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An Algorithm of Minimal Sensor Placement Using for Safety Monitoring and Controlling System

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Abstract: The problem of the sensor placement is an important studying direction in the study of the safety monitoring and controlling system to excogitating how to reach the maximal performance of the detecting and monitoring net of the sensor based on the minimal cost, in which the basic studying content is the problem of the minimal sensor placement. An algorithm of the minimal sensor placement is put forward based on a kind of quantitative model using for the description of the complex system which can offer a sensor net with minimal freedoms of the complex system. The qualitative model is called directed graph has the ability to describe the deep influence relations in the complex system which is used as the model to describe the monitored system. The procedures of the algorithm based on the directed graph is described in detail which is a basis to study the optimal placement based on the different performance target such as the reliability, the economics, etc. to help achieving better effect of the safety monitoring and controlling system. A case study is provided to proving the validity and the easiness to understand about the algorithm.

Key words: Minimal sensor placement, safety monitoring and controlling system, quantitative directed graph

INTRODUCTION

It has become the prominent characteristics about the modern production process that the complexity and diversity and the safety production can not persist without the advanced safety monitoring and controlling system increasingly. The safety monitoring and controlling system should include manifold contents (Lu, 1997), such as: signal detection and measurement, fault diagnosis, information procession and decision exporting, etc.

In the safety monitoring and controlling system, it is often necessary to detecting and measuring a given parameter of the monitored system from the different positions with different sensors which is correlative to the safety index. It should be lucubrated about the overall arrangement, selection and manufacture of the equipments for detecting and monitoring such as the detectors, the sensors, etc. The sensor location problem has a multitude of applications, such as online process situation monitoring, fault detection and diagnosis, etc. (Madron and Veverka, 1992; Kotecha *et al*., 2007). A naïve solution should be to place a maximum of sensors on the plant but, in addition to the important extra-cost due to this instrumentation, an afflux of non-pertinent information should be detrimental for the operator to easily assess the situation. It has multifarious parameters monitored in a complex production processing which also has multifarious types and forms to selecting manifold sensors. It is a significative problem to excogitating how to reach the maximal performance of the detecting and monitoring net of the sensor based on the minimal cost and the basic studying content is the problem of the minimal sensor placement. The traditional placement of the sensors can not be elaborated by the scientific research and analysis which is always placed by the experience and the parameters monitored are always those weightily relevant to the techniques and those used for measure. The problem of the minimal sensor placement is essentially a coverage problem, place sensors in a service area so that the entire process is covered and all the necessary variables can be observed or be deduced by those observable variables. Current optimization approaches to sensor placement include heuristics, genetic algorithm, dynamic programming and diffusion boundary methods, etc., Quintao *et al*. (2004) used a genetic algorithm methodology to solve on-demand coverage problem. They formulated the coverage problem as finding a minimal set of active sensors from a prior set of placed sensors; however, the algorithm has to focus on how to determine the initial set of sensors that would best cover the overall process.

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In this study, an algorithm of the minimal sensor placement is brought forward based on a qualitative process modeling. The qualitative process modeling based on Directed Graph (DG) is used to simulate the system quantitative behavior based on the resolution of energy and mass balances, thermodynamic equilibrium equations, etc. Once the DG model is established, it means that the numbers of maximal sensors observing the whole variables of the process has been determined. And the problem is became to an optimization problem how to remove those variables that can be deduced from the other variables, so as to ensure that all the variables in the process can be observed directly or indirectly.

THEORETICAL FOUNDATIONS OF DG AND MODELING

Qualitative modeling concerns the construction of knowledge models that capture insights domain experts have of the structure of systems and their behavior which deals with symbolic representations of continuous properties of physical systems and have been presented as a promising approach for conceptual modeling (Bredeweg *et al*., 2006). Qualitative modeling has been used in solving process problems by simulation (Feray *et al*., 1991), in process analysis (Chung, 1993), fault diagnosis (Gujima *et al*., 1993; Venkatasubramanian and Rich, 1988), in explanation of measurement, safety engineering, optimization and operation decision support (Hurme *et al*., 1994).

Directed Graph (DG) is one branch of the graph theory. A DG model is this kind of qualitative model which can obtain potential information of the system on a large scale. A set of descriptions accepted widely for DG is presented here (Venkatasubramanian and Rich, 1988),. The DG model $\gamma = (G, \varphi)$ is a combination of a directed graph G and a function φ. The directed graph G is composed of four portions, $G = (V, E, \delta^+, \delta^-)$, where the nodes set is $V = \{v_i\}(i = 1, 2, \ldots, m)$; the branches set is $E = \{e_k\}(k = 1, 2, \ldots, n)$; the initial node of a branch is δ^+: $E \rightarrow V$; and the terminal node of a branch is δ^-: $E \rightarrow V$; δ^+ and δ^- is called adjacent associative sign which represents the initial node $\delta^+ e_k$ and the terminal node $\delta^- e_k$ of each branch. The function φ: $E>\{+, -\}$, $\varphi(e_k) = \varphi(v_i, v_j)(e_k = (v_i, v_j) \rightarrow E)$ is the sign of the branch e_k. A DG model is composed of several nodes and branches, shown in Fig. 1a. Each node denotes variables in the system and the directed branches denote the relationships between the nodes. If the variation of one node can result directly in the variation of another node, a directed branch will be drawn between these two nodes, from the upstream node (cause variable) to the downstream node (consequence variable).

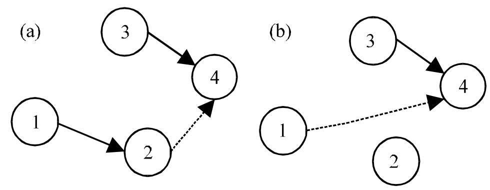

Fig. 1(a-b): Directed graph model (a) A sample directed graph model and (b) A simplified directed graph model of (a)

Two kinds of relationships can exist between any two joined nodes, namely positive influence relation and negative influence relation. For example, consider the branch from the node 1 to the node 2 in the Fig. 1a. If an increase of the value of the node 1 increases that of the node 2, there is a positive influence relation from the node 1-2 and the sign of the branch from the node 1-2 is "+" which is described as a solid line with arrow in the DG model. In contrast, if an increase of the value of the node 1 decreases the value of the node 2, there is a negative influence relation from the node 1-2 and the sign of the branch from the node 1-2 is "-" which is described as a dotted line with arrow. The influence relation along the branch's direction is the relation that the cause node points to the consequence node and the influence relation is certain. If the influence relation is reverse to the branch's direction that is the consequence node points to the cause node, the influence relation is uncertain. Figure 1a, from the node 4-3 is reverse to the branch's direction which is the consequence node points to the cause node and is an uncertain relation that is, it cannot be deduced if the node 4 increases, the node 3 will certainly increases. If and only if the node 1 influences the node 2 and the node 2 influences the node 4, at the same time, the influence relation is along to the branch's direction, then it can be simplified the node 1 influence and only influence the node 4 and the influence relation is along to the directed branch's direction, the sign of the branch is the product of that of those merged branches, shown as Fig. 1b.

The DG model can be built by analyzing the process. There are three main methods for modeling a DG model which are method based on mathematical equations, method based on physical model (Maurya *et al*., 2004) and method based on experience aand knowledge (Zhang *et al*., 2005). A synthesized method has been proposed by the author's research group. The recommended procedure follows as: divide the system by the pipe and instrument diagram, select process variable element, list relationship equation, attach external influence node such as equipment node, import link node

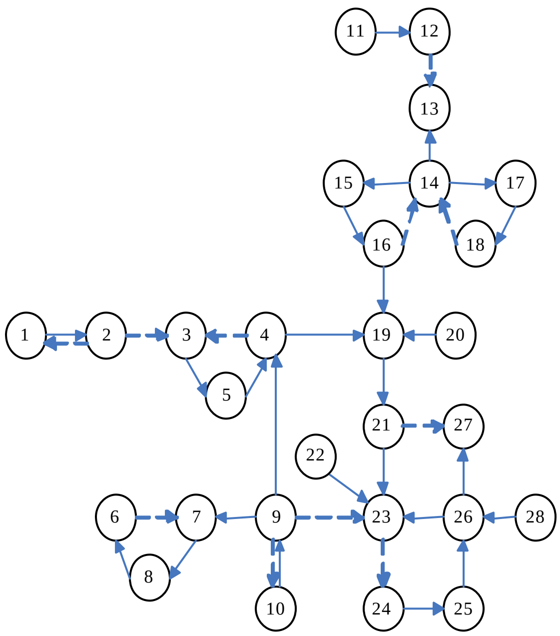

Fig. 2: The DG model of rectifying tower

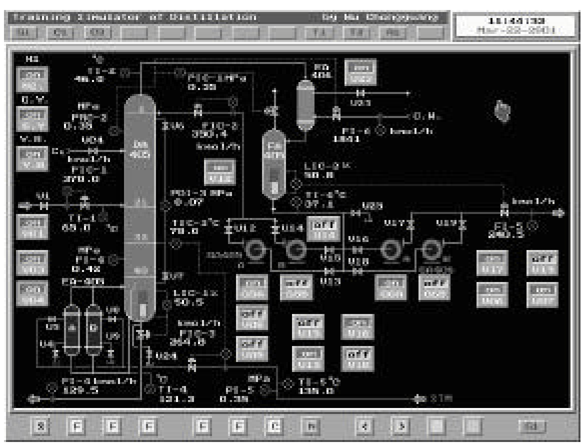

Fig. 3: The process flow of rectifying tower

and do some modification at the end. Following these procedures, a DG model of rectifying tower is built as Fig. 2 and the simulating process flow is shown in Fig. 3 (Wu, 1999). The rectifying tower is designed to separate the butane from the propane which is produced from the top. A condenser and a reflux's tank are allocated beside the top which supply some of the production as reflux and a reboiler is allocated beside the bottom.

The physics meanings of every node are shown in Table 1.

Table 1: The physics meanings of every node

Node's No.	The physics meaning
1	Regulating valve of the reflux
2	Quantity of the top reflux
3	Level of the top reflux's tank
4	Top produced flow
5	Regulating valve of the top produced flow
6	Bottom produced flow
7	Level of the bottom
8	Regulating valve of the bottom produced flow
9	Inlet flow
10	Regulating valve of the inlet flow
11	Steam pressure
12	Pressure of the bottom
13	Pressure difference between the top and the bottom
14	Pressure of the top
15	Regulating valve of the cooling water
16	Flow of the cooling water
17	Regulating valve of the flow to the flare header
18	Flow to the flare header
19	Temperature of the reflux
20	Inlet temperature of the cooling water
21	Temperature of the top
22	Inlet temperature
23	Temperature of the sensitive plate
24	Regulating valve of the reboiler's steam
25	Steam flow of the reboiler
26	Temperature of the bottom
27	Temperature difference between the top and the bottom
28	Temperature of the steam

ALGORITHM OF MINIMAL SENSORS PLACEMENT BASED ON DG MODEL

Characteristic classification of the node: The nodes and the branches in the DG model have four basis relations:

- **Single in node (SI node):** The node is a downstream node only. There is one and only one branch pointing to the node but there is not a branch coming out from the node and pointing to the other nodes, such as the Fig. 4a
- **Single out node (SO node):** The node is an upstream node only. There is one and only one branch coming out from the node and pointing to another node but there is not a branch pointing to the node, such as the Fig. 4b
- **Multi in node (MI node):** The node is a downstream node only. There are some branches pointing to the node but there is not any branches coming out from the node and pointing to the other nodes, such as the Fig. 4c
- **multi out node (MO node):** The node is an upstream only. There are some branches coming out from the node and pointing to the other nodes but there is not any branches pointing to the node, such as the Fig. 4d

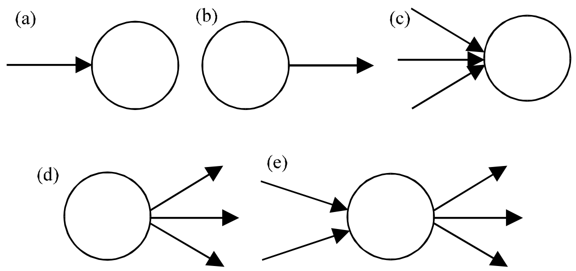

Fig. 4(a-e): Several relations between the nodes and the branches (a) SI node, (b) SO node, (c) MI node, (d) MO node and (e) I and O mode

The four basic relations can generate three combinations:

- **only in node (OI node):** The node is a SI Node or a MI node
- **only out node (OO node):** The node is a SO Node or a MO node
- **in and out node (I and O node):** The node is not any of the four basic relations which is an upstream node and a downstream node at the same time. There are one or several branches pointing to the node and there are one or several branches coming out from the node and pointing to the other nodes, such as the Fig. 4e

The OO node must be selected as original observed node that is such nodes must be set sensors. Because the influence relation reversing to the branch's direction uncertain which is the consequence node pointing to the cause node. The OI node can be deleted directly for that it can be derived from residual nodes in the DG model; the influence relation along to the branch's direction is from the cause node to the consequence node that is certain.

If there is only one branch pointing to the I and O node and only one branch coming out from the I and O node to point to the other node, the I and O node can be merged along to the branch's direction. If there is single circle structure in the DG model after merging, such as the relation between the node 1 and the node 2 in Fig. 5, the sensor can be located on any one of the two nodes. Otherwise, if there is double circle structure or even more, the sensor must be located on the common core node of these circle structures. In Fig. 5, there is a double circle structure, where the node 3 and the node 4 make up a single circle structure; the node 3 and the node 5 make up a single circle structure also, the sensor should be located on the node 3.

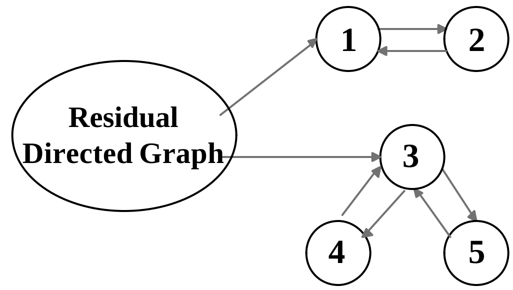

Fig. 5: Single circle structure and double circle structure

Procedures of the algorithm: The calculated procedures of minimal sensor placement are described as follows:

- Determining the original observed nodes. All of the OO nodes are determined as the original observed nodes. The set of these nodes is marked as OOS and called these nodes as the root nodes
- Constructing a set DS, where the nodes are that all nodes can be deduced from the root nodes in OOS. For one node, if those branches that point to it are fully come out from the root nodes, the node belongs to the set DS which can be treated as a known node. Furthermore, the nodes that its upstream nodes are fully in the set DS or OOS can be added in the set DS
- Determining the OI Nodes whose set is marked as OIS. Next procedure is that obtaining a new sub directed graph from the original directed graph by deleting all the nodes in the set OOS, DS and OIS and the branches between any of two deleted nodes
- Searching the nodes that there is only one branch pointed to it in the new sub directed graph, such as the node 2 in Fig. 1a. These nodes should be independent and called zero circle nodes. Deleting the branches pointing to it, a branch is drawn directly from the upstream node of the zero circle node to the downstream nodes of the node, such as the branch from the node 1 to the node 4 in Fig. 1b. All these zero circle nodes make up a set ZCS. Finally, the directed graph is consisted of zero circle nodes, single circle structure, double circle structure, multi circle structure and the nodes with multi branches pointing to it
- Searching the double circle structure and multi circle structure. If there are such structures, those common core nodes are added in the set OOS. The other nodes and the branches in the double or multi circle structures should be deleted. Those nodes used for deriving the double or multi circle structures in ZCS should be deleted correspondingly

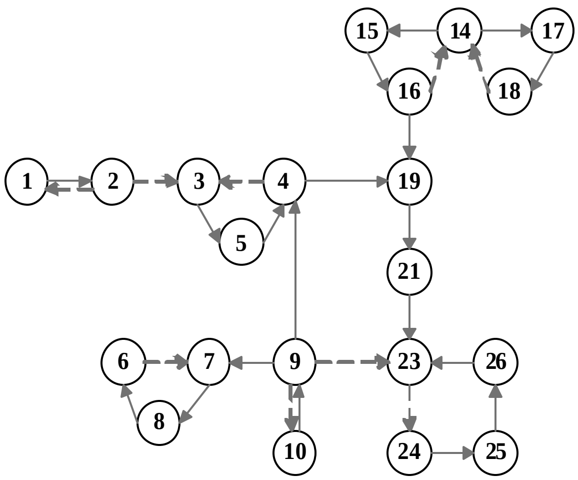

Fig. 6: The new sub directed graph of rectifying tower after simplified

- Repeating the Step 4 to delete the nodes in the set ZCS. If there are single circle structures occurring which have the same nodes with the single circle structures obtained in the Step 4, a substituting circle structure SCS can be constructed by the nodes in the set ZCS and the nodes in the single circle structures
- The minimal sensors that must be placed are that all the nodes in the set OOS and any one of the nodes in the structure SCS.

Case studies: The algorithm is used on the DG model of rectifying tower shown in the Fig. 2 to place the minimal sensors. The set OOS can be determined through the step 1, OOS = {11, 20, 22, 28}. The set DS = {12} which is determined by the step 2 and the set OIS = {13, 27} through the step 3. Deleting these nodes and corresponding branches and then, a new sub directed graph is obtained shown as the Fig. 6. After the step 4, the directed graph is arranged as the Fig. 7, where the node is in a circle structure or having multi branches pointing to it. The core node of the double circle structure is found as the node 14 and the corresponding nodes and branches are deleted. The directed graph treated after the step 5 is shown in the Fig. 8. The set OOS is updated as OOS = {11, 14, 20, 22, 28}. After the step 6, five substituting circle structures are found shown as the Fig. 9.

At the end, the sensors must be installed at those nodes in the set OOS and in each substituting circle structures, a sensor can be installed at any of the nodes in the given SCS. Thus, the set of the minimal sensors can be obtained.

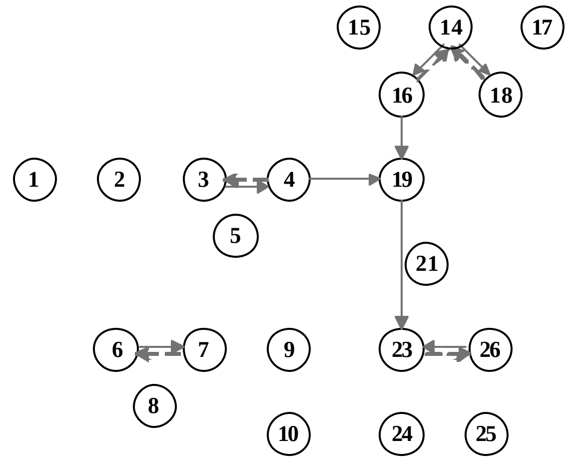

Fig. 7: The simplified directed graph after the step 4 executed

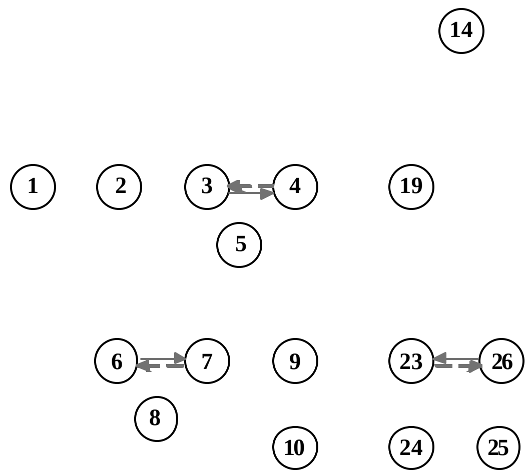

Fig. 8: The simplified directed graph after the step 5 executed

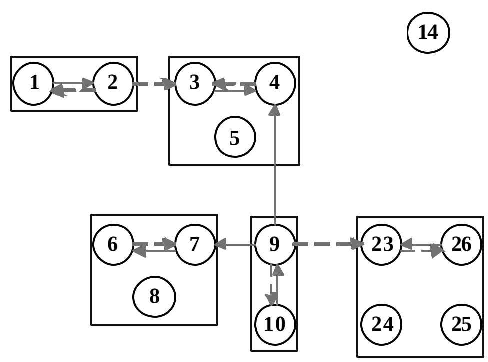

Fig. 9: The substituting circle structures in the directed graph after the step 6

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CONCLUSION

It is an important problem how to place sensors optimally to assistant the application of the safety monitoring and controlling system. In this study, an algorithm about the minimal sensors placement is put forward based on the quantitative directed graph which can offer a sensor net with minimal freedoms of the complex system. The characteristic of the directed graph is used in the algorithm skillfully to deal the problem of the minimal sensor placement with the merging and simplifying of the modes in a graph model. Furthermore, because the nodes in the given substituting circle structure can substitute each other, whose nodes represent different parameters that may be place cheap or expensive sensors according the condition of detection and transmission, the demand of monitor and control, etc. it will be studied following about the optimal placement based on the different performance target such as the reliability, the economics, etc. to help achieving better effect of the safety monitoring and controlling system.

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