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Methodology of neural modelling in fault detection with the use of chaos engineering

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ABSTRACT

The paper deals with the problem of robust fault detection using recurrent neural networks and chaos engineering. The main part of the proposed approach is a locally recurrent neural network that is composed of complex dynamic neural units for which chaotic behaviour can be obtained. Selected global and local optimization methods are connected to have diphase strategies for training this kind of neural networks. And beyond this, chaos engineering is incorporated into both the evolutionary and simulated annealing algorithm in order to improve the efficiency of the tuning procedure. The problem of selecting the most relevant input variables is solved by means of extended Hellwig's method of integral capacity of information. Criteria isolines and a sensitive-based method are used to identify the suitable architecture of a neural network. Moreover, the issue of stability analysis of neural models is also considered in this paper. Recurrence quantification analysis is proposed for residual evaluation in order to have the comprehensive methodology of neural model-based fault detection. The preliminary verification of the elaborated methodology in modelling tasks was carried out for both simulation and industrial data. The fundamental verification was conducted for the data made available within DAMADICS benchmark problem. The achieved results confirm the effectiveness of the proposed approach.

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1. Introduction

Recent technical matters are more and more complex, heterogeneous, dynamic, and of various forms. Industrial systems such as chemical and oil refineries, nuclear power and thermal power plants, aircrafts and many others are composed of dedicated hardware and software parts. These components are often quite complex, thus increasing their potential for failures. When any failure occurs, then the standard solution is to stop a plant, and employ a servicing personnel for repairing every faulty component in the object. Therefore, the problems of reliability, maintainability, survivability of technical matters and especially their ability of fault tolerance have become a major concern in the last years. Effectively detecting and adapting to software and hardware faults allow the system to continue working until repairs can be realistically scheduled. Currently, it is known to be one of the most important issues in advanced control system design and analysis (Blanke et al., 2006; Caccavale and Villani, 2003; Isermann, 2006; Korbicz et al., 2004; Patton et al., 2000).

Fault tolerance in dynamic systems is traditionally achieved using hardware redundancy. This technique is rather straightforward to apply, and it is essential in the control of aircrafts, space vehicles and critical process plants. The most important problems encountered with this approach are an additional cost of the redundant hardware, weight increase, additional space required to accommodate the equipments and usually additional sources of energy such as batteries. On the other hand, analytical or information redundancy is a practical alternative to the previous one and can be really used in fault-tolerant control architectures. The main advantage of this technique is that it improves the capability of fault tolerance by adding fewer extra components and increasing computation power (Korbicz et al., 2004; Patton et al., 2000). The general schematic arrangement appropriate to many active fault tolerant systems has four main components: the system itself (including sensors and actuators), the fault diagnosis unit, the controller and the supervision system (with the control reconfiguration mechanism). Fault diagnosis using analytical or information redundancy is one of the most popular approach in the domain of the process diagnostics. Model-based fault diagnosis makes use of quantitative and/or qualitative models of the supervised object in order to detect, isolate and identify faults affecting its components. Real-time fault diagnosis systems usually realize each of these three tasks independently. The typical fault diagnosis scheme in practical applications is rather impossible to achieve. Therefore, fault detection

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and isolation is sufficient for designing fault-tolerant control systems (Blanke et al., 2006; Korbicz et al., 2004). Fault detection is an absolute must for any practical systems. Furthermore, a fault has to be detected as fast as possible, even it is tolerable at its early stage, in order to avoid more serious consequences.

In recent years, artificial neural networks, especially recurrent ones have attracted considerable research interest in the fields of model-based control and diagnostic systems. On the one hand, results and data from industrial applications confirm human safety and economic efficiency of such approaches, but on the other hand, there is still the need to elaborate much more general neural models that might be used for modelling both deterministic and stochastic processes simultaneously. Recurrent neural networks are a class of parametric, nonlinear dynamic models that have found widespread use in fault diagnosis and fault-tolerant control systems, including identification of dynamic systems and modelling problems (Korbicz et al., 2004). In general, recurrent neural networks can be viewed as universal approximators for spatiotemporal data (Gupta et al., 2003; Patan, 2008a). They can be classified into two categories (Korbicz et al., 2004; Patan, 2008b): globally (totally or partially) recurrent and locally recurrent networks. In the first class, there are structures with feedback connections between simple static neurons of different layers or/and these of the same layer. The second one encompasses neural structures similar to static feed-forward topologies, however they include dynamic neural units with internal feedback connections. The locally recurrent architecture is basically obtained by introducing dynamic elementary processors into the structure of a feed forward network (Korbicz et al., 2004; Patan et al., 2008). Numerous examples of the most important strategies for developing dynamic units and locally recurrent topologies and their applications in areas of fault diagnosis can be found e.g. in the papers (Ayoubi, 1994; Korbicz, 2006; Korbicz et al., 2004; Patan, 2008a; Patan et al., 2008) and monograph (Patan, 2008b).

Taking into account the current state of the art in the field of neural model-based fault detection it was stated that it was necessary to develop more advanced neural modelling methods in order to reduce uncertainties caused by various sources. On the other hand, it is well known that it is impossible to entirely eliminate such origins of uncertainties as measuring noise, unknown disturbances and modelling errors. Therefore, there is also the need to elaborate robust fault detection methods by enhancing the robustness of the decision making block. These considerations were the basis for the hypothesis that the proposed methodology for neural modelling of dynamic systems with the use of some parts of the chaos theory, allows creating efficient fault detection systems, to be robust enough to disturbances and modelling errors.

Chaos together with the theory of relativity and quantum mechanics is considered as one of the three monumental discoveries of the twentieth century. In turn, Zadeh (1994) indicates chaos theory as one of the principal constituent of soft computing. There are a lot of areas where chaos engineering is successfully applied, such as medical diagnostics (West, 1990), control systems (Fradkov and Evans, 2005), communication systems (Stavroulakis, 2005), mechanical systems (Moon, 2004), and many others. Moreover, chaos engineering contributes to develop various prototypes of everyday devices (such as washing machines, heaters, and microwaves) raising their efficiency and reliability (Hirota, 1995; Moon, 2004). Theoretical and experimental studies on applications of chaos engineering in technical diagnostics can be divided into two groups: passive and active approaches. The first group of methods makes full use of nonlinear data analysis, that is fractal analysis, recurrence quantification analysis, and others (Boguś and Merkisz, 2005; Bi-qiang Du et al., 2008; Nichols et al., 2006; Tykierko, 2008), whereas the second one depends on using chaotic systems in direct way (Li and Qu, 2007; Song et al., 2009).

The rest of the paper is organized as follows. In Section 2 the detailed description of the proposed approach is given. In particular, there are contained investigations on a locally recurrent neural network as a tool for modelling purposes and biphasic hybrid algorithms that are used for tuning adjustable network parameters. This section includes also a formal description of two procedures proposed for architecture selection as well as the method which is based on recurrence quantification analysis of residual signals that is suggested to robust fault detection. Section 3 contains the results of verification experiments, and the last section is devoted to concluding remarks.

2. Neural model-based fault detection using chaos engineering

The proposed methodology can be viewed as the extension of the most often used model-based fault detection approach, where a neural model is created for faultless state of the system, cf. Korbicz et al. (2004), Fig. 1. 6 at p. 22, or Chapter 9 at pp. 333–379. The novelty in this study is the use of chaos theory in the development of fundamental parts of such fault detection architecture. This means that chaos engineering is employed to advance artificial neural networks and decision blocks of model-based fault detection schemes. The application of chaos theory in this matter is well founded because of two facts. Firstly, neural models with chaotic neurons are able to be much more sensitive to abrupt as well as incipient faults (chaotic systems are very sensitive to even small changes in the initial conditions). Secondly, advanced nonlinear time series analysis methods developed in the background of chaos theory can be used in residual evaluation process. It is reasonable due to the fact that such analysis techniques were elaborated to better understand phenomena related to chaotic systems (in our case residual signal is generated by using chaotic neural network). The proposed scheme of fault detection is presented in Fig. 1. There are two main parts: a neural model of the system for residual generation and a decision block for residual evaluation.

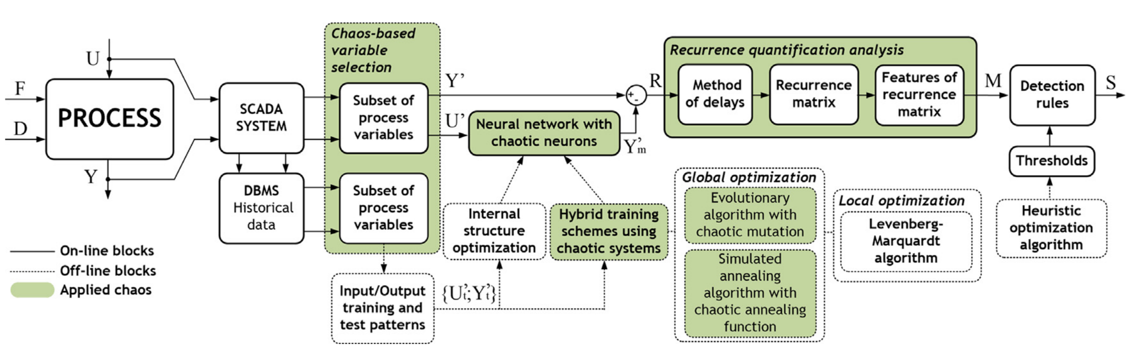

Fig. 1. A data flow diagram of neural model-based fault detection using chaos engineering.

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