COMPLEMENTARY SETS OF SEQUENCES-BASED CODING FOR ULTRASONIC ARRAY SENSOR

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ABSTRACT

In this paper, an improved ultrasonic system for detection of falling objects or alive beings intrusion in railways is presented. The basic ultrasonic array sensor is composed of four emitters and six receivers and can be easily extended to a higher coverage area repeating this elementary structure. The receivers are able to distinguish among the signals coming from the four different emitters thanks to the signal coding with complementary sets of sequences, which also gives to the reception module an excellent process gain. The signal processing has been accomplished by means of the *Efficient Set of Sequences Correlator* which has been recently developed by the authors.

1. INTRODUCTION

Many technologies such as artificial vision, infrared sensors or microwave radars have been used in all those systems intended for obstacle detection on railway tracks. Recently a novel ultrasonic sensor system based on the transmission of Golay sequences-coded signals has been proposed by the authors [1]. This system behaves quite well under any meteorological conditions as long as the length of the transmitted sequences is large enough. However, it is only able to discriminate between two different emissions, a fact which strongly limits its performance when the transmitted signals suffer from any type of reflection. This system is described in detail in section 2. In section 3 an improved system based on the transmission of complementary sets of four sequences instead of Golay pairs is presented. Finally, the main advantages of the new system are discussed in section 4.

2. PREVIOUS SYSTEM

The ultrasonic detection system proposed by the authors in [1] is based on the array of sensors shown in figure 1a. As it can be seen, this elementary array consists of four emitters (EA, EB, EC and ED) and two types of receivers (RAB and RCD) symmetrically placed on both sides of the tracks. In this structure each receiver detects simultaneously the signal transmitted from the emitters on the other side. The receiver is able to distinguish between these two emitters thanks to the Golay sequences-based signal coding. A pair of Golay complementary sequences (a_1,a_2) of length L shows the property that the sum of their autocorrelations R_{a1a1} and R_{a2a2} yields an ideal result [2]:

$$\begin{aligned} R_{a1a1}(n) + R_{a2a2}(n) &= 2L \qquad \text{if } n = 0 \\ R_{a1a1}(n) + R_{a2a2}(n) &= 0 \qquad \text{otherwise} \end{aligned} \qquad (1)$$

If (b_1,b_2) is another pair of complementary sequences, (a_1, a_2) and (b_1,b_2) are said to be orthogonal whenever the sum of the corresponding cross-correlations equals 0:

$$R_{a1b1}(n) + R_{a2b2}(n) = 0 \qquad \text{for all n} \qquad (2)$$

This property was used to code the signals emitted from EA and EB with two orthogonal pairs (a_1,a_2) and (b_1,b_2) and the signals emitted from EC and ED with two different orthogonal pairs (c_1,c_2) and (d_1,d_2). The simultaneous emission of both sequences in each pair was fulfilled by means of a QPSK digital modulation, which allowed us to centre the spectrum of the emitted signal around the maximum frequency response of the ultrasonic transducers [3]. In this modulation a symbol of two periods of a 50 kHz square signal was used.

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 figure 1b. 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 pairs of complementary sequences. Finally, a peak detection process is carried out after the sum of both correlations.

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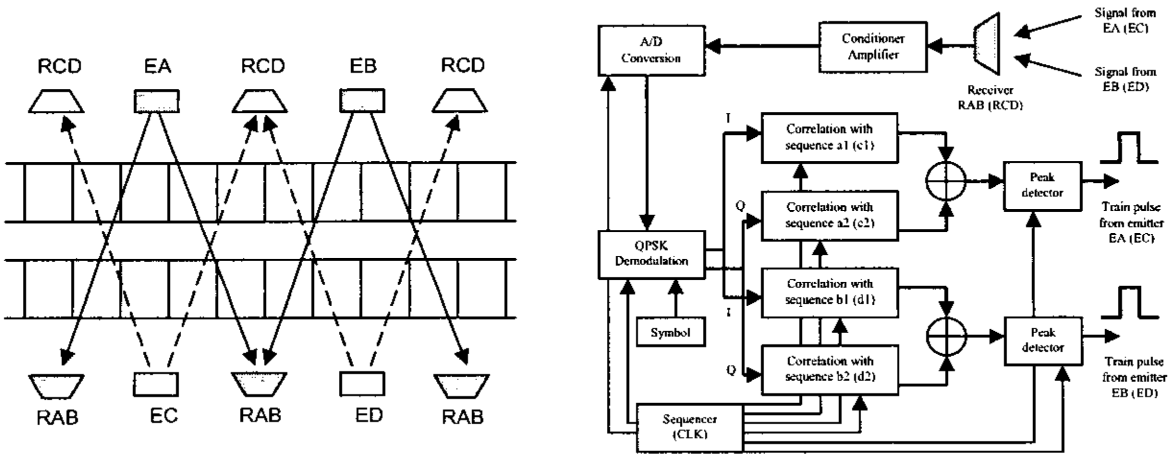


(a) (b)

Figure 1. Ultrasonic Detection System: (a) Elementary sensor array, (b) Block diagram of the detection process.

This process permits 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. In addition to the discrimination capability of the receivers the signal coding gives the system a great process gain, which allows it to work under unfavorable meteorological conditions.

However, the ideal process gain of *10·log(2L)* dB is not achieved in practice due to the fact that part of the signals transmitted from de emitters placed on one side of the tracks is detected by the receivers on the same side. This effect can be caused by ground reflection as well as by scattering from atmospheric turbulence. The receivers are able to distinguish between the signals emitted from the emitters placed on the other side of the tracks but they are not able to distinguish the signals emitted from the ones placed on their own side. The reason is that sets of more than two pairs of mutually orthogonal Golay sequences do not exist. The reflected signals become apparent in the detection process as new peaks which force us to increase the detection threshold. This effect can be clearly seen in figure 2 where we have simulated the detection process in both types of receivers. In this figure two 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 -6 dB and we have assumed that the power of the reflected signals is 3dB below the power of the direct ones. As it can be seen the detection algorithm is capable of discriminating the signals transmitted from the direct emitters despite the noise power is higher than that of the signals itself, but the presence of the peaks associated with the reflected signals strongly deteriorate the system performance. Atmospheric turbulence could cause losses in the energy of the transmitted signals decreasing the amplitude of the peaks associated with the direct signals below the detection threshold and misleading this way the system which would understand these losses as the presence of a falling object [1].

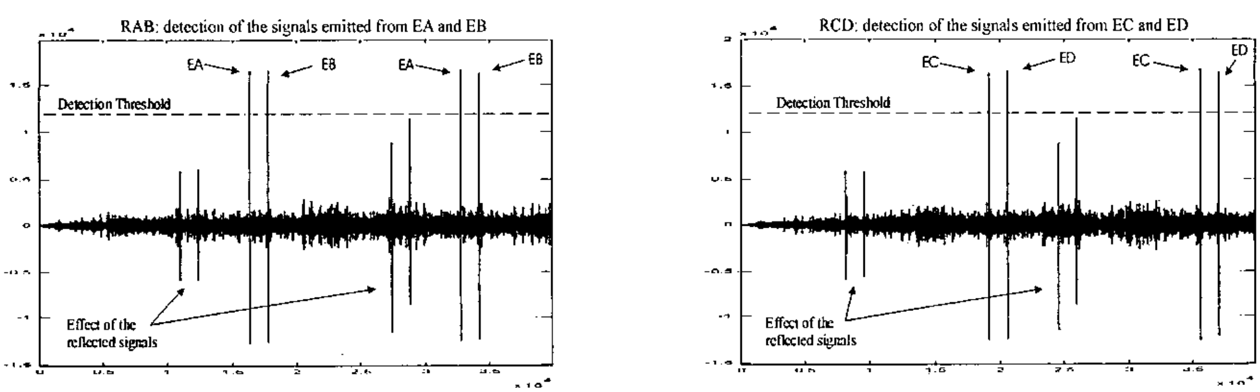


Figure 2. Simulation of the detection algorithm in the previous system (SNR=−6dB).

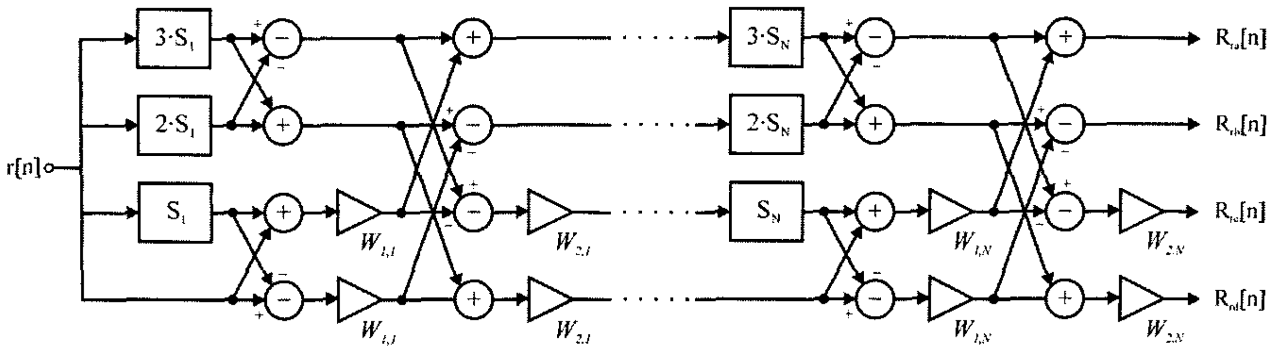


Figure 3. Efficient Set of Sequences Correlator.

3. IMPROVED SYSTEM

An important modification of the detection system described in the previous section has been introduced in this paper. This modification consists in the transmission of complementary sets of sequences instead of Golay pairs. Complementary sets of sequences are a generalization of Golay pairs which may contain more than two sequences [3]. Now, for a set of N sequences of length L we have:

$$\begin{aligned} &R_{a1a1}(n)+R_{a2a2}(n)+\cdots+R_{aNaN}(n)=N\cdot L && \text{if } n=0 \\ &R_{a1a1}(n)+R_{a2a2}(n)+\cdots+R_{aNaN}(n)=0 && \text{otherwise} \end{aligned} \quad (3)$$

The main advantage of using complementary sets of sequences is that it is possible to generate more than two mutually orthogonal sets. In the new system, the signals emitted from EA, EB, EC and ED have been coded with four complementary sets of four sequences each: (a_1, a_2, a_3, a_4), (b_1, b_2, b_3, b_4), (c_1, c_2, c_3, c_4) and (d_1, d_2, d_3, d_4).

These sets are mutually orthogonal so that the sum of their cross-correlation functions equals 0:

$$\begin{aligned} &R_{x1y1}(n)+R_{x2y2}(n)+R_{x3y3}(n)+R_{x4y4}(n)=0 \\ &\forall n \quad \forall\, x,y\in\{a,b,c,d\} \quad x\neq y \end{aligned} \quad (4)$$

The sets were generated making use of a new algorithm recently devised by the authors [5]. This algorithm has the property of easily generating sets of 4 sequences mutually orthogonal and leads directly to the *Efficient Set of Sequences Correlator* (ESSC) which will be used in the later correlations.

For L-bits length sequences the ESSC performs the correlation with only $4\cdot log_2(L)$ operations, a number which compares very well with the $2\cdot L-1$ operations needed by the straightforward correlator. The ESSC is shown in figure 3, where S_i represents a positive delay of $L/2i$ samples and $W_{1,i}$, $W_{2,i}$ are coefficients having values +1 or −1. These coefficients determine the set of sequences with which the ESS correlates the input signal.

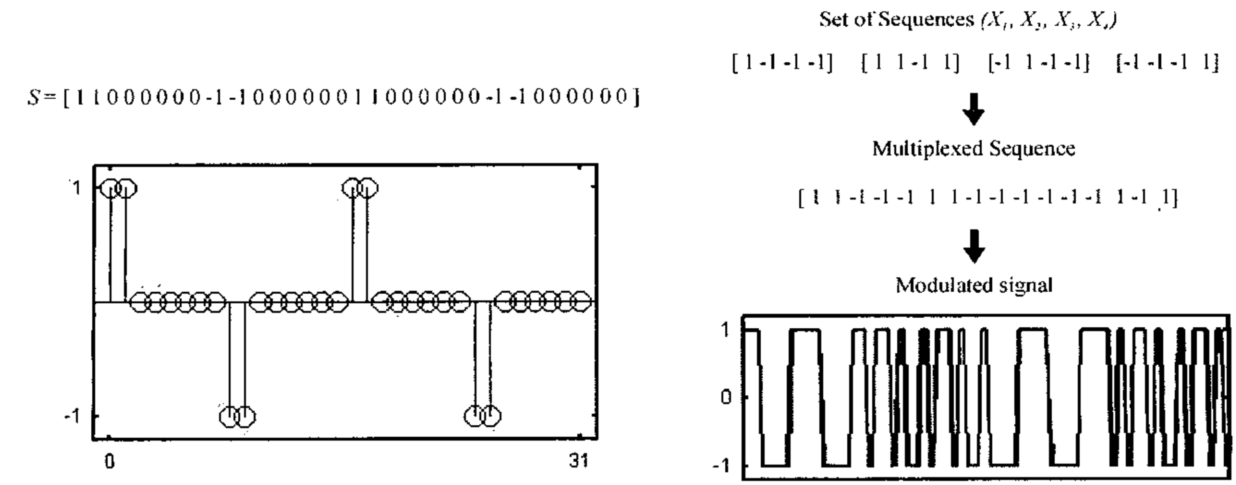
A new modulation scheme has been developed in order to simultaneously transmit the four sequences in a set through the ultrasonic transducers. This scheme is based on the QPSK digital modulation used in the previous system to transmit the Golay pairs and can be viewed as a 2-step process:

1- The four sequences in a set (X_1, X_2, X_3, X_4) are multiplexed generating this way a new sequence of 4L bits.

2- The bits of the new sequence are grouped in quartets $(x_{1i}\ x_{2i}\ x_{3i}\ x_{4i})$ and each quartet is combined with the modulation symbol $S[k]$ to generate a 32 samples signal which is defined as follows:

$$x_{1i}\cdot S[k]+x_{2i}\cdot S[k-2]+x_{3i}\cdot S[k-4]+x_{4i}\cdot S[k-6] \quad (5)$$

The modulation symbol is shown in figure 4a while figure 4b shows an example of this modulation process for a set of 4 sequences with length $L=4$. When the sampling period is $1.25\ \mu s$ ($fs=800\ kHz$) most of the energy of the modulated signal falls into the bandwidth of the ultrasonic transducer [6] and the sequences can be recovered from the transmitted signal by correlation. This usable energy is less in this modulation than in the QPSK modulation of Golay sequences, but this drawback will be compensated by the higher process gain achieved when working with complementary sequences. This compensation has been experimentally verified comparing the real process gain obtained when transmitting both kinds of signals under the same meteorological conditions. The actual data shows that the real process gain achieved with the new signal coding is slightly higher than that obtained with Golay pairs and QPSK modulation. Therefore, it can be state than the loss of energy in the bandwidth of the transducer associated with the new modulation scheme is completely compensated by the extra 3dB gain obtained when complementary sets of four sequences are correlated instead of Golay pairs.



(a) (b)

Figure 4. Modulation process: (a) Digital Symbol, (b) Example of modulation for sequences of 4 bits

The main advantage of using this modulation scheme is that it is necessary only one correlator to demodulate the received signal. This correlator is matched to the modulation symbol and extracts the four sequences from the received signal with 2 samples delay between one sequence and the following, i.e. $S_{X1}[k] = S_{X2}[k-2] = S_{X3}[k-4] = S_{X4}[k-6]$, where S_{Xi} represents the demodulated sequence *Xi*. Furthermore, the ESSC simultaneously performs the correlation of the input signal *r[n]* with the four complementary sequences (X_1, X_2, X_3, X_4). Both properties can be combined to detect the signal from each emitter with only one correlator and three delay stages, as it can be seen in figure 5. In this figure, the ESSCs have the same structure shown in figure 3 with the only difference that the positive delays *Si* have been multiplied by 32 (number of samples in the modulation symbol). The reason is that these filters do not correlate the original sequences *Xi[k]* but the demodulated sequences *Sxi[k]*, which are interpolated versions of the former ones.

The transmission of complementary sets of sequences introduces a great improvement in the new system. The receivers are able to distinguish among the signals transmitted from the four emitters and the reflected signals have no effect on the detection algorithm. This phenomenon can be seen in figure 6 where the same simulation as above has been carried out but assuming the transmission of complementary sets of four sequences (L=1024 bits, SNR=-6dB). In this figure the peaks associated with the reflected signals have disappeared and the detection threshold can be decreased, allowing in this way the system to work under strong turbulence conditions.

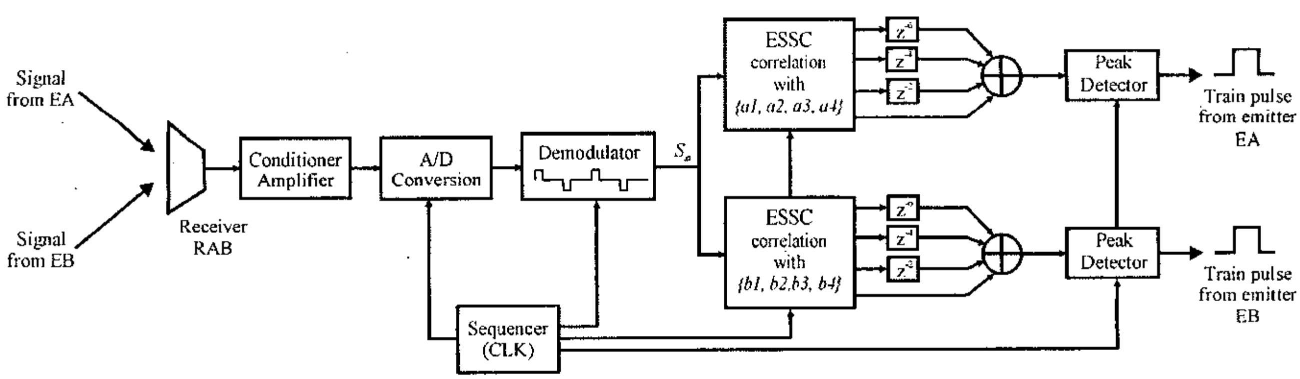


Figure 5. Detection process in the new system

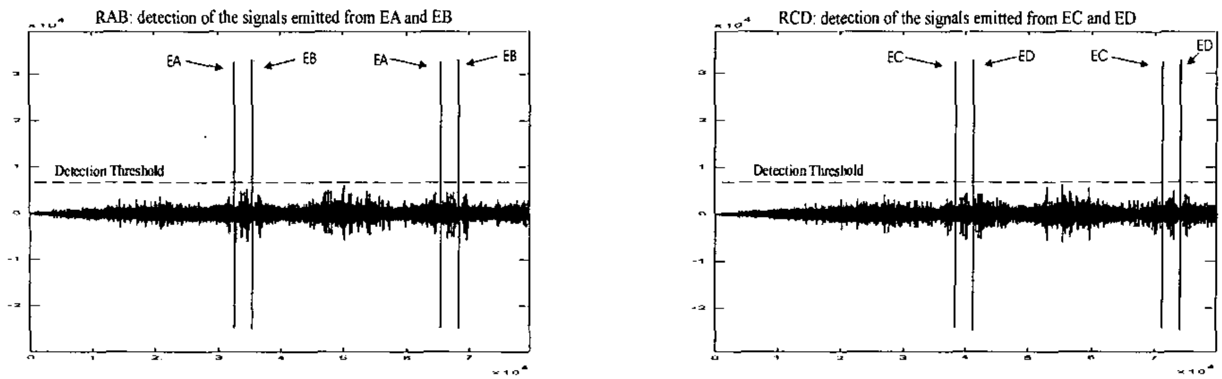


Figure 6. Simulation of the detection algorithm in the new system (SNR=–6 dB)

4. CONCLUSIONS

In this paper an improved ultrasonic sensor system for falling objects detection in railways has been presented. This system is based on the transmission of complementary sets of sequences and the Efficient Set of Sequences Correlator recently developed by the authors. The emission of these sequences through the ultrasonic transducer has been accomplished by means of a new modulation scheme which allows the signal to be demodulated with only one correlator. It has been shown that the new signal coding gives the system an enhanced process gain and allows it to distinguish among the signals transmitted from four different emitters, eliminating this way the effect of reflected signals on the detection process.

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