved additional objects like a thick blanket or wooden comfort mat. The cargo transported on the seat included 5, 10 and 15 kg metal load stamps, 6x2L water containers and a 5 kg backpack. The data from the empty seat was also collected.

In total, the performance validation sample consisted of not less than 153 tests repeated up to 8 times, which resulted in more than 163 hours of elapsed testing time. Final performance evaluation was run with 8 second samples without any higher level decision, smoothing or filtering. Thus, the system was required to classify the occupant within 8 seconds for performance evaluation.

Results and discussion

The parked vehicle discrimination evaluation was performed with motionless passengers and separately with passengers behaving normally (moving) on the seat. The test population included various adults as well as 6 year old children on boosters. The test cargo was manually agitated by the test operator during the moving testing scenario, which had a significant impact on the sensor response (Tab.2).

Table 2.
Discrimination performance in parked vehicle with engine on and with steady and moving seat occupants. Decision exclusively based on algorithm features addressing human vital signs.

SEAT OCCUPANT	Steady	Moving
adults	100%	100%
Children on boosters	75%	92%
cargo	92%	20%

In many cases of manually agitated seat cargo the signal was saturated to the point that precise occupancy discrimination was no longer feasible, except for the classification of an occupied seat. According to this logic, the detection of empty seat and occupied seat has reached 100% performance. In both, steady and moving passenger scenarios in the vehicle with engine on, the system seemed to reach its detection limit for 3 year old children seated on booster seats. With the engine off, this limit seemed to be much lower but was still very dependent on the design and materials of the CRS hosting the child.

More exhaustive, driving tests conducted with a Ford Taurus covered 3 different vehicle velocities and 3 different road types.

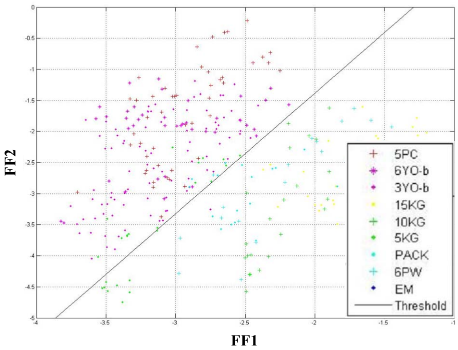

Figure 10. Example of discrimination among the most critical occupants from the last test campaign. Three different road styles and vehicle velocities of 50, 70 and 90 kph.

As vehicle vibrations become more prominent, seat occupancy discrimination occurred principally through the algorithm features addressing human body vibration properties and less via vital signs. Figure 10 depicts separation achieved by two principal "dynamic" features FF1 and FF2. There were very few issues with classification of the 5th percentile female, but signals generated by 3YO children in boosters were usually below the preset sensitivity threshold, and are therefore not shown in the Table 3 below.

Table 3.
Estimated discrimination performance in driving test with static passengers.

SEAT OCCUPANCY		Smooth paved road		Rough paved road		Gravel road	
		Car seat	boosters	Car seat	boosters	Car seat	boosters
Human	5th%ile female	100%	-	100%	-	100%	-
	6YO child A	-	91%	-	100%	-	97%
	6YO child B	-	78%	-	100%	-	85%
Cargo	Backpack	100%	-	63%	-	88%	-
	9L water pack	100%	-	41%	-	100%	-
	10kg stamp load	67%	-	71%	-	100%	-
	Empty seat	100%	-	100%	-	100%	-

The performance was moderately affected by the quality of the road, with the rough paved road being the most difficult for cargo discrimination. Also, additional objects in the seat (thick blanket, wooden comfort mats) and occupant motion (still, moving) seemed to have little influence on the spectra of adult passengers (Fig. 11).

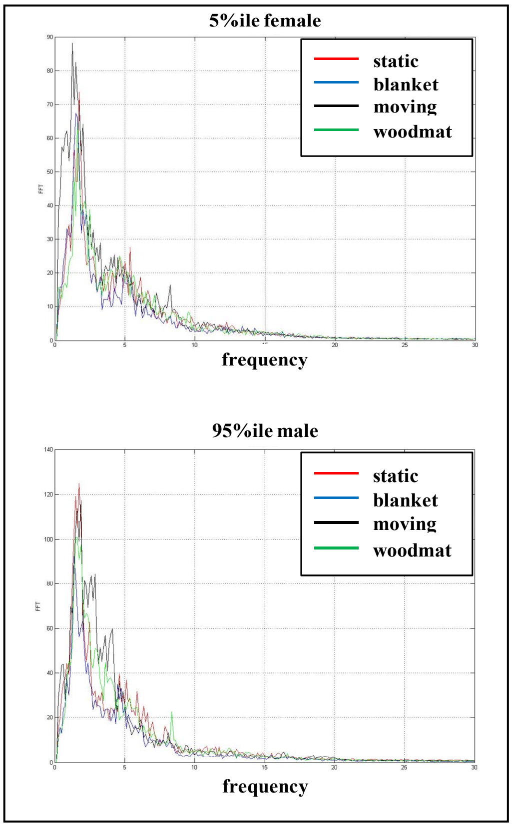

Figure 11. Seat resonance spectra of 5th percentile female (top) and 95th percentile male (bottom) sitting on other objects (blanket, wooden mat).

OUTLOOK

This study suggests some limitations of the concepts evaluated due to the core functional material employed. Additional research is necessary to evaluate these shortcomings in more detail.

The ultrasensitivity of the highly porous, charged polymer led to detection performance reduction as far as vehicle rear seating positions are concerned. Seating position which are not physically separated or at least, not mechanically decoupled will have the potential to generate vibration crosstalk in case of simultaneous bench occupation by passenger(s) and by cargo. The latter can then be misclassified as a human being.

The stability of the sensitivity over a broad temperature range for the material evaluated in this study has not been demonstrated. Preliminary analysis of deliberately degraded (aged) sensors suggests that a minimum sensitivity of 50-80 pC/N would have to be preserved over the seat and sensors lifetime to guarantee successful detection of human vital signs. The current ferroelectric material will probably not meet these requirements as it is based on polypropylene film injected with nitrogen and corona charged air pockets, which seem to progressively lose their charge and polarization in temperature ranges above 75°C. Therefore it will be necessary to investigate alternative materials further in view of an application in automotive environment.

CONCLUSIONS

This paper describes the use of a conceptual electromechanical, ferroelectric polymer for advanced occupant detection and occupancy discrimination in a variety of vehicle scenarios.

It also demonstrates the possibility of the capture of human vital signals (especially respiration) by the detector fitted into the seat cushion. A means to address the limitations caused by chassis vibrations is presented.

Based on this study, further research into the utilization of ultrasensitive vibration sensor as an occupant detection technology is warranted. If researchers can address the material-related limitations, this technology may become a viable approach to monitoring human body physiological characteristic in a motor vehicle environment.

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