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Ultrasonic Sensor System for Detecting Falling Objects on Railways

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Abstract

The current rail security rules require, more and more, the automatic detection of possible obstacles on tracks, above all in areas where a large probability of alive beings intrusion or falling objects exists. In this paper an ultrasonic sensor system is proposed for this aim, paying special attention to the signal coding and processing. This signal coding, based on the use of complementary sequences, makes the system robust against atmospheric turbulence, the phenomenon which turns out to be the most problematic when transmitting ultrasonic waves outdoors.

1. Introduction

Railway security applications are one of the priority R&TD areas in the railway field. Among other aspects which determine this security, one of the most important is the automatic detection of possible obstacles in tracks. Nowadays the installed systems are limited to specific areas where the probability of alive beings intrusion or falling objets is larger. These systems are based on different technologies (artificial vision, infrared sensors, microwaves) all of them having drawbacks which are strongly dependent on meteorological conditions. In this paper a new ultrasonic sensor system for detecting falling objects on railways in proposed, considered at first as a possible complement to any of the systems mentioned above.

2. Using ultrasonic sensors outdoors.

Ultrasonic sensors have been rarely used in outdoor environments, the reason being the many mechanisms involved in the propagation of acoustic waves in the atmosphere. Three of these mechanisms are always present: atmospheric absorption, refraction and turbulence (in addition to geometrical spreading depending on the emission source) [1]. Atmospheric absorption causes an additional attenuation on the transmitted signal that can be calculated systematically from a standard method [2]. Refraction is only important for long distance transmissions and it will not have any influence on this system. Turbulence is the most problematic phenomenon when transmitting acoustic signals outdoors, mainly due to its random character. Random fluctuations of the index of refraction due to atmospheric turbulence cause the scattering of sound waves, which is translated into random fluctuations of the amplitude of the transmitted signal. The magnitude of these fluctuations is proportional to the structure parameter $\langle\mu^2\rangle$, which characterizes the turbulence intensity [3]. Therefore, it can be stated that an ultrasonic sensor system intended for outdoor obstacle detection should present the following basic characteristics:

- A wide dynamic margin of operation, so that the system can adapt itself to situations where the attenuation of the ultrasonic waves could be considerable.
- Insensitivity against momentary losses of energy in the received signal caused by turbulence. The system should not mistake these losses for the ones caused by falling objects.

3. Sensor configuration and signal processing.

The proposed sensor configuration is shown in Fig. 1. Emitters and receivers are alternately placed on both sides of the tracks. Besides, there are two types of emitters which differ from each other in their signal coding. In this way, the signal transmitted from one emitter on one side of the track is detected by the nearest two receivers on the other side. At the same time, each receiver detects simultaneously the signal transmitted from two different emitters. The receiver is able to distinguish between these signals thanks to the signal coding.

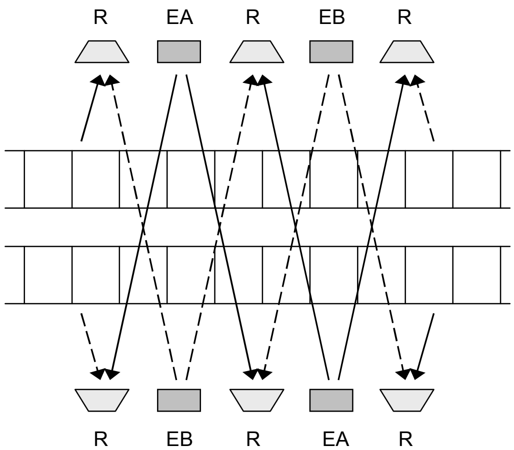

Fig. 1: Ultrasonic sensor arrangement on both sides of the railway.

In addition to this discrimination capability, signal coding gives the system a great process gain, which allows it to work under low signal-to-noise ratios. It also gives immunity against momentary fluctuations in the signal level. In previous works the possibility of using complementary sequences for continuous emission detection has been demonstrated [4]. Other works have studied the possibility of discriminating two different emissions taking advantage of the orthogonality of two pairs of complementary sequences [5]. These sequences were originally described by Golay [6], who also considered their mathematical properties and possible applications in communication systems. A pair of Golay complementary sequences (a, b) of length L shows the property that the sum of their autocorrelations C_{aa} and C_{bb} yields an ideal result:

$$\begin{aligned} C_{aa}(n) + C_{bb}(n) &= 2L \qquad \text{If } n = 0 \\ C_{aa}(n) + C_{bb}(n) &= 0 \qquad \text{Otherwise} \end{aligned} \qquad (1)$$

If (c,d) is another pair of complementary sequences, (a,b) and (c,d) are said to be orthogonal whenever the sum of the corresponding cross-correlations equals 0:

$$C_{ac}(n) + C_{bd}(n) = 0 \quad \text{for all } n \qquad (2)$$

This property is used to code the signal emitted from EA with the pair (a,b) and the signal emitted from EB with the pair (c,d). The sequences are generated by means of an *Efficient Golay Generator* [7] which allows us to perform the later correlation using an *Efficient Golay Correlator* [8]. This system only needs $\log_2(L)$ operations to carry out the correlation of sequences of length L and can be implemented on reconfigurable hardware.

The simultaneous emission of both sequences in each pair is fulfilled by means of a QPSK digital modulation, which allows us to centre the spectrum of the emitted signal around the maximum frequency response of the transducers [9]. In this modulation a symbol of two periods of a 50 kHz square signal has been used. The block diagram of the EA emitter is shown in Fig. 2 (the same diagram is valid for the EB emitter just by changing the encoding complementary pair).

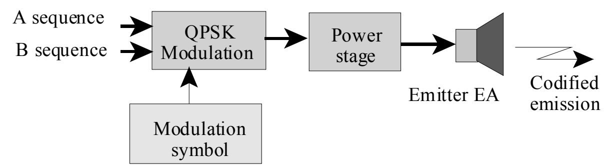

Fig. 2: Block diagram of the emitter module.

After the amplification and the digitalisation of the received signal, a digital process is carried out in every receiver. The main stages of this process are shown in Fig. 3.

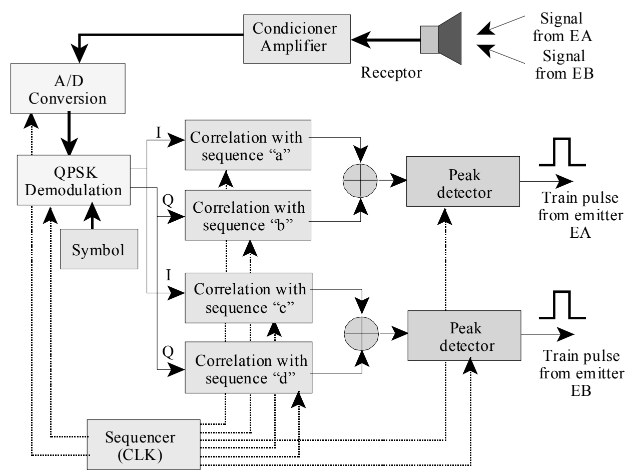

Fig. 3: Block diagram of the receiver module

The first stage consists in the QPSK demodulation of the received signal, making use of the symbol employed in the modulation process. Secondly, a double correlation process is carried out with every component of the demodulator output signal in order to extract the complementary sequences pairs:

- On the one hand, the operation $C_{Ia}(n) + C_{Qb}(n)$ is accomplished to detect the signal emitted from EA, which is coded with the pair (a,b).

- On the other hand and at the same time, the operation $C_{Ic}(n) + C_{Qd}(n)$ is accomplished to detect the signal emitted from EB, which is coded with the pair (c,d).

Finally, a peak detection process is carried out after the sum of both correlations. This process will permit us to obtain the final train of pulses whenever the emitted signal reaches the receiver, that is to say, when the emission has not been obstructed.

4. System simulation.

In this paper, the system performance from the signal processing point of view has been simulated. The aim is to determine the maximum loss of energy able to be produced during the transmission of a period without affecting the detection algorithm. Fig. 4 shows an ideal situation in which the emitted signals from EA and EB reach the receptor without losses of energy.

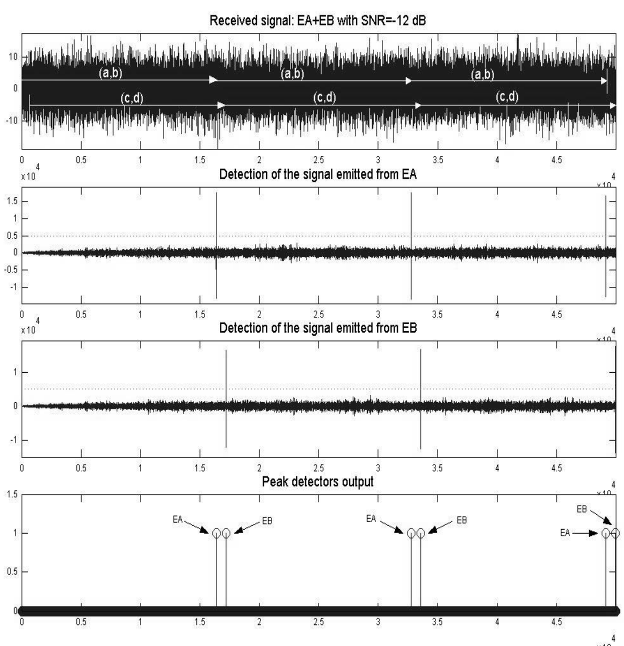

Fig. 4: Simulation of the detection algorithm (I): signals received without losses

In this figure, three 41 ms periods of reception (sequences of 1024 bits) are represented together with a Gaussian noise. These periods have a signal-to-noise ratio equal to – 12 dB and a slight phase difference between the signals transmitted from both emitters. As it can be seen, the algorithm is capable of discriminating the signals transmitted from both emitters despite the noise power is much higher than that of the signal itself.

To analyse how robust the system is with respect to losses of energy in the transmitted signal, we have assumed that during the second period the signal is completely lost for some time. This loss has a double effect on the processed signal: on the one hand, the peaks which appear when the emitted sequences are detected decrease in amplitude, and on the other hand, new peaks arise around these peaks, having the new ones a considerable magnitude as a consequence of the fact that equations (1) and (2) are no more fulfilled, which forces us to increase the detection threshold. Both effects can be clearly seen in figure 5 where we have assumed a 60% loss of the received energy during the second period. In spite of this loss, the system still detects the signal from both emitters.

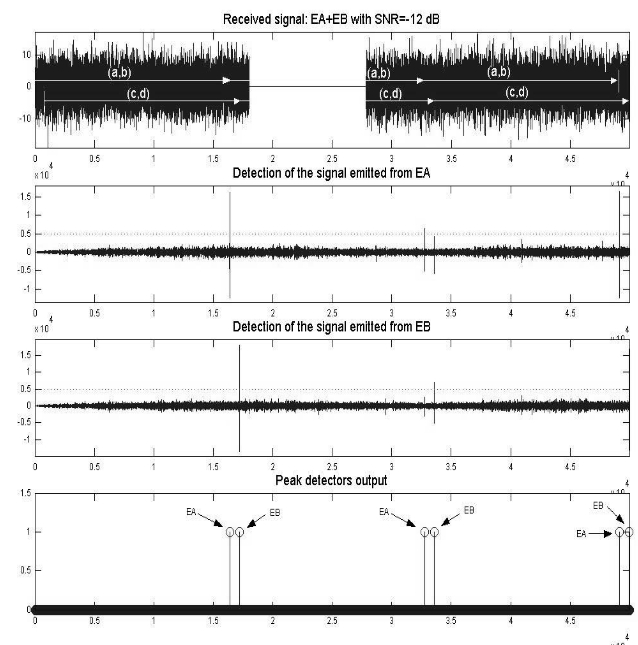

Fig. 5: Simulation of the detection algorithm (II): 60% loss of energy during the second period

When dealing with sequences of 1024 bits and a signal-to-noise ratio of – 12 dB the system stops detecting the signals if the loss of energy during a period is higher than 68%. The same simulations have been carried out for sequences of 2048, 4096 and 8192 bits and for two noise levels, SNR = 12 dB and – 12 dB. The results are shown in table I.

TABLE I

Maximum loss of energy admissible by the detection system in the reception of sequences of L bits (as % of total energy transmitted)

SNR	L=1024 (41 ms)	L=2048 (82 ms)	L=4096 (164 ms)	L=8192 (328 ms)
12 dB	82%	86%	88%	88%
- 12 dB	68%	78%	84%	86%

5. Experimental analysis.

Finally, a statistical analysis has been carried out in order to determine the maximum loss of energy that a 50 kHz ultrasonic signal, similar to those emitted from the detection system, can experience when propagating outdoors under different turbulence conditions. To achieve this objective, we have made 5-second-long emissions in which we have calculated the maximum loss of energy produced assuming the transmission of sequences of 1024, 2048, 4096 and 8192 bits. In total, we have analysed 360 distinct emissions for every one of the five types of atmospheres that have been considered regarding their turbulence intensity. This classification of the atmosphere has been accomplished on the basis of the experimental values of the structure parameter obtained by Johnson, Rasped and Bobak [10] who found out a relation between these values of $<\mu^2>$ and the meteorological variables *wind speed* and *cloud cover*. Figure 6 shows a real example of three signals acquired under weak, medium and strong turbulence conditions. The signals represented in this figure are 200 ms long which approximately corresponds to 5 detection periods when emitting sequences of 1024 bits. It can be clearly seen the effect of atmospheric turbulence on the amplitude of ultrasonic signals propagating outdoors. The distance between the emitter and the receiver was 8 m and both of them were placed 130 cm above level ground.

The received signals have been digitalised with a 400 kHz sampling frequency and filtered with a digital band-pass filter which removed all frequencies below 25 kHz and above 100 kHz. All 5-second-long emissions have been analysed by defining a rectangular window whose length in samples N is the length of a complementary sequence of L bits modulated with a symbol of two periods of a 50 kHz signal and sampled with a 400 kHz sampling rate:

$$N = L \times 2 \times 400/50 = 16L \tag{3}$$

Sliding this window along the 2 million samples contained in a 5-second-long emission we have calculated the short-term energy function in each emission, defined as:

$$E_n = \sum_m \left[x(m) \cdot w(N+n-m)\right]^2 \tag{4}$$

where *x(m)* represent the samples of the received signal, $n = 1, 2, \ldots (2 \cdot 10^6 - N + 1)$ is the time index of the short-time energy function and *w(k)* is the rectangular window of length N, i.e.

$$w(k) = \begin{cases} 1 & 1 \le k \le N \\ 0 & otherwise \end{cases} \tag{5}$$

This energy function has been already used to represent the amplitude variation over the time of audio signals [11].

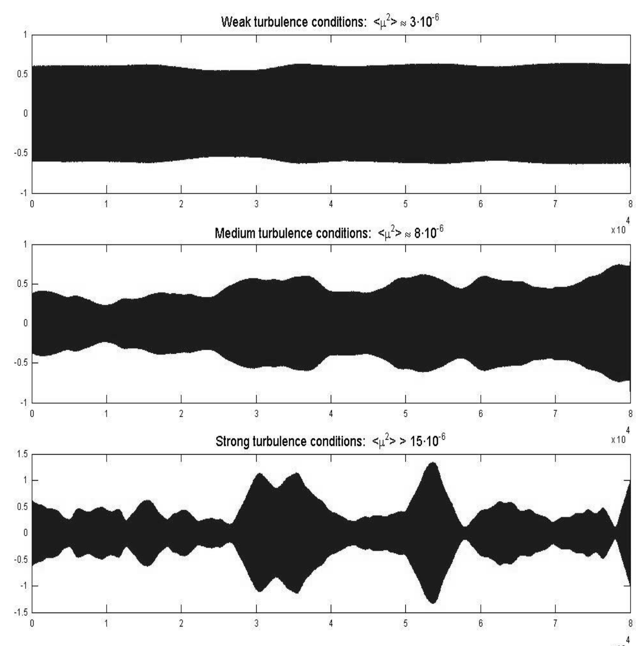

Fig. 6: Effect of atmospheric turbulence on the amplitude of the transmitted signals

The maximum loss of energy (*MLE*) produced in the transmission of a pair of sequences has been calculated in percentage as:

$$MLE = \frac{\langle E_n \rangle - E_{\min}}{\langle E_n \rangle} \times 100 \ (\%) \qquad (6)$$

where $<E_n>$ and E_{min} represent the mean value of the energy function and its minimum value in each emission respectively. Once the *MLE* has been calculated in all the emissions for the four sequence lengths under analysis, we have searched for the probability functions which better fit the obtained data. It has been observed that the losses of energy associated with the transmission of sequences of 2048, 4096 and 8192 bits are normally distributed around the mean whereas the ones associated with the transmission of sequences of 1024 bits fit better to a Weibull distribution. In all cases, the maximum foreseeable loss of energy has been estimated as the one corresponding to 0.99 in the cumulative distribution function. The results of this analysis are shown in table II.

TABLE II

Maximum loss of energy estimated from actual data during a period of L bits (as % of total energy received without turbulence)

Turbulence Intensity	L=1024 (41 ms)	L=2048 (82 ms)	L=4096 (164 ms)	L=8192 (328 ms)
$<\mu^2> \approx 3\cdot10^{-6}$	83.4 %	75.9 %	62.9 %	48.5 %
$<\mu^2> \approx 5\cdot10^{-6}$	89.6 %	80.1 %	65.3 %	48.7 %
$<\mu^2> \approx 8\cdot10^{-6}$	95.3 %	91.3 %	77.9 %	53.3 %
$<\mu^2> \approx 10\cdot10^{-6}$	95.5 %	90.8 %	72.8 %	54.8 %
$<\mu^2> > 15\cdot10^{-6}$	97.5 %	92.1 %	78.9 %	64.7 %

Comparing these results with those obtained in the system simulation (table I) it can be concluded that the proposed detection system will be insensitive to atmospheric turbulence effects on the amplitude of the ultrasonic signal when transmitting sequences of 4096 bits. This length corresponds to a detection period of 164 ms, which approximately represents the minimum time that a falling object must block the transmission to be detected. However, this length can be made shorter if the system is designed to operate under weak turbulence conditions as the ones which characterize a foggy atmosphere. In this case the transmission of sequences of 2048 bits will avoid the effects of atmospheric turbulence with a detection period of 82 ms, which for instance allows the detection of an object with a surface of 1m^2 normal to the transducer face falling from a height of 10 meters.

6. Conclusions

In this paper an ultrasonic sensor system for detecting falling objects on railways has been proposed. It has been shown that the signal coding, based on the use of complementary sequences, makes the system robust against random fluctuations on the amplitude of the transmitted signals caused by atmospheric turbulence. This robustness allows the system to detect any static obstacle blocking the transmission and any falling object large enough to block this transmission for a detection period. This detection period is proportional to the length of the emitted sequences, which has to be selected depending on atmospheric turbulence conditions.

The system performance is especially good in foggy conditions so that it will be an appropriate complement to all those systems which have severe problems of operation in these conditions (such as the ones based on infrared sensors).

In addition to the robustness mentioned above, the signal coding gives the system a discrimination capability that allows the receivers to distinguish between the signals coming from two different emitters.

Acknowledgments

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References

[1] T. F. W. Embleton, "Tutorial on sound propagation outdoors", Journal of the Acoustical Society of America, Vol. 100 No. 1, pp. 31-48, 1996.

[2] Sub-Committee SC 1 (Noise), Technical Committee ISO/TC 43 (Acoustics), "Attenuation of sound during propagation outdoors. Part 1", International Organization for Standardization (ISO), CH-1211 Gèneve, 1993.

[3] V. I. Tatarski, *The effects of the turbulence atmosphere on wave propagation*, Israel Program for Scientific Translation, Jerusalem, 1971.

[4] J. Ureña, J.J García, M. Mazo, A. Hernández, V. Díaz, D. Herranz, J. C. García, "Detección de emisiones continuas en condiciones de muy baja relación S/N", TELEC'02. Santiago de Cuba, 2002.

[5] A. Hernández, J. Ureña, J. J. García, M. Mazo, J. P. Dérutin, J. Serot, “Ultrasonic sensor performance improvement using DSP-FPGA based archiquectures”, IECON’02, pp. 2694-2699. Seville, 2003.

[6] Golay, M. J. “Complementary Series”, IRE Transactions on Information Theory, Vol. IT-7, pp. 82-87, 1961.

[7] Budisin, S. Z. “Efficient Pulse Compressor for Golay Complementary Sequences”, IEE Electronics Letters, Vol. 27, No. 3, pp. 219-220, 1991.

[8] Popovic, B. M. “Efficient Golay Correlator”, IEE Electronics Letters, Vol. 35, No. 17, pp. 1427-1428, 1999.

[9] V. Díaz, J. Ureña, M. Mazo, J. J. García, E. Bueno, A. Hernández, “Multi-mode ultrasonic operation using Golay complementary sequences and QPSK modulation”, TELEC’2000. Santiago de Cuba, 2000.

[10] M. A. Johnson, R. Raspet and M. T. Bobak, “A turbulence model for sound propagation from an elevated source above level ground”, Journal of the Acoustical Society of America, Vol. 81, No. 3, pp. 638-646, 1987.

[11] Zhang, T. and Kuo C. C. “Content-based Classification and Retrieval of Audio”, SPIE's 43rd Annual Meeting - Conference on Advanced Signal Processing Algorithms, Architectures, and Implementations VIII, San Diego, 1998