Safe protection of railroad critical areas by using radar technology

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ABSTRACT

The rail network is one of the most important parts of the transport infrastructure in Italy, with a total length of 10,391 miles and a rail density double with respect to the USA rail network density. Italy was the first country to adopt the ERTMS/ETCS system for the high speed trains running at a maximum speed of 185 miles per hour since 2009. The Italian infrastructure manager RFI is promoting the development of solutions for enhancing the current level of safety by using the most innovative technologies. Intecs is currently studying solutions for the safe protection of railroad critical points such as:

- Tunnel entries and exits;
- Bridges;
- Level crossings.

The main concern is the presence of obstacles on the railroad. Obstacles can be detected by using several technologies, radar one being one of the most
promising and IDS, basing on a consolidated know how in radar applications, is analyzing and developing radar solutions dedicated to railways safety. However the *a priori* non-deterministic behavior of sensors implies a deep analysis to demonstrate the achievement of the adequate safety level set, by the Italian infrastructure manager (RFI), to SIL4 (the highest safety level in accordance to the European CENELEC standards).

The paper will address the following points:

1. A clear identification of the safety level prescribed by the CENELEC Standards;
2. The challenges implied by the adoption of the radar technology and the possible solutions;
3. Examples of real applications such as:
   - obstacles falling from bridges;
   - obstacles remaining within level crossing barriers.
INTRODUCTION


The same report provides recommendations for the adoption of systems for obstacle detection and monitoring of Level Crossings.

Obstacle detection can be based on different technologies; the most used are:
- Image processing
- Induction loops (mainly for metallic objects)
- Ultrasonic sensors
- Strain gauges
- Lidar
- Radar

All of them have pro and cons, due to the specific detection principle. This paper does not intend to provide a comparison between the different technologies, but is limited to presenting the benefits and drawbacks linked to the adoption of a solution based on Radar technology.

The Italian Infrastructure Manager (RFI) has established that whatever technology is used, it must achieve the maximum Safety Integrity Level (SIL4) in all conditions (i.e. critical weather). The achievement of the SIL4 requirement must be certified by an Independent Safety Assessor authorized by ANSF.

APPLICABLE RULES AND ITALIAN SAFETY ORGANIZATION

ANSF is the Italian national organization in charge of ensuring the safety of the entire Italian Railway System. The tasks assigned to ANSF are:
- Issuing of norms/rules;
- Issuing of authorizations;
- Monitoring and Control.

All of the above must be accomplished in the framework established by the European rules (Decisions, Directives, Recommendations and Regulations). This framework enforces the adoption of the CENELEC Standards EN 50129 [3].

The latter is derived from the International Standard IEC 61508 and adopts a similar scheme for the evaluation of the risk associated to a Railway application. The risk is quantitatively and qualitatively ranked by using the table below:

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1 As identified in the CENELEC European Norm EN 50129 [3].
2 The authorized Independent Safety Assessors are listed on the ANSF web site: www.ansf.it/verificatori-indipendenti-di-sicurezza

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### TABLE 1: SIL-table

<table>
<thead>
<tr>
<th>Tolerable Hazard Rate per Hour and Function</th>
<th>Safety Integrity Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-9} \leq \text{THR} &lt; 10^{-8}$</td>
<td>SIL4</td>
</tr>
<tr>
<td>$10^{-8} \leq \text{THR} &lt; 10^{-7}$</td>
<td>SIL3</td>
</tr>
<tr>
<td>$10^{-7} \leq \text{THR} &lt; 10^{-6}$</td>
<td>SIL2</td>
</tr>
<tr>
<td>$10^{-6} \leq \text{THR} &lt; 10^{-5}$</td>
<td>SIL1</td>
</tr>
</tbody>
</table>

In the left column a quantitative target is given to be demonstrated by using quantitative system evaluation methods. The right column is used to select the methods and technical constraints to be used in the system design (both Hardware and Software).

The achievement of the target Tolerable Hazard Rate (THR) can be demonstrated using well established computation techniques such as Fault Tree Analysis (FTA), Failure Mode and Effect Analysis (FMEA), and so on. However the application of such methods to radar based applications must face the uncertainty linked to the use of electronic devices.

**RADAR TECHNOLOGY BENEFITS AND DRAWBACKS**

**Quantitative Evaluation**

Obstacle detection aims at identifying the presence of an object in a specific area and to provides information to guide a suitable response so that collision can be avoided or the consequences minimized. In addition, an Obstacle Detection System shall not cause train delays (False Alarms).

Consequently an Obstacle Detection System must be evaluated on both:
- the capacity to detect dangerous objects
- the capacity to *not* detect not dangerous objects.

Independently from the used technology, Italian Railway Infrastructure Manager (RFI) set a threshold in terms of object size to define if an object must be considered dangerous, a small object is not considered worth detection. In the radar domain a better measure is the Radar Cross Section.

The Radar Cross Section (RCS) is the measure [m²] of a target's ability to reflect radar signals in the direction of the radar receiver and represents of how detectable an object is with a radar. A number of different factors determine RCS: material, size and shape of the target, incident angle, reflected angle and polarization.

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3 The tables applies to continuous mode systems.
The radar detection is performed by putting a threshold on the amplitude of the receiver signal. Once the threshold has been established, the Probability of Missed Detection (PMD) and the Probability of False Alarm (PFA) can be theoretically computed.

From a Safety point of view only the PMD is relevant; however if we compare the THR target (missing an object every $10^8$ hours) with the usual radar PMD (missing an object every 4 attempts, PMD=25%) there is clearly a gap to be covered.

In TABLE 2 a number of technical options are reported. The list does not intend to be exhaustive but is based on experience.

<table>
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<tr>
<th>Technical options</th>
<th>Advantage</th>
<th>Drawback</th>
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<td>Multiple beams exploring the same area provide information on the object location.</td>
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<td>The radar is less reactive.</td>
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<td>Increment the number of sensors by locating them in different places around the monitored area</td>
<td>A greater level of confidence in the object detection can be reached by voting the sensor results.</td>
<td>Sensors observe different RCS and results cannot always be directly voted</td>
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</table>

TABLE 2: Technical options

Not only the radar PMD has to be taken into account for the THR evaluation. A hardware failure can prevent the system from detecting an obstacle. For this specific purpose the already-mentioned techniques of FTA and FMEA apply.

In this context a 2oo2 architecture can help in reaching the THR objectives.

**Qualitative Evaluation**
The CENELEC EN 50129 [3] requires a Safety Integrity Level SIL4 to be fail-safe. There are a number of options allowed by the standard:
- Dual electronic structure based on composite fail-safety with fail-safe comparison;
- Single electronic structure based on inherent fail-safety;
- Single electronic structure based on reactive fail-safety;
- Diverse electronic structure with fail-safe comparison.

In all cases the failure shall be detected and negated before the system commanding is completed. In most cases this time is equivalent to the relay excitation time (around 100 ms.)
REAL EXAMPLE OF SOLUTIONS
Detection of falling objects
The SIRIO (Sistema per la Rilevazione di Ostacoli) System has been conceived to satisfy the RFI request to protect the area in proximity of tunnels or below bridges. The system is part of the trackside equipment to be installed on the high-speed line between Rome and Naples.

In FIGURE 1, the typical installation in proximity of a bridge is presented.

FIGURE 1 – SIRIO

The system monitors the two areas at the opposite sides of the bridges to detect falling objects. The monitored areas have a typical size of 9x14 meters. The overall node is composed by 4 Radar Sensors, 4 Reflecting Units and 1 Elaboration Unit. On each side of the bridge a camera is installed to observe the scene.

The node is connected to a remote control center via a GSM-R connection. On the Rome-Naples line (200 km.), the installation of 10 nodes is planned.

Each Radar sensor is continuously transmitting its pulse to a reflecting unit; if this pulse is not received back the entire system enters in a degraded mode (from SIL4 to SIL2) using the remaining sensors. The SIL2 function is kept if at least one sensor is correctly working in each area.

The Radar sensor is completed by an additional Doppler Radar with the task to observe the line to detect an incoming train. An incoming train will temporarily
disable the system detection capabilities to avoid that a train is considered an obstacle. When the train is out the detection capabilities are restored.

The system operates autonomously, raising an alarm when an obstacle is detected. The alarm indication and, optionally, the video captured during the previous 5 seconds by the installed camera are sent to the remote control center to take the appropriate action automatically or by operator.

![FIGURE 2 - The SIRIO System](Image)

The SIRIO System’s main technical data are:
- Detected obstacles: RCS>0.25 m$^2$
- Time to alert: < 20 seconds
- Safety Integrity Level: SIL4
- Reliability: >10 years

The system is currently submitted to ITALCERTIFER (Independent Safety Assessor) to obtain SIL4 certification.

**Level crossing protection**
The SIRIO concepts can be applied to the level crossing where the focus is on obstacles located inside the area when barriers are closed. The requirements identify two types of obstacles and areas:
- Small obstacle (obstacle with 0.3 m$^2$<RCS≤1.25 m$^2$);
- Major obstacle (obstacle with RCS>1.25 m$^2$);
- Train area (the area that can be occupied by the train with an additive margin of 25 cm.).
- Level Crossing area (the area between barriers).

The alarm shall be raised when a stable small object is detected in the Train Area or a major obstacle is detected in the level crossing area. A moving small object is usually associated to a human being trying to cross the train area; the system adopts the policy to wait a certain amount of time for his exit.

FIGURE 3 presents the logic implemented in the system through the following steps:
1. When the level crossing barriers are lowered, the system starts to check the area;
2. If a major object is detected in the level crossing area, the detection information is sent to the remote center and the system does not enable the train to approach the level crossing;
3. If a minor object is detected in the Train area and is moving, the system waits, with a timeout, for the object to come to a standstill or exit the area.
4. If the detected minor object is standing still or the timeout elapsed, the detection information is sent to the remote center and the system does not enable the train to approach the level crossing;
5. If either a small or a major obstacle is detected, the system enables the train to approach the level crossing.

![FIGURE 3 The Level Crossing Detection Logic](image-url)
The area is monitored within 10 seconds from the barrier closure; if the area is free the enabling signal is given.

The system architecture is presented in FIGURE 4 and is based on a sensor located on top of a 4-meter high post. The sensor is a phased array radar observing the whole area and detecting objects using the proper RCS thresholds depending on the location on the field (that is, in the train or in the level crossing area).

![FIGURE 4 The Level Crossing Detection System](image)

A complete solution to protect a level crossing is composed by 1 Radar unit (containing multiple sensors), 1 Reflecting Unit, and 1 Elaboration Unit. Optionally a video camera can be installed to observe the scene.

**CONCLUSION**

Radar technology can be effectively used for the safe protection of critical areas. The detection uncertainty linked with the technology can be overcome adopting suitable techniques. Redundancies and longer observation time can greatly help in fulfilling the safety requirements established in the CENELEC EN 50129 [3] standard.

The RCS concept must be accepted by the customer. Railway Infrastructure Managers are used to thinking of an obstacle in terms of size rather than cross section and reflectivity. It is true that the consequences of a collision are independent of the reflectivity, but is also true that the size is not a good parameter since very large but lightweight objects can cause very low damage.
to the hit train. The weight, possibly combined with the size, could be a much better parameter to measure. Currently, however, there are no good solutions for such a measure.

Radar technology is very promising with respect to adverse weather. We ran an extended test campaign to check the behavior of the radar under different weather conditions without logging any problems (although we have not yet experienced extreme conditions such as heavy snow or icing).

The installation of a radar based system is quite simple and there are no stringent requirements on the installation geometry. The limited number of sensors reduces the cabling and the maintenance effort to keep the system working with the SIL4 capability.

The radar solution is not cheap, but the features offered are such that they constitute a valuable solution for the protection of railroad critical areas.

ACKNOWLEDGEMENTS
Special thanks to Mr. John Favaro (Intecs-I) for his review and contribution of valuable suggestions.

REFERENCES
[1] ERA - Level crossing safety in the European Union

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FIGURE 3 The Level Crossing Detection Logic
FIGURE 4 The Level Crossing Detection System

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TABLE 2: Technical options
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Intecs SpA – Pisa – Italy
The Italian Network

- Total length of 10,391 miles
- 404 miles - High Speed Lines
- 9,987 miles - Traditional Lines

*Europe is implementing the “TEN-T European Corridors” project for freight trains. Three corridors are through Italy and will use High Speed Technology.

The European Safety Standards

- Total Railway System
- Complete Railway Signalling System
- Individual Sub-System
- Individual Item of Equipment

EN 50159  EN 50128  EN 50129

Relationship with the IEC Standards

The Safety Integrity Levels

- The quantitative requirement of a THR must be supplemented by the corresponding qualitative measures to achieve the related SIL.

<table>
<thead>
<tr>
<th>THR (per hour, per function)</th>
<th>SIL</th>
</tr>
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<tbody>
<tr>
<td>$10^{-4} \leq \text{THR} \leq 10^{-3}$</td>
<td>4</td>
</tr>
<tr>
<td>$10^{-3} \leq \text{THR} \leq 10^{-2}$</td>
<td>3</td>
</tr>
<tr>
<td>$10^{-2} \leq \text{THR} \leq 10^{-1}$</td>
<td>2</td>
</tr>
<tr>
<td>$10^{-1} \leq \text{THR} \leq 10^{0}$</td>
<td>1</td>
</tr>
</tbody>
</table>

- THRs are a qualitative measure associated to the systematic failures (ex: design errors).

Protection against what

- Objects falling from:
  - Bridges
  - Tunnel Entries
  - Tunnel Exits

- Obstacles in the Level Crossing area

  Major Requirements
  1. Size of the Area to be monitored
  2. Minimum size of the object to be detected
Detection Technology
- Image processing
- Induction loops (mainly for metallic objects)
- Ultrasonic sensors
- Strain gauges
- Lidar
- Radar

Why Radar Technology
- Working day and night
- No mechanical parts
- Independency from weather conditions
- Easy to be installed (few sensors)
- Easy tuning/calibration (not critical from a geometry point of view)

Challenges raised by Radar
- Object size vs RCS* (Radar Cross Section)
- Probability of Failure Detection analysis
  - PFD ➔ Safety
- Probability of False Alarms analysis
  - PFA ➔ Availability

* RCS depends on material, size and shape of the target, incident angle, reflected angle and polarization

Falling Objects Detection
- 2 Radar Sensors on each side
- 2 Passive Reflective Units on each side
- 1 Elaboration Unit

Level Crossing protection
- 2 Radar Sensors (in one case)
- 1 Passive Reflective Unit
- 1 Elaboration Unit

Level Crossing Detection Logic
- Barriers down
- Major Obstacle?
  - Yes ➔ Send detection info
  - No
- Small Obstacle?
  - Yes ➔ Moving?
    - Yes ➔ Timeout elapsed?
      - Yes ➔ Send detection info
      - No ➔ Yes ➔ Send detection info
    - No ➔ No
- No
- Enabling Signal
  - Yes ➔ Send detection info
  - No ➔ No

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Lessons Learned

Requirements
- The infrastructure manager asked for the detection of obstacle bigger than a cube with a side of 0.8 meters
- We provide a RCS>0.25 square meters

Radar PMD
- A good Radar has a PMD between 25% and 5%.
- For Random Hw Failure the probability of a fault in a 20 years mission with a $\lambda=10^{-8}$ is $Q=0.175\%$

Radar technology is very promising with respect to adverse weather conditions
- Quite simple installation and low maintenance effort
- Medium initial costs, low maintenance costs
- Special care shall be taken to avoid false alarms for objects with high reflectivity

Falling object detection solutions...

Objective: Quantitative Safety $\Rightarrow$ THR$\leq10^{-8}$

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... Falling object detection solutions...

Objective: Qualitative Safety $\Rightarrow$ SIL4

<table>
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<tr>
<th>Design</th>
<th>SIL4 Nominal Mode</th>
<th>SIL2 Degraded Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Elaboration unit</strong></td>
<td>1 Elaboration Unit</td>
<td>1 Elaboration Unit</td>
</tr>
<tr>
<td>Dual electronic structure based on composite fail-safety with fail-safe comparison</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Radar unit</strong></td>
<td>4 Radar Units</td>
<td>3 Radar Units 2 Radar Units if faulty on different sides</td>
</tr>
<tr>
<td>Single electronic structure based on reactive fail-safety</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

... Level Crossing solutions...

Objective: Quantitative Safety $\Rightarrow$ SIL2

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<th>SIL4 Nominal Mode</th>
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Level Crossing solutions...

Objective: Qualitative Safety $\Rightarrow$ SIL4

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Conclusion

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- Quite simple installation and low maintenance effort
- Medium initial costs, low maintenance costs
- Special care shall be taken to avoid false alarms for objects with high reflectivity