High Speed Video Inspection of Joint Bars Using Advanced Image Collection and Processing Techniques

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ABSTRACT
Broken joint bars have been identified as one of the major causes of main line derailments in the U.S. Currently, joint bars are inspected visually by railroad maintenance personnel during regular track inspection from a moving hy-rail vehicle. Realistically, an inspector cannot see small defects in joint bars while driving a hy-railer. Even large cracks and broken bars are often missed by this method of inspection. Visual inspection on foot can provide better results, but this is a very slow, tedious and labor-intensive process. Normal rail traffic and revenue services are often interrupted when an on-foot inspection is performed.

In 2002, Federal Railroad Administration (FRA) Office of Research and Development (OR&D) started a program to build a proof of concept prototype visual inspection system that can detect the cracks on the joint bars. After successful demonstration of the proof of concept prototype, a system was developed to detect the cracks in the joint bars on the field and gage side of each rail. With new U.S. Federal mandates to increase joint bar inspection frequency, it has become evident that the industry is in need of more effective and efficient inspection procedures. In 2004, the U.S. National Transportation Safety Board (NTSB) investigated a series of derailments caused by joint bar defects and concluded that current hy-rail inspection processes were inadequate. These findings led the FRA to set forth an Interim Final Rule which requires the railroads to perform frequent walking inspections based on the track speed and line density. In response to this challenge, an image-based system for joint bar inspection was developed and tested with the goal of capturing high quality digital video images of joint bars from a moving vehicle. The system, developed with support from the FRA OR&D consists of high speed, high resolution line scan cameras which capture images of the joint bars, a lighting system, and computers which process images taken of the rail and report defects to the operator. The computers employ a series of advanced image processing algorithms to detect joint bar defects. Joint bars are tagged with milepost and footage information as well as precise GPS coordinates. All significant track features are inventoried and stored in a permanent database.
The video inspection solution presented here greatly increases the speed of the inspection process. The system operates up to speeds of 105 km/hr (65 mph) and can be mounted to either a hy-rail or rail-bound vehicle. In addition to the defect detection features, the system also gives the operator the ability to record all significant track features and their locations, such as joints, bridges, switches and frogs in a comprehensive database.

DESIGN CONCEPT

The system is designed to acquire high resolution images of the rail and process these images in real time using advanced computer algorithms. The system capitalizes on the capabilities of computational image analysis in order to detect the presence of joints and their defects. The entire system has been designed with optimization of image quality in mind. A lighting subsystem provides optimal lighting conditions for the selected cameras. A mechanical mounting structure positions the cameras and lights for the most favorable view of the rail web.

Once images are captured they are assembled by state-of-the-art computers. A series of image processing algorithms are then applied to the images to determine the position of the joint bar. Once the joint bar is located in the image, a set of classifiers are applied to the image to search for cracks and other defects in the joint bars.

A user interface provides the operator with a platform to easily evaluate and interpret data.

Figure 1: Visual Inspection System Concept
SYSTEM DESCRIPTION

The Automated Optical Joint Bar Inspection System (JBIS) consists of several major subsystems: a lighting subsystem, an image acquisition system, image processing algorithms to detect joint locations and defects, and a user interface that allows the user to manage and review the data.

Lighting Subsystem

The lighting system provides even and consistent illumination of the rail with high-powered Xenon lights. It is designed to temper variations in illumination caused by ambient light while also providing sufficient shadowing properties. The intensity of the light emitted is great enough to eliminate the need for light shields and the wavelength of the light is optimized to operate within the maximum sensitivity range of the camera. The lights are mounted on a beam exterior to the car and the beam pattern emitted by the lights is aligned with the field of view of the line scan cameras. The orientation and intensity of the lights is designed to illuminate the rail in such a way that the image is optimized for both brightness and contrast.

![Figure 2: Xenon Lights Illuminating the Rail](image)

System Installation and Implementation

The lights and cameras are mounted on a mechanical beam. The beam can be designed for installation on both rail-bound and hy-rail vehicles. The system is designed to fit within Plate C Clearance when fully deployed (Figure 3). When installed on a hy-railer, the beam is designed to be folded for highway passage (Figure 4). All components installed exterior to the car body are shock mounted and weather proofed.
Most of the interior system components are rack-mounted to optimize storage space and cable routing. Rack mounted chassis provide conditioned power to the lights, cameras and camera heaters. The power chassis for the lights was designed with LED indicators to alert the operator when a light bulb is burned out. Image acquisition computers, data storage devices and networking components are also rack mounted (Figure 5).
Figure 5: Rack Mounted Components

**Image Acquisition System**

The line scan cameras are positioned on the beam in a manner that optimizes the view of the rail web while still falling within Plate C requirements. The system is composed of four cameras, one each for both field and gage sides of the left and right rails. The cameras continuously image the rail as it is traversed. A high resolution encoder supplies the cameras with a 0.5 mm (0.02 inch) fixed distance trigger. Upon receipt of each trigger pulse, the camera acquires a grayscale line scan of the rail from the top of the rail head extending to the ballast. The cameras then send the images to a data collection computer for assembly and analysis.

Frame grabbers housed within the computers receive the images from the camera. High speed, multiprocessor computers assemble the images from the cameras line by line. The images are assembled and tagged with synchronization information supplied by a counter timer board.
Image Processing Algorithms

After the images are assembled, the first image processing algorithm evaluates the images for the presence of a joint bar. The joint bar is detected when the algorithm identifies a specific joint bar pattern within an image (Figure 6).

![Figure 6: Illustration of Joint Bar Detection Algorithm](image)

Joint bar images are extracted from the rest of the data. GPS coordinates and milepost/footage location are received through a serial port on the computer and the images get tagged with this information.

Once a joint bar is detected, a second algorithm scans the image for cracks in the joint bar. The algorithm identifies different areas on the bar where a crack is more likely to be present (Figure 7). Anomalies in the pixilation of the image are acknowledged and rated on their likeness to the characteristic pattern of a crack. The length, width, aspect ratio, contrast, defining shape, and other features of the suspected defect are all considered by the algorithm (Figure 8). Based on these criteria, the algorithm prescribes a probability rating to the defect. Images tagged with a high defect probability are flagged and sent to the operator for consideration.

All image processing occurs in real time. A compression board compresses the images and sends them to the user interface computer for operator evaluation and inventory reporting.
Operator Interface and Software

All joint bar images, whether deemed defective or not, are sent to a database with corresponding milepost and footage data as well as GPS coordinates. Detected defects are sent to the operator interface and are accompanied by an on-board alarm. The image of the defect is presented to the operator with the defect highlighted for easier consideration. The resolution of this image is very high, enabling the operator to easily evaluate the defect. The image can be panned, zoomed and scrolled, and the operator can add comments to the image, delete an image, or accept it as a defect.
An automated report of the data may be generated. The operator can choose to generate defect reports of confirmed cracks. Inventory reports of all joints present on a line may also be generated. The inventory reports include GPS coordinates of each event as well as milepost and footage location.

Track features such as switch points, frogs, bridges, and road crossings may also be entered into the database via an operator console in order to create a complete inventory of all significant track elements. The database and corresponding images can be accessed at any time in the future, allowing for evaluation of track wear over time.

Figure 9: Operator Interface

INDUSTRY USAGE AND SYSTEM PERFORMANCE METRICS

The prototype system developed for FRA OR&D was tested on several major railroads through the course of development. Once the system was deemed fully functional, it was tested on three major railroads across the United States. The purpose of these tests was to acquire data to train the algorithm with. After completion of each test, the crack detection algorithm was reviewed and modified based on the real-time performance of the system during the test. Defects in the dataset were used to refine the algorithm in order to decrease the false detection rate and increase the number of true defects detected.

After high confidence in the system was achieved, ENSCO presented this technology under the Trademark VisiRail for the North American market. The first production VisiRail system was installed on a rail-bound geometry car owned by one of the seven Class 1 Railroads in North America. This installation began in late 2006; the system was commissioned and went into full time operation in October 2007. A second VisiRail system installed on a hy-rail vehicle was
commissioned in August 2007 and surveyed track for both Short Line Railroads and Class 1 Railroads.

FRA’s system is also operational and is used to collect data for research and development purposes, as well as to augment testing by FRA Office of Safety. Additional VisiRail systems will be deployed on both rail-bound and hy-rail vehicles in 2008.

Mileage

In total, the three systems that were in full operation by the end of 2007 surveyed approximately 2,850 miles of Continuously Welded Rail (CWR) and 1,315 miles of jointed rail for a total of 4,165 miles.

Joint Count

The system inventories all joints present on a line, and this information is stored in a comprehensive database complete with GPS coordinates and milepost and footage information. From the three operational systems, a total of 357,000 joints were inventoried by the system (714,000 joint bars). This averages to 86 joints per mile.

The algorithm’s ability to correctly identify a joint depends largely on the quality of the image. Under good track conditions, the joint detection accuracy is 98%, meaning that the algorithm will detect 98% of the joints. With compromised image quality the ability of the system to identify a joint is decreased to 85%. The largest contributor to compromised image quality is wet rail, which darkens the image and decreases the contrast.

The false joint detection rate is also affected by image quality and track conditions. False joint rates can either be presented as a percentage of total joints, or as a number of joints per mile. Using the joint per mile statistic normalizes the false joint by accounting for the difference in joints per mile on CWR versus jointed rail.

With clean, dry rail conditions, the false joint detection rate is 0.4 joints per mile. Under poor conditions and water-streaked rail, the false joint rate is 1.6 joints per mile.
Automated Crack Detection Statistics

As with the joint detection statistics, the crack detection statistics depend largely on rail condition. With clean and dry rail conditions, the system will accurately identify over 80% of the cracked or broken bars present. Overall, the algorithms will flag ~5% of all joints inventoried as defective. Typically, one in ten of the flagged bars will contain a true crack.

Wet rail conditions again pose the greatest challenge to the algorithms. When the rail is streaked with water, the likelihood of a false joint detection increases. Often when a false joint is detected, a false crack will also be detected on the image. Under these conditions, false joints account for 45% of the false cracks.

The sensitivity level of the crack detection threshold can be adjusted to increase the detection rate of defects; however, adjusting this variable also reduces the filter for false positives. Therefore, as the true detection rate is increased, the false detection rate will increase as well. At some point, the value of an increase in the true positive detection rate is significantly compromised by the corresponding increase in the false detection rate. This concept is best presented by a Receiver Operating Characteristic (ROC) Curve. The Crack Detection ROC Curve (Figure 10) shows that for a true positive detection rate of 80% or less, the false detection rate is reduced to around 3%. However, for a 10% increase in the positive detection rate, to 90%, the false detection rate increases by 20%.

The most common cause of a false detection is detection of a crack on an image which does not contain a joint bar. This often occurs on water-streaked rail. Other common causes of false positives are frayed bond wires, rust and grease spots, weeds, and debris.

Several examples of verified joint defects identified by the system are provided (Figures 11-14). An example of an image that resulted in a joint bar being falsely identified as a defective joint is also provided (Figure 15).

![Crack Detection ROC Curve](image)

Figure 10: Crack Detection ROC Curve
Images of Detected Defects

Figure 11: Tiny Hairline Center Crack Detected by Automated System

Figure 12: Hairline Center Crack Detected by Automated System

Figure 13: Center Break on Field and Gage Bars, Field Verification Image and Top View of Breaks
CONCLUSION
Advanced image processing techniques can greatly increase the speed and effectiveness of joint bar inspection. The system presented in the paper demonstrates the ability to capture high resolution images of rail at speeds up to 105 km/hr (65 mph). The system can also operate under certain adverse weather conditions such as rain and light snow.
Through the course of development of this system, many capabilities and limitations of line scan and image processing technologies have been discovered by the development team. Establishing a lighting system which would provide optimal lighting conditions for the railroad environment was a large part of the developmental process. Detailed image analysis pointed to further areas of improvement as the system approaches maturity.
Further work is being done to improve the detection algorithms. Different classifiers are being introduced to increase the likelihood of detecting a crack without impacting the false detection rate. A filter specifically designed to detect the shape and location of bolts will eliminate many of the false detections. Adding dynamic image correction features will also reduce the effects of uneven illumination and poor rail conditions on the statistical performance of the system. Improvements to the user interface will also speed the review process.
The capabilities of this system will be expanded in the next year to include missing bolt detection, rail gap, and rail batter. The technology is also being applied to inspect other track features such as fasteners, tie plates, switch points and frogs.

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Boris Nejikovsky is a Chief Engineer of ENSCO, Inc Applied Technology and Engineering Division. He holds advanced degrees in electrical and civil engineering. His career has been dedicated to advancing the state of the art in railroad and civil engineering instrumentation, measurement techniques, and inspection technologies. Mr. Nejikovsky has been with ENSCO, Inc. for 15 years. While at ENSCO, he managed development of multiple track and vehicle inspection systems based on various technologies. He has broad expertise in the areas of track geometry, ride quality, track strength, rail profile, and rail corrugation measurements. He is also an expert in automated track video inspection, vehicle track interaction monitoring, and vehicle testing and evaluation. Mr. Nejikovsky is a member of the American Railway Engineering and Maintenance of Way Association Committee 2 for Track Inspection Systems. He has authored numerous papers and technical reports on track inspection and vehicle testing and holds several patents in the area of instrumentation and railroad inspection technology.

Ali Tajaddini is a Program Manager in Office of Research and Development of Federal Railroad Administration. He received his B.S. in Civil and Environmental Engineering in 1980 and M.S. in Structural Engineering and M.S. in Engineering Mechanics in 1984 from University of Wisconsin-Madison. He is registered as Professional Engineer in states Maryland and Wisconsin. He has been working in FRA since 1999. Prior to working at FRA he worked as structural engineer and analyst for Auto industry and he worked for 10 years at research and test Department of Association of American railroads in Chicago Technical Center and Transportation Technology Center and two years at ENSCO, Inc doing research in area of vehicle track interactions, Track geometry and wheel Impact loads.