Cutting-edge machine vision technology for automatic inspection of track and overhead line infrastructure

Giuseppe Aurisicchio
Electronic Engineer (Master of Engineering)
Product Line Manager, Diagnostics Business Unit
MERMEC Group
giuseppe.aurisicchio@mermecgroup.com

Summary
The increasing competition between transport modes forces Rail Operators to improve passenger/freight service in terms of speed, capacity, and safety within an operating environment of constrained maintenance budgets. Maintaining a high quality of infrastructure is an important goal. To do this, it is essential to frequently monitor the condition of the infrastructure without obstructing the train operations and putting at risk the infrastructure inspection workers. These important goals can be achieved with the use of a brand new type of diagnostic system which is able to check in a fully automated way the condition of the railway infrastructure.

Machine vision and pattern recognition technology as well as systems integration and system reduced sizes, allow the realization of vision inspection equipments for fast and accurate analysis of the condition of the railway infrastructure.

The Automatic Vision System developed by MERMEC Group is able to identify, in a fully automated way, up to 26 Permanent Way Infrastructure defects and up to 10 Overhead Line Infrastructure defects.

Keywords: Monitoring of the Railway Infrastructure, Diagnostic Systems, Diagnostic data, Data correlation, Machine-vision, pattern-recognition, digital image analysis, automatic inspection, railway asset management, trend analyses of railway infrastructure, Condition-Based Maintenance Management, Predictive maintenance, Decision Support System.

1. INTRODUCTION
The increased availability of train paths, the improvement of safety features and the reduction of maintenance costs depends on the appropriate use of railway infrastructure data collection, analysis, activity planning and control methods. As traffic on railway networks grows and the demand for commercial train-passage increases, fewer slots are available for infrastructure monitoring and maintenance. In addition, speed increases impose specific constraints on the infrastructure and monitoring methods. More trains and higher tonnage mean greater railway infrastructure wear and tear, hence an increased need for monitoring the quality of the railway infrastructure. Nowadays, innovative opto-electronic and vision technologies allow for simultaneous monitoring of several infrastructure aspects using systems installed on board of dedicated vehicles as well as commercial trains (e.g. passenger, freight, etc.). These systems allow for a greater data set to be collected compared to the past. Monitoring technologies have the capacity to provide more data than what the maintenance professional is able to make effective use of.

Proper data storing and automatic processing methods are required to provide efficient and effective responses to maintenance engineering departments.

Moreover, during the processing phase it is important to correlate different types of railway infrastructure data in order to drive the maintenance and the renewal works. This means that all data must be integrated and synchronized in time and in space. For example, any diagnostic system should be somehow integrated with the other systems at least at the data level. The data integration has to guarantee a high accuracy for the synchronization in space of all the measurements with reference to the kilometrage along the line as well as a correct location of the measurements in reference to the monitored assets e.g. switches, poles, signalling devices, etc.

All data shall be collected and stored on an on-board database and sent to the main database for archiving and for allowing for further data analysis. As used in this paper, automatic data collection and analysis means the process of measuring and inspecting the
railway infrastructure in order to assess its quality, and thus safety, as well as the required maintenance actions in an automated manner.

In order to analyse the collected data in an efficient way it is fundamental to carry out the analysis in quick and simple ways, where possible in an automated way. The data analysis has to generate information to determine whether, when, where and how to intervene, i.e. by performing “condition-based” maintenance, for optimizing the available resources as well as minimizing speed reductions and traffic interruptions.

It is clear that condition-based maintenance can only be accomplished by having a proper set of tools in place to support planning and control of maintenance.

New practices to assess railway infrastructure performances based on diagnostic as well as decision support technologies are being introduced by a number of Rail Operators. The type of assessment can depend on traffic type (heavy haul, freight, transit, traditional and high speed), asset type, maintenance processes in place and other aspects.

This paper will describe the main enabling practices involved in the collection and analysis of condition data for condition based and predictive maintenance; in particular it will illustrate how data can be used for both assessing the current asset condition and optimizing maintenance.

2. CONDITION BASED MAINTENANCE

Nowadays measuring systems and vehicles are able to continuously monitor the railway infrastructure status and to collect a wide range of diagnostic data. Such data is processed to generate failure reports, defect reports based on predefined thresholds, user-defined parameters, quality indexes, etc. and then used for condition-based maintenance. Advanced condition-based maintenance requires more complex and time consuming data analysis based on several rules aimed at capturing the evolution of defects in time. The analysis of the railway infrastructure over time is based on railway infrastructure “models” that take into account many correlated aspects causing its deterioration; to the scope of building the models, additional data (not only diagnostic data but also asset data, operational data, maintenance data etc.) and decision support tools are required.

For most infrastructure managers, the task of data collection and analysis requires a major commitment of both human and financial resources not to mention the rising and pressing requirements regarding high quality and objective data to maintain the track to the required operational standard. The assessment of the data used for condition based maintenance can be carried out by analysing the condition-based maintenance chain that is traditionally composed by the following main processes (Figure 1):

- **Data Acquisition**, including both measurements made by measuring vehicles and other inspections that produce the “diagnostic data” (Refer to the table below).
- **Data Analysis**, including the processing of the diagnostic data and the correlation with other data producing new information like failure and defect reports, quality indexes, etc.
- **Planning**, including preparation of the maintenance plans to be scheduled requiring additional data to assess where, when and what maintenance is really required.
- **Control**, including the final step oriented to check the outcomes of the executed activities.

The main categories of measuring systems for the railway infrastructure available on the market and produced by MERMEC Group [1,2] include:

- Track – Permanent way
- Overhead line
- Ride quality
- Signalling diagnostics
- Telecommunications

For each “Diagnostic Sectors” an exhaustive set of parameters is measured. In the following Table 1, an example of set of parameters (almost 100) is provided.
| TRACK - PERMANENT WAY | Track Geometry | • Track Gauge  
| | | • Longitudinal Level  
| | | • Alignment  
| | | • Cant  
| | | • Twist  
| | | • Curvature  
| | Switches | • Switches check and control  
| | Rail Profile | • Rail Profile coordinates  
| | | • Equivalent Conicity  
| | | • Horizontal Wear  
| | | • Vertical Wear  
| | | • 45° Wear  
| | | • Area Wear  
| | Rail Corrugation | • Rail Corrugation in different wavebands  
| | Track Surface Defects Detection | • Area defects  
| | | • Linear defects  
| | | • Fastenings  
| | | • Rail Pads  
| | | • Marking detection  
| | | • Head Check detection  
| | | • Sleeper cracks detection  
| | | • Excess or lack of ballast  
| | | • Mud detection  
| | | • Dancing Sleepers  
| | | • Vegetation  
| | Track Surface Measurement | • Clearance Profile Measurement  
| | | • Tunnel Walls Inspection  
| | Tunnel | • Ballast Profile  
| | | • Geo-Radar inspection  
| | Ballast | • Stagger  
| | | • Height  
| | | • Slope  
| OVERHEAD LINE | Overhead Line Geometry | • Contact Wire Wear  
| | | • Contact Wire Wear  
| | Contact Wire Wear | • Pantograph/Catenary Interaction Forces  
| | Pantograph Interaction Forces | • Pantograph/Catenary Interaction Forces  
| | Arc Detection | • Electric Arc Detection  
| | Electric Parameters | • Voltage  
| | | • Current  
| | OHL Defect Automatic Detection | • Droppers  
| | | • Steady Arms  
| | | • Insulators  
| | | • Fixed points  
| | | • Joints  
| | | • Pulleys  
| | | • Paralleling Points  
| RUNNING DYNAMICS | Ride Quality | • Axlebox accelerations  
| | | • Bogie accelerations  
| | | • Train coach accelerations  
| | Wheel/Rail Interaction Forces | • Horizontal forces  
| | | • Vertical forces  
| SIGNALLING DIAGNOSTICS | Continuous Signalling Diagnostic | • Spectrum  
| | | • Carriers Frequency  
| | | • Carriers Intensity  

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3. INFRASTRUCTURE MEASUREMENT

More Rail Operators are adopting automated infrastructure measuring systems. These systems use innovative techniques based on no-contact opto-electronic or inertial technologies, as opposed to traditional systems, which adopt mechanical devices in contact with rails.

Typical measured parameters include track geometry (e.g. twist, alignment, etc.) and rail profile (e.g. rail wear). These measuring systems support the norm-based maintenance that sometimes is referred to as the condition-based maintenance carried out according to fixed quality levels (e.g. applicable technical standards of the operating railway). The analysis of the mutual impacts of track asset component conditions (e.g. track and rail) require measurements to be carried out in an integrated way.

For example, MERMEC Group chord-based track geometry and rail profile measuring are fully integrated. In fact, geometrical parameters of the track are obtained from the measurement of the real profile of the rails. The system measures rail profiles first, then it detects the running tables and the gauge points. This operation is realized through lasers, special sensors and cameras and is obtained at every 0.25 m of track. At any speed the vehicles should travel, every 0.25 m, a profile of the two rails is taken. Then, through software analysis, the system measures the gauge from the rail profile. The rail profile and the gauge points serve as the basis for detection of the longitudinal level and alignment of both sides. An inertial system, constituted mainly by inclinometer and rate sensors, is adopted for the measurement of cant and twist. As showed in Figure 2, the measure of the rail profile is obtained by means of a laser band sheet. This system lights the entire surface of the head of the rail (top and gauge sides). No part of the system moves and each component is rigidly fixed to the vehicle frame. The track geometry measuring system carries out the measurement of the following main parameters:

- Gauge
- Alignment of the right and left rails
- Longitudinal level of the right and left rails
- Cant
- Twist

All measurements can be effectively carried out in the entire speed range of 0-400 km/h. The rail transversal profiles are also sampled every 0.25 m in the same speed range. The system is also provided with a filter for cutting noise to increase the accuracy of
Vehicle dynamics measurements are carried out using systems based on Strain Gauge instrumentation on wheels making use of telemetry systems for signal extraction, non-contact laser displacement and accelerometer sensors. In particular, accelerometer sensors detect the mechanical vibrations of railway vehicles. The vibrations depend on the quality of the rolling plane which depends on a combination of vehicle characteristics as well as the line defects such as:

- Longitudinal level, alignment, twist defects
- Irregular wear of the rail-wheel contact profile
- Defects in rail joints
- Change of track stiffness in level crossings, bridges, tunnels, etc.
- Track Singularities (switches, curves, etc.)
- Vehicle dynamics due to the wheel conicity
- Quality of the primary and secondary suspensions

In the study of the interaction forces which act in the wheel-rail contact point and of the oscillatory motions to which the vehicle is subjected during the running, different parameters have been introduced to quantify the vehicle safety against derailment, its aggressiveness towards the track and the passengers’ comfort. Moreover, there are also some types of track defects that can be detected from this kind of analysis. Three main classes of systems are available for measurement of:

- Wheel-Rail Interaction Forces
- Bogies and coach real time accelerations
- Wheel-Rail Contact Geometry

Many International Standards require the direct measurement of the lateral force Y and of the vertical force Q, acted by the wheel on the track, in order to demonstrate safe running conditions (i.e. UIC 518). For this purpose, the following monitoring aspects are required:

- Real time Y & Q force
- Real time Y/Q ratio
- Lateral acceleration correlation.

Furthermore, additional analysis can be carried out using:

- Wheel profiles measurements

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- Wheel-rail coupling, delta-r calculation, angles of contact and equivalent conicity at several values of sigma.

Overhead line parameters such as catenary stagger, height and wear of the contact wire can also be measured without any contact with the overhead line. The systems are made up of lasers and cameras, which monitor the conditions of the overhead line, pick up defects, if any, and transmit where they are located on the network to the operators. The pantographs placed on the roof can also carry out dynamic measurements, i.e. the measurement of the effects arising from the pressure exerted on the overhead lines by the pantograph, of the tension, temperature and the so-called “contact-strip roll”. Railway vehicles can host also equipment for the quality measurement of telecommunication, i.e. GSM.

4. AUTOMATIC INFRASTRUCTURE INSPECTION

Track inspections play an important role in the track condition monitoring. For example rail defects like head checks can propagate along the rail; when they reach a dangerous depth they can propagate downward transversely, producing the sudden fracture of the rail. Therefore it is important to keep rails under inspection and recover the defective rails; inspection can be done on foot (by walking) or by vehicle adopting innovative Vision Systems for automatic defects detection. Compared to vehicle inspections, walking is too time consuming, requires additional safety measures to allow people access on the network lines, and elevated costs due to the limited inspection speed.

Vision system for automatic defect detections represent an evolution of Video Inspection Systems mounted on board of trains/vehicles for video recording. Vision Systems makes it possible to check the entire environment surrounding the track and the track itself. If a vision system is integrated with other diagnostic systems, it allows for:

- Linkage of some infrastructure defects to environmental conditions that might have caused the defect.
- Monitoring trends in the track environment; so controls may be put in place to prevent degradation of the track.
- Analysis of the track images in fixed track sections for safety and control purposes.

Vision inspection methods can be applied also to track components such as rail, joints, welds, etc. The no-
contact high speed optical rail surface defects detection system is designed to:

- Acquire images of both rails
- Record these images in a digital format
- Automatically generate measurements and detect the defects.

The rail surface inspection system is based on the digital images using cameras. Synchronization with the vehicle odometry allows it to identify its position on the track and its kilometic location. Acquisition, storage and image analysis are performed by a computer. The analysis can be done image by image. In real time, the system extracts the rail images, and identifies its position by means of an odometer. The data processing analyses each image to automatically locate the defects according to their size, positions, etc. In particular, it makes reviewing all acquired data related to rail surface possible and to process them to detect in automated manner the rail defects (Figure 3). The surface defects are classified into different classes according to the user configuration.

Examples of vision inspection being adopted in the rail industry includes monitoring of railway structures such as tunnels. Today, the measurement of tunnels can be automated (e.g. with MER MEC tunnel inspection system) creating a new set of data available for both maintenance planning and control.

The tunnel inspection system adopts optical triangulation to convert the laser lights measured objects, as the object moves through the laser beam, contour slices are generated and the complete object shape is reconstructed by joining the acquired sections.

The tunnel inspection system produces an accumulated image; all objects inside the cross section are scanned by the laser beam and acquired by high speed cameras.

![Figure 4 - Scanned Tunnel Section.](image)

The tunnel inspection system can recognize defects with a resolution of 2mm travelling at 30km/h. The information acquired by the scanner can then be used to produce computer renderings of the infrastructure. The scanner module and software can automatically detect some types of infrastructure defects almost instantly (e.g. clearance defects, Figure 4), and profiles can be viewed in real time, although detailed analysis is normally made after the recording run because the tunnel inspection system produces such vast quantities of data – 4 million points are measured per second.

![Figure 5 - Wayside scanning image.](image)

The system has a 360° measurement field which means it can also be used to measure various...
Giuseppe Aurisicchio
MERMEC Group

infrastructure clearances such as ballast profiles and track alignment. The tunnel inspection system can detect abnormal swelling or subsidence of the ballast, as well as deviation from the normal 3D profile (Figure 5).

Figure 5 - Tunnel inspection system

The tunnel inspection system can measure the position of weights used to tension catenary contact wire. Fluctuations in temperature cause the contact wire to expand and contract, which means the height of tensioning weights relative to the ground changes according to climatic conditions (Figure 6).

Because of its high-frequency scanning capabilities, the system can establish whether these fluctuations exceed the operator’s specified limits, allowing catenary to be maintained to a safe standard. The system is also capable of measuring station platform clearances and the distance between adjacent tracks.

5. DECISION SUPPORT PRACTICES

Generally speaking, diagnosis and maintenance are not always fully integrated, that is the data and maintenance planning process may be missing or unstructured. Usually, maintenance planners – the few key maintenance persons having high expert knowledge - are entitled to have the last word on how the maintenance is planned. In order to introduce a more systematic process, some knowledge belonging to maintenance planners could be codified in maintenance rules and incorporated in proper decision tools so at least a part of manual subjective planning can be replaced by automatic objective planning. Moreover, condition-based modelling can provide valuable information to the support maintenance planners’ decision making processes. [3, 4].

Condition data is not the only data required to support maintenance planning and control, other information to be considered when planning maintenance regimes include:

<table>
<thead>
<tr>
<th>Groups</th>
<th>Types</th>
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| Infrastructure  | • Asset Registry - Properties (type of rail, date of laying, etc.)  
                 | • Layout Information (curves, etc)  
                 | • Geographical Information (GPS coordinates)             |
| Operational     | • Annual Tonnage                                         
                 | • Number of trains                                       
                 | • Speed Limits                                           |
| Diagnostic      | • Detected Assets                                        
                 | • Measurements & Quality Indexes                        
                 | • Failures                                               
                 | • Defects                                                |
| Work History    | • Corrective, Preventive and Cyclic Maintenance Activities 
                 | • Renewal Activities                                     |
| Financial       | • Cost of maintenance                                   
                 | • Renewal budgets                                        |

Such data needs to be collated and then visualised in an integrated manner. The integrated analysis of data facilitates an accurate analysis of defect causes. This feature is fundamental for all the kinds of measurements and inspections allowing correlation of different aspects such as track, catenary, environmental factors, etc.

Figure 7 – Integrated visualization of data

In Figure 7 the data correlation including asset and condition data resulting from traditional measurement systems and vision technologies is enabled by different visualization modes e.g. GIS, text-based, linear, etc.
The correlations among data are essential in discovering:

- **Critical situations.** In fact sometimes a single isolated defect may not be safety critical. But if two or more defects are combined, the situation may become safety critical. In Figure 8 there is an example of an alignment defect combined with more than one missing fastening. The alignment defect not exceeding the IAL (Immediate Alert Limit) should not be critical. But as the defect is together with another problem (some missing fastenings), it must be considered critical.

- **Real causes of defects.** It is important to identify and remove the cause of defect at the time of repairing the defect. An example could be a rail corrugation problem causing defects on longitudinal level parameter. If only longitudinal level defects are corrected, the defects will periodically appear again. In this case a combined maintenance action, made by grinding and tamping, is required to correct both rail corrugation problem and longitudinal level defects.

![Figure 8. Correlation of asset properties, track geometry and track surface data](image)

The core part of any decision support tool for maintenance planning and control is not only the data analysis capability but also the set of business rules used to process all the above data types in an automatic way. In general, 3 main types of rules should be available:

- Condition-based rules, prescriptive planning of activities based on pre-fixed thresholds and intervention times (e.g. activities to eliminate some defects are scheduled in few months time)

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- Predictive rules, planning of activities based on proper deterioration modelling to estimate the residual asset life (e.g. degradation speed, etc.).

- Data Validation rules, oriented to evaluate data quality, consistency and consequently their reliability.

Such business rules cannot be executed in manual mode i.e. analysing each data for each location of the railway network so proper automatic processing is required.

MERMEC’s RAMSYS decision support system offers both capabilities (manual vs automatic). RAMSYS software is a single, integrated platform (suite) for the management of all the data related to: railways maintenance (e.g. assets, defects, activity history, measurements, etc.) fully supporting condition-based & predictive maintenance; long and short-term planning; maintenance control and key performance indicators monitoring.

As a matter of fact, ERP (Enterprise Resource Planning) systems are designed and developed top-down, considering the requirements across multiple industries as opposed to a bottom-up system that meets only the requirements of railway diagnostic and maintenance engineers. An enhanced asset data usage, supported by RAMSYS, includes:

- Accessibility to asset data from both the office and the field via dedicated railway oriented forms

- Management of both singular and linear assets (rolling stock and infrastructure assets)

- Data quality check and invalid data handling

- Business rules registry for inspection, maintenance and renewal decision support

- A set of deterioration models dedicated to railway assets

- Automatic maintenance planning and control engine using selected business rules of the registry

There are currently no enterprise systems dedicated to rail operators and available on the market that capture asset management data, diagnostic data, etc. for railway infrastructure in an integrated manner like RAMSYS does.
RAMSYS does complement existing EAM, CMMS and/or ERP systems by providing a set of tools oriented to support railway asset management, in particular maintenance and renewal decisions for condition-based maintenance (Figure 9).

So far several railway companies that have implemented EAM and ERP systems have introduced or are evaluating the introduction of RAMSYS in order to improve their maintenance.

6. CONCLUSIONS

With new practices, based on no-contact and vision technologies and decision support tools, it is possible to monitor the complete railway as well as consequently generated information to be used for maintenance planning and control.

MERMEC Group systems are aimed at providing a unique and comprehensive solution including the proper set of measuring, inspection, data analysis and decision support tools.

The acquired data described plays a fundamental role not only in the diagnostic of infrastructure but also in decision support, thus optimising the planning around maintenance and renewal works. Important aspects discussed in the paper include:

- The different “Diagnostic Sectors” related to the railway infrastructure able to generate a wide range of data
- New sets of condition data (e.g. vision defects) in addition to traditional conditional data (e.g. track geometry and rail profile)
- Enhanced decision support in converting data into more valuable information for maintenance planning optimisation

This is aimed at increasing infrastructure safety and availability at the minimum level of maintenance costs and in the long term a positive return on the capital investment made.

7. REFERENCES

Giuseppe Aurisicchio
MERMEC Group

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