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Ultra-Wide Bandwidth Systems for the Surveillance of Railway Crossing Areas

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Abstract

Level crossings are critical elements of railway networks where a large number of accidents take place every year. With the recent enforcement of new and higher-safety standards for railway transportation systems, dedicated and reliable technologies for level crossing surveillance must be introduced in order to comply with the safety requirements. In this survey the worldwide problem of level crossing surveillance is addressed, with particular attention to the recent European safety regulations. In this context, the capability of detecting, localizing and discriminating the vehicle/obstacle that might be entrapped in a level crossing area is considered of paramount importance to save lives and, at the same time, to avoid costly false alarms. In this paper the main solutions available today are illustrated and their pros and cons discussed. In particular, the recent ultra-wide bandwidth technology, combined with proper signal processing and backhauling over the already deployed optical fiber backbone, is shown to represent a promising solution for safety improvement in level crossings.

I. Introduction

Level crossings (LCs), where almost 50% of all train accident events caused by third parties take place, are very difficult for the railway sector to control. In the US there are about 270 deaths a year at public and private grade crossings and nearly every 180 minutes someone is hit by a train [1]. The Federal Railroad Administration (FRA), through the efforts of its Highway-Rail Crossing and Trespasser Prevention Division, is committed to reduce that number. Federal funding for installing automatic warning devices and other improvements for public highway-rail crossings is managed by the Federal Highway Administration and commonly referred to as the Section 130 program.

In 2010 the European Railway Agency (ERA) disclosed the European benchmark in LC safety reporting 619 significant LC accidents resulting in 359 fatalities and 327 serious injuries. In EU LC accidents represented 27% of all significant railway accidents and 28% of all fatalities on railway, suicides excluded [2]. There are currently about 1.2 million LCs in the EU and, on average, there are five LCs per 10 line-km. Half of them are active LCs with some sort of user-side warning, while the reminders are passive LCs typically equipped only with the St. Andrew's cross traffic sign. A similar active/passive percentage (43%/57%) applies also to the reported 250/523 highway-rail grade crossings in the United States [1]. LCs with automatic user-side warning (typically flashing lights and sound) are in Europe the most common type of active crossings (38%) closely followed by the LCs with automatic user-side protection and warning (barriers with lights) (34%).

The economic impact of fatalities and serious injuries in LC accidents was estimated in 350 million Euros in 2010 [2]. The 2004/49 CE directive is oriented to promote the development and improvement of safety on EU Community's railways by harmonizing the regulatory structure in the member states. The concepts of *common safety targets* and *common safety methods* have been here introduced to ensure that a high level of safety is maintained and possibly enhanced, and one of the most critical points is the protection of *LCs*, which is defined in the common safety indicator (CSI) of this directive. CSIs are based on common definitions and calculation methods. The data set is structured following significant accidents, deaths and serious injuries, economic impact of accidents, technical aspects (level crossings by type and automatic train protection systems) and management of safety [3]. In order to maximize the LC safety level while preserving a reliable and fast network, companies are then required to develop technical solutions complying with the EU safety requirements.

In this context, the availability of large backhaul communication networks based on fiber-optic technology which have been deployed in several countries along railway lines in recent years paves the way to a new generation of LC surveillance systems, such as those relying on ultrawide-band (UWB) signals.

In this paper we illustrate the application of UWB technology to LC safety and, successively, we propose a solution exploiting the combination of UWB and fiber-optic links to centralize all signal processing tasks to a remote central unit.

The paper is organized as follows. In Sec. II the most recent technologies for LC surveillance are surveyed by illustrating their main characteristics and limitations with reference to the current safety requirements. Our proposed solution is then presented in Sec. III, where a case study is also reported to show the performance achievable using such a system. Finally, in Sec. IV potential future developments are described and conclusions are drawn.

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II. RAILWAY CROSSING SAFETY SYSTEMS

A. Safety Requirements

Safety requirements and regulations are specific to each country and, in some cases, to single rail infrastructure operators, therefore in the following we use the European scenario as a reference.

Passive safety requirements for railway vehicles are defined in the Commission Decision UE 291/2011 (par. 4.2.2.5), and refer to all subsystems, comprising surveillance system for LC areas, which can operate independently from the railway infrastructure. This definition fits the LC scenario where, despite the automatic user-side warning as well as barrier closing, a road vehicle could be entrapped inside a LC generating an extremely dangerous situation that could lead to a collision with the incoming train. Two reference collision cases are classified for LCs: the impact of the train with a *large obstacle* or a *small obstacle*. The entrapped object of the first case is described in EN15227/2008 (Table 2, Sec. 5), as a heavy truck or a tank. In the second case the EU decision does not provide specific information about the smallest size of the obstacle. To fix a requirement, it is reasonable to consider the minimum size of a vehicle which must be detected inside the LC and generate an alarm. This can be approximated with a parallelepiped volume placed on the ground with dimension equal to $2 \times 1.1 \times 1.3\,\mathrm{m}^3$. This dimension is slightly smaller than that of the smallest minicar available in the market. Under a conservative setting, the critical dimension for the performance assessment of different surveillance systems can be chosen equal to one cubic meter. Therefore one of the key performance parameter is the capability of the system to discriminate the volume of the obstacle (when present), as only obstacles larger than one cubic meter must generate an alarm with consequent stop of the train.

According to current EU regulations, LC surveillance systems must also satisfy functional requirements in terms of robustness to weather conditions, cost, and ease of installation on existing infrastructures, making their design challenging. In particular, the *tolerable hazard rate* is defined as a target measure of both systematic and unpredictable failure integrity. For instance, LC surveillance systems must guarantee a *false alarm rate* (i.e. the detection of obstacles even if they are not present in the area) less than $1.9 \cdot 10^{-4}$, which is equivalent to one false alarm per year with a traffic of 20 trains per day. On the other hand, the *misdetection rate* (i.e. the missed detection of an obstacle when it is effectively present in the area) must be below 10^{-8} [3]. In the following, we describe current possible solutions which aim to preserve safety in LC areas. Specifically, only systems that can be integrated with the railway infrastructure without human interaction will be considered here. As a consequence, other solutions such as those that rely on car speed reduction through bumpers, on traffic signals improvement, or on TV-based surveillance are out of the scope of this work.

B. Surveillance Systems State of the Art

In recent years several systems have been proposed for LC surveillance, each supported by a different technology:

- Microwave/millimeter-wave Radar;
- Inductive Loops Detector
- Laser Imaging Detection and Ranging (LIDAR);
- Stereo Camera Detection.

The radar concept was born with microwave technology with the main intent to detect the presence of an intruder inside a monitored area. A key radar indicator is the radar cross section (RCS), which represents the projected area of a metal sphere that would scatter the same power in the same direction as the target does. Most of radar systems rely their capability in discriminating the dimension of the object on RCS estimate by analyzing the reflected signal (backscatter). Several operating frequency bands as well as radar architecture configurations have been exploited. For example, in [4], two UWB mono-static radars cover half-portion of the monitored area, respectively (see Fig. 1a). Each UWB radar detects obstacles eventually present in its covered area portion by analyzing the backscattered signal to obtain only a rough approximation of the obstacle's size. Unfortunately the coverage area separation among sensors determines a low localization resolution and makes the system performance particularly sensitive to single sensor outage. In [5], the multiple-input multiple-output (MIMO) antenna array concept is developed for a frequency modulated continuous wave (FMCW) radar operating at 25 GHz. Even though the dimension of obstacle still relies on RCS, the MIMO configuration allows for a 2D angular resolution in azimuth.

With the liberalization and the possibility to use the Ka-band and higher bands (e.g. V-band), different systems exploit these new frequencies that are characterized by a low level of interference. In particular, [6] adopts FMCW at 36.5 GHz using up to 9 sensors, whereas [7] investigates a spread spectrum radar at 60 GHz using the correlation of pseudo-noise codes to detect the obstacle in distance and azimuth, respectively.

A common limitation of all these systems is that RCS is not a reliable indicator of object's dimension as it strongly depends on object reflection characteristics and shape which are not known a priori. Moreover, since electromagnetic waves propagation cannot be confined in a specific area, false alarms caused by objects located outside the LC area are possible. This is actually the main limitation of radio-based systems that can be mitigated only if high-accuracy localization capabilities are implemented, as detailed in Sec. III.

The solution based on Inductive Loops [8] was among the first to be proposed. The loops are excited with signals whose frequencies range from 10 KHz to 50 KHz, and when a vehicle stops on or passes over, their inductance is decreased. Depending on the resonance frequency generated by the wire loop it is possible to identify specific metal portions of the vehicle. This system is very simple but extremely inaccurate in estimating obstacle's dimension. The massive presence of metal in the railway causes problems in threshold setting and, additionally, wire loops are subjected to traffic stresses and temperature effects.

Another solution is represented by the LIDAR technology, which exploits ultraviolet, visible, or near infrared light to illuminate a target with a laser. Objects detection and 3D image reconstruction are based on the time-of-flight (TOF) of the electromagnetic wave. In [9], environment scanning is performed through a single-head 3D laser range finder which is tilted to create a 3D image of the scene, as shown in Fig. 1c. As for the stereo camera solutions, several works have been published extracting 3D information from digital images by comparing the same scene taken from two advantageous locations.

A common problem of image detection methods is the static background estimation, which causes the necessity to detect and track incoming, staying or outgoing objects in the LC area, as investigated in [10], where the 3D localization is performed by hierarchical belief propagation algorithms. Differently, [11] assumes that the displacement of the image contents between two nearby instants (frames) is small and approximately constant within a neighborhood of the point under consideration. Thus the optical flow equation can be assumed to hold for all pixels within a window centered at that point.

The main characteristics of current technologies are summarized in Table I, where it can be noted that present microwave and millimeter-wave solutions do not provide any or only rough information about the obstacle volume and position. On the other side, the solutions based on image detection, while exhibiting very high resolution in obstacle shape detection, might suffer from image degradation when working in non-optimal weather conditions. In table I the different solutions are compared also in terms of cost of the technological apparatus. We must point out that other related costs, such as those site-specific deriving from the installation of the supporting infrastructure, might have a determinant impact and can be hardly generalized.

Another important parameter is the maintainability, which falls into the so called management of RAMS (reliability, availability, maintainability and safety). One of the figures of merit defined in the EN-50126 European Standard for Railway Applications, adopted also by other international projects like the California High Speed Train (CHSTP), is the mean down time (MDT), which is the average time when a system is not operational. All the considered systems exhibit a degree of quantifiable self-imposed down time for periodical calibration. However, the times related to repairing, corrective and preventive maintainance, and logistic or administrative delays depend again on the individual instance considered, and therefore a general comparison in terms of MDT has not been included in Table I.

III. UWB RADAR/IMAGING SYSTEMS

In this section we discuss how it is possible to design a LC surveillance system to enhance LCs safety by exploiting the UWB radar technology with a partial multi-static architecture.

A. UWB Radar

A promising wireless technique to detect, localize, and estimate the dimension of obstacles is the UWB technology characterized, in its impulse radio implementation, by the transmission of sub-nanosecond duration pulses. The employment of UWB signals enables the resolution of multipath and extraordinary localization precision based on TOF estimation of the signal. The UWB radar is therefore considered as an interesting option for surveillance tasks in terms of spatial resolution. UWB radar architectures can be *multi-static*, where one or more transmitters send the interrogation signal and more receivers, located in different positions, process the signals backscattered by the environment, as shown in Fig. 1b. When transmitters and receivers coincide and the receiver manages only its own backscattered signals we obtain a *mono-static* radar architecture illustrated in Fig. 1a. Both solutions are well investigated but their direct application to the problem of LC surveillance could be problematic. Indeed, as regards multi-static radars, the potentially large size of obstacles prevents from the adoption of classical solutions that are implicitly based on unrealistic assumptions such as isotropic scattering, moving objects, and punctual obstacle size [12]. On the other hand, mono-static UWB imaging systems (UWB scanners) provide high-accuracy obstacle imaging but require a large amount of antennas mounted on a mechanical arm that circumnavigates the obstacle contour, which is obviously not feasible in the application under consideration. For these reasons, in the following we discuss a possible solution recently proposed in [13] to counteract the above mentioned issues.

B. The Partial Multi-static UWB FOS

As previously discussed, classical UWB multi-static radar schemes work under quite unrealistic assumptions and might fail when applied to railway crossing areas. In fact, the finite size and the anisotropic scattering of the obstacle might prevent some nodes (e.g., those located in the opposite direction) from receiving the backscattered signal. Therefore the absence of expected components (e.g., obstruction, high angle of incidence of the wave on the object) and the presence of unexpected components in the received signal (e.g., multipath) might generate unsolvable ambiguities when detecting and estimating the right position of the object thus seriously compromise the image formation, as it will be shown in Sec. III-D.

To overcome such limitations, we describe a recently proposed solution, namely fixed object scanner (FOS), capable of detecting, localizing and estimating the obstacle's volume, even in static conditions. It makes use of a fixed set of UWB nodes to obtain the information about the volume of the obstacle and discriminate between large or small obstacles. Specifically, the surveillance system is composed of a set of transmitter (TX) and receiver (RX) nodes, located at different heights at the vertices of the monitored area, as shown in Fig. 2. The sounding of the environment via UWB interrogation signals and subsequent analysis of backscattered signals is split in different phases to which only a subset of nodes participate leading to a partial multi-static radar configuration. In particular, the FOS algorithm performs 5 phases, 4 for the lateral sides and one for the top of the area. During each phase, only the TX-RX pairs located in the considered side are activated, thus miming the presence of several mono-static imaging scanners with fixed nodes. In this way, the resulting partial multi-static radar operates most likely in conditions where the incident angle of the electromagnetic wave impinging the obstacle is $< 90°$, with a consequent significant mitigation of the aforementioned ambiguities during the imaging process in Fig. 2.

With the purpose to facilitate the 3D imaging algorithm, the monitored area is subdivided into small 3D cubic pixels. The 3D imaging process of the obstacle can be summarized in the following steps: *clutter removal, pixel detection, imaging,* and *volume estimation*.

a) Clutter Removal: An important issue when detecting the presence of steady obstacles is the static environment response (*static clutter*) caused, for example, by the rail and poles. This component is removed by using an *empty-room* approach in which the reference signals, recorded in the absence of obstacles, are subtracted from the actual received signals. Note that when an obstacle is present, part of the static clutter could be hidden leading to imperfect clutter suppression. To counteract this *ghost effect*, only the signal components corresponding to positive variations in the received energy are taken into account during the clutter removal process.

All measurements are successively collected by a fusion node responsible for taking an overall decision on the event. To reduce the number of LCs to be monitored by a given fusion center, an interesting opportunity is to connect the sensor nodes and the fusion center through fiber-optic links, as it will be discussed in the next section.

b) Pixel Detection and Imaging: Obstacle detection and image formation consist in checking whether the generic pixel is a candidate for containing part of the obstacle (if present). This is accomplished by performing, during each phase and for each pixel, a specific binary detection test where the corresponding likelihood ratio is compared with a threshold as described in [13]. This procedure is repeated for each pixel and phase. In the end, all binary test outputs are combined to form the 3D image. In particular, the presence of part of an obstacle in a 3D pixel is detected if at least one pixel is above the threshold during the scanning phases.

c) Volume Computation: The result of the 3D image formation is used as input for volume computation to estimate the size of the obstacle, if present, and generate an alarm to stop train if the estimate value is greater then 1 cubic meter. One possible approach is to compute the average parallelepiped volume starting from the moment of the pixels along each dimension with respect to the barycentre as proposed in [13].

Note that the FOS algorithm can be considered as a hybrid approach combining the UWB multi-static radar and the mono-static imaging scanner configurations. As a consequence, it allows for gaining some of the advantages of both configurations and mitigating their drawbacks. Indeed, it overcomes the limitations of optical based systems [9], [10] and, at the same time, offers good obstacle detection and localization performance inside the LC as it will be shown in Sec. III-D.

C. Remote Processing using the Optical Fiber Infrastructure

The implementation in loco of all signal processing tasks involving UWB signals could be costly and imply difficult maintenance procedures. Therefore, remote operations would be preferable. On the other hand, the transmission of raw UWB measurements coming from sensor nodes is extremely demanding in terms of the required bandwidth. Fortunately, most of countries in Europe have deployed dedicated fiber-optic communication infrastructures that could be exploited to move the signal processing tasks from LCs to a central unit. For instance, the Italian railway operator Rete Ferroviaria Italiana (RFI) has developed an optical network which covers more than 10,000 km. The cable deployment started in the ’80s to develop a high capacity network and fulfill the growing technology demand on railways process. The 50% of fiber links are available for future applications. To eliminate the need of extremely high-speed analog-to-digital converters at sensor nodes, the *UWB radio-over-fiber (RoF)* approach is of particular interest. This technique is indeed widely utilized in many applications for antenna remotization, since it allows the transparent transmission of the received signal to the central unit [14]. Each antenna is then equipped with a RoF link, which in turn is formed by a RoF transmitter, based on a Distribution Feed Back (DFB) laser, a strand of G-652-compliant optical fiber, and a RoF receiver based on a PIN-photodiode followed by an RF amplifier. The modulation bandwidths of today’s DFB lasers extend easily to some GHz, and this allows their direct modulation, avoiding the use of costly external electro-optical modulators. The wavelength of operation for the DFB has been chosen as $\lambda = 1310$ nm, so that, operating in the second optical window, where the chromatic dispersion is very low, the distortion effects due to the laser frequency chirp become negligible. The same effects hold for laser non-linearities, which in the case of DFB are more limited with respect to other kinds of lasers (e.g. Fabry Perot or Vertical Cavity) and, considering also the low power levels of the input UWB signals, can be neglected as well. Consequently, the main detrimental effect in the RoF transmission results from the increase in the noise figure of the system caused by the RoF link. For short link lengths the increase is mainly caused by the relative intensity noise of the DFB and by the shot noise of the PIN, while for longer link lengths the thermal noise of the receiver RF amplifier becomes dominant.

D. Case Study

Now we show a case study where a classical UWB multi-static approach and the FOS algorithm are compared to assess their capability in discriminating the volume of the obstacle.

The surveillance area is divided in 3D pixels of side $\Delta = 10\,\text{cm}$. The channel transfer function between each TX–RX pair has been simulated with the aid of the 3D ray tracing (RT) software described in [15]. In addition to specular reflection and edge/corner diffraction, modeled through geometrical optics (GO) and uniform theory of diffraction (UTD), the RT tool accounts for the effect of diffuse scattering, modeled through the effective roughness (ER) approach [15]. One of the main parameters of the ER model is the scattering parameter S, where S^2 represents the amount of power which is diffused in all directions at the expenses of specular reflection, due to the presence of surface and volume irregularities. The obstacle is modeled as a metal box, whereas ground, barriers, tracks and antenna poles are modeled as slabs.

The 3D imaging approach previously described has then been applied to the output of RT simulations, for obstacles having volume 5.83, 1, and 0.34 m^3 placed inside the surveillance area.

Figure 3 shows the 3D image output of the FOS algorithm for a metal box of 5.83 m^3, located in the middle of the area. A typical value for outdoor environments of $S = 0.3$ has been used in this case, thus meaning that about 10% of the reflected power is diffused in non-specular directions [15]. The actual geometry of the object, as modeled in RT simulations, is also included as a reference in the figure (green line). The volume yellow parallelepiped juxtaposed can be taken as representative of the actual volume of the obstacle.

For comparison, the same simulation set up has been used to derive the results in Fig. 4 where the classical UWB multi-static radar approach is considered [12]. Even though the presence of the obstacle is detected, a huge number of outlier pixels arise due to ambiguities, thus making impossible a realistic volume computation and/or localization of the obstacle. Comparing with Fig. 3, the gain introduced by the FOS algorithm is evident.

Table II summarizes the volumes computed for some simulation set up, i.e. different volumes and positions of the metal box, and exploiting optical fiber connection. As can be noticed, the classic approach makes it impossible a realistic volume computation and/or localization of the obstacle. Instead, the same volume computation exploiting FOS detection/imaging provides an approximate estimation of the actual volume of the obstacle. Moreover, the stability of the FOS approach is tested for increasing lengths of the optical connection between sensors and central unit. As can be noted the noise introduced by RoF link irremediably corrupts UWB signals after $40\,\text{km}$. We can conclude that up to 40 km optical links are tolerable without creating a significant performance degradation in terms of obstacle imaging.

IV. CONCLUSIONS AND FUTURE PROSPECTS

Recent safety requirements adopted in Europe as well as in other countries for the surveillance of railway level crossing areas are very demanding, and therefore new and sophisticated technologies for automatic surveillance are necessary. Some existing solutions have been discussed concluding that a technology change is unavoidable to fully meet the safety requirements. An important step towards this direction is represented by the adoption of the UWB technology in conjunction with UWB radio-over-fiber communication exploiting the fiber-optic networks already deployed in most railway networks. In this paper we have shown that this technology, if opportunely paired with the FOS approach, can enhance the capability of the surveillance system in discriminating the dimension of the objects inside the monitored area, thus overcoming the limitations of other approaches. Extensive studies corroborated by experimental campaigns considering a wider set of requirements are necessary to confirm the validity of this and other solutions.

Anyway, it could be pretentious to rely completely on a single technology: higher levels of safety could be achieved through a smart integration of different ones (UWB, video, laser, etc.) and by designing advanced data fusion algorithms and communication schemes.

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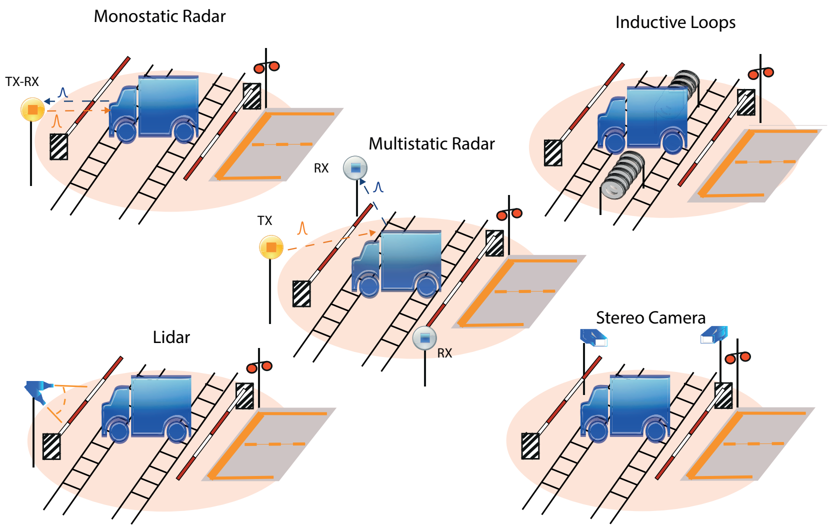

Fig. 1. Different technologies available to detect the presence of an entrapped object inside the level crossing area.

TABLE I
COMPARISON BETWEEN THE CHARACTERISTICS OF DIFFERENT MONITORING TECHNOLOGIES.

Technology	**System Architecture**	**Dimension Estimation**	**Localization Capability**	**Heavy Rain**	**Dense Fog**	**Cost Range**
Mono-static radar	two sensors [4]	RCS estimation	none	reliable	reliable	low
Ka-band radar	independent multiple sensors [6]	RCS estimation	none	reliable	reliable	Medium
V-band radar	antenna array [7]	RCS estimation	approximated 2D localization	reliable	reliable	Medium
MIMO radar	antenna array [5]	RCS estimation	approximated 2D localization	reliable	reliable	Medium
FOS radar	multiple sensors [13]	good resolution	good 3D localization	reliable	reliable	Medium
Iductive loops	multiple buried turns [8]	low resolution	none	reliable	reliable	Low
LIDAR	single head [9]	high resolution	high 3D localization	blind spot	unreliable, image degradation	High
Stereo Camera	single head [10], [11]	high resolution	high 3D localization	unreliable, image degradation	unreliable, image degradation	High

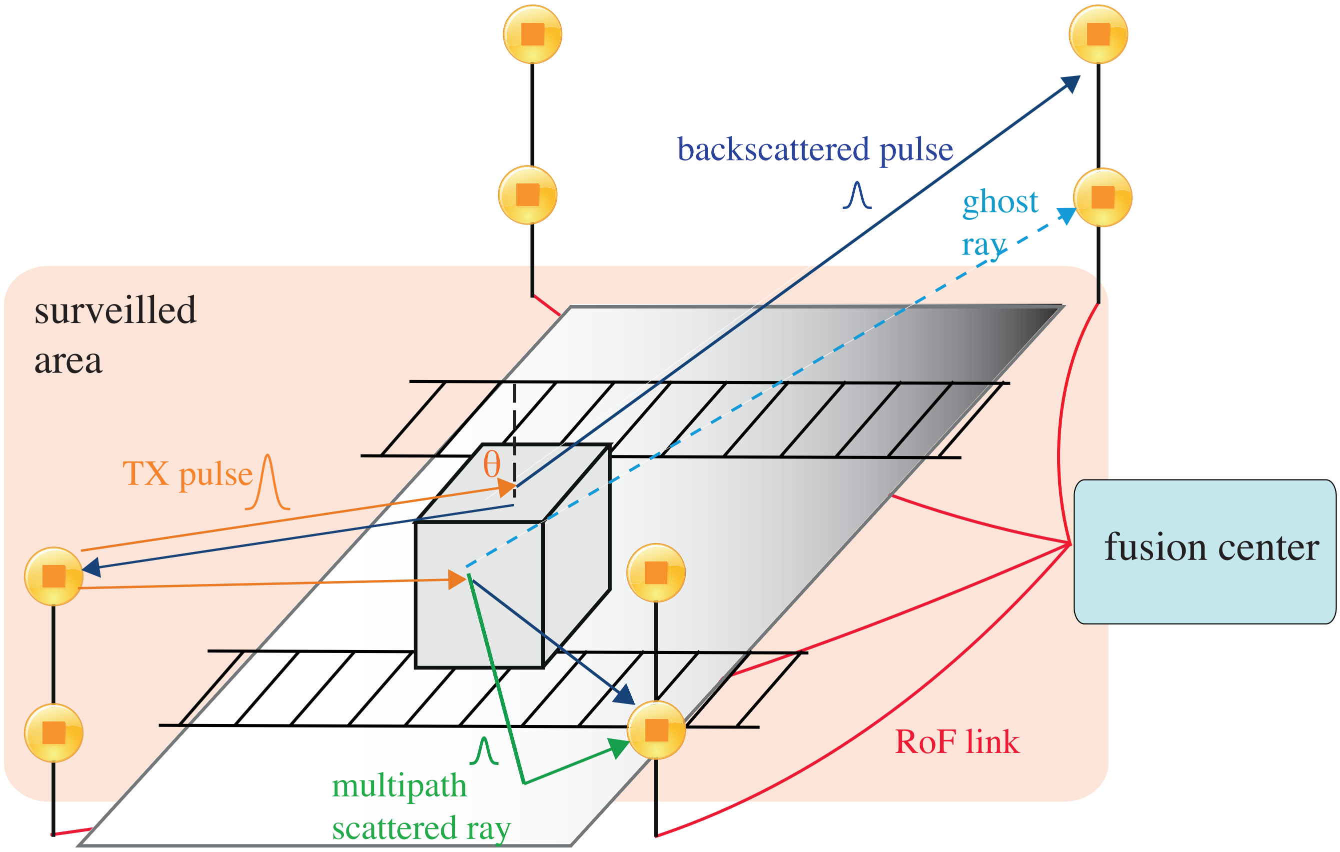

Fig. 2. Architecture of the level crossing surveillance system with the FOS UWB radar

TABLE II
OBJECT VOLUME ESTIMATION CAPABILITIES IN DIFFERENT CONFIGURATIONS.

Box Volume $[\mathrm{m}^3]$	**Position**	**Classical Approach $[\mathrm{m}^3]$**	**FOS $[\mathrm{m}^3]$ for different RoF links**				
			0 km	10 km	20 km	30 km	50 km
5.83	middle	>10	6.49	6.52	6.52	6.53	11.01
1.00	middle	>10	1.14	1.14	1.14	1.16	3.15
1.00	corner	≈ 10	1.23	1.28	1.23	1.12	13.45
0.34	middle	>1	0.24	0.37	0.37	0.41	1.13

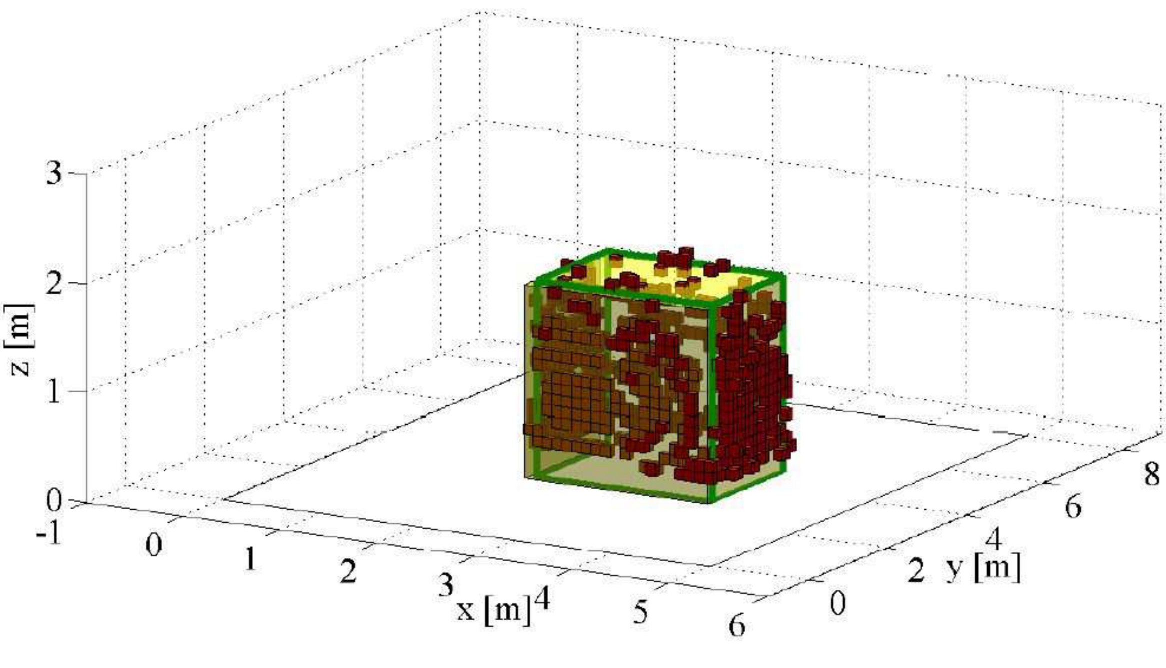

Fig. 3. 3D image of a metal box of 5.72 m^3 in the middle of the surveillance area using the FOS approach.

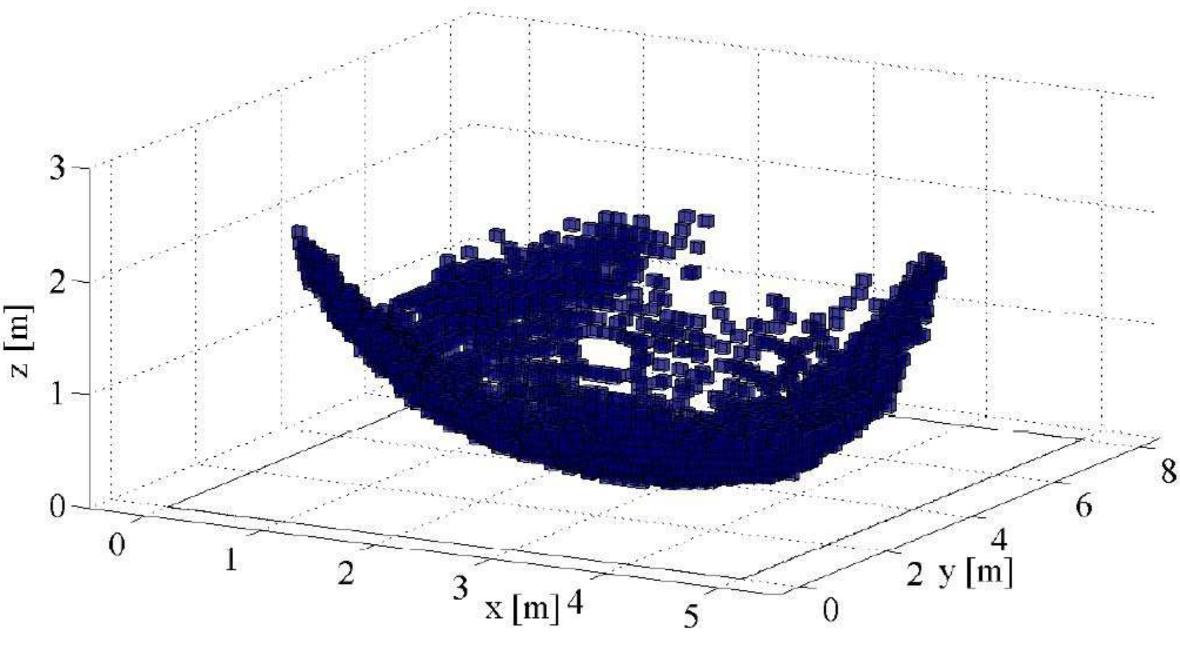

Fig. 4. 3D image of a metal box of 5.83 m^3 in the middle of the surveillance area using the classic UWB multi-static radar approach.