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Multi-sensory system for obstacle detection on railways

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Abstract – *In the current railway systems, it is becoming more necessary to have safety elements in order to avoid accidents. One of the causes that can provoke serious accidents is the existence of obstacles on the tracks. In this work, a multi-sensory barrier -consisting of infrared (IR) and ultrasonic (US) sensors- and a vision system, is proposed in order to inform the monitoring system of the existence of obstacles. Due to the fact that any sensor has detection problems which are strongly dependent on meteorological conditions, the use of different sensors for the same task is justified so that the drawback of one sensor is compensated for by the others. The high degree of reliability needed in these environments, where the safety is fundamental, recommends the use of a multi-sensory system. Principal Components Analysis is applied to the data obtain from the barrier and from the vision system. The use of this technique with the barrier permits concluding if there are obstacles on the tracks; and with the vision system information about moving objects is obtained.*

Keywords – *Multi-sensory system, sensor emission codification, principal components analysis, false alarms reduction*

I. INTRODUCTION

In all transport systems, especially in the case of the railway, there are two important concepts: safety [1][2][3] and reliability [4]. Because of the ever constant need to improve railway safety, several European research projects [5] are carrying out research into whatever circumstances that exist which may pose a threat to railway safety. One such circumstance has received particular attention in the case of some of these projects [6]: the existence of objects on the tracks.

On high-speed lines, zones close to bridges are considered to be quite critical, since obstacles can easily fall onto the track. This can be caused by the fall of a vehicle, or material being transported by a vehicle, onto the line. Landslides can also happen at the entrances and exits of tunnels. In these critical areas, if there is a system to detect the presence of obstacles, railway traffic can be halted and possible accidents avoided. According to Spanish Railway Regulations [7], a system is required to detect obstacles in such areas on the high-speed lines (see Figure 1). This system, called "Object Fall Detector", analyzes if those zones are free of objects so that railway traffic may pass unhindered. Given the considerable growth and the expected development of the Spanish high-speed lines [8][9], the pressing need to carry out research into this area is becoming ever more clear.

The majority of the published solutions address the question of level crossings which do not, however, exist on high-speed lines. Nevertheless, published works that dealt with obstacle detection at level crossings can still prove useful. There are two types of proposals based on: a) individual sensory systems, placed in situ; and b) multi-sensory systems, placed on-board trains. Individual sensorial systems placed in situ are based on: cameras, mainly using stereo vision [10] [11][12], being the main problems with this technique the high amount of information processed and the necessity for good lighting conditions; ultrasonic sensors [13][14], having a low level of efficiency in outdoor applications; radar [15][16][17], being suitable for the detection of large obstacles such as vehicles, but reliability decreases in the case of small objects; laser [18][19], being unsuitable in the case of outdoor applications because of the use of moving mirrors.

Multi-sensory system proposals (placed on board trains) use the same sensors dealt with above, and follow the same tendencies as in the case of the road transport sector. Such sensors are carried on-board, thus providing the train with an independent obstacle detection capability [5][6][20][21]. But all the on-board proposals have the same problem: the train's speed. Spanish high-speed lines have been designed to permit a top speed of 350 km/h. A train running at 350 km/h needs a distance of 2.5 km to come to a complete halt.

(a)

(b)

Fig. 1. Critical zones: (a)Tunnel; (b) Overpass.

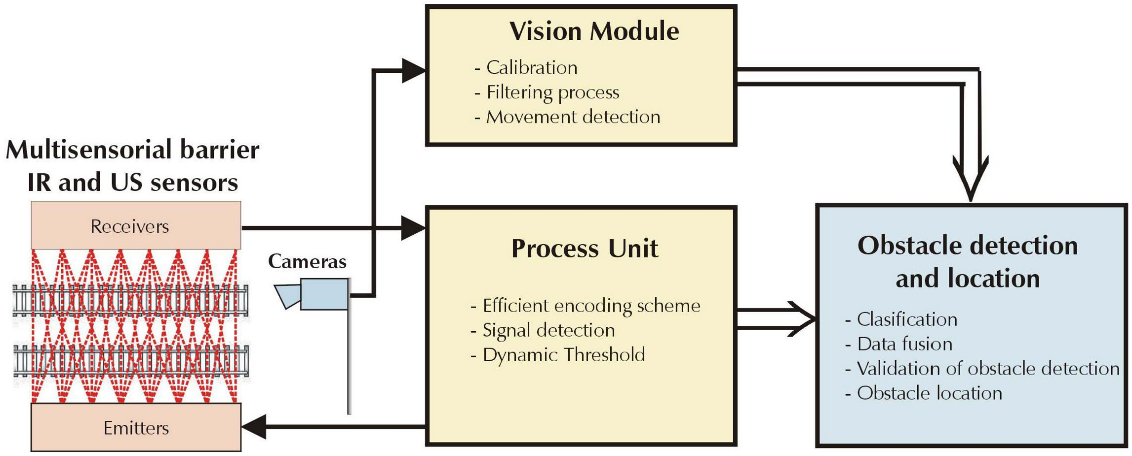

Fig. 2. Block diagram of the proposed detection system.

For the above mentioned reasons, multi-sensory system proposals placed on board trains are rejected. In a railway environment working conditions can be really adverse, and the affectation can be quite different depending on the sensor used, since all the sensors have inherent weaknesses. Such detection systems based on individual sensors also present the problem of generating false alarms, thus creating financial losses whenever the system detects an obstacle which does not, in reality, exist. The most reliable solution therefore is a multi-sensory system placed in situ, taking advantage of all the positive aspects of every type of sensor, in order to avoid the false alarms.

The rest of the paper is organized as follows: section II describes the sensory system; section III explains the data processing carried out; section IV shows some of the obtained results, and finally, some conclusions are discussed in section V.

II. SENSORY SYSTEM

A. Proposed system

According to the conclusion reached in the previous section, the proposal is to use a multi-sensory system, so that the drawback of one sensor is compensated for by the others. In this particular case, the proposal is based on a multi-sensory barrier -consisting of infrared (IR) and ultrasonic (US) sensors- and a vision system, as Figure 2 shows.

The barrier and the vision system are continuously analyzing the same area. The barrier generates information about the existence of obstacles larger than 50x50x50cm (Spanish Regulation, [22]), and the vision system analyzes if there are moving objects. Both systems automatically detect the presence of obstacles in the area, informing the monitoring system about it. In this work, authors only analyze the high level process, based on Principal Components Analysis (PCA) [23], carried out with the IR barrier and the vision system, in order to obtain the required information. As well as the detection of the objects, it is very important to avoid false alarms.

The vision system sensor is based on one camera and the output is a matrix containing the image information. The barrier has a special topology, and it needs a further description.

B. Description of the barrier

The multi-sensory barrier is composed of two IR-US barriers, one emitting and the other receiving, placed at both sides of the railroads, as is shown in Figure 3.

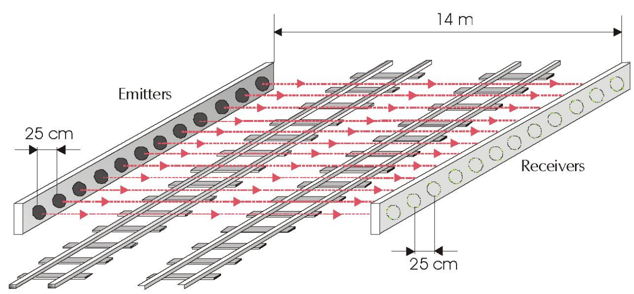

Fig. 3. Scheme of the multi-sensory barrier.

This scheme produces a net of links among emitters and receivers. Due to the fact that the minimum dimensions of the object to be detected are 50x50x50cm, the distance between contiguous transducers has been fixed to 25cm. In this way, if an object with minimum dimensions is in the scanned area, at least two links are interrupted. On the other hand, the distance between emitters and receivers is 14m, given by the width of the railroads, although it could be higher.

Because the emitters, either IR or US, are not punctual, every emitter reaches a group of receivers. This allows multiple connections to be established in the sensorial system, apart from those on the axial axis shown in Figure 3. For example, an infrared emitter with an aperture angle of $\pm 2°$, with a distance between emitters and receivers of

14m, excites up to 5 receivers, establishing therefore five connections for every emitter. On the contrary, five emissions reach each receiver. Fig. 4 shows the IR links for a segment with 10 emitters (2.25 m). In this sensory structure, whenever an object with dimensions larger than the minimum ones appears, at least 10 links are interrupted.

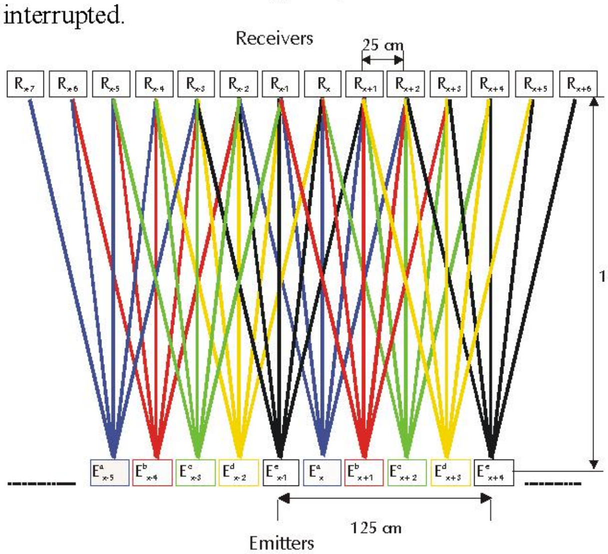

Fig. 4. IR Links at a segment of 2.25m.

This capacity of multi-emission and multi-reception (known as multi-mode), requires a codification scheme in order to distinguish the source of the emissions and to conclude which links are interrupted by the object. The proposed codification scheme is based on mutually orthogonal complementary sets of sequences (MO-CSS), and it is analyzed by the authors in [24]. The detection of the different emissions is carried out by means of a correlation process, where the output from every receiver provides a vector with several measurements, corresponding to the correlation values obtained for each link. In the particular case of the IR barrier, each receiver provides a vector with five measurements, as shown in (1).

$$\mathbf{y}_k^{(x} = \left[y_k^{(1,x} \quad y_k^{(2,x} \quad y_k^{(3,x} \quad y_k^{(4,x} \quad y_k^{(5,x} \right]^T \tag{1}$$

where x is the position of the receiver in the barrier; and k is the instant when data are captured. The emitters transmit periodically, being the correlation output obtained for every link as follows:

$$y_k^{(j,x} = G \cdot \theta_k \cdot \sum_{i=0}^{i=\infty} \delta[k - i \cdot T] + \phi_{\eta,k} \tag{2}$$

where G is the process gain, according to the encoding scheme; T is the emission period; θ_k is the atmospheric attenuation; $\phi_{\eta,k}$ is the noise component after the correlation; and $j=1, 2, 3, 4$ and 5. In (3) the matrix $\mathbf{Y_k}$ contains the correlation output of all the links in the barrier. The $\mathbf{Y_k}$ matrix is processed by PCA to globally validate the existence of objects in the scanned area.

$$\mathbf{Y}_k = \begin{bmatrix} y_k^{(1,1} & \cdots & y_k^{(1,x} & \cdots & y_k^{(1,X} \\ y_k^{(2,1} & \cdots & y_k^{(2,x} & \cdots & y_k^{(2,X} \\ y_k^{(3,1} & \cdots & y_k^{(3,x} & \cdots & y_k^{(3,X} \\ y_k^{(4,1} & \cdots & y_k^{(4,x} & \cdots & y_k^{(4,X} \\ y_k^{(5,1} & \cdots & y_k^{(5,x} & \cdots & y_k^{(5,X} \end{bmatrix}_{5 \times X} \tag{3}$$

III. DATA PROCESSING

Because the detection of objects by the barrier is based on the radiation lack at the receivers, this circumstance does not always imply the existence of a dangerous object for the railway. For example, it is possible for some receivers not to detect the emission because a small object has temporarily interrupted the link. Typical sporadic cases of cuts of the links can be either moving leaves or small animals. Only permanent objects, larger than 50x50x50 cm, have to generate an alarm. Principal Component Analysis (PCA) [23] is applied, so that the above mentioned situations do not cause alarm activations. Furthermore, PCA technique has been applied to the vision system, in order to detect if there are moving objects.

A. PCA technique

In general, PCA is divided into two phases. The first one is carried out *off-line*, when different operational conditions have been taken into account (conditions of sunlight, meteorology, noise levels, illumination, etc), together with the section of track free of obstacles. In this situation a data set is captured, and it is used to obtain the transformation matrix **U** between the original space and the transformed one, or vice versa. The **U** matrix is obtained from the eigenvectors associated with the most significant eigenvalues of the covariance matrix of the data set. The second phase is *on-line*. By using the transformation matrix **U**, the measurements received from the processing unit (vector of measurements taken from the receivers or the captured image by the camera) are projected into the transformed space according to:

$$\mathbf{\Omega} = \mathbf{U}^T \mathbf{\Phi} \tag{4}$$

Later the reconstruction is computed using:

$$\hat{\mathbf{\Phi}} = \mathbf{U}\mathbf{\Omega} \tag{5}$$

where $\mathbf{\Phi}$ is the vector of characteristics with zero mean, on which the transformation is carried out; $\mathbf{\Omega}$ is the resulting vector from the transformation; and $\hat{\mathbf{\Phi}}$ represents the reconstruction vector. The reconstructed information will differ from the original in different magnitudes depending on the degree of similarity existing between the new data and those used to obtain the transformation matrix **U** when there were not obstacles on the tracks. This difference is known as the reconstruction error:

$$\varepsilon_{PCA} = \left\| \Phi - \hat{\Phi} \right\| \qquad (6)$$

In the case of the barrier, if error ε_{PCA} is higher than a determined threshold, it is concluded that there exists an object; whereas with the vision module it is concluded that there exists a moving object.

IV. RESULTS

A. Detection results with the IR barrier

To analyze the viability of the PCA technique, the measurements from a 3m IR barrier (see Figures 3 and 4) have been processed. This section of barrier is composed of 15 emitters and 12 receivers. In this situation, $\mathbf{\Phi}$ is a 60-dimensional vector. Because the different receivers are very close, there exists a high global correlation among the different components of the vectors, so that PCA notably reduces any redundant information. In order to consider the most possible scenarios of detection without obstacles, the information from the *off-line* process has been obtained for different SNR (Signal-to-Noise-Ratio) values (from -6dB up to 6dB), as well as in different visibility conditions (from dense fog to a clear day) [25].

Figure 5 shows the reconstruction error when the track is free of obstacles, and SNR=0dB. Whenever the section of track is free of obstacles, the reconstruction error provides small values. Figure 6 shows the reconstruction error when a pedestrian is crossing the tracks transversely. At every time instant a group of receivers detects the presence of the above mentioned obstacle. Since this obstacle interrupts several links, the similarity between the spaces decreases, and the reconstruction error suddenly increases over the threshold: its value is proportional to the number of links cut by the obstacle. The reconstruction error is higher than the threshold during the time that the obstacle is present. The original covariance matrix has 60 eigenvectors, but in this case, only one eigenvector has been used in the final transformation, what implies a high reduction in redundant information.

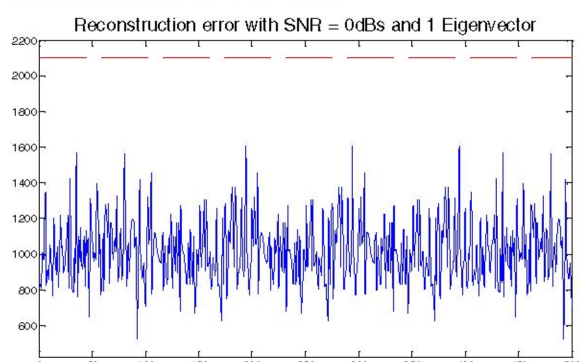

Fig. 5. Reconstruction error when the section of track is free.

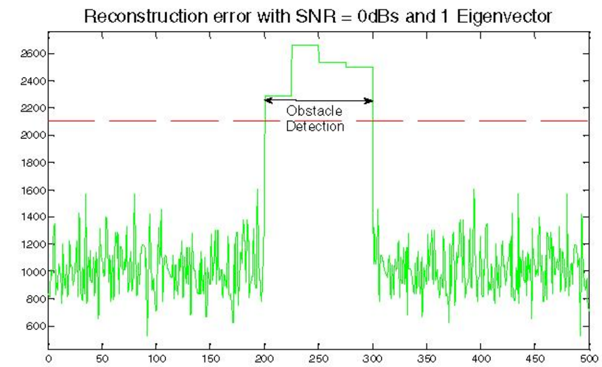

Fig. 6. Reconstruction error when the section of track is not free.

In Figure 7 another situation appears when there is a random lack of radiation at the receivers for a short time. This is typical in the case of flying leaves, or for the flight of birds inside the detection area. These situations are filtered by PCA because the reconstruction error is always lower than the threshold.

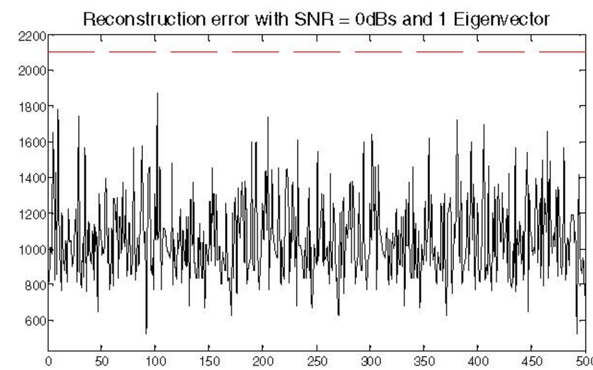

Fig. 7. Reconstruction error when there exist random cuts.

B. Detection results with the vision system

Figure 8 shows the proposed algorithm, based on PCA. The details of the algorithm (mainly the selection of the threshold) are analyzed by the authors in [10]. In the *off-line* phase, *M* stationary images (being *M=20*) have been processed to obtain the model, represented by the transformation matrix **U**, with different weather and illumination conditions, always with the tracks free of obstacles. The algorithm was successfully evaluated with changeable illumination conditions, and using only the eigenvector associated with the highest eigenvalue. As example, Figure 9 shows a pedestrian crossing the tracks in a foggy day. The white box in each image shows where the PCA algorithm detects motion.

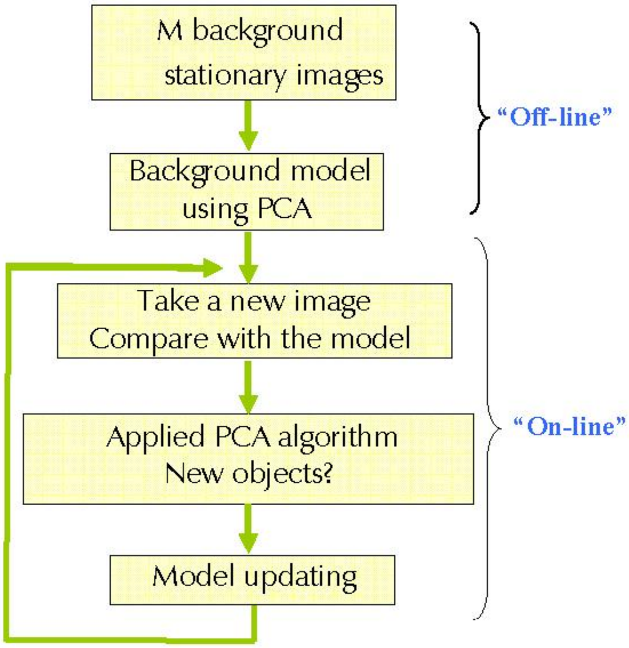

Fig.8. PCA application to the vision system.

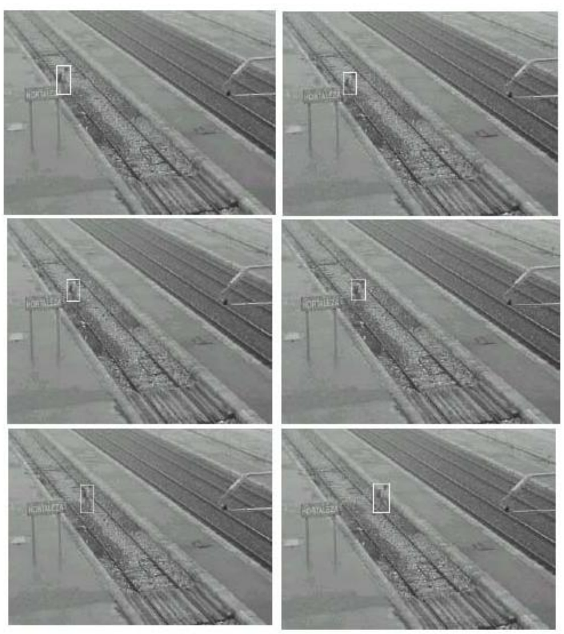

Fig. 9. Detection of a pedestrian crossing the tracks.

V. CONCLUSIONS

In this paper a multi-sensory system for obstacle detection on railways has been presented, based on a multi-sensory barrier (consisting in IR and US sensors) and a vision system.

Due to the fact that detection carried out by the barrier is based on the lack of radiation in the receivers, the channel degradation can be mistaken with the existence of obstacles. Since there is a large amount of correlated information in the barrier, Principal Component Analysis has been proposed to reduce such information before a decision is taken. Furthermore, PCA filters the situations of random interrupted links, such as in the case of small objects entering and leaving the scanned area for a short period of time. With PCA, binary information about the existence of obstacles is obtained. Results show that this technique is suitable to validate the obstacle detection, and it increases the reliability of the system.

Alternatively, PCA has also been applied to the vision system to detect moving objects. A model of the background representing stationary scenarios has been obtained. The experimental results show that the proposed algorithm can compensate changeable illumination conditions.

Currently authors are working in the algorithm to fuse the information between US and IR sensors in order to obtain from the barrier one reliable measurement about the existence of obstacles. This algorithm is taking into account the drawback of each sensor and the weather conditions.

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