

Machine-Vision Inspection of Railroad Track

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ABSTRACT

Railroad engineering practices and Federal Railroad Administration (FRA) regulations require track to be inspected for physical defects at specified intervals, which may be as often as twice per week. Most of these inspections are conducted visually by railroad track inspectors and include detecting defects relating to the ballast section, ties, fasteners, rail, and special trackwork. Enhancements to the current manual inspection process are possible using machine-vision technology, which consists of recording digital images of track elements of interest and analyzing them using special algorithms to identify defects or their symptoms.

Based on analysis of FRA accident data, consultation with railroad track engineering experts and Association of American Railroads researchers, this project focuses on using machine vision to detect irregularities and defects in wood-tie fasteners, rail anchors, crib ballast, and turnout components. Development of a machine-vision-based inspection system will permit more efficient, effective, and objective inspection of these track elements. The system will be adaptable to inspect in accordance with FRA track safety regulations as well as railroad-specific track standards that may involve additional parameters of interest. Also, because data will be stored digitally, recall and quantitative comparative analysis is possible thereby enabling relative comparisons and trend analysis. This will enhance the ability for longer-term predictive assessment of the health of the track system and its components, and lead to more informed preventative maintenance strategies and a greater understanding of track structure degradation and failure modes.

1. 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 Federal Railroad Administration (FRA) regulations. Although essential, track inspection requires both financial and human resources as well as consuming track time. The objective of the research described in this paper is to investigate the feasibility of using machine-vision technology to make track inspection more efficient and effective.

The initial focus of this project is inspection of Class I railroad main and siding tracks, as these generally experience the highest traffic densities. Heavy traffic leads to more frequent inspection and maintenance requirements but less time to accomplish it. The cost associated with removing track from service due to inspections or the repair of defects is most pronounced on these lines, making them the most likely to be cost-effective locations for investment in new, more efficient but potentially more capital-intensive inspection technology.

2. DETERMINATION OF INSPECTION TASKS

2.1. Survey of Existing Technologies

We first conducted a survey of existing technologies for non-destructive testing of railroad track and track components. This provided insight regarding which tasks were best suited to vision-based inspection for which technology was not already under development. This survey encompassed well-established inspection technologies (e.g. ultrasonic rail flaw testing) and more experimental technologies currently under development (e.g. inertial accelerometers). In the next section, we provide a brief review of the technologies currently in use or development that were of greatest relevance in the determination of the scope of our research.

2.1.1. Light Detection and Ranging (LIDAR)

Light Detection and Ranging (LIDAR) uses a light source, such as a laser, that reflects off of objects. The properties of the scattered light are then analyzed to determine the object's distance. LIDAR systems in use by the railroads employ a rotating laser emitter that has high cross-sectional resolution due to the large number of sampling points along the inspection arc. However, the longitudinal resolution along the track is dependent on the speed of the inspection vehicle (*I*). To allow for greater resolution at high speeds, LIDAR systems have been improving their laser emitters to use multiple beams or to rotate at higher speeds; however, these features also increase the cost. An advantage of this technology is the ability to accurately measure an entire cross section at high speed irrespective of light level. Disadvantages include the relatively low longitudinal resolution, and the inability to obtain measurements from objects at oblique angles or from the surface of water.

2.1.1.1. Clearance/Ballast Measuring System Plasser American has developed a clearance/ballast measuring system that uses LIDAR to measure tunnel clearances and the shoulder ballast section (*I*). Their system currently uses a laser mirror scanner that operates using an electro-optical range detection method. This rotating laser array covers a 350 degree range, with a ten-degree gap in the measurements at the center of the track that is used for system recalibration purposes, and has an accuracy of 25mm (0.98in). It is currently being used by the New York City Transit Authority, Long Island Rail Road, Taipei Transit, Union Pacific Railroad, and CSX Transportation.

2.1.2. Machine Vision

Machine-vision systems are currently in use or under development for a variety of inspection tasks, including inspection of joint bars, surface cracks in the rail, and gauge measurement.

Machine-vision systems have three main elements. The first element involves the data collection system, in which digital cameras are used to obtain images or video in the visible or infrared spectrum. The next component is the image-analysis system, where the images or videos are processed using machine-vision algorithms to find the items of interest. The last component is the data-analysis system, which uses specialized algorithms to assess some aspect of the condition of the detected items.

The advantages of machine vision include greater objectivity and consistency compared to manual, visual inspection, and the ability to record and organize large quantities of data in a quantitative format. This combined with data archiving and recall capabilities provides powerful trending capabilities. Some disadvantages include difficulties in coping with unusual or unforeseen circumstances and the need to control and augment lighting.

2.1.2.1. Joint Bars The FRA began development of a machine-vision-based joint bar inspection system in 2002 (2). The system uses high-resolution, line-scan cameras along with high-powered xenon lights to capture images of joint bars at inspection speeds of up to 65 mph (105 km/hr). ENSCO has incorporated this technology into their VisiRail™ Joint Bar Inspection system, which is currently undergoing development and testing. The system primarily finds external cracks in joint bars, and under good track conditions, can detect joints with 98% accuracy. For clean and dry rail, the system has a crack detection rate of 80%. However, under non-ideal track conditions, especially when the rail is wet, the joint detection accuracy rate declines to 85%, with more false positive crack detections, although half of these are due to the increase in false joint detections. The system as currently in use requires manual interpretation to determine true joint condition. ENSCO is continuing to work on improvements to their algorithms to increase the crack detection rate without also increasing false positives. Planned

enhancements to this system include the capability to inspect for missing bolts, rail-gap width, and rail batter.

2.1.2.2. Elastic Rail Clips The National Taiwan University of Science and Technology, in cooperation with the Taiwan Ministry of Transportation and Communications, is developing a machine-vision system to inspect elastic rail clips (3). The goal is to improve the safety, comfort, and efficiency of mass transit in Taiwan. This system is capable of inspecting the German VOSSLOH clip, which is the most prevalent type in use on Taiwanese rapid transit lines. The system uses area-scan cameras with a resolution of 640x480. It can inspect clips on concrete or ballasted track to determine if they are broken and has a 77% recognition rate for broken clips. Future work includes improving the lighting system and image processing algorithms, and inspection of the bolts that secure the elastic rail clips.

2.1.2.3. Rail and Track The University of Central Florida, in association with the Florida Department of Transportation, is developing a machine-vision system for the inspection of surface cracks in the rail, missing or misaligned tie plates, presence of fasteners, and improper gauge (4). Initially, they used a small, self-propelled track cart to gather video data and are now adapting the system for use on a high-rail vehicle. A downward-facing, high frame rate, 640x480 area-scan camera is used in combination with strobe lights, lasers, and sun shields to gather the video data. Images are captured approximately every 1.5 feet, with the exact interval determined using Global Positioning System data. Future work consists of adapting the system for use on high-rail vehicles.

2.2. Prioritization Based on Accident Statistics

In order to prioritize the tasks that are most conducive to machine-vision inspection, the FRA Accident Database was analyzed to identify the most frequent causes of track-related railroad

accidents from 2001-2005 (5). The three most frequent causes are broken rail, wide gauge, and cross-level. However, several extant technologies are already being used by railroads to detect these defects. The principal defects that contribute to the next three most common, buckled track, switch points, and other turnout defects, are currently inspected primarily using manual, visual inspection. Therefore these may be amenable to use of machine-vision inspection, and were selected for further consideration.

2.3. Defect Severity Levels

In order to characterize the level of severity of track-component defects and determine the required action, we grouped defects into three categories: critical, non-critical, and symptomatic.

2.3.1. Critical Defects

We define critical defects as those that pose either an immediate or near-term hazard to safe and efficient operation. They represent a potentially severe condition such as a track buckle. These types of defects are what preventative maintenance and periodic track inspection are intended to prevent.

2.3.2. Non-critical Defects

Non-critical defects are those that cause sub-optimal track structure conditions but do not present an immediate hazard to train operations. An example of a non-critical defect would be low crib ballast between a single pair of ties. Such a condition may result in a small degradation in the longitudinal stability of the track, but is unlikely to pose an immediate hazard. However, if there is low crib ballast along an extended portion of track, longitudinal stability may be lost to the point where, in combination with high thermal stresses, a track buckle might occur.

2.3.3. Symptomatic Defects

Symptomatic defects do not necessarily represent defects, but may be indicative of a possible problem. An example of a symptomatic defect would be shiny spots on the base of the rail near anchors or other rail fastening devices. These are not defects per se, but they indicate possible rail running due to excessive longitudinal forces in the rail, a possible precursor to a track buckle.

2.4. Selected Inspection Tasks

In the initial selection of specific inspection tasks to be developed in this project, we took into account the lack of available technology, severity of defects, and their potential contribution to preventing accidents. We then sought and reviewed input from Class I railroad track maintenance managers, track inspectors, and experts in track-related research. The result of this process was the selection of the following inspection tasks:

1. Inspection for raised, missing or inappropriate patterns of cut spikes
2. Inspection for moved, missing, or inappropriate patterns of rail anchors
3. Inspection for an appropriate level of crib ballast
4. Inspection of switch points and other turnout components

3. DATA COLLECTION

3.1. Determination of Camera Views

3.1.1. Track Simulation Model

A track simulation model was developed to evaluate camera views and to provide images for initial machine vision algorithm development (Figure 1). This enabled experimentation on varying camera locations in the laboratory. The simulation model was developed using AREMA track specifications and representative Class I railroad track standards. Association of American Railroads (AAR) clearance plate diagrams were incorporated into the simulation model to ensure

that cameras were not being placed in infeasible positions to obtain the desired views of the track (6). The virtual cameras were then manipulated within the model until they enabled the viewing of the relevant components of the track and assessment of conditions of interest that were conducive to algorithm development.

3.1.2. Selected Camera Views

Three camera views are being used to record images of components on each side of the rail: an over-the-rail view and gauge and field-side lateral views (Figures 2 and 3). In the over-the-rail view the camera is positioned directly above the rail, looking longitudinally downward at the rail. The field and gauge-side spikes are visible in this view. This view is also used to determine the level of crib ballast. The field and gauge-side lateral views are perpendicular to the rail, looking downward, so that the base of rail and fastening system are visible. The over-the-rail view is taken parallel to the track from 12 inches above the top of the rail head (TOR), at an angle 30 degrees below horizontal. Both lateral views are taken perpendicular to the rail from a point 24 inches laterally from the center of the rail and 12 inches above the TOR at a 45 degree angle below horizontal.

3.2. Preliminary Data Collection

In our initial collection of digital images, we used handheld cameras to take photographs at the selected camera views. These photographs were taken at various representative locations, and provided insight into challenges such as lighting and the degree of variation in components. This was an iterative procedure in which we found more effective views that had not been evident in the initial track simulation.

3.3. Video Acquisition Cart

A small track cart was modified to support cameras for use in our initial field data acquisition. Experiments on camera views and lighting can be conducted using this cart on low density trackage during system development. Ultimately, the system will be adapted for vehicles suitable for use on mainline track such as detector cars or high-rail vehicles.

3.4. Lighting Challenges

As with many vision-based inspection systems, optimizing lighting is a challenge, especially for our over-the-rail view. We reviewed lighting arrangements of other machine-vision systems to gain insight into possible solutions. ENSCO's Joint Bar Inspection system uses high-powered xenon lights that eliminate the need for sun shields. However, unlike our system, they use line scan cameras that require a much smaller area of illumination, so this method could not be directly adapted to our system (2). The University of Central Florida's track inspection system uses a strobe light that operates synchronously with the camera, and has sun shields to limit the surrounding light. Like our system, they use area-scan cameras; however, their cameras are closer to the rail than some of our subjects. Consequently we may encounter difficulty using sun shields. Methods to control and augment light levels are one of the areas we are continuing to study.

4. ALGORITHM DEVELOPMENT

4.1. Inspection Guidelines

It is important to understand the specific track components and defects associated with them when developing the algorithms. We used the FRA Track Safety Standards, Class I track engineering standards, and the Track Safety and Condition Index (TSCI) to determine guidelines used for inspection procedures (7)(8)(9)(10). Our guidelines are currently under development

and include the height that would constitute a raised spike, and how many need to be raised before they would be considered critical.

4.2. Track Simulation Model

The track simulation model was used to produce images of component defects for initial algorithm development. The simulated track enabled general algorithm development in which we created various types of track defects so we could evaluate different algorithmic approaches for detection. Defects such as raised spikes, moved anchors, and low ballast were all simulated, along with varying the environmental conditions that could affect detection reliability.

4.3. Track Inspection Algorithms

We began our algorithm development with spike detection, and have now begun work on anchor detection, with ballast and turnout algorithms planned for 2009. The algorithms must be robust to changing environmental conditions and slight changes in appearance (e.g. differing types or material corrosion) of the track components. Edges are frequently used to detect objects in computer vision since object boundaries often generate sharp changes in brightness (*11*). Image gradients (edges) should be consistent among differing ties and rails, but unanticipated track obstacles could create spurious edges, causing confusion for the algorithms. For this reason, texture information from the ballast, tie, and steel was incorporated into an edge-based algorithm to improve its robustness.

4.3.1. Image Decomposition

The algorithm operates in a global-to-local scheme, with the largest, most consistently detectable objects being located first, followed by smaller objects, such as anchors. The strong gradients of the rail make it the most distinct and detectable object in all three views. However, gradients

alone do not allow consistent detection of the ties, so texture classification is used to make the tie located closest to the camera detectable in all three views.

Textures can be characterized by certain spatial frequencies in two dimensions. Gabor filtering is used to summarize these spatial frequencies, which can be used in texture discrimination (11). Differentiating the ballast texture from non-ballast textures was found to be reliable. Labeled examples of ballast, tie, and steel textures are created from a previously stored image. Gabor filtering is applied to analyze the spatial frequencies, and the results are stored for each texture example. When presented with a previously unseen image, texture patches are extracted and classified as either “ballast” or “non-ballast”. Though the “non-ballast” area may contain spurious edge noises due to occluding objects (e.g. leaves or ballast on ties), this method robustly provides a region that is centered on the tie. The rail is isolated, as is the part of the tie visible on the field-side of the rail (Figure 4A). Though the boundaries are inexact, in all test images, the area is reliably isolated for subsequent processing.

After isolation of the portion of the tie in the foreground, an accurate boundary for both the tie plate and tie must be obtained to determine if an anchor has moved from its proper position. Also, if the tie plate is delineated (Figure 4B), prior knowledge of the known dimensions of a tie plate can be compared to the image to calibrate its scale. Texture information is incorporated to ensure that the edge between the rail and tie plate occurs between two steel textures, whereas the edge between the tie and tie plate is between the steel and tie textures. After delineation of the two horizontal edges, the vertical edges are found since they are reliably detected only if their search space is restricted. The need for the restriction in search space is due to the effect of shadows and the possible presence of occluding ballast on the tie. The vertical tie edge is the dominant gradient that exists on both sides of the line between the tie and

the tie plate, and the vertical tie plate edge is the dominant gradient that exists only above the line between the tie and the tie plate.

4.3.2. Spike Inspection

The spikes are located with spatial correlation using a previously developed template (Figure 5A). The search area for the spikes is limited after the tie plate and rail are both delineated because within this area, spikes will only be found in certain positions. These locations include a row next to the base of the rail and another row further from the rail. Missing spikes are detected by a two-dimensional filter that consists of a dark square surrounded by a steel-colored square. The color of the steel is extracted from the currently isolated tie plate. Our detection of spike heads is not yet robust due to environmental variability and different wear conditions, but when the search area is limited, the accuracy improves.

4.3.3. Anchor Inspection

Rail anchors, when installed correctly, generally are easier to see and have more distinctive visual characteristics when viewed from the gauge-side. Therefore, our anchor inspection occurs primarily using the gauge-side lateral view (Figure 5B). The anchors are located and the distance to both the tie and tie plate is measured. Again, the search area for the anchor is restricted to where the rail meets the ballast, and outside the tie plate location. Anchors are detected by their parallel edges. Color intensity information is also included to ensure that any parallel edges have similar intensity distributions. This scheme provides robustness to interference from shadows, since they will result in similar intensity distributions for parallel edges in the same anchor. It also reduces sensitivity to slight rotation of the anchors since the detected edges are parallel, but not necessarily vertical.

5. DISCUSSION

In order to obtain information needed for trending, diagnosis, and prediction of problems, inspections must be conducted at regular intervals. The duration of these intervals will vary depending on the particular component. We anticipate that the system we are developing could be mounted on one of three commonly used track inspection vehicles: track geometry cars, detector cars, or high-rail inspection trucks, each of which is operated at different intervals.

Determining the inspection frequency depends on a variety of factors, the two principal ones being the rate of track deterioration, which is generally estimated based on annual gross tonnage, and the normal track speed, which in turn determines the FRA track class. The FRA defines nine track classes, ranging from the lowest, Class 1, to the highest, Class 9 (7). Each class is defined by allowable operating speeds and maintenance tolerances relating to gauge, cross-level, and various other parameters.

Most Class I railroad mainline trackage is FRA Class 4 or 5 (12), so we first considered the FRA requirements for the most restrictive case, Class 5 track. High-rail inspections are required twice a week, with one calendar day in between. Detector cars are required to run at least once for every 40 million gross tons of traffic, and no less than once per year. There are no regulations pertaining to operation of geometry cars on Class 5 track. Railroads may run all three of these inspection vehicles more frequently than required by regulations, based on the rate of track deterioration and their own criteria for safety and efficiency.

For an initial implementation, the inspection frequency provided by a detector car would be sufficient, and as an operation platform, has an advantage over high-rail vehicles in that crews have greater training with advanced inspection systems. Also, these vehicles are already equipped to handle the large amount of data upload and storage that would be necessary for our

system. Once the system has been proven on detector cars, it may be possible to equip high-rail vehicles.

6. CONCLUSIONS

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

The goal of this machine-vision track inspection system is to supplement current visual inspection methods, allowing consistent, objective inspection of a large number of track components. Based on analysis of railroad accident statistics and expert judgment, we are focusing our initial research and development efforts on inspection of cut spikes, rail anchors, crib ballast, switch points, and other turnout components.

Our algorithms use edge detection and texture information to provide a robust way of detecting rail, ties and tie plates, narrowing the search area. Within this restricted area, knowledge of probable component locations allow our current algorithms to determine the presence of spikes and rail anchors.

Future work involves refinement of the algorithms to improve the reliability of spike and anchor detection. In addition, we will conduct lighting experiments to achieve better results from the algorithms. Once the algorithms and lighting for inspection of spikes and anchors have

been refined using the video acquisition cart, we intend to begin working on adapting the system for use on a rail detector car.

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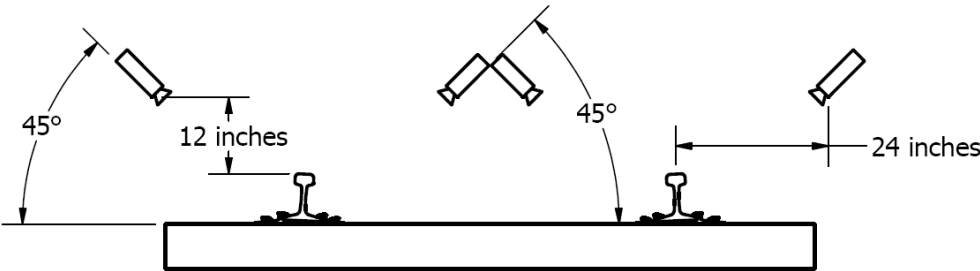
FIGURE 1: Image from Track Simulation



A: Gauge-side Lateral View



B: Field-side Lateral View

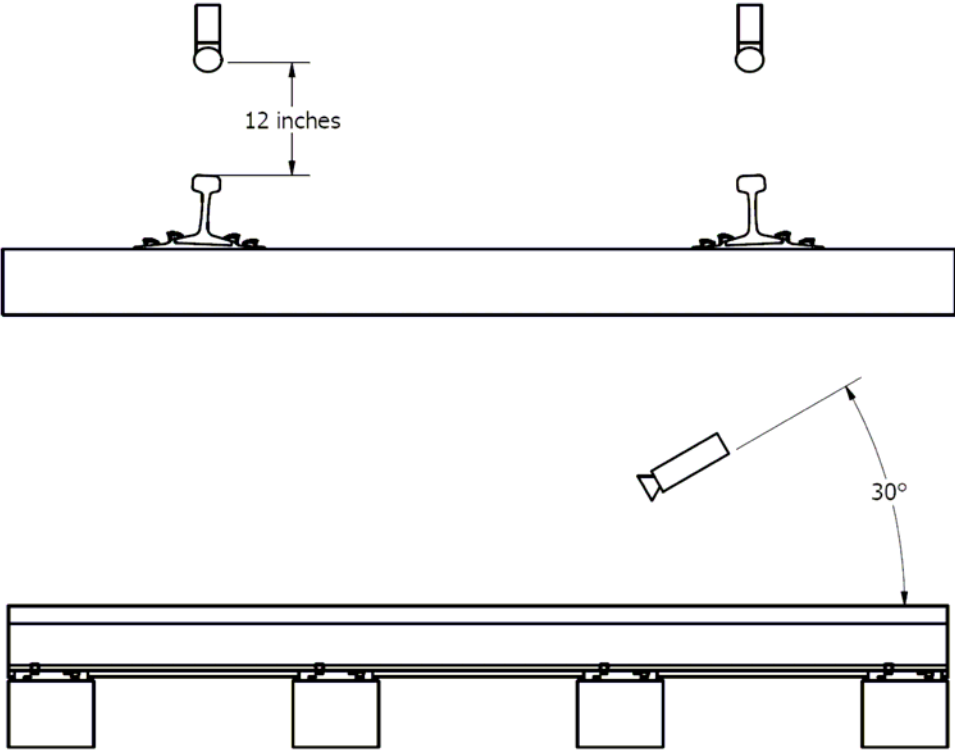


C: Lateral Camera Placement

FIGURE 2: Images and Placement of Camera Views Perpendicular to the Rail



A: Over-the-rail Camera View

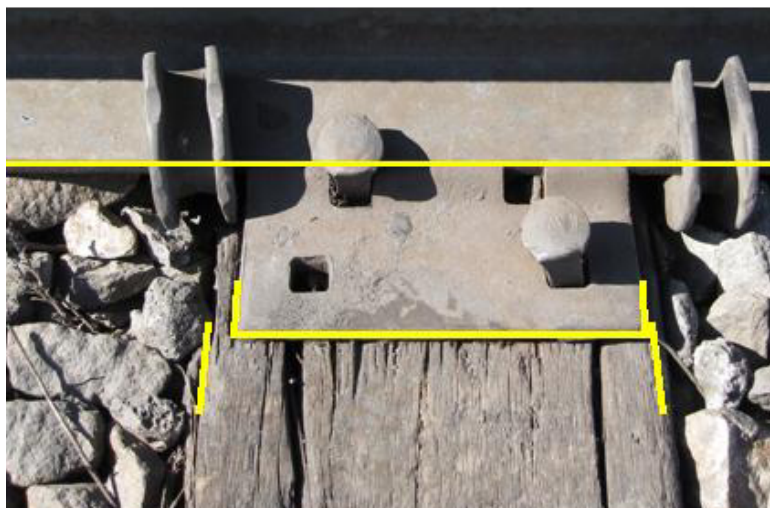


B: Over-the-rail Camera Placement

FIGURE 3: Images and Placement of the Over-the-rail Camera View

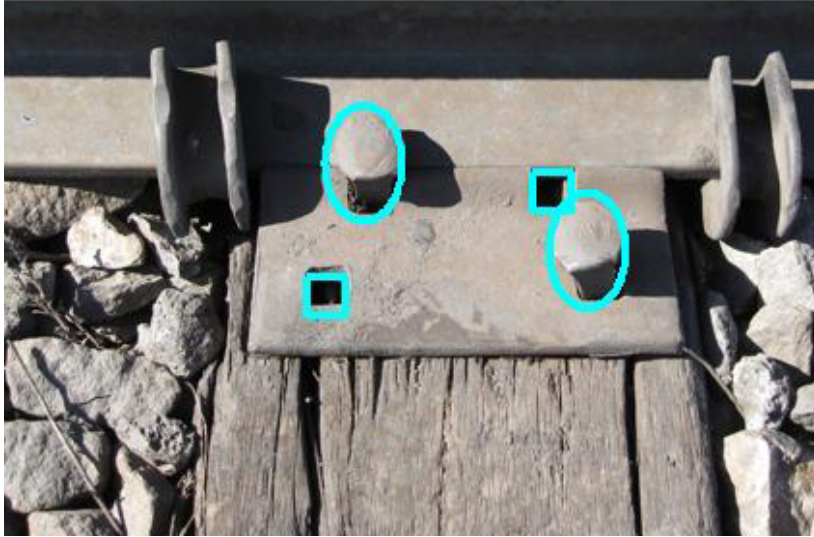


A: Isolated Non-Ballast Objects from FIGURE 2A



B: Delineated Tie Plate and Tie

FIGURE 4: Image Decomposition Process



A: Spike Detection Results



B: Anchor Detection Results

FIGURE 5: Track Component Detection Results