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Multi-level condition-based maintenance planning for railway infrastructures – A scenario-based chance-constrained approach

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ABSTRACT

This paper develops a multi-level decision making approach for the optimal planning of maintenance operations of railway infrastructures, which are composed of multiple components divided into basic units for maintenance. Scenario-based chance-constrained Model Predictive Control (MPC) is used at the high level to determine an optimal long-term component-wise intervention plan for a railway infrastructure, and the Time Instant Optimization (TIO) approach is applied to transform the MPC optimization problem with both continuous and integer decision variables into a nonlinear continuous optimization problem. The middle-level problem determines the allocation of time slots for the maintenance interventions suggested at the high level to optimize the trade-off between traffic disruption and the setup cost of maintenance slots. Based on the high-level intervention plan, the low-level problem determines the optimal clustering of the basic units to be treated by a maintenance agent, subject to the time limit imposed by the maintenance slots. The proposed approach is applied to the optimal treatment of squats, with real data from the Eindhoven-Weert line in the Dutch railway network.

1. Introduction

Maintenance is crucial for the proper functioning and lifetime extension of a railway network, which is composed of various infrastructures with different functions. The Dutch railway network, one of the most intensive railway networks in Europe, consists of tracks (6830 km), tunnels (5100), overhead wiring (4500 km), switches (7508), signaling systems, stations (388) and safety control systems. The degradation of an infrastructure can severely impair the performance of the whole railway network. One example is a squat, a typical type of Rolling Contact Fatigue (RCF), that accelerates rail degradation, which can potentially lead to derailment if not treated properly (Sandström and Ekberg, 2009). Grinding is effective for the treatment of early-stage squats, while rail replacement would be the only solution for severe-stage squats. Another example is ballast degradation, which can affect track geometries, causing unreliable support for sleepers and potential rail buckling and derailment (Ling et al., 2014; He et al., 2015). In this case, tamping is applied to correct the track geometry.

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1.1. Maintenance for infrastructures

Maintenance can be either reactive or proactive. A shift from reactive maintenance to proactive solutions can be identified in several European countries in recent years (Zoeteman, 2001; Al-Douri et al., 2016). Condition-based maintenance (Kobbacy and Murthy, 2008; Ben-Daya et al., 2016), a proactive maintenance strategy where decision making is based on the observed "condition" of an asset, has received growing attention in various industrial fields (Jardine et al., 2006; Fararooy and Allan, 1995). We apply the concept of maintenance optimization (Dekker, 1996) in the planning of maintenance interventions[1] for railway infrastructures based on an explicit mathematical model describing the deterioration process of the condition (Scarf, 1997). This is different from data-driven approaches based on an expert system (Guler, 2012) or machine learning techniques (Li et al., 2014), where no explicit model of the deterioration dynamics is required (Scarf, 1997). Markov decision process and its variations are the most popular stochastic models used in maintenance planning of transportation infrastructures (Smilowitz and Madanat, 2000; Durango-Cohen and Madanat, 2008). A bi-variate Gamma process considering both longitudinal and transverse level is used to schedule tamping intervention for a French high-speed line in Mercier et al. (2012). In Zhang et al. (2013), a Weibull distribution is assumed for the condition deterioration time probability density function, and an optimal timetable of maintenance activities is determined for a regional railway network considering multiple tamping crews to minimize the negative effects on train schedule and maintenance cost. Not all stochastic approaches model the deterioration dynamics as a stochastic process (Frangopol et al., 2004). One example is the grey-box model proposed in Quiroga and Schnieder (2012) for the ageing process of track geometry. Deterministic models are relatively few in literature. A linear model is applied in Wen et al. (2016) to describe the degradation of track quality, and a quality-dependent-recovering upper bound is used to ensure that the improvement of track quality by tamping can never outperform the previous operation. An exponential model is used in Famurewa et al. (2015) to describe the nominal degradation of track geometry, where the improvement brought by tamping is modeled by an empirical regression model.

In this paper, we focus on the optimal planning of maintenance interventions for a railway infrastructure using a condition-based maintenance strategy. Our aim is to develop a comprehensive, systematic approach that is able to support the maintenance decision making for a wide range of railway infrastructures. In particular, we consider a railway infrastructure as a multi-component system (Nicolai and Dekker, 2008) with independent deterioration dynamics, which can be either linear or nonlinear. Moreover, we do not restrict the condition to take only discrete values, thus avoiding the suppression of the rich deterioration dynamics brought by the discretization of the originally continuous condition in most stochastic models (Frangopol et al., 2004).

1.2. Maintenance intervention planning

An optimization-based, multi-level approach is developed in this paper for the optimal planning of maintenance interventions for railway infrastructures like rail and ballast. A schematic plot for the multi-level approach is provided in Fig. 1. Three optimization problems, namely the intervention planning problem, the slot allocation problem, and the clustering problem, are solved at the high, middle, and low level, respectively. Based on the component-wise discrete-time prediction model of the condition of the infrastructure, at each time step the high-level intervention planning problem determines the optimal maintenance intervention for each component over a given prediction horizon. The sampling time, i.e. the length of each time step, is usually larger than one month because of the slow deterioration dynamics of a railway infrastructure. If a maintenance intervention is suggested at any time step at the high level, it should be performed within a traffic-free time slot (4–8 h at night) to avoid any disruption to the train service. However, it is not always possible to complete an intervention within such a short time slot, and a new operation must then be scheduled into a new time slot to finish the required intervention, resulting in an additional setup cost including machinery, logistic, personnel, etc. This gives rise to the middle-level slot allocation problem, which determines the time slots that optimize the trade-off between traffic disruption and the total setup cost associated with each maintenance slot, while guaranteeing that the total duration of the resulting maintenance slots is no less than the estimated maintenance time. According to the intervention plan, the low-level clustering problem then groups the basic units into clusters that can be treated within the allocated time slots. If the resulting clusters cannot cover all the basic units that need to be treated according to the high-level intervention plan because of insufficient time slots, then the slot allocation problem is solved again with a longer estimated maintenance time. This iterative procedure between the slot allocation problem and the clustering problem repeats until all the basic units that need to be treated are covered by a cluster. This cluster-wise work plan is then applied to the infrastructure, and the condition of each component is then regularly measured or updated by estimation.

1.3. State-of-the-art

We use Model Predictive Control (MPC) (Camacho and Alba, 2013; Rawlings and Mayne, 2009) as the basic scheme for the long-term optimal planning of maintenance interventions over a finite planning horizon. MPC has been applied to various

[1] Renewal is also considered as a maintenance intervention.