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An anti-jamming artificial immune approach for energy leakage diagnosis in parallel-machine job shops

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ABSTRACT

Energy leakages lead to enormous economic losses and environmental pollution for many manufacturing systems. Thus, energy leakage diagnosis becomes an essential requirement for an economical and environment-friendly production. However, for parallel-machine job shops, it is still a challenge to isolate leaking machines from a jamming environment with limited energy measurements, stochastic parallel jobs, and a fluctuating energy supply. To address this challenge, an anti-jamming artificial immune approach that combines the *danger model* with an immune network is proposed in this study. The proposed approach involves strategies, namely a danger-model-inspired framework, an anti-jamming antigen feature, and an anti-jamming *aiNet* (*AJ-aiNet*) algorithm, which are specifically dedicated to overcome the jamming factors. The danger-model-inspired framework realizes the collaboration between danger (energy loss) detection at shop level and antigen (process behaviour) isolation at machine level. The anti-jamming antigen feature, called the difference in process behaviour fluctuation (DPBF), acquires characteristics that are sensitive to energy leakage from the process parameter time series. Antibody ageing and antigen killing strategies are embodied within *aiNet* to mitigate the disturbance of jamming antigens between leaking and normal clusters. In order to evaluate the proposed approach, several experiments were performed in a tyre vulcanization shop floor to diagnose the steam leakage of steam traps. The results show that the proposed approach achieved the isolation of leaking machines without energy consumption measurements at the machine level. As anti-jamming strategies, DPBF can separate leaking and normal process behaviours effectively, *AJ-aiNet* can achieve clustering of DPBF samples with jamming antigens correctly, and the collaboration of danger detection can significantly suppress false diagnoses and improve the time efficiency of diagnosis.

1. Introduction

With the increasing level of complexity and automation in manufacturing processes, manufacturers need more effective and efficient techniques to monitor the operation status and diagnose process faults of machines to enable a sustainable, economical, and environment-friendly production [1–3]. Energy leakage, such as steam, compressed air, and cool air leakage from broken pipelines or worn valves, is a typical fault in job shops with high-energy consumption. This fault tends to cause enormous economic losses and environmental pollution [4–6], and hence, its diagnosis becomes an essential requirement for an economical and environment-friendly production.

Energy leakage diagnosis is a combination of fault detection (which identifies if there is an energy leakage) and isolation (which determines the location of the energy leakage) [7]. Owing to the complexity of the industrial environment, energy leakage diagnosis is a very challenging activity. Bayar et al. [1] and Wang et al. [8] pointed out that in order to develop a fault diagnosis system, several limitations (e.g. data acquisition and processing, tolerances and sensitivity to change, and alarm frequency and quality) should be considered. For energy leakage diagnosis in many industrial environments, energy consumption is measured at the shop/group level rather than at the machine level owing to the issues of technology, such as too small branch pipe, too narrow installation space, strong vibration of machine, etc. The limited energy measurements increase the difficulty in isolating the leaking machines. Moreover, stochastic parallel jobs with multi-process and random operation rhythm reduce the sensitivity of energy consumption to energy leakage. Furthermore, the fluctuating energy supply and environmental dynamics confuse the fluctuation of process parameters caused by energy leakage. In particular, for parallel-machine job shops, independent

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machines and parallel jobs make energy leakage isolation more complicated. Therefore, for parallel-machine job shops, an energy leakage diagnosis approach needs to overcome a jamming environment with limited energy measurements, stochastic parallel jobs, and a fluctuating energy supply.

In recent years, many approaches for energy leakage diagnosis have been presented based on fluid mechanics. These approaches, such as pressure-based diagnosis [9–11], negative-pressure-wave-based diagnosis [12], electromagnetic-wave-based diagnosis [13], or hybrid techniques [14], focus more on identifying a disruption or mutation of parameters in energy transmission pipelines with regular topology and stable flow, rather than on isolating a potential leaking machine from a jamming industrial environment. These approaches are not suitable for energy leakage diagnosis in parallel-machine job shops because they ignore the fluctuating energy supply, environmental dynamics, and limited data acquisition.

In addition, based on energy consumption mechanisms, various energy consumption models were proposed to diagnose energy leakage. Duflou et al. [15] proposed an organizational energy consumption model including five levels: device/unit process, line/cell/multi-machine system, facility, multi-factory system, and enterprise/global supply chain. Rahimifard et al. [16], Wang et al. [17], and Li et al. [18] proposed productive energy consumption models including three levels: process, product, and production. Bi and Wang [19] and Pfefferkorn et al. [20] suggested technological energy consumption models including three levels: theoretical, technical, and real. The energy leakage diagnosis approaches based on these models focused on evaluating energy consumption baselines at different levels. The authors [21,22] suggested to build energy consumption baselines from historical data using artificial neural networks [23] and support vector machines [24], or to evaluate leakage risks from energy balances and mass balances [25,26]. However, the authors found that these approaches have two deficiencies in real applications. First, the feasibility of isolating leaking machines is heavily dependent on energy measurements at the machine level. Second, the false alarm rate is high owing to the insensitivity of energy consumption caused by stochastic parallel jobs.

Biological immunity inspired the design of promising approaches for fault diagnosis in manufacturing fields [1,27–29]. These approaches focused on designing conceptual frameworks for fault diagnosis with the inspiration from immune mechanisms (e.g. collaboration, pattern recognition, learning, and memory) [28,30,31], or on suggesting artificial immune algorithms for a specific machine or system fault diagnosis [32–35]. However, only few immune approaches for hidden faults such as energy leakage or dealing with a jamming environment are found.

Therefore, for parallel-machine job shops, it is still a challenge to isolate leaking machines from a jamming environment with limited energy measurements, stochastic parallel jobs, and a fluctuating energy supply. In this study, three hypotheses are under consideration. First, an energy leakage is associated with individual machine in a parallel-machine job shop. Second, energy consumption at shop/group level and process parameters at machine level can be acquirable. Third, energy leakage can't be accurately isolated by analysing jammed process parameters. Thereafter, an anti-jamming artificial immune approach (*AJAI approach*) that combined the danger model with an immune network is proposed. The main contributions of this paper rely on three main suggestions to overcome the jamming environment: a danger-model-inspired framework, an anti-jamming antigen feature, and an anti-jamming *aiNet* (*AJ-aiNet*) algorithm. The danger-model-inspired framework realizes the collaboration between danger (energy loss) detection at the shop level and antigen (process behaviour) isolation at the machine level. This dual activation strategy aims to suppress false alarm rates caused by the jamming environment. An anti-jamming antigen feature, called the difference in process behaviour fluctuation, is presented to enhance the separability between leaking and normal process behaviours. Antibody ageing and antigen killing strategies are embodied within *aiNet* to mitigate the disturbance of jamming antigens between leaking and normal clusters.

The paper is organized as follows. Section 2 overviews the main principles and applications of the danger model and artificial immune network. The proposed approach is presented in Section 3. The computer-based implementation is presented in Section 4. Section 5 introduces an application case. The experiments and results are described in Section 6. The advantages and limitations of the proposed approach are discussed in Section 7, and the conclusions drawn are presented in Section 8.

2. Danger model and artificial immune network

The proposed approach is inspired from the danger model and artificial immune network. In this section, the principles and applications related to these two immunity concepts are overviewed.

2.1. Danger model

Before the proposal of the danger model, immunologists focused their thoughts and applications on the functions of the immune system by making a distinction between self and non-self (SNS model) [36,37]. However, this paradigm has failed to explain problems associated with self-change. The danger model proposed by Matzinger [38–40] outlines a model of immunity based on the idea that the immune system is more concerned with entities that do damage than with those that are foreign.

One of the important affirmations of the danger model is that the

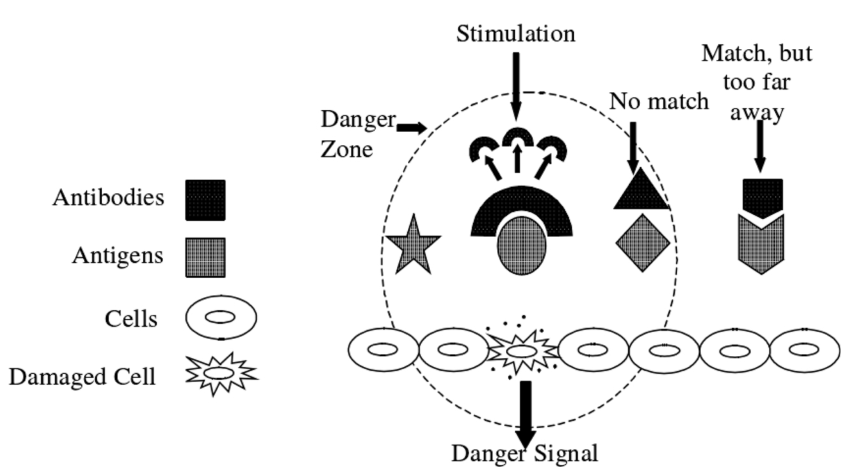

Fig. 1. Diagram of danger model [29].