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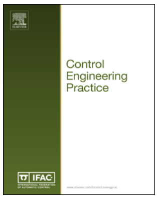

Hybrid approach to casual analysis on a complex industrial system based on transfer entropy in conjunction with process connectivity information

R. Landman*, S.-L. Jämsä-Jounela

Aalto University, School of Chemical Technology, Process Control and Automation Research Group, P.O Box 16100, FI-00076 Espoo, Finland

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ABSTRACT

Industrial processes often encounter disturbances that propagate through the process units and their control elements, leading to poor process performance and massive economic losses. Thus, one major concern in the chemical industry is the detection of disturbances and identification of their propagation path. Causal analysis based on process data is frequently applied to identify causal dependencies among process measurements and thereby obtain the propagation path of disturbances. One significant challenge in data-based causal analysis is investigating industrial systems with a high degree of connectivity due to multiple causal pathways. This paper proposes a new hybrid approach for detecting causality based on the transfer entropy (TE) method by incorporating process connectivity information using an explicit search algorithm. Based on the hybrid approach, initially, the TE is only calculated for pathways that are considered as direct pathways based on the process topology. Then, the direct transfer entropy (DTE) is employed to discriminate spurious and/or indirect pathways obtained by the initial TE results. To facilitate the DTE calculation, the search algorithm is invoked once again to extract the intermediate pathways. This concept is demonstrated on an industrial board machine. In particular, the propagation path of an oscillation due to valve stiction within multiple control loops in the drying section of the machine is studied. Finally, the results are discussed and evaluated.

1. Introduction

Industrial systems are often subjected to abnormal conditions, known as faults, which lead to a deviation in one or more of the system properties (Isermann & Ball, 1996). Undesired process conditions deteriorate the product quality, increase operational costs, and potentially lead to hazardous situations. Furthermore, the complexity of modern industrial systems imposes additional challenges in the control and monitoring of those conditions. In recent years, there has been an increasing demand from the process industry for an efficient tool that can detect and diagnose disturbances (Thornhill, Cox, & Paulonis, 2003; Yang, Shah, & Xiao, 2012). In particular, when an abnormal event occurs, one major challenge is to identify the root cause of the event and the fault propagation path. The identification is usually performed by investigating the causal dependencies among the process measured variables. Essentially, identifying the cause-and-effect relationships among the process variables is a crucial step in fault diagnosis, alarm management, and incident investigations (Shu & Zhao, 2013; Yu & Yang, 2015).

In recent years, data-driven methods have been widely used for investigating the causal interactions among process variables in the form of a time series. Methods such as the cross-correlation (Bauer & Thornhill, 2008), Granger causality (Granger, 1969), and transfer entropy (Schreiber, 2000) have attracted attention of many scientists and engineers since they do not necessarily require deep process knowledge in order to obtain satisfactory results. In addition, the process measurements are usually readily available. However, recent studies (Landman, Kortela, Sun, & Jämsä-Jounela, 2014; Thambirajah, Benabbas, Bauer, & Thornhill, 2007; Yang et al., 2012) suggest that process knowledge, in particular, the information on process connectivity, is essential for validating the results of data-based methods. Therefore, there have been several attempts to combine data-driven causal analysis with topology-based models (Di Geronimo Gil, Alabi, Lyun, & Thornhill, 2011; Landman et al., 2014; Thambirajah et al., 2007, Thambirajah, Benabbas, Bauer, & Thornhill, 2009; Yang et al., 2012). Topology-based models describe the physical connectivity among the process elements and are typically derived from a process flow

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* Corresponding author.
E-mail address: rinat.landman@aalto.fi (R. Landman).

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diagram (PFD) or from the piping and instrumentation diagram (P&ID) (Di Geronimo Gil et al., 2011).

This study is focused on the transfer entropy (TE) method. The TE method is perhaps the most commonly used method for evaluating causal relationships in non-linear systems by quantifying the amount of information transfer among time series (Schreiber, 2000). TE can be seen as an approximation of the predictability improvement when estimating series y based on the past values of series x and y compared with the past values of y alone. TE has been successfully applied to various applications for estimating causal dependencies between time series (Bauer, Cox, Caveness, Downs, & Thornhill, 2007; Duan, Chen, Shah, & Yang, 2014; Lee et al., 2012; Yang et al., 2012; Yu & Yang, 2015). Recently, the literature has emerged that offers modifications to the method, and several new measures based on TE have been proposed. Feldmann and Bhattacharya (2004) introduced the concept of predictability improvement, which is analogous to the concept of TE, but it is also applicable to short time series by considering nearest neighbors. Shu and Zhao (2013) introduced a modification to the TE method, which enables effective estimation of the time delay based on the prediction horizon. Vakorin, Krakovska, and McIntosh (2009) introduced the partial TE, which considers the environmental variables in an interacting network. Duan, Shah, Chen, and Yan (2014) proposed a new measure for causal analysis, the transfer 0-entropy method based on 0-entropy and 0-information without the assumption of probability space.

The main complexity of the TE implementation arises from the probability density function (PDF) computations, which is required for estimating the multi-dimensional conditional and joint probabilities. Typically, the kernel estimation method is used for the PDF estimation; however, the computational burden of this method significantly increases with the dimensionality of the analysis. Despite recent investigations, no alternative method has been presented that would offer more accurate and less burdensome estimation. Furthermore, determining the TE parameters such as the prediction horizon and the embedding dimensions is not a straightforward task and requires a significant computation time. Numerous studies have proposed methods for selecting the embedding dimensions (Kim, Eykholt, & Salas, 1998; Small & Tse, 2004). Bauer et al. (2007) performed several simulations on a reference case study and provided guidelines for setting the initial TE parameters. Based on those recommendations, Duan, Yang, Chen, and Shah (2013) proposed a procedure for determining the embedding dimensions.

Moreover, the traditional TE method is suitable for bivariate analysis, i.e., it does not distinguish between direct and indirect interactions. When investigating large-scale systems with a high degree of connectivity, it is essential to determine whether the interactions occur along direct or indirect pathways in order to obtain the propagation path. Vakorin et al. (2009) proposed the partial transfer entropy method, which considers the effect of indirect influences on the causal interactions in a multivariable environment. However, partial TE is defined such that all the environmental variables are considered to be intermediate, which is not necessarily true in chemical processes. On the other hand, Duan et al. (2013) introduced the direct transfer entropy (DTE) method, which discriminates between direct and indirect causal relationships in both linear and non-linear processes. More specifically, the DTE method is able to reveal whether the interaction is direct or indirect by considering the connectivity among intermediate variables. Furthermore, Duan et al. (2013) suggested quantification of the TE magnitude by defining the normalized differential TE (NTE_{diff}) and the normalized differential DTE ($NDTE_{diff}$), which provide an estimation of the strength of the interactions (Duan et al., 2013). Difficulties arise, however, when the DTE/NDTE method is implemented on a large complex system.

The main challenge in applying the TE on a complex system can be attributed to the following factors: PDF estimation, TE parameter estimation, determination of a statistical threshold for the results, and the treatment of highly connected networks. The primary aim of this investigation is to consider the latter issue by reducing the computational load. Large-scale systems do not only increase the computational burden of the analysis but also extend the difficulty of interpreting the results, especially if the network topology is complex. For example, the topologies of processes with numerous recycle streams and/or multiple pathways originating from a single unit are difficult to capture precisely.

Thus, this study proposes a new hybrid approach for applying the TE method by considering the process connectivity information in the form of an adjacency (i.e., connectivity) matrix (Jiang, Patwardhan, & Shah, 2008), which can be extracted from a P&ID of the process. The connectivity information is incorporated into the TE analysis by means of an explicit search algorithm (Landman et al., 2014). The search algorithm is employed for two purposes: first, to determine whether a path between two controllers is direct or indirect, and then to extract the indirect pathways between two controllers using the adjacency matrix. The analysis consists of two phases. In phase I, the bivariate TE is calculated only for the interactions that are considered as direct according to the output of the search algorithm and an initial causal model is obtained. In phase II, the interactions that are suspected to be spurious or indirect are further examined by calculating the DTE. In this phase, the search algorithm is utilized once again to retrieve the intermediate variables of the indirect pathways. Consequently, this approach has several advantages over the traditional TE analysis: First, the computational time is reduced since not all the TE values are calculated, but only the ones that correspond to interactions that are considered as direct based on the process topology. Second, the results are easier to interpret and an initial causal model can be obtained without determining a statistical threshold. Third, we tackle the complexity of a highly connected system in phase II by extracting the intermediate variables via the search algorithm. Consequently, the analysis becomes more automated and efficient.

The investigation takes the form of a case study of an industrial board machine with a persistent oscillation in its drying section due to valve stiction. In particular, this study examines the propagation path of an oscillation among controllers in the drying section . This paper is organized as follows. In Section 2, the overall approach for the TE implementation using process connectivity information is described, including the extraction of connectivity information from a P&ID and the implementation of TE and DTE. The case study, the analysis and the results are introduced in Section 3. Finally, the summary and conclusions are given in Section 4.

2. The overall approach for TE analysis

The overall hybrid approach for implementing the TE using a dedicated search algorithm is shown in Fig. 1. Initially, a topology-based model in the form of a connectivity matrix is generated from a P&ID. The TE analysis is performed in two phases: in phase I an initial causal model is generated according to the TE while in phase II the model is further refined to exclude indirect interactions according to the DTE. The search algorithm is utilized to incorporate the connectivity information into both phases of the TE analysis as depicted in Fig. 1. In the following subsections a detailed description of each step in the analysis is given. First, a procedure of generating a topology-based model is described. Next, the logic of the hybrid approach for TE analysis and the search algorithm are explained in detail. Finally, a description of the TE implementation is given.