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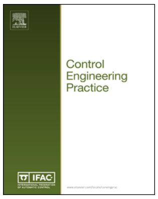

Plant-wide root cause identification using plant key performance indicators (KPIs) with application to a paper machine

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ABSTRACT

Previously, plant-wide disturbance analysis has looked into the propagation of faults through an industrial production process by investigating process measurements. However, the extent of the analysis has mostly been limited to a section of a plant. In this work, we propose a top-down approach which investigates measurements of the complete plant and identifies a section where the disturbance originates. Root cause analysis is carried out thereafter to pinpoint the faulty asset. The proposed approach has three novel elements: Using key performance indicators (KPI) as reference and starting point of the analysis, restricting measurements to a measurement type (e.g. flow) thus focusing on a section and applying the novel method of contribution plots of spectral PCA T^2 statistic to find the contribution of each measurement towards the disturbance observed in the KPI. The approach is described and carried out on a paper machine where a quality KPI showed an established oscillation.

1. Introduction

In the process industries – such as pulp and paper, chemicals, metals or minerals processing – the performance of the controllers is an important measure to evaluate whether the process is operating efficiently. There are many ways to assess the performance of single control loops (Jelali, 2006) based on operating data. The methods range from simple statistical evaluations such as standard deviation of the controller error to nonlinearity assessment. Since the introduction of the Harris index nearly three decades ago (Harris, 1989), there have been significant advancements in the computation of relevant and tailored indices. There are indices to identify certain time trends such as oscillations (Hägglund, 1995; Miao and Seborg, 1999) as well as measures which focus on the most prevalent faults such as control actuator malfunctions such as valve stiction (Choudhury, Shah, & Thornhill, 2008).

Poorly performing loops fluctuate around the setpoint upsetting the process and decreasing its efficiency. Worse still, these disturbances not only affect single loops but travel through the interconnected process equipment and show up in several measurements in the process and result in what is often termed 'plant-wide disturbances' (Thornhill and Horch, 2007). To find the root cause of the plant-wide disturbances, methods exploit not only the data of the plant but also the topology. Thambirajah, Benabbas, Bauer, and Thornhill (2009) capture connectivity information in XML descriptions and combine it with process data analytics described by Bauer, Cox, Caveness, Down, and Thornhill (2007a) while Yang, Shah, and Xiao (2012) and Faghraoui, Kabadi, Sauter, Boukhobza, and Aubrun (2014) use these data analytics to create causality digraphs connecting the process measurements.

The terminology 'plant-wide' is debatable because a plant often comprises hundreds if not thousands of control loops while the algorithms described in the references mentioned above deal with a few dozen of loops. Methods and frameworks that are termed 'plant-wide' look at more than one but usually less than 50 measurements by focusing on a plant section. For the purpose of this paper we will re-label the term plant-wide approach to 'section-wide' to avoid confusion.

A plant-wide analysis is conducted by Farenzena and Trierweiler (2009) who consider all loops in a plant by using both process data as well as heuristics to 'rank' loops according to their relevance in the plant, similar to the Google rank function. However, the loop rank index does not account for the impact of disturbances on the process KPIs.

Most of the plant-wide performance monitoring of control loops, as part of control loop monitoring, (CPM) in the process

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industries is conducted following standard procesdures. Many industrial production companies use CPM software packages which compile continuously, weekly or monthly reports with which action items such as tuning initiatives, control structure modifications or maintenance actions are triggered. The commonality between the different tools is that all use a bottom-up approach. That is, CPM indices are computed for all control loops in a plant. These indices rate the performance and identify loops that are performing poorly, i.e. loops that are oscillating, excessively deviate from their setpoints, or loops that are in saturation. The results of such assessments are generally presented in Top *X* lists, most often, the Top 10 worst performers are highlighted and addressed in a related meeting.

In this paper, we propose a top-down approach which focuses on key performance indicator (KPI) exhibiting degradation and then drills down to the root cause of the degradation, eventually identifying the faulty equipment. KPIs evaluate the performance of a process, not only on the control level but also on a business level reflecting the overall plant efficiency. KPIs help plant managers to assess the performance of the production at enterprise, plant or process level. A recently published standard describes KPI for manufacturing operations management (ISO22400-1, 2014) and highlights KPIs that are related to the control loop performance. The important thing about KPIs is that they capture the essence of the production process and are therefore specific to the application. In this paper, we consider KPIs specific to a three layer board paper machine. The use of KPI monitoring for fault detection has been considered previously in Faghraoui et al. (2014) for section-wide analysis of a paper board machine.

To facilitate the top-down approach, a new method is proposed to find the 'correlation' between the KPI in question and a selected number of process measurements from across the entire plant. The method is based on spectral principal component analysis (PCA) and uses the contribution plots of Hotelling's T^2 statistic. The novelty here is the use of contribution plots for specific frequency bins. Contribution plots for time-domain data was discussed by Miller, Swanson, and Heckler (1993) and were applied to process data by Kourti and MacGregor (1995). The shortcomings of the T^2 statistic is that it does not always identify the correct root cause because the contribution of one variable is passed on to other variables implicitly, see Alcala and Qin (2009). This is referred to as the smearing effect. In this analysis we will isolate a group of variables so that the effect is less pronounced. We accept that there is an error but in the individual contribution which becomes negligible when conducting the root cause analysis to identify a section. The specific root cause is identified in a second investigation round on considering only the section identified.

The paper is organized as follows. In Section 2 we discuss the proposed top-down approach and compare it to the traditional bottom-up approach. Section 3 introduces the case study of the paper machine explaining its specific KPI and describes the nature of the disturbances affecting the plant. Section 4 describes the top-down approach in detail using contribution plots of spectral PCA and applies it to the paper board machine case study. Results are discussed and summarized in Section 5.

2. Overview bottom-up versus top-down approach of CPM

2.1. Traditional bottom-up approach

The procedure of control loop performance monitoring (CPM) is a bottom-up approach and we will briefly review this traditional approach. Measurements in an industrial process can be arranged according to sections. Fig. 1 shows the measurements in an industrial process. Circles represent measurements or "process tags" such as temperature, level, pressure or flow variables. These variables may be controlled or only measurement points. The variables are grouped into sections of a plant. In the chemical industry, this could be a fermentation, drying, reformer or distillation section. In a paper machine, the process sections are forming, press, drying and calendaring. The sections are often situated in sequence but at the same time the section may share peripheries such as steam, electricity and are therefore interlinked. This is an important fact since faults can travel downstream but also through interlinked peripheries. Cecílio, Chen, and Thornhill (2011) looked at the interaction between process measurements and electrical measurements from electrical motors and compressors and identify fault propagation paths through peripheries.

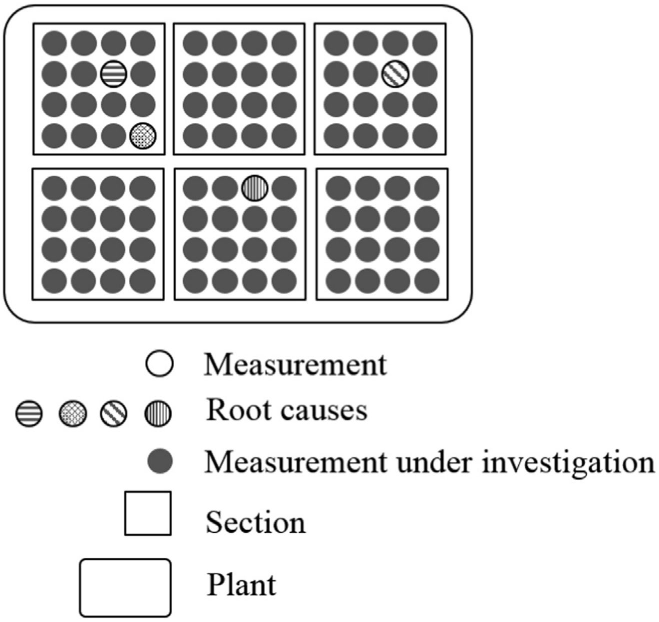

Fig. 1. Bottom-up approach of control loop performance monitoring.

The bottom-up approach includes the computation of indices for control loop process variables across the sections and the plant. For an industrial process, this can range from a few dozens to more than 1000 measurements. In the bottom-up approach, information about which section the measurement resides in is usually not exploited.

The bottom-up approach has been successfully applied in the process industry and several case studies have been reported as success stories (Jelali, 2006; Horch, Cox, & Bonavita, 2007). The major disadvantages of the bottom-up approach relates to the economic impact of CPM. There is no guarantee that the loops addressed are relevant to the efficient operation of the plant. For example, the performance of a flow controller dealing with the slurry feed of a by-product stream may be completely irrelevant to the overall productivity of the main production process, even if it may be doing a shockingly bad job. In particular, the economic impact of 'fixing' the Top 10 loops cannot be measured. Control engineering departments have to justify the effort they spend on certain tasks and estimate the financial impact of certain activities. Some attempts have been made to calculate the economic benefit of regulatory control (Bauer et al., 2007a) but there is no generic way to directly link the improvement of the control loop performance and a monetary value for all process variables. The bottom-up approach does not consider any information which measurement is in which section and which section comprises which plant is usually available with only little expert knowledge. In nearly all case studies the authors have dealt with, the tag name contained