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PEDESTRIAN DETECTION USING AN ACTIVE ACOUSTIC ARRAY EMBEDDED IN A CAR

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ABSTRACT

Automatic pedestrian detection in vehicles is crucial for Advanced Driver Assistance Systems (ADAS), but current sensors (cameras, radars, and lidars) lose performance in low visibility conditions, such as at night, in smoke, or fog. This study validates the use of a 150-MEMS (Micro-Electro Mechanical Systems) microphone active array integrated into a conventional car in real urban traffic conditions. The system operates in real-time with a detection rate of 8 detections per second. Along with beamforming, Constant False Alarm Rate (CFAR) detection, and lane detection algorithms, a crucial algorithm has been incorporated to discriminate pedestrian detections from false alarms caused by road imperfections. With 6000 captures performed at 30 km/h, the typical speed in urban environments, the system detected pedestrians at distances between 5 and 20 meters, with a detection probability of 0.91 and a false alarm probability of 0.01. The results demonstrate that active acoustic arrays are effective for pedestrian detection and position estimation in urban environments. Fusion with current systems would improve vehicle safety by reducing possible pedestrian collisions, especially in low-visibility conditions, thus enhancing overall safety.

Keywords: *Pedestrian detection, MEMS microphone array, onboard system, moving vehicle.*

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1. INTRODUCTION

The widespread use of road vehicles results in approximately 1.35 million traffic accidents annually, with 23% involving pedestrian fatalities, leading to over 300,000 deaths each year [1]. The automotive and transport sectors are actively working to reduce these numbers, especially in urban environments where pedestrian presence is higher. The development of autonomous cars has further boosted the search for solutions to this problem.
Over the past decades, many vehicles have been equipped with Advanced Driver Assistance Systems (ADAS) to improve comfort, efficiency, and safety. One such system, Autonomous Emergency Braking for Pedestrians (AEB-P), focuses specifically on pedestrian detection [2-4]. However, current detection systems based on RGB cameras are only effective under adequate visibility conditions.
To address this limitation, various studies have explored alternative detection systems, including infrared sensors [5], LIDAR [6], ultrasonic sensors [7] and radars [8], as well as systems that fuse RGB cameras with other detection technologies [9, 10]. The work presented in this paper proposes using an acoustic array mounted on a moving vehicle to detect pedestrians, leveraging the advantage that acoustic systems are not impaired by reduced visibility.

2. SYSTEM DESCRIPTION

The acoustic system developed for pedestrian detection has the next characteristics, that can be observed in Fig. 1:

- It is mounted on the front part of the vehicle to detect pedestrians in the vehicle's path.
- Based on the RADAR principle, it generates an acoustic signal using a HPC tweeter, which is reflected off pedestrians.

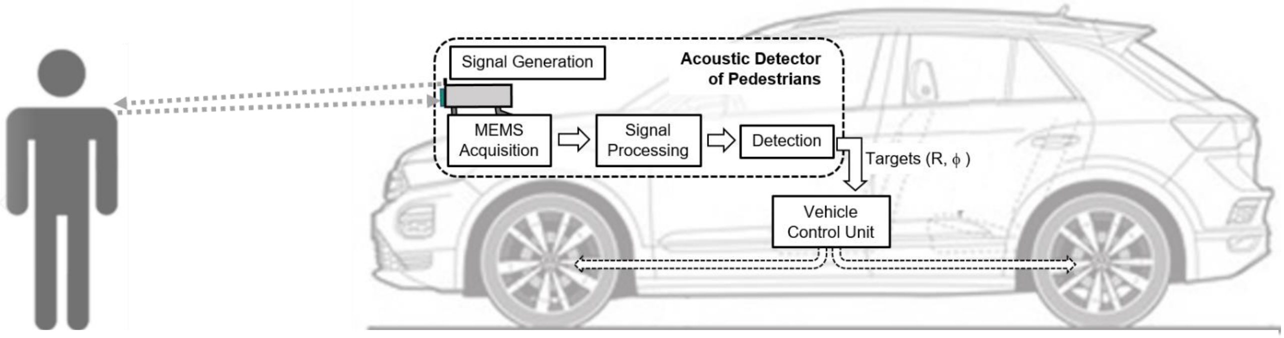

Figure 1. System block diagram.

- The reflected signal is captured by an array of digital MEMS microphones. The array consists of 5×30 MEMS microphones uniformly spaced every 0.9 cm.
- The 150 acoustic signals captured by the microphones are processed using a Delay & Sum beamforming algorithm to generate discrete beams covering the vehicle's path. Relative maxima of each beam are identified, focusing on potential targets within the detection lane. These detections are then validated.
- Upon detection, the system communicates with the vehicle's control unit to alert the AEB system or the corresponding ADAS system. The pedestrian detection system is designed to work effectively within urban speed limits.

The base unit of the processing and detection subsystems is a National Instruments sbRIO 9629 board, which includes an FPGA Artix-7 200T and a Quad-Core Intel Atom processor that allows the system to work in real time by means of distributing the internal algorithms among the processing units included in the sbRIO 9629 card, as shown in Fig. 2.

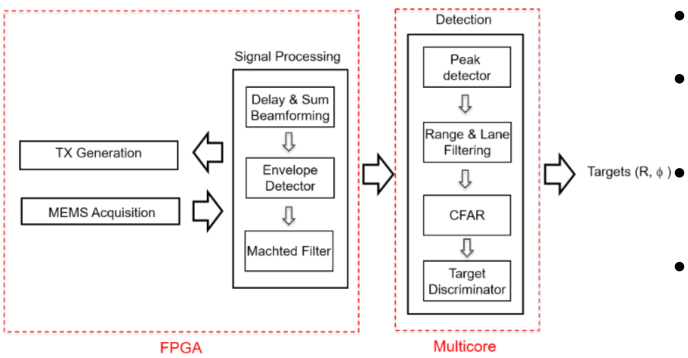

Figure 2. Processing algorithms.

The specific blocks implemented in the FPGA are:

- Transmission Block: that synthesizes and transmits pulsed acoustic signals using a HPC tweeter for signal transmission. The transmitter generates two analog pulses separated by a preset value to help discriminate between signals from the transmitter and external sources. The transmitted signal is repeated every 125 ms, allowing the detection of targets at a maximum distance of 21 meters.
- Acquisition Block: Synchronously acquires the 150 signals received by the MEMS microphones.
- Signal Processing Block: Mixes the signals captured by each microphone using a Delay & Sum algorithm followed by an evelope detector and a matched filter and generates a set of 17 discrete beams equispaced in azimuth 3º covering from -24º to 24º containing information from each pointing direction.

These beams are transferred to the main memory for further processing in the Atom cores included in the sbRIO board where the the detection block is implemented in order to identify and validate target detections by means of four subsystems:

- Peak Detector: Identifies relative maxima in each beam that exceed a minimum detection threshold.
- Range and Lane Filter: Eliminates targets outside the detection range (5 to 21 meters) and lane width (typically 4 meters).
- CFAR Detector: Analyzes the energy adjacent to detected maxima to generate an adaptive threshold for validation.
- Target Discriminator: Validates detections by checking for two consecutive pulses, reducing false alarms caused by road noise.

Figure 3. On-vehicle system installation.

3. SYSTEM VALIDATION AND TEST

Although in a possible final system, the array and processing system would be integrated into the car, in order to carry out the system tests, a compact system has been developed, with all its components included in a box that is placed at the front of the vehicle, as it is shown in the diagrams and photographs in Fig. 3.

3.1 Test setup

The system was tested in a real scenario on a 2-lane avenue with a width of 8 meters and a length of several hundred meters, allowing the vehicle to travel at a constant speed. The test setup included:

- Pedestrian Placement: Two people were positioned 25 meters apart on the right edge of the lane to increase the number of detections per pass. For safety reasons, the pedestrians remained stationary.
- Vehicle Speed: The vehicle traveled at a constant speed of 30 km/h, managed by the car's speed control system.
- Test Sessions: The vehicle made a total of 200 trips, performed in 5 sessions, with a cadence of 8 acoustic images per second.
- Data Collection: A differential GPS with RTK was used to obtain the position of the vehicle for each acoustic capture. The range between the car and the pedestrian was calculated based on the known fixed position of each pedestrian.

3.2 Qualitative results

Fig. 8 shows the detections for a specific trip in front of pedestrian P1. On the left, 6 images equispaced in range have been selected showing the pedestrian position as the car approaches. The left side of the figure the detections are displayed as blue dots in Cartesian coordinates, while the steering angles of the beams where they have been detected are represented by red dashed lines.

It can be observed that as the pedestrian is closer to the vehicle, the steering angle increases from 6º to 24º. Logically, since the beams are defined in 3º intervals, there is an error in the estimation of the X coordinate. These errors have been taken into account when defining the lane filter parameters.

Taking in account the travel speed, the pedestrian is detected between 14 to 15 times for each vehicle pass

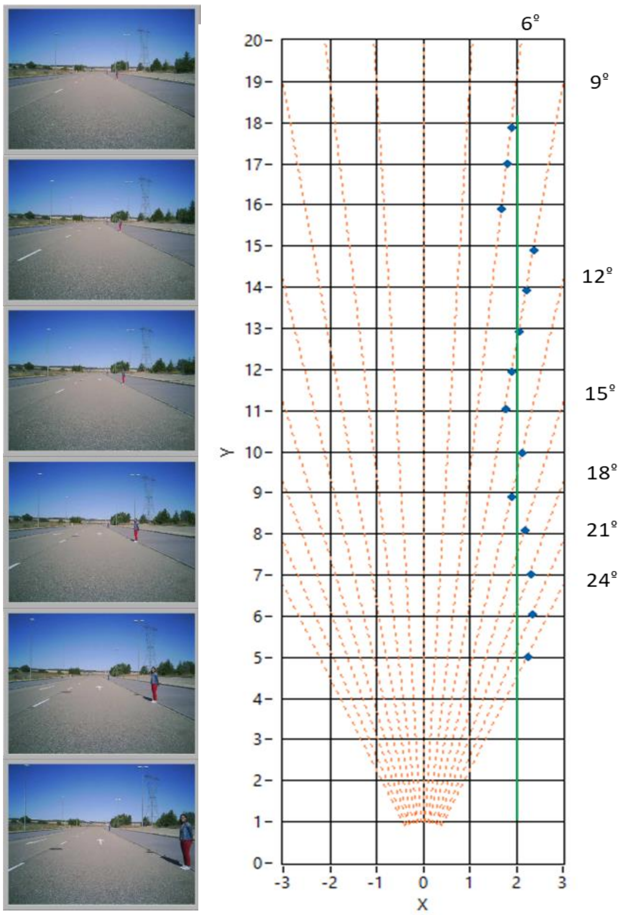

Figure 4. Detections for a specific trip.

3.3 Quantitative results

During the 200 trips of the vehicle 5690 captures were obtained, resulting in 5225 detections, of which 5165 were correct and 60 were false alarms. Based on these experiments, the detection probability (Pd) and false alarm probability (Pfa) estimated were a Pd=0.91 and a Pfa=0.011.
A detailed analysis of the Pd and Pfa as a function of the distance of the pedestrian has been carried out within a range of 5 to 21 meters, defining 7 intervals of 2.5 meters each, with the last interval being 1 meter wide. The results are shown in Table 1.

Table 1. Detection and false alarm probabilities for pedestrians at different ranges.

Pedestrian range (m)	**Pd**	**Pfa**
5-7.5	0.80	0.014
7.5-10	0.87	0.016
10-12.5	0.90	0.006
12.5-15	0.92	0.008
15-17.5	0.97	0.007
17.5-20	0.97	0.010
20-21	0.92	0.018
Total	**0.91**	**0.011**

It is observed that the probability of detection decreases for close ranges where the clutter associated with the road is very significant as well as for far ranges where the reflected pulse energy is lower. In relation to the false alarm probability, it increases for close ranges due to the presence of the clutter as well as for far ranges, where the signal to noise ratio (SNR) is lower.

4. CONCLUSIONS

A pedestrian detection system based on an active acoustic array has been thoroughly evaluated under real operating conditions, that is: mounted on a vehicle moving in an urban environment, with real-time processing and taken in account real conditions such as rolling noise, engine sound, clutter, and road imperfections. The feasibility of the system under real conditions has been revalidated with the obtained the detection (Pd) and false alarm (Pfa) probabilities.

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] World Health Organization, Technical Documents. WHO: Geneva, Switzerland. *Global Status Report on Road Safety 2018*: Summary

[2] BJ. Kim, SB. Lee: “A Study on the Evaluation Method of Autonomous Emergency Vehicle Braking for Pedestrians Test Using Monocular Cameras”, *Appl Sci*, 2020;10(13):4683.

[3] A López-Rosado, S. Chien, Li, Q.Yi, Y. Chen, R. Sherony: “Certainty and Critical Speed for Decision Making in Tests of Pedestrian Automatic Emergency Braking Systems”, *IEEE Trans Intell Transp Syst* 2017;18(6):1358-1370.

[4] HK. Le, SG. Shin, DS.Kwon: “Design of emergency braking algorithm for pedestrian protection based on multi-sensor fusion”, *Int J Automot Technol* 2017;18:1067–1076.

[5] Z. Wang, J. Feng, Y.Zhang: “Pedestrian detection in infrared image based on depth transfer learning”, *Multimed Tools Appl* 2022;81:39655–39674.

[6] RC. Miclea, C. Dughir, F. Alexa, F. Sandru, I. Silea: “Laser and LIDAR in a system for visibility distance estimation in fog conditions”, *Sensors* 2020;20(21):6322.

[7] T. Schlegl, T. Bretterklieber, M. Neumayer, H. Zangl: “Combined capacitive and ultrasonic distance measurement for automotive applications”, *IEEE Sens J*, 2011;11:2636–2642.

[8] I. Gresham, A. et al.: “Ultra-wideband radar sensors for short-range vehicular applications”, *IEEE Trans Microw Theory Tech* 2004;52:2105–2122.

[9] ZA. Shaikh, D. Van Hamme, P. Veelaert, W. Philips: “Probabilistic Fusion for Pedestrian Detection from Thermal and Colour Images”, *Sensors* 2022;22:8637.

[10] P. Wei, L. Cagle, T. Reza, J. Ball, J. Gafford: “LiDAR and camera detection fusion in a real-time industrial multi-sensor collision avoidance system”, *Electronics* 2019;7(6):84.