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EMERGING CONDITION MONITORING TECHNOLOGIES FOR RAILWAY TRACK COMPONENTS AND SPECIAL TRACKWORK

Luis Fernando Molina Camargo
G a a R a A a
a 1@ . ; (217) 244-6063
Ra a E P a
U I a U a a-C a a

J. Riley Edwards
L
a 2@ . ; (217) 244-7417
Ra a E P a
U I a U a a-C a a

Christopher P. L. Barkan
P
a a @ . ; (217) 244-6338
Ra a E P a
U I a U a a-C a a

ABSTRACT

North American Railroads and the United States Department of Transportation (US DOT) Federal Railroad Administration (FRA) require periodic inspection of railway infrastructure to ensure the safety of railway operation. Tracks that are subjected to heavy haul or high-speed traffic necessitate frequent inspection and more stringent maintenance requirements, but present railroads with less time to accomplish it. The international railroad community has undertaken significant research to develop innovative applications for advanced technologies with the objective of improving the process of visual track inspection. Some of these technologies are currently in use or under development for a variety of railroad inspection tasks, both wayside and mobile. This paper presents an overview of different systems for condition monitoring applications for inspection of railway components. These technologies, in conjunction with defect analysis and comparison with historical data, will enhance the ability for longer-term predictive assessment of the health of the track system and its components, more informed and proactive maintenance strategies, and improved understanding of track structure degradation and failure modes.

INTRODUCTION

Railroads conduct regular inspections of their track in order to maintain safe and efficient operation. In addition to internal railroad inspection procedures, periodic track inspections are required under the Federal Railroad Administration (FRA) Track Safety Standards. The importance of high quality data for track condition monitoring has led to the development new technologies for data collection and defect analysis. Interim approaches to automated track inspection are also possible, which have the potential to improve inspection effectiveness and efficiency.

Heavy haul or high speed rail (HSR) infrastructure requires frequent inspection and more stringent maintenance requirements, and leave railroads less time to accomplish it due to frequent train operation. This makes them excellent candidates for cost-effective investment in new, more efficient, but potentially more capital-intensive inspection technologies.

This paper presents an overview of innovative systems for condition monitoring applications currently in use or under development for the inspection of railway track components. These technologies, in conjunction with defect analysis and comparison with historical data, will enhance longer-term predictive health assessment of the track system and its components, more informed and proactive maintenance strategies, and improved understanding of track structure degradation and failure modes.

EMERGING CONDITION MONITORING TECHNOLOGIES FOR TRACK INSPECTION

The international railroad community has conducted significant research to develop innovative applications for advanced technologies with the objective of improving track inspection. Automatization of the inspection tasks has been developed in conjunction with the different technologies (cameras, sensors, computer processers, etc.) to best match the needs of the railway industry and improve safety, planning, and maintenance strategies. The technological advances presented in this paper have occurred in the past ten years, including applications in revenue service and under continuous improvement with others still in the research stage.

Emerging Track Inspection Technologies Using Machine Vision

Machine vision systems are currently in use or under development for a variety of railroad inspection tasks, both wayside and mobile, including inspection of joint bars, surface defects in the rail, rail profile, ballast profile, track gauge, intermodal loading efficiency, railcar structural components, and railcar safety appliances (1). The University of Illinois at Urbana-Champaign (UIUC) has been involved in multiple railroad machine-vision research projects sponsored by the Association of American Railroads (AAR), BNSF Railway, NEXTRANS Region V Transportation Center, and the Transportation Research Board (TRB) High-Speed Rail IDEA Program (1-10).

Rail Surface Defects

The Institute of Digital Image Processing (IDIP) in Austria has developed a machine vision system for rail surface inspection during the rail manufacturing process (11). Currently, rail inspection is carried out by inspection personnel and complemented with eddy current systems. The objective of this machine vision system is to replace visual inspections on rail production lines. The machine vision system uses a spectral image differencing procedure (SIDP) to generate three-dimensional (3D) images and detect surface defects in the rails (Figure 1). The cameras can capture images at speeds up to 37 miles per hour (mph) (60 kilometers per hour (kph)). Although the system is currently being used only in rail production lines, it can also be attached to an inspection vehicle for field inspection of rail.

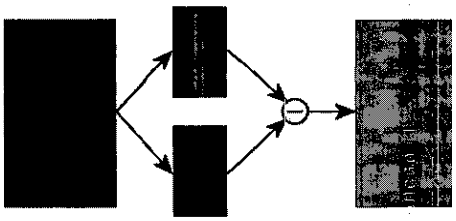

Figure 1. Diagram showing equipment layout for rail surface inspection during the manufacturing process (11)

Additionally, the Institute of Intelligent Systems for Automation (ISSIA) in Italy has been researching and developing a system for detecting rail corrugation (12). The system uses images with 512x2048 pixels in resolution, artificial light, and classification of texture to identify surface defects (Figure 2). The system is capable of acquiring images at speeds of up to 125 mph (200 kph). Three image-processing methods have been proposed and evaluated by IISA: Gabor, wavelet, and Gabor wavelet. Gabor was selected as the preferred processing technique. Currently, the technology has been implemented through the patented system known as Visual Inspection System for Railways (VISyR).

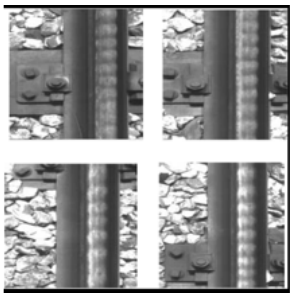

Figure 2. Example images from the ISSIA system for detecting rail corrugation (12)

Rail Wear

The Moscow Metro and the State of Common Means of Moscow have developed a photonic system to measure railhead wear (13). The system consists of 4 CCD cameras and 4 laser lights mounted on an inspection vehicle. The cameras are connected to a central computer that receives images every 20 nanoseconds (ns). The system extracts the profile of the rail using two methods (cut-off and tangent) and the results are ultimately compared with pre-established rail wear templates.

Tie Condition

The Georgetown Rail Equipment Company (GREX) has developed and commercialized a crosstie inspection system called AURORA (14). The objective of the system is to inspect and classify the condition of timber and concrete crossties (Figure 3). Additionally, the system can be adapted to measure rail seat abrasion (RSA), also known as rail seat deterioration (RSD), and detect defects in fastening systems. AURORA uses high-definition cameras and high-voltage lasers as part of the lighting arrangement and is capable of inspecting 70,000 ties per hour at a speed of 30-45 mph (48-72 kph). The system is capable of replicating results obtained by track inspectors with an accuracy of 88%.

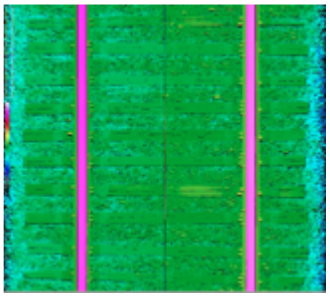

Figure 3. Example output from Georgetown Rail Equipment Company crosstie inspection system (AURORA) (14)

Since 2008, Napier University in Sweden has been researching the use of machine vision technology for inspection of timber crossties (15). Their system evaluates the condition of the ends of the ties and classifies them into one of two categories: good or bad. This classification is performed by evaluating quantitative parameters such as the number, length,

and depth of cracks, as well as the condition of the tie plate (Figure 4). Experimental results showed that the system has an accuracy of 90% with respect to the correct classification of ties. Future research work includes evaluation of the center portion of the ties and integration with other non-destructive testing (NDT) applications.

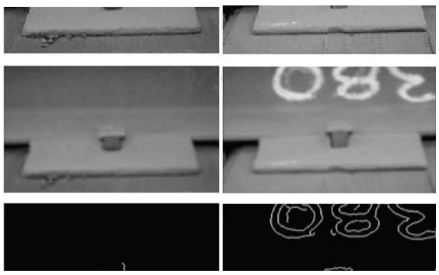

Figure 4. Sample image from the Napier University system for inspection of timber crossties (15)

In 2003, the University of Zaragoza in Spain began research on the development of machine vision techniques to inspect concrete crossties using a stereo-metric system to measure different surface shapes (16). The system is used to estimate the deviation from the required dimensional tolerances of the concrete ties in production lines. Two CCD cameras with a resolution of 768x512 pixels are used for image capture and lasers are used for artificial lighting (Figure 5). The system has been shown to produce reliable results, but quantifiable results were not found in the available literature.

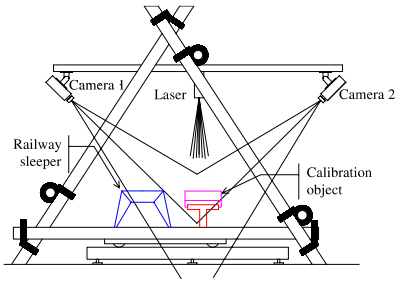

Figure 5. Schematic of the University of Zaragoza MV system to inspect concrete crossties (16)

Ballast

The ISSIA has also been developing a system capable of reconstructing 3 dimensional (3D) surfaces of the ballast section (17). The objective of the system is to detect anomalous conditions within the ballast surface that are indicative of situations that could result in a loss of track stability. The system finds the depth of ballast voids from a set of 2D images. Next, the system uses high definition cameras of 2048 pixels per line and uses stereo matching techniques to generate the 3D images. Since the method employed to process images requires significant computational power, future work will be aimed at improving the analysis technique in order to make the system feasible for revenue service.

Fastening Systems

Visual Inspection System for Railways (VISyR) is a patented commercial system that has been developed for detecting hexagonal bolts in European fastening systems (18). VISyR collects real-time image data at a maximum speed of 125 mph (200 kph). Cameras capture images of 1,024 pixels per line and artificial lighting (OSRAM 41 850 FL) is used to provide adequate illumination for image capture (Figure 6). The image processing system uses discrete wavelet transforms for bolt detection in real-time. VISyR also includes a module for detecting rail surface defects. The system has an accuracy of 99.6% for detecting visible bolts and 95% for detecting missing bolts. It has also been tested for the detection of elastic fasteners with similar accuracies.

Figure 6. Image of the VISyR system for detecting hexagonal bolts in European fastening systems (18)

The University of Loughborough (England) has developed a machine vision system capable of detecting missing elastic fastening clips on concrete ties (19). The system was tested using a camera mounted near a train wheel and it also incorporated artificial lighting (Figure 7). The images were obtained using a resolution of 384x288 pixels. Experimental results showed accuracies of 84.7% in detecting missing clips and 95.3% in clip recognition.

Figure 7. Images from University of Loughborough's system for detecting missing elastic fastening clips on concrete ties (19)

General Track Structure Inspection

The University of Central Florida has been developing a system for measuring track gauge and inspecting fasteners (20). The system uses high-speed CCD cameras with a resolution of 1,024x768 pixels. The camera is synchronized with strobe lights to minimize the difference in contrast during the day. Additionally, sun shields were mounted in the cart to eliminate the effect of shadows in the images. The system detects the edges of the rails, and by exploiting the known distance between the two cameras, provides an estimate for track gauge

(Figure 8). Future work includes the implementation of the system for revenue service and the development of algorithms to detect other types of track component defects.

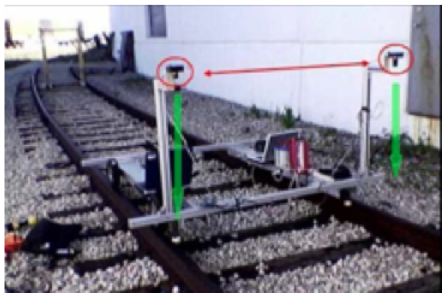

Figure 8. Image of University of Central Florida's system for measuring track gauge and inspecting fasteners (20)

The FRA and ENSCO began development of a machine-vision-based joint bar inspection system in 2002 (21). The system uses high-resolution cameras with high-powered xenon lights to capture images of joint bars. It collects images at a maximum speed if 50 mph (80 kph). ENSCO has incorporated this technology into their VisiRail™ Joint Bar Inspection System (Figure 9). The system primarily finds external cracks in joint bars, but is also capable of inventorying the different types of bolted joints. Currently, the system requires manual interpretation of image data to determine true joint condition. Experimental results showed an accuracy of 98%, but under non-ideal track conditions the joint detection accuracy rate is 85%. ENSCO is continuing research and development efforts to improve their algorithms and increase the crack detection rate without increasing the number of false positives.

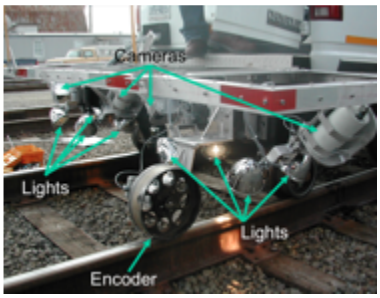

Figure 9. Joint bar inspection system developed by FRA and ENSCO (21)

Commercial Systems

Cybernétix, in conjunction with the French National Railways (SNCF), has developed a commercial system for inspecting rails, fastening systems, the rail gap between joint bars, and reconstructing the ballast profile (22) (Figure 10). The system uses an optical system and machine vision to capture data at speeds of up to 200 mph (320 kph). The system is currently being used by the SNCF for track inspection.

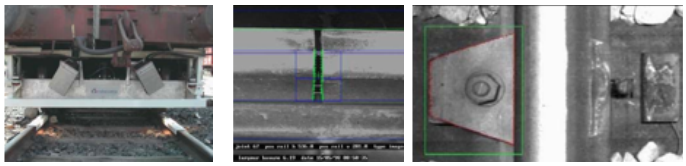

Figure 10. Images of the Cybernétix system for inspecting rails, fastening systems, the rail gap between joint bars, and reconstructing the ballast profile (22)

Since 1990, Bildverarbeitungssysteme (bvSys) has developed a system for inspecting rails, fastening systems, ties, vegetation, cracks (concrete ties, slabs), surface analysis (ballast), object measurement, and video documentation (23). For rail inspection, the system uses monochrome, high-resolution, high-speed cameras and machine vision to capture data at speeds of up to 62 mph (100 kph). Special headlights ensure optimum illumination. For a complete inspection of the rail structure (ties, fastening system) the system is able to capture measurements at speeds higher than 124 mph (200 kph). The camera system is arranged vertically above the rails and consists of monochrome line scan cameras with a fixed focal length. Powerful halogen headlights illuminate the inspection area (Figure 11).

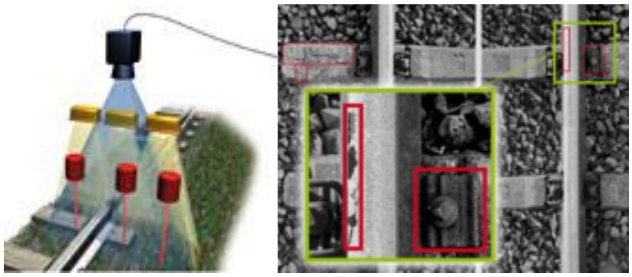

Figure 11. Overvew and example image from bvSys' RailCheck system (23)

Beena Vision (Unites States) has developed SurfView, a machine vision system for rail and track inspection (24). The system can be attached to an inspection vehicle for field inspection of rail. One on-board computer for data acquisition and display, and up to six cameras composes the system, known as Surfview (Figure 12). The system was also design to detect missing, worn or broken track components.

Figure 12. Overview and example image from Beena Vision's SurfView system (24)

Since 2005, EURAILSCOUT (Netherlands) has been working toward the development of a machine vision system for turnout inspection (25). Using advance computer vision algorithms the system is able to automatically analyze and examine missing fasteners, cracks in concrete ties, and ballast deficits. Two panorama cameras are used, and the system has a resolution of up to 1392x1032 pixels. Four color line-scan cameras with a resolution of 1x1 mm record the field and gage side of the track (Figure 13). Two black and white cameras with resolution of 1x1 mm are used to record ties. Four halogen lights are used for the color cameras and 6 for the black and white cameras. The system has a reported reliability of over 98%.

Figure 13. Example data from EURAILSCOUT's Turnout inspection system (25)

In 2009, EURAILSCOUT added a switch geometry measurement system to the previous developed system (Figure 14). The system uses laser to scan the track every 20 mm at a speed of 25 mph (40 kph), resulting in a quantitative three-dimensional profile. Also, horizontal and vertical wear can be obtained as well as cross-sectional measurements. Additionally, different geometry parameters including gauge, and cross-level can be also calculated.

Figure 14. Image of the EURAILSCOUT turnout inspection system (25)

OTHER EMERGING TRACK INSPECTION TECHNOLOGIES

Ballast/Subgrade inspection using the GPR

GPR is able to continuously characterize the condition of ballast, sub-ballast and subgrade, and locate potentially problematic areas for further evaluation or maintenance (26). Track conditions can vary over short distances; therefore, GPR constitutes an optimal tool for the inspection of the ballast and subgrade. GPR uses electromagnetic pulses to detect objects, changes in materials, and voids (Figure 15). A transmitting antenna radiates short pulses of high frequency, and when the wave hits an object or boundary with different dielectric constants, the receiving antenna records variations in the signal. Systems measuring at 500 MHZ are primarily used for the evaluation of sub-ballast and the subgrade, while the 2 GHz antennas provide sufficient penetration and resolution to detect the degree of fouling of the ballast even under the ties. GPR can be used to identify trapped water areas with low bearing capacity, inappropriate ballast thickness, fouled ballast, and permanent deformations in the subgrade.

Figure 15. Image showing a typical Ground Penetrating Radar (GPR) system (26)

Dynamic Track Stiffness Measurement

Track modulus measurement provides important information on the performance of the track relative to subjected loads. Additionally, it can identify potential problems with the track superstructure or structures. Adequate track support leads to a better ride quality and less problems associated with vehicle/track interaction (27). Different countries have developed equipment to measure the stiffness of the track, including United States (TTCI and University of Nebraska), China, The Netherlands, Sweden, and Czech Republic. In most cases, the basic equations of the theory of a beam on an elastic foundation are used to obtain the track modulus. The difference lies on how the response of the track is obtained.

The system that has been developed in The Netherlands (Figure 16a) uses a technology called high-speed deflectograph, which is based on Doppler and inertial sensors. The system measures the bending velocity of the rail under the wheel then outputs and estimate of track modulus. TTCI has developed the Track Loading Vehicle (TLV). This vehicle is able to measure the vertical and lateral stiffness of the track. The TLV measures the total deflection of the track using laser sensors. The Swedish National Rail Administration has developed a model to calculate the track stiffness measuring force and dynamic excitation of the track (Figure 16b). Further work includes the correlation of the dynamic track stiffness measurements with GPR data.

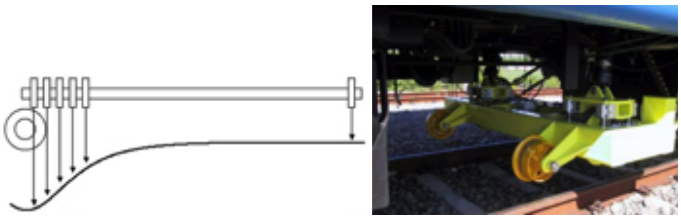

Figure 16. Dynamic Track Stiffness measurement techniques and equipment in (a) The Netherlands and (b) Sweden (27)

The University of Southampton has been developing a method to measure the track modulus in fixed points using geophones and normal service high-speed trains (28). Their system measures the dynamic response of the track in real conditions. The theoretical model is based on the equation of a beam on an elastic foundation. Low frequency geophones are attached to the end of the ties (Figure 17) to measure the dynamic response of the track (velocity) and then uses different mathematical algorithms to obtain the track modulus.

Figure 17. Geophone attached to the end of a tie as a part of the measuring system (28)

Since 2006, the University of Wollongong in Australia has been researching the dynamic response of heavy haul track using the impact hammer procedure (28). Initially the track is instrumented with accelerometers and a hammer in used to excite the track (Figure 18). The accelerations are measured and using a two-degree-of-freedom (2DOF) model the dynamic response is calculated. Based on the results a dynamic integrity evaluation of the track is performed.

Figure 18. Impact Hammer Equipment developed by the University of Wollongong (29)

Switch Bolts

Virginia Polytechnic Institute and State University (Virginia Tech) has been working to develop an effective method for monitoring the loosening of the bolted joints (switch point rods). Loose bolts were found as one of the main causes of crack formation in the bolted joints (30). Early detection of loosening of bolted joints in railroad switches is of great importance in mitigating the risk of derailment and reducing the need for frequent visual inspection of the switches' mechanical condition. The study focuses on the use of smart materials and structures for the health monitoring of bolted joints using piezoelectric transducers (Figure 19) and an impedance-based structural health monitoring technique. Additionally, the concept of self-healing bolted joints is applied in order to automatically retighten the loosened bolts to their functional conditions.

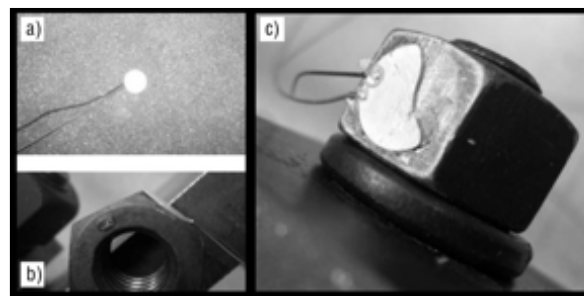

Figure 19. Piezoelectric transducers used for health monitoring of bolted joints by Virginia Technological University (30)

Aided Visual Track Inspection

The objective of aided visual track inspection technology is to help and guide inspectors through their daily tasks. However, they still rely on human judgment to identify defects in different track components. The advantage of these systems is digitalization of information that can later be used for a more realistic maintenance strategy.

Visual Crosstie (Sleeper) inspection – PDA

TieInspect is a comprehensive computerized crosstie inspection system that has been developed by ZetaTech, to accurately and efficiently collect tie condition data, based on a tie inspector's condition assessment (31). The system is outfitted with a handgrip input device, which is connected to a palmtop computer (Figure 20). All inspection data is stored on the handheld and is downloaded to any computer for analysis and reporting. Tie inspectors walk every tie with the unit and give a grade based on condition using a handgrip that is attached to the computer. Four different grades can be given to a tie by an inspector: Good, Marginal, Bad, and Failed.

Figure 20. Image of ZetaTech's TieInspect PDA (31)

Turnouts Inspection

SwitchInspect is a PDA Computer-based system that has been developed by ZetaTech to be used for conducting turnout inspections and collecting and evaluating data (32). The system is designed to inspect in accordance with FRA track safety regulations, but can be adapted to railroad-specific track standards. SwitchInspect guides the inspector through all of the inspection steps to ensure that every required inspection task is performed to include all specific component measurements and condition checks (Figure 21).

Figure 21. Image of ZetaTech SwInspect PDA (32)

DISCUSSION AND CONCLUSIONS

The inspection of most railroad track components is currently conducted using manual, visual inspections. These inspections are labor intensive and lack the ability to easily record and compare data needed for trend analysis. Moreover, they are subject to variability and subjectivity in different inspectors' abilities and interpretation of what they observe. Also, it is impractical to manually catalog the condition of such a large number of track components, thus it is difficult to develop a quantitative understanding of exactly how the non-critical or symptomatic defects may contribute to the occurrence of critical defects or other track problems.

The goal of the emerging technologies for track inspection that are presented in this paper is to supplement current visual inspection methods and traditional technologies, allowing consistent, objective inspection of a large number of track components. These systems have demonstrated the potential to enhance the inspection of railway infrastructure. Future work may include further experimentation to improve reliability and study the integration of these technologies with current systems or other NDT methods to perform real-time data analysis.

In addition, these systems, in conjunction with defect analysis and comparison with historical data, will enhance the ability for longer-term predictive assessment of the health of the track system and its components, more informed and proactive maintenance strategies, and improved understanding of track structure degradation and failure modes.

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REFERENCES

(1) Resendiz, E., Molina L.F., Hart, J.M., Edwards, J.R., Sawadisavi, S., Ahuja, N., Barkan, C.P.L. "Development of a Machine-Vision System for Inspection of Railway Track Components." 12th World Conference on Transport Research, Lisbon, Portugal, July 2010.

(2) Sawadisavi, S., J. Edwards, E. Resendiz, J.M. Hart, C.P.L Barkan, and N. Ahuja. "Machine-Vision Inspection of Railroad Track." Proceedings of the TRB 88th Annual Meeting, Washington, DC, January 2009.

(3) Sawadisavi, S., Edwards, J.R., Hart, J.M., Resendiz, E., Barkan, C.P.L., Ahuja, N., "Machine-Vision Inspection of Railroad Track." 2008 AREMA Conference Proceedings, American Railway and Maintenance of Way Association (AREMA), Landover, Maryland.

(4) Edwards, J.R., Hart, J.M., Sawadisavi, S., Resendiz, E., Barkan, C.P.L., Ahuja, N., "Advancements in Railroad Track Inspection Using Machine-Vision Technology." 2009 AREMA Conference Proceedings, American Railway and Maintenance of Way Association (AREMA), Chicago, Illinois.

(5) Hart, J. M., N. Ahuja, C. P. L. Barkan and D. D. Davis. "A Machine Vision System for Monitoring Railcar Health: Preliminary Results." Technology Digest: TD-04-008, Association of American Railroads, Pueblo, Colorado, 2004.

(6) Edwards, J.R., Hart, J.M., Sawadisavi, S., Resendiz, E., Barkan, C.P.L., Ahuja, N., "Machine Vision Inspection of Railroad Track". Technology Digest: TD-09-032, Association of American Railroads, Pueblo, Colorado, 2009.

(7) Edwards, J. R., J. M. Hart, S. Todorovic, C. P. L. Barkan, N. Ahuja, Z. Chua, N. Kocher and J. Zeman. "Development of Machine Vision Technology for Railcar Safety Appliance Inspection." Proceedings of the International Heavy Haul Conference Specialist Technical Session - High Tech in Heavy Haul, Kiruna, Sweden, 2007, pp. 745-752.

(8) Hart, J. M., E. Resendiz, B. Freid, S. Sawadisavi, C. P. L. Barkan, N. Ahuja. "Machine Vision Using Multi-Spectral Imaging for Undercarriage Inspection of Railroad Equipment." Proceedings of the 8th World Congress on Railway Research, Seoul, Korea, 2008

(9) Lai, Y. -C., C. P. L. Barkan, J. Drapa, N. Ahuja, J. M. Hart, P. J. Narayanan, C. V. Jawahar, A. Kumar, L. R. Milhon and M. P. Stehly. "Machine vision analysis of the energy efficiency of intermodal freight trains." Journal of Rail and Rapid Transit 221, 2007, pp. 353-364.

(10) Schlake, B.W.,J.R. Edwards, J.M. Hart, C.P.L Barkan, S. Todorovic, and N. Ahuja. "Automated Inspection of Railcar Underbody Structural Components Using Machine Vision Technology." Proceedings of the TRB 88th Annual Meeting, Washington, DC, January 2009.

(11) Deutschl, E., Gasser, C., Niel A., Werschonig, J. "Defect Detection on Rail Surfaces by a Vision based System". 2004 IEEE Intelligent Vehicles Symposium, Parma, Italy, June 2004.

(12) Mandriota, C., Nitti, M., Ancona, N., Stella, E., Distante, A. "Filter-based feature selection for rail defect detection", Machine Vision and Applications, July 2004, pp.179-185.

(13) Popov, D.V.,Titov, E.V., Mikhailov, S.S. "Rail head wear measurements using the CCD photonic system". Proceedings of SPIE Volume 3901, October 1999, pp.32-36.

(14) Wamani, W.T. ,Villar, C. "AURORA Automated Railroad Tie Condition Assessment System: The Quest for Accuracy". ." 2009 AREMA Conference Proceedings, American Railway and Maintenance of Way Association (AREMA), Chicago, Illinois.

(15) Yella, S., Dougherty, M., Gupta, N.K. "Condition monitoring of wooden railway sleepers". Transportation Research Part C 17, 2009, pp.38–55.

(16) Aguilar, J.J., Lope, M., Torres, F., Blesa, A. "Development of a stereo vision system for non-contact railway concrete sleepers measurement based in holographic optical elements". Measurement Volume 38, Issue 2, September 2005, pp.154-165.

(17) Labarile, A., Stella, E., Ancona, N., Distante, A. "Ballast 3D Reconstruction by a Matching Pursuit Based Stereo Matcher". 2004 IEEE Intelligent Vehicles Symposium Parma, Italy, June 2004.

(18) Marino, F., Distante, A., Mazzeo, P. L., Stella, E. "A Real-Time Visual Inspection System for Railway Maintenance: Automatic Hexagonal-Headed Bolts Detection". IEEE Transactions on Systems, Man, And Cybernetics—Part C: Applications And Reviews Vol. 37, May 2007, pp. 418-428.

(19) Singh, M., Singh S., Jaiswal J., Hempshall J. "Autonomous Rail Track Inspection using Vision Based System". IEEE International Conference on Computational Intelligence for Homeland Security and Personal Safety, Alexandria, Virginia, October 2006, pp.56-59.

(20) Babenko, P. "Visual Inspection of Railroad Tracks". Ph.D dissertation, University of Central Florida, Fall 2009.

(21) Berry, A., Nejikovsky, B., Gilbert, X., Tajaddini, A. "High Speed Video Inspection of Joint Bars Using Advanced Image Collection and Processing Techniques". In Proceedings of the 2008 World Congress on Railway Research, Seoul, Korea.

(22) Cybernetix Group (France), "IVOIRE: a system for rail inspection" http://www.cybernetix.fr

(23) bvSys Bildverarbeitungssysteme GmbH. (Germany). http://www.bvsys.de/index.php/products_2/

(24) Beena Vision Systems Inc. SurfView. (USA) http://www.beenavision.com/products_surfview.html

(25) EURAILSCOUT Inspection & Analysis. (Germany). http://www.eurailscout.com/1-2-switch-measurement_en.html

(26) Robert, R., Al-Qadi, I., Tutumler, E., Boyle, J. "Surface Evaluation of Railway Track Using Ground Penetrating Radar". Federal Railroad Administration. 2008.

(27) Berggre E. Dynamic Track Stiffness Measurement: A new Tool of Condition Monitoring of Track Substructure. Licentiate Thesis. 2005.

(28) Priest J. A., Powrie, W. "Determination of Dynamic Track Modulus from Measurement of Track Velocity during Train Passage". Journal of Geotechnical and Geoenvironmental Engineering, November 2009, pp. 1732-1740.

(29) Kaewunruen S., Remennikov, A. M. "Integrated Field Measurements and Track Simulations for Condition Assessment of Railway Track". 1st International Conference on Structural Condition Assessment, Monitoring, and Improvement, Perth, Australia, December 12-14, 2005, 391-398.

(30) Afshari, M., Marquié, T., Inman, D. J. "Automated Structural Health Monitoring of Bolted Joints In Railroad Switches". Proceedings of ASME 2009 Rail Transportation Division Fall Conference. October 2009, Fort Worth, Texas, USA.

(31) Zarembski A. M. "Enhanced Tie Condition Inspection Using Hand Held Recording Systems". ZETA-TECH Associates, Inc.

(32) ZETA-TECH Associates, Inc. "SwitchInspect: Electronic Switch inspection Tool". http://www.zetatech.com/Track%20Insp/Brochures/SwitchInspect_new_.pdf