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Track-monitoring from the dynamic response of an operational train

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ABSTRACT

We explore a data-driven approach for monitoring rail infrastructure from the dynamic response of a train in revenue-service. Presently, track inspection is performed either visually or with dedicated track geometry cars. In this study, we examine a more economical approach where track inspection is performed by analyzing vibration data collected from an operational passenger train. The high frequency with which passenger trains travel each section of track means that faults can be detected sooner than with dedicated inspection vehicles, and the large number of passes over each section of track makes a data-driven approach statistically feasible. We have deployed a test-system on a light-rail vehicle and have been collecting data for the past two years. The collected data underscores two of the main challenges that arise in train-based track monitoring: the speed of the train at a given location varies from pass to pass and the position of the train is not known precisely. In this study, we explore which feature representations of the data best characterize the state of the tracks despite these sources of uncertainty (i.e., in the spatial domain or frequency domain), and we examine how consistently change detection approaches can identify track changes from the data. We show the accuracy of these different representations, or features, and different change detection approaches on two types of track changes, track replacement and tamping (a maintenance procedure to improve track geometry), and two types of data, simulated data and operational data from our test-system. The sensing, signal processing, and data analysis we propose in the study could facilitate safer trains and more cost-efficient maintenance in the future. Moreover, the proposed approach is quite general and could be extended to other parts of the infrastructure, including bridges.

1. Introduction

While continuous monitoring of engineered assets has become cost effective in fields like manufacturing and aerospace, the majority of civil assets are still monitored by visual inspection [1,2]. This paper focuses on railroad infrastructure, which is monitored by a combination of visual inspections and specialty track inspection vehicles, known as track geometry cars [3]. Inspection cars are expensive to operate, and as such, they are used to inspect the tracks infrequently [4]. A number of researchers have proposed using vibration-based monitoring to assess the track profile as a lower-cost alternative to the type of optical sensors

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currently employed on track geometry cars [5–10]. All of these studies assume that the sensors are placed on the axle of the train so that they have a direct mechanical connection to the track. In addition, they assume the position of the train is known, typically achieved by requiring that the inspection car operates at a constant speed.

In this paper, we explore a more economical approach: using operational trains and allowing the sensors to be placed inside the cabin [11]. By using operational trains, no dedicated monitoring vehicles are required, track closures are avoided, and tracks can be interrogated more frequently. The high frequency of interrogation not only means that issues can be flagged more rapidly, but also more passes over areas of interest can be collected, meaning greater statistical confidence about the state of the track. Lastly, by allowing the sensors to be placed in the cabin, the sensors can be installed more easily and can be protected from the external environment.

There are numerous challenges that must be overcome for this method to become practical, two of which we explore in detail in this paper. The first is that a train's speed over a section of track differs with each pass, so methods robust to train speed must be found for comparing data between passes. This is particularly challenging when the sensors are in the train's cabin, because the train's suspension filters the roughness from the track differently depending on speed. The second challenge is that we do not know the precise location of the train due to GPS noise, so position uncertainty must be considered in attempting to detect track changes from the vibration signal.

We learned about these challenges through our long-term monitoring project in partnership with the Port Authority of Allegheny County. We have placed accelerometers and a GPS antenna on an operational light-rail vehicle and have been collecting data over the last two years. We have focused on determining which analysis techniques are best suited for train-based monitoring and understanding why certain techniques work better than others. To gain insight into the vehicle-based monitoring problem, we also modeled a simplified version of the train-track interaction using a single degree-of-freedom oscillator travelling over a rough track. This parametric simulation allowed us to explore the effects of variable speed and position uncertainty in a controlled setting before validating on the light-rail data.

Simulation has three main benefits. First, we can generate much more data than we could collect from instrumented vehicles. Although we have been collecting data from the light-rail system for two years, there are relatively few recorded maintenance events in the rail-network each year that we can use to test our approach. With simulation, we can rapidly generate hundreds of track changes. Second, we can simulate a wider range of parameters than the narrow band we have observed in our operational system. For example, while the fundamental natural frequency of the instrumented light-rail vehicle has a single value, we can simulate numerous oscillators with different fundamental frequencies to ensure that the analysis techniques we find are general. Third, in the data we have collected, we do not have the ground-truth of the train's position. Through simulation, we can study the effect of position error, and propose techniques that work well for the level of error we expect in operational systems.

While our ultimate objective is to build a complete track-monitoring system, we focus in this paper on two main components required for automated track monitoring: meaningful feature extraction from the raw vibration signals and detection of track-changes from these features. For the first component, we examined four different features, and then used supervised classification to determine which one provides the most reliable information about the state of the track. The objective is to determine which features are most robust to the sources of uncertainty inherent in train-based monitoring. The fact that the train's speed varies between each pass (or the speed of the travelling damped oscillator in simulation) made comparing the data from multiple passes challenging. The signals are recorded in the time domain, but given that track changes are localized in space, the spatial domain is often more useful for detecting track changes. We examined features based on the spatial-domain representation of the signal, spatial frequency domain and temporal frequency domain as well as features based on the energy in the signal. We show the discriminate power of these features on data from our parametric simulation as well as on the light-rail dataset.

The second component in our automated detection system, change detection, is a challenging task because we do not know a-priori the type of change we are trying to detect [12]. The most closely related study of automated track anomaly detection from the vibration signal of a train is that done by Molodova et al. [13] where a system for detecting track squats (a type of rail-surface indentation) was proposed. In the study, a detection event was triggered by a vibration signal above a pre-defined threshold. We aim to build a broader detection system where anomalies are defined as changes relative to historical behavior. This ensures that areas with consistently high vibrations (like track switch gear or joints) are not labeled as anomalies, while changes, even in areas with low vibration-amplitude, are detected. For example, we will show that our method detects changes in track geometry due to tamping that can have safety implications despite their small amplitude. This historical detection technique allows for the monitoring of an entire network without manually tagging problematic areas as the method in Molodova et al. requires.

To perform change detection, we experimented with common methods like cumulative sum chart control (CUSUM) [14] and generalized likelihood ratio (GLR) [15], as well as a simplistic Haar filter [16,17] borrowed from the field of signal processing and computer vision. We report the performance of these approaches both on our simulated data as well as on the light-rail dataset.

As a validation, we apply these feature extraction and change detection approaches to data we collected from the instrumented light-rail vehicle. We examine our ability to detect a broken rail (a localized spike in the track profile) which is then replaced, as well as tamping, a maintenance procedure which subtly corrects track geometry. In both cases, information about when and where the maintenance took place can be found in the track maintenance logs, thus detection accuracy for our system can be evaluated.

2. Rail-monitoring method

Our proposed rail-monitoring method uses data collected from accelerometers inside a train to identify changes over time in rail infrastructure. In thinking about how to analyze the data, our first goal was to understand how track roughness, filtered by the train's