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Optimal design of linear sensor networks for process plants: A multi-objective ant colony optimization approach

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ABSTRACT

This investigation is performed to study nonredundant linear sensor network design problems that simultaneously optimize three objectives, namely cost, precision and reliability. In this article, a novel ant colony algorithm is proposed to efficiently tackle this multi-objective combinatorial problem. Both heuristic information and phenomenon are described as multiple matrices and a dynamic random weighted strategy is introduced to compute selection probability. A linear independent relationship is presented to guide a feasible solution construction process. An external archive is used to improve the convergence speed. Moreover, the TOPSIS method is adopted to aid in multi-criteria decision making with respect to Pareto-optimal solutions. The proposed method is successfully applied to a multi-objective design problem of a steam metering network of a methanol production plant. The results illustrate that the proposed method could find a set of global Pareto-optimal solutions, which is helpful for understanding the relationship among cost, precision and reliability, and consequently is helpful for final decision support. Therefore, the integrated methodology of a multi-objective ant colony algorithm and a multi-criteria decision making technique provides a promising tool for the optimal design of sensor networks by simultaneously considering multiple conflicting objectives.

1. Introduction

Economic realities, process safety and product quality have created an ever-increasing demand to obtain accurate and reliable data acquisition systems. Without careful optimal selection of the measuring variables, the process behavior is hardly understandable, which in turn deteriorates the performance of any monitoring, control or real-time optimization system, and finally the performance of process plants. In the last two decades, the problem of optimally locating sensors in process plants, known as sensor network design problem (SNDP), has gained lots of attention from both academia and the industrial community.

Based on different purposes, prior works on the sensor network design problem (SNDP) can be roughly divided into two classes: [1] one is for a process monitoring purpose, and the other is for a process fault detection and identification purpose. Different criteria, such as cost, observability, reliability and precision, are addressed in the optimal selection of sensors. However, the most common objective of SNDP is minimizing sensor cost with a certain number of pre-specific performance requirements on observability, reliability and precision. In any case, SNDP can be transformed into a combinatorial optimization problem subjected to constraints. Both deterministic and stochastic approaches have been adopted to tackle SNDP. Madron and Veverka [2] proposed a multiple Gauss–Jordan elimination approach to obtain the minimum-cost linear sensor network with a requirement on the observability of key variables. Ali and Narasimhan [3,4] proposed a graph-theoretic algorithm for the optimal design of a nonredundant sensor network for both linear and bilinear processes that maximize system reliability. Moreover, these authors extended that procedure for the optimal design of a redundant sensor network [5]. Gala and Bagajewicz [6] presented a cutset-based tree enumeration search method for the optimal design of a sensor network for linear systems. In the subsequent paper, [7] a more efficient graph decomposition technique was developed instead of the tree enumeration method. Nguyen and Bagajewicz [8] have extended the cutset-based methods to the nonlinear sensor network problem by introducing an equation-based variable elimination technique. However, this approach fails to perform well in realistic large-scale nonlinear problems [9]. Recently, a new efficient breadth-first/level traversal tree search method was proposed by Nguyen and Bagajewicz [9] for the design and upgrade of nonlinear sensor networks, which showed a considerably computational time reduction by comparing with a depth-first strategy.

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Raghuraj et al. [10] and Bhushan and Rengaswamy [11–13] studied sensor network design problems for fault diagnosis criteria. Raghuraj et al. [10] introduced a direct graph-based approach for the problem of sensor location for the identification of faults, where various graph algorithms that used the developed digraph in deciding the location of sensors based on the concepts of observability and resolution were investigated. Bhushan and Rengaswamy [11] extended to use the signed directed graph representation of the process instead of directed graph [10]. Later, Bhushan and Rengaswamy [12,13] have extended to the sensor network design problem by considering maximization of reliability. Most recently, Bhushan et al. [14] proposed a framework for designing a robust sensor network for reliable process fault diagnosis. Then, the problem was solved by Kotecha et al. [15,16] using a constraint programming approach, where different optimization criteria, such as cost, robustness, reliability and unobservability, were investigated.

Apart from the above deterministic approaches, stochastic approaches were proposed to solve SNDP. Sen et al. [17] presented a graph-based genetic algorithm to optimize a single criterion of cost, reliability or estimation accuracy, for linear nonredundant sensor networks. Carnero et al. [18] proposed an evolutionary approach for the multi-objective design of nonredundant linear sensor networks. In a subsequent paper, [19] the evolutionary technique was modified to tackle the optimal design of a sensor network subject to quality constraints on a set of key variable estimates. Heyen et al. [20] presented a genetic algorithm to solve cost-optimal SNDP with a required precision for redundant nonlinear sensor networks.

Most of the aforementioned works were applied to a single objective sensor network design problem. Few published works were focused on the multi-objective sensor network design problem. One such effort was presented by Bagajewicz and Cabrera [21] who investigated two Pareto optimal solution visualization methodologies for the multi-objective design and upgrade of sensor networks, enabling the decision maker to see several candidate solutions for the network configuration and narrow down the number of candidates to satisfy the decision maker's specifications. Carnero et al. [18] and Viswanath and Narasimhan [22] proposed a multi-objective genetic algorithm for the optimal design of sensor networks. Kotecha et al. [15] adopted a constraint programming approach to the determination of multiple solutions with an explicit knowledge of the precedence in objective functions, and also the determination of the Pareto optimal front in the absence of an explicit precedence ordering. Most recently, Nguyen and Bagajewicz [1] have systematically investigated value-optimal SNDP for balancing the trade-off between cost and performance, where the performance of the sensor network was characterized and quantified as an economic indicator and then the difference between the economic indicator and cost of the sensor network was maximized. However, the multi-objective sensor network design problem appears to be relatively poorly investigated, especially for the development of an efficient method to obtain well distributed Pareto optimal solutions, and should be further explored.

Ant colony algorithm [23,24] is a kind of stochastic algorithm and has been successfully applied to solve many combinatorial optimization problems, such as the traveling salesman problem [24,25], sequential ordering problem [26], scheduling problem [27], network routing problem [28], pattern classification [29,30], etc. Great achievements of the ant colony algorithm have attracted lots of attention from different disciplinary researchers, and its application fields have been expanded from combinatorial optimization to continuous optimization problems [31], single-objective problems to multi-objective problems [32], static problems to dynamic problems [33], etc. However, to our knowledge, studies about the application of the ant colony algorithm in sensor network design and retrofit problems for process plants are rare. In addition, systematical studies of multi-objective sensor network design are also rarely investigated [1,15,18,21,22], especially for the development of high-performance SNDP-specified multi-objective combinatorial optimization method. In this work, a new multi-objective ant colony algorithm for the optimal design of linear sensor networks is presented. Three sensor network characteristic objectives, i.e. cost, reliability and overall precision, have been simultaneously optimized. It should be noted that the scope of this work is limited to the design of a non-redundant linear sensor network, but giving a systematical multi-objective solution approach.

This paper is structured as follows. In Section 2.1, the mathematical formulation of the multi-objective design of linear sensor networks is briefly introduced. A detailed implementation of the multi-objective ant colony optimization algorithm for simultaneously solving a multi-objective sensor network design problem is proposed in Section 2.2. Section 3 presents the results for an industrial steam metering network. Conclusions and future research directions are addressed in Section 4.

2. Methodology

2.1. Problem description

Assume that the mass balance equations of a steady-state process can be represented as follows:

$$\boldsymbol{Dz} = \boldsymbol{Ax} + \boldsymbol{Bu} = 0 \tag{1}$$

where $\boldsymbol{D}$ is the $m \times n$ incidence matrix; $\boldsymbol{z}$ is the n-dimensional vector of flow rates; $\boldsymbol{x}$ and $\boldsymbol{u}$ are the vector of measured and unmeasured variables, respectively; and $\boldsymbol{A}$ and $\boldsymbol{B}$ are the compatible submatrices of $\boldsymbol{D}$. For an observable measurement system, the unmeasured variables can be computed from Eq. (1) given the measured variables.

The sensor network design problem can be viewed as the optimal partition of the flow rate variables, namely optimal selection of a set of $n–m$ variables, with respect to several optimization objectives. It is noted that optimal sensor network design should guarantee the observability of all unmeasured variables, where matrix $\boldsymbol{B}$ should have full rank. The sensor network design problem is a combinatorial optimization problem involving binary variables. The general mathematical formulation of the multi-objective sensor network design problem is as follows:

$$\begin{aligned} &\min \boldsymbol{F}(\boldsymbol{q}) = [f_1(\boldsymbol{q}), f_2(\boldsymbol{q}), \cdots, f_O(\boldsymbol{q})]^T \\ &s.t.\ \ rank(\boldsymbol{B}(\boldsymbol{q})) = m \\ &q_i \in \{0,1\} \quad i = 1, \cdots, n \end{aligned} \tag{2}$$

where $\boldsymbol{q}$ denotes a n-dimensional binary vector such that $q_i = 1$ if the process variable i is measured and $q_i = 0$ otherwise; $\boldsymbol{F}$ is the O-dimensional objective function vector; $f_o(\boldsymbol{q})$ indicates the oth objective function.

Cost, precision and reliability are commonly used metrics for measuring a sensor network performance. Let c_i, σ_i and p_i be the cost, standard deviation of error and failure probability of the sensor for measuring the flow of stream i, respectively. The total cost of a non-redundant sensor network is given by

$$\text{Cost} = \sum_{i=1}^{n} c_i q_i. \tag{3}$$

The sensor network reliability, defined by Maquin et al. [34] as the probability of estimating all variables, is shown as

$$R_s = \prod_{i=1}^{n} [r_i q_i + (1 - q_i)] \tag{4}$$

where $r_i = [1 - p_i]$ denotes the reliability of sensor i. It should be noted that the above reliability measure is designed for a non-redundant sensor network, where even if one senor fails, some flow variables