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Understanding ART-based neural algorithms as statistical tools for manufacturing process quality control

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Abstract

Neural networks have recently received a great deal of attention in the field of manufacturing process quality control, where statistical techniques have traditionally been used. In this paper, a neural-based procedure for quality monitoring is discussed from a statistical perspective. The neural network is based on Fuzzy ART, which is exploited for recognising any unnatural change in the state of a manufacturing process. Initially, the neural algorithm is analysed by means of geometrical arguments. Then, in order to evaluate control performances in terms of errors of Types I and II, the effects of three tuneable parameters are examined through a statistical model. Upper bound limits for the error rates are analytically computed, and then numerically illustrated for different combinations of the tuneable parameters. Finally, a criterion for the neural network designing is proposed and validated in a specific test case through simulation. The results demonstrate the effectiveness of the proposed neural-based procedure for manufacturing quality monitoring.

Keywords: Statistical process control; Artificial intelligence; Adaptive resonance theory; Cluster analysis; Neural network design

1. Introduction

Neural networks have recently received a great deal of attention in a wide variety of applications where statistical methods have usually been employed. As an example, neural networks are used for classification and regression problems because of their ability to elaborate large amounts of data in real-time, and their capacity for handling noisy and uncertain data. Ripley (1994) provided a comparison study between statistical methods and neural networks for classification problems. Stern (1996) introduced the use of neural network models from the perspective of an applied statistician using a regression problem as an example. There is also an increasing emphasis on reviewing neural networks theory from a statistical perspective. Cheng and Titterington (1994) have shown that some statistical procedures can be given a neural network expression. Hwang and Ding (1997) and De Veaux et al. (1998) considered the problem of constructing confidence intervals for neural networks in nonlinear regression applications. A comprehensive reference on neural network theory is provided by Haykin (1999), while Bishop (1995) provided a general introduction of neural networks for statisticians.

Since neural networks are able to recall learned patterns from noisy or incomplete representations, they were also extensively exploited in statistical process control (SPC) applications where quality characteristics of a process are monitored in order to detect any unusual event that may occur (Zorriassantine and Tannock, 1998). The application of neural networks to SPC can be commonly classified into two categories, i.e. pattern recognition and unnatural behaviour detection.

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The pattern recognition provides a mechanism for identifying different types of unnatural patterns in real time on the series of process quality measurements. The patterns identified then serve as the primary information for identifying the causes of unnatural process behaviour. Reports of using neural networks for pattern recognition can be found in Hwarng and Hubele (1993a,b), Hwarng and Chong (1995), Cheng (1995, 1997), Chang and Aw (1996), Cook and Chiu (1998), Guh and Hsieh (1999), Guh and Tannock (1999), Chang and Ho (1999), Perry et al. (2001), Cook et al. (2001).

In the other category, detecting unnatural process behaviours, one of the earliest applications can be found in Al-Ghanim (1997) which proposed a system that is capable of signalling any change in the structure of a manufacturing process. In particular, the binary implementation of adaptive resonance theory (ART) was trained on a set of natural data in order to cluster them into groups with similar features. After training, the neural network can provide an indication that a change in process outputs has occurred when the series of process data does not fit to any of the learned categories. Although the work of Al-Ghanim represented a remarkable new use of neural networks for quality control, the author found that his pioneering methodology did not have the same degree of sensitivity as is possible using other neural network approaches. This drawback can be mainly ascribed to the binary coding of the ART algorithm as it is a less flexible way of using process data than a method based on graded continuous number encoding.

Our recent researches in manufacturing process quality control extend Al-Ghanim's methodology and present outperforming ART-based approaches for unnatural behaviour detection (Pacella et al., 2004a,b). In particular, simplified ART algorithms (based on the Fuzzy ART), which do not require binary coding of input data, have been investigated. In Pacella et al. (2004a) the neural network was trained using a series of process natural output data in a similar manner to that of Al-Ghanim. In Pacella et al. (2004b) it was demonstrated that the training set can even be limited to a single vector whose components are equal to the process nominal value. In the post-training phase, Fuzzy ART compares input vectors to learned categories and produces a signal if the current input does not fit to any of the natural templates.

These approaches can achieve similar performances in signalling a sustained change of process mean with those of the cumulative sum (CUSUM) control chart (Montgomery, 2000), but at the same time, they are also capable to detect a wide set of potential unnatural changes that cannot be addressed by a sole CUSUM chart. Indeed, for transient or dynamic changes of process mean, Fuzzy ART can outperform traditional charting techniques, which are designed to detect these particular changes, as a Shewhart control chart with a set of run rules and sensitizing rules (Montgomery, 2000). Since it can model different control strategies simultaneously, the proposed approach can be exploited as the sole tool for signalling a generic modification in the state of the process, so it provides a powerful diagnostic tool for detecting assignable causes in actual industrial processes.

Fuzzy ART was mainly chosen because its responses to input stimulus can be easily explained, in contrast to other neural networks, where typically it is more difficult to realise why an input produces a specific output. Indeed, one of the major features of using the aforementioned neural networks is that they are "black box" models as the effects of their parameters are generally not interpretable. On one hand, this is not a problem for many applications in which the emphasis is on prediction rather than on model building or model understanding. On the other hand, the method of choosing the values of neural network parameters is not well implemented as it is based on an experimental process where different values are used and evaluated. The problem with this is that it can be very time consuming, especially because neural networks typically have slow convergence rates. In the SPC field, this leaves the user with empirically developing, for the process control case at hand, the relationship between neural network performances and its parameters.

The aim of this paper is to provide a detailed description of the proposed Fuzzy ART approach, as a tool for detecting unnatural process behaviours, to quality practitioners with a statistical background. We achieve this by deriving a statistical model of Fuzzy ART algorithm in a very specific case in order to understand the capabilities and potentials of neural networks for manufacturing quality control. Fuzzy ART is firstly described by means of geometrical concepts, and then a probabilistic model is applied to it in order to estimate the effect of three tuneable parameters on the performance of the control procedure. Statistical methods are then used in order to derive analytically bound limits for monitoring performances. A practical result, which is obtained from such a statistical model, is a criterion for deciding on the values of network parameters which should be used in order to obtain a predefined monitoring performance for the process control case at hand.

An overview of this paper is as follows. In this section, a brief outline of the paper, have been provided. In Section 2, the characteristics of Fuzzy ART neural network are summarised through geometrical arguments, while the reference manufacturing process model is illustrated in Section 3. The proposed neural system and the training procedure are both presented in Section 4. In Section 5, the neural network is analysed by means of statistical arguments. In Section 6, upper bound limits