Automatic Track Inspection Using 3D Laser Profilers to Improve Rail Transit Asset Condition Assessment and State of Good Repair – A Preliminary Study

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ABSTRACT

Track inspection is a critical process for both freight and transit rail safety. Currently, many rail transit agencies rely heavily on visual inspection, which is time and resource consuming, inefficient, and sometimes unreliable. Although some rail transit agencies do use ultrasound or track geometry cars for track inspections, these devices can only identify certain types of defects and are usually expensive. Many small- or medium-sized transit agencies cannot afford to purchase them and only hire consultants to do inspections once or twice a year, even though they do have the need to conduct the inspections more frequently. To address this issue, this research introduces a new computer vision framework specially designed for the automatic inspection of railroad tracks. The proposed framework is based on the Laser Crack Measurement System (LCMS), which consists of two high-performance 3D laser profilers that are able to measure complete transverse railroad profiles with 1mm resolution at high speeds. Compared to ultrasound and track geometry cars, the developed system is much more affordable and can be readily mounted on a hi-rail vehicle that virtually every rail transit agency owns. Based on the 3D depth map generated by the LCMS, new methods have been developed for measuring rail gauge, detecting missing or broken fasteners, and identifying cracks in concrete ties. Preliminary results reveal that the newly proposed computer vision framework is a promising cost-effective and reliable alternative to the existing inspection methods.

KEYWORDS

State of good repair, laser, track, fastener, tie, gauge, transit, inspection, safety

1. INTRODUCTION

A 2008 United States Federal Transit Administration (FTA) report [1] estimated that about 25% of the rail and bus assets in the U.S. were close to or beyond their useful life. For the nine largest transit agencies, the corresponding percentage was nearly 35%. The National Transportation Safety Board (NTSB) was seriously concerned about the safe operations of the current rail transit industry after investigating the July 2006 Chicago Transit Authority Blue Line derailment accident, concluding that the accident was caused by the failure of the tie plates and fastening systems. A member of the NTSB warned that this accident was a “wake up call ... to all transit agencies ... with equipment and infrastructure that age with each passing day.”

Defects in railroad tracks are also responsible for thousands of accidents annually around the world. In Canada, in 2012 alone a total of 1,011 rail accidents were reported to the Transportation Safety Board (TSB) [2] with a large percentage being attributed to track defects. In the United States, the Federal Railroad Administration (FRA) reported that track defects were responsible for more than 33% of all registered rail accidents. Thus, the reliable detection of defects in railroad tracks is of great importance for both freight and transit rail safety.

A critical aspect of the transit state of good repair is the inspection of rail transit infrastructure. During the last few decades, the practice of railroad inspection has evolved to include a wide variety of inspection methodologies, including human visual inspection (done by inspectors), ultrasound inspection methods [3,4], electromagnetic acoustic transducer inspection [5], and Ground Penetrating Radar (GPR) inspection [6]. Many existing methods require inspection staff to be physically on or beside the track in order to set up the testing apparatus as shown in Figure
For instance, at Metro St. Louis, ultrasound is used for rail inspection twice a year, and an inspection vehicle is used to check the rail geometry once every year. For all other structures and facilities (e.g., ties and fastening systems), they are inspected manually on a weekly or monthly basis, which requires considerable time and efforts. This practice is very typical for other transit agencies in the United States. Such approaches are slow, labor intensive and ultimately pose a safety risk to inspection workers. An FTA statement [7] released in May 2007 reported that 11 track workers died in heavy rail and commuter rail accidents over an 18-month period in the United States.

Remote sensing technologies have been used by many state Departments of Transportation (DOTs) for highway pavement and bridge inspections. Among them, laser has been tested in several states such as Tennessee, Texas, and Georgia for mapping highway and identifying pavement defects. Due to the encouraging results obtained, laser recently has been receiving increasing attention from state DOTs [8,9]. However, its applications in rail industry are still limited. The ones we found were to use laser for measuring railway clearance [10] and wheel/rail profile [11,12], which are different from the proposed study. Although some companies [13,14] have developed sophisticated inspection vehicles based on laser for track inspection, these vehicles are usually very expensive. Many small- and medium-sized rail transit agencies can only afford to hire these companies to do track inspections once or twice a year, even though they do have the need to conduct automatic inspections more frequently.

In recent years, a number of researchers have studied the potential to use laser or computer vision as an alternative for the automatic inspection of railroad tracks [15,16,17,18,19,20,21,22]. This paper builds upon these studies and introduces a new computer vision-based framework for the automatic inspection of railroad tracks. The proposed framework is based on the Laser Crack Measurement System (LCMS) [23,24]. The LCMS sensor has been used around the world for high-speed highway inspections. By combining high vertical accuracy, intense artificial illumination, and rapid scanning rates, the LCMS is capable of collecting extremely precise and detailed data at speeds up to 100 km/h, day or night, on a wide variety of surface types. Further details as to the performance of the LCMS are provided in the section that follows. The objective of this research is to develop an automated rail infrastructure inspection system based on LCMS for monitoring the health conditions of rail gauge, concrete ties, and fastening systems. This system integrates global positioning systems and geographic information systems and is able to automatically detect and locate those surface safety hazards. Compared to the current manual and automatic inspection methods, this proposed system is a promising cost-effective and reliable alternative.
2. HARDWARE CONFIGURATION

The LCMS (see Figure 2) combines 3D laser profilers that use high power laser line projectors, custom filters and a camera as the detector [23,24]. During operations, a strip of laser light is projected onto the railroad track and its image is captured by the integrated camera.

Images from the cameras are sent to a frame grabber to be digitized and then processed by a high-performance computer. Using lossless data compression algorithms, the raw data is compressed. This enables the data to be collected at rates of approximately 20 MB/s or 720
MB/km compared to raw data rates of upwards of 30 GB/km at 100 km/h. The key specifications for the LCMS can be found in Table 1.

Table 1 LCMS specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of laser profilers</td>
<td>2</td>
</tr>
<tr>
<td>Sampling rate (max.)</td>
<td>11,200 profiles/s</td>
</tr>
<tr>
<td>Vehicle speed</td>
<td>100 km/h (max)</td>
</tr>
<tr>
<td>Profile spacing</td>
<td>Adjustable</td>
</tr>
<tr>
<td>3D points per profile</td>
<td>4,096 points</td>
</tr>
<tr>
<td>Transverse field-of-view</td>
<td>4 m</td>
</tr>
<tr>
<td>Depth range of operation</td>
<td>250 mm</td>
</tr>
<tr>
<td>Z-axis (depth) accuracy</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>X-axis (transverse) resolution</td>
<td>1 mm</td>
</tr>
</tbody>
</table>

3. AUTOMATIC INSPECTION OF RAILROAD

For railroad scanning, the LCMS is mounted on a hi-rail vehicle as seen in Figure 3. The right sensor images the right rail (red triangle) and the left sensor images the left rail (blue triangle). The overlapped area covered by both the left and right sensors is used to merge the data from the two sensors, which makes it possible to obtain a complete view of the entire cross section of the track.

The 3D shape of the railroad (see Figure 4) is acquired as the hi-rail inspection vehicle travels along the tracks. The 3D data can be collected at user specified distance intervals (e.g., one image every 1mm or 4 mm) depending on the purpose of the data collection and analysis. This is
done by synchronizing the laser line projectors with the vehicle odometer or an encoder installed on the hi-rail vehicle.

Figure 4 3D Shape of the railroad track acquired by the LCMS.

LCMS sensors simultaneously acquire both “Range” (height of each pixel) and “Intensity” (the intensity of the reflected laser light for each pixel) images of the scanned surfaces. By merging the range and intensity data, 3D profiles of the scanned surfaces can be obtained. Figure 5 shows the results of the different types of images (i.e., intensity, range, and merged 3D image) that can be produced from the LCMS data.
The range data acquired by the LCMS system measures the distance from the sensor to the surface (e.g., roadway pavement or railroad track) for every sampled point. The center image in Figure 5 is produced by translating range data values into a grayscale image where farther away points (e.g., the railroad ties) are represented by darker pixels and closer points (e.g., the top of the rails) by lighter pixels.

### 3.1. Rail Gauge Estimation

Rail gauge is the measured distance between two rails at a specific point along the track. It is an important inspection data element as variations in gauge are typically associated with other track defects and can cause devastating accidents. For example, missing fasteners can often lead to changes in rail gauge as the rail is free to move and is no longer properly held in place. To address this key need, this research develops a new vision-based algorithm for rail gauge estimation. This algorithm utilizes the 3D range data from the LCMS sensor as follows:

1. Based on the realistic assumption that the rail head is the nearest object to the imaging system (the LCMS), the algorithm searches for the coordinate of the shallowest point in the generated range data. It is assumed that this point is on the rail head (see Figure 4).

2. A new range image is defined by applying a double threshold operator to the original range image from Step 1. The thresholds are a function of the shallowest point value. As a result, this refined range image only contains the area of interest for inspection: the rail head.
3. A remapping process is applied to convert the new range image (from Step 2) to a grayscale image (pixel values between 0 and 255).


5. The Canny method [26] is applied in order to extract the rail head contour.

6. The extracted contour often includes discontinuities. In order to address this issue, a technique was developed for closing and refining the rail head contour. In addition, at this step the actual positions of the rail edges are calculated.

7. Finally, we apply a “Blob Coloring module” which detects and recognizes (extraction of characteristics) blobs in a given binary image. A blob is a region of a digital image in which all the pixels are similar to each other. The final result of this step is that the edges of the rail in a given image are detected and highlighted.

Figure 6 illustrates the result of this process for a rail segment; the rail edges are correctly detected and highlighted in red. Once the rail positions are localized, the next step in the inspection process is to identify a new Region of Interest (ROI) to detect and recognize other features requiring inspection such as tie-plates and fasteners.

Figure 6 Detection and localization of the rail positions.

3.2. Detection of Fasteners

Missing fasteners are critical flaws to detect during track inspection. In order to detect missing fasteners, the first step is to detect all of the fasteners in the ROI. In order to do so, a vision-based approach (as opposed to 3D depth) was developed as follows:

1. First, a new 3D ROI is established based on the detected rail positions from the rail gauge detection algorithm. The new ROI dimensions are established using the known dimensions of the rail. Rail height is used to determine the ROI in terms of vertical/depth space and tie plate (see Figure 7) width is used to define the horizontal ROI. As is the
case for the rail heads in the rail gauge detection algorithm, a new range image which
targets fasteners specifically is produced by this process.

![Pandrol tie plate](image)

**Figure 7 Pandrol tie plate.**

2. Similar to the rail gauge algorithm, a remapping process is applied in order to convert the
range image from Step 1 to a grayscale image (pixel values between 0 and 255)

3. The Canny method is applied in order to extract the contours of fasteners.

4. Two morphological operations (dilation followed by erosion) are applied in order to fill
small holes and to eliminate isolated points in the detected fasteners.

5. Finally, a “Blob Coloring module” is applied which detects and recognizes (extraction of
characteristics) blobs in a given binary image. In the final output, fasteners are detected
and highlighted.

The developed algorithm is applied to some sample data collected from St. Louis, Missouri. The
experimental results, shown in Figure 8 and Figure 9, reveal the successful detection of fasteners.
More importantly, four missing fasteners (three on the right rail and one on the left rail) are not
detected as false positives in Figure 8. Also, all fasteners, except for those three missing ones in
Figure 9, are correctly identified and highlighted. False positives refer to missing fasteners that
are failed to be detected by the algorithm. When this happens, the algorithm considers there are
fasteners (e.g., false positives) at those missing spots, although in fact they do not exist. The fact
that missing fasteners are not detected as false positives demonstrates the robustness of our
algorithm for missing fastener detection. Currently, the team is working on getting additional rail
data with missing fasteners to fine tune the developed algorithm.

In summary, the detection of fasteners is done within a specific 3D ROI around the rail position.
The recognition of fasteners is conducted via a template matching method, which allows
distinguishing between fasteners and ballast/foreign object debris (FOD). Theoretically, it can
identify and recognize different kinds of fasteners (e.g., dog spikes, E-clips). In order to detect
different types of clips, we simply need to identify the entire set of existing clips and include
them in the template models. However, one may encounter situations where the fastener is
partially or fully occluded. In this case, the detection and recognition of fasteners can fail.

Figure 8 Detection of fasteners in railroad tracks.

Figure 9 Another Example of the Detection of fasteners in railroad tracks.
3.3. Detections of Cracks

Railroad track structure often suffers from the presence of cracks (see Figure 10). Due to the natural variability of cracking patterns, detecting cracks reliably is far more complex than the approach of applying a threshold on a range image as was adopted for rail gauge and fastener detection. This is especially true for hairline cracks as shown in Figure 11.

Figure 10 A crack (circled in red) in a concrete-tie.

Figure 11 Hairline crack in a concrete tie at Metro St. Louis.

Given the collected 3D LCMS data, the algorithm developed for crack detection involves:
1. The first step is to apply a set of mathematics-based detection operations upon the 3D data set (i.e., the range image) in order to obtain a binary image where the remaining active pixels are potential cracks.

2. The binary image from Step 1 is then filtered to remove many of the false detections which are caused by various design features and general distress on the railroad ties/sleepers which are not cracks.

3. At this point in the processing, most of the remaining pixels can correctly be identified as cracks. However, many of these crack segments need to be joined together in order to avoid multiple detections of the same crack.

4. After the detection process, the next step consists of the characterization of the identified cracks.

5. Finally, the severity level of cracking is determined by evaluating its width (opening). Severity can be further grouped into categories such as low, medium and high by defining width ranges for each level.

The developed algorithm has been applied to both concrete and wood ties. For the hairline crack (see Figure 11) in a concrete tie in St. Louis, we were unable to detect it. However, for large cracks in concrete ties and especially wood ties, the developed algorithm has demonstrated reasonably good performance. Figure 12 shows the range data of a sample wood tie and the detected cracks are highlighted in red. In fact, those hairline cracks in concrete ties do not pose safety concerns that require immediate attention. Also, wood ties tend to develop cracks as they age and most of those cracks do not affect the wood ties’ performance. The developed algorithm allows the filtering of such cracks according to their characteristics (e.g., size, area, orientation).

![Image](image_url)

**Figure 12** Detection of cracks in wood cross-ties.

4. CONCLUSIONS AND FUTURE WORK

The reliable and automatic inspection of railroad track structures is critical for both freight and passenger rail safety. Most rail transit agencies rely heavily on manual inspection methods,
which are time consuming, labor intensive, and sometimes unreliable. Although some agencies
do employ automatic tools (e.g., ultrasound and geometry cars) for track inspections, these tools
are usually very expensive and rail transit agencies (especially small- or medium-sized agencies)
cannot afford to own them. They can only hire contractors to do the inspection work using these
tools on an annual or bi-annual basis, even though they do have the need to inspect tracks more
frequently.

The use of computer vision techniques has recently been identified as a promising method for
railroad inspection. This paper introduced a new computer vision based framework with the goal
of automatic inspection of railroad tracks. The current version of the framework is based on the
LCMS that consists of two high-performance laser profilers. The developed framework is
capable of estimating rail gauge, detection of existing/missing fasteners and the identification of
cracks in railroad ties/sleepers. The developed framework has been tested based on the rail data
collected from Chicago and Metro St. Louis. The result suggests that the framework is able to
accurately measure rail gauge and identify missing fasteners and cracks in cross ties. Also, the
developed framework is much more affordable than existing ultrasound and geometry cars. It can
be readily mounted on a hi-rail vehicle and is a promising alternative to existing manual and
automatic inspection methods.

The research team is currently working on collecting and analyzing additional rail data from
Metro St. Louis and Massachusetts Bay Transit Authority (MBTA), to further test and fine tune
the developed framework under various conditions (e.g., different types of ties and fasteners).
Since the LCMS can collect rail profiles at 1mm horizontal accuracy and 0.5 mm vertical
accuracy, a lot of useful information can be extracted from the acquired detailed 3D profiles.

Other than rail gauge, fasteners, and ties, the system setup may be adjusted to allow it to assess
the conditions of ballast, running surface, track bed slope, fishplates and their fasteners,
wheel/rail profile compatibility, corroded railroad tracks, and overhead power and signal lines.
The same system setup can also be used for broad and narrow gauge railways. Additionally, our
next steps include a web-based decision support system and a mobile app that can facilitate the
data visualization and management, decision making, and field asset inspection. Moving
forward, it is expected that the proposed framework will serve as a platform to develop a
complete system for the automatic inspection of railroad tracks.

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