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An Integrated Diagnostic System Based on the Cooperative Problem Solving of Multi-Agents: Design and Implementation

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Abstract – Enhanced methodologies for process diagnosis and abnormal situation management have been developed for the last two decades. However, there is no single method that always shows better performance over all kinds of diagnostic problems. In this paper, a framework of message-passing, cooperative, intelligent diagnostic agents is presented for improved on-line fault diagnosis through cooperative problem solving of different expertise. A group of diagnostic agents in charge of different process functional perform local diagnoses in parallel; exchange related information with other diagnostic agents; and cooperatively solve the global diagnostic problem of the whole process plant or business units just like human experts would do. For their better understanding, sharing and exchanging of process knowledge and information, we also suggest a way of remodeling processes and protocols, taking into account semantic abstracts of process information and data. The benefits of the suggested multi-agents-based approach are demonstrated by the implementations for solving the diagnostic problems of various chemical processes.

Key words : Fault diagnosis, Decisions support, Distributed artificial intelligence, Cooperative reasoning, Intelligent agents, Knowledge sharing, Constraint satisfaction

1. Introduction

In the chemical and energy industries, there always have been pushes and pulls to produce higher quality products, to reduce product rejection rates, and to satisfy stringent safety and environmental regulations [18]. The company's business environment is under increasing level of turbulences, characterized by a restricted possibility to plan upcoming events and short cycled, erratic changes in supplier and consumer markets. Thus, under the term "reconfigurability," new production paradigms are being emerged. Process operations that were at one time considered acceptable are no longer adequate. While process controllers can compensate for many types of disturbances occurring in the process, there are changes, which cannot be handled adequately by the controllers. These changes are called faults. To ensure that the process operations satisfy the performance specifications, the faults in the process need to be detected, diagnoses, and removed. As industrial systems become enlarge, the total amount of energy and material being handled increases, making early and precise fault detection and diagnosis imperative from the viewpoint of plant safety as well as reduced

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manufacturing costs [7,23].

A dynamic structure designed according to reconfigurable concepts means that, in case of a reorganization of the respective production unit, the information and communicational relations especially have to be redesigned as well. The on-line diagnosis of operating status of process plants or business units is one of the most important components in obtaining the reconfigurability successfully. The Multi-Agent System (MAS) technology has been emerging to solve problems in complicated and distributed systems such as Internet and human bodies. Advent and immediate acceptance of agent technology is due to the benefits that agent-based organization and coordination allow in designing cooperative problem-solving systems [13]. MAS is one area of the distributed artificial intelligence (DAI) field and is known to be very appropriate to the problem solving in distributed systems. It has modularity, speed and reliability, which are the benefits of distributed intelligence, because of the enhancement of the distributed computing ability. Moreover, MAS has advantages of operation in knowledge level, easy maintenance and reusability [3].

Agent-based computing has been hailed as the next significant breakthrough in software development, with the potential to affect many aspects of computer science, from artificial intelligence to the technologies and models of distributed computation. Agent-based systems are capable of autonomous action in open, dynamically-changing environments. Agents are currently being applied to the domains as diverse as business information systems, computer games and interactive cinema, information retrieval and filtering, user interface design and industrial process control. Though the concept of agents has various definitions among the researchers and different research fields, it can be defined narrowly in the domain of process operations support system, we are mainly concerning, as all the software and hardware that may be used to complete the operation related tasks on behalf of human operators. Because the communication between agents are possible regardless of the various types of hardware, especially in this era of emerging widely accepted communication protocols, MAS has a great possibility in the application to the fault diagnosis of chemical processes, which have lots of heterogeneous process units required to be solved with specific knowledge.

Multi-agent systems have been known to provide distributed and collaborative problem solving environment [3,8,24]. In the process systems engineering, there have been some efforts to apply agents in modeling and design of processes in the concept of concurrent engineering [2]. However, only a few efforts [1,10,17], including the authors' work as part of IMS/CHEM [5,9], have been made in the application of agents as software components and agenthood in the process fault diagnosis domain. In this paper, the development of topologically distributed multi-agent systems for chemical process fault diagnosis is presented. This system uses a congregation of diagnostic agents managing different process units and makes them communicate with each other to solve the global fault diagnosis problem in a distributed, collaborative fashion.

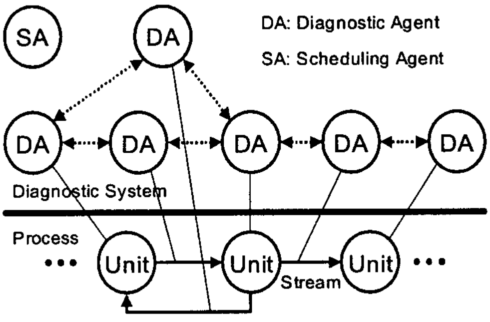

Fig. 1. Multi-agent diagnostic system.

2. Cooperative Fault Diagnosis for Distributed Constraint Reasoning

Agent-based systems offer a powerful framework to handle situations that demand a complex combination of multiple heterogeneous knowledge and problem solvers. However, we can benefit from distributed computing only if this is supported by concrete and useful schemes of cooperation [13]. The concept of distributed fault diagnosis using topology-based multi-agents in chemical processes is shown in Fig. 1. Diagnostic Agents (DA) corresponding to existing process units are placed in accordance with the topology of the process units; each DA has fault detection module, knowledge bases and inference engine [15], which performs reasoning as well as local diagnosis. The fault detection module has the information on possible fault types, measured and unmeasured variables of individual process unit: it can determine if certain faults exist. Knowledge base determines the relationship between variables based on the function-behavior model [6,14].

To perform the cooperative fault diagnosis based on process topology, interpreting process units, their functions and the status variables of the units by the DAs, an approach different from Oh [14], is required. Basically, every equipment in a process carries out tasks related to mass, energy and components. Mass, energy, components, etc. become objects of functions of process units; these objects are defined as keyword. The status of the keyword, *keyword status*, describes the unit's behavior depending on the function of equipment. For example, the abnormal, high mass flow in a pipe may be described as MASS_HIGH.

All process units have such keywords, and each keyword-related behavior of units can be interpreted together with behaviors of other units via keyword. Keyword status such as MAYBE_HIGH, MAYBE_NORMAL or MAYBE_LOW describes the status estimated from that of nearby equipment when the corresponding variable of the equipment is not measured. UNKNOWN is the status that is not measured and cannot be estimated from nearby equipment. In case of keyword COMPONENT, which represents component composition, it can be extended as COMPONENT1, COMPONENT2, etc.

3. Diagnostic Agents

Key issues related to agent-based cooperative systems are discussed in [21]: representation, ontology management, agent structure, system architecture, communications, system dynamics, overall system control, conflict resolution, legacy problems and external interfaces. Most of these issues are also applicable in designing and implementing the proposed agent-based, fault diagnostic system.

3.1. Agent Activities

The diagnosis by a DA is carried out by exchanging status information and local reasoning, through collaboration with the neighboring DAs as needed. Therefore, a DA sends queries for what it wants to know, performs reasoning on its status based on the answers to queries, and then notifies the operator/system and neighboring units of the faults detected. The Process Specification Language (PSL) recently proposed by STEP (Standard for the Exchange of Product Model Data) and the National Institute of Standards of Technology (NIST) is one of those initiatives to ensure complete and correct exchange of process information among all established manufacturing applications [19].

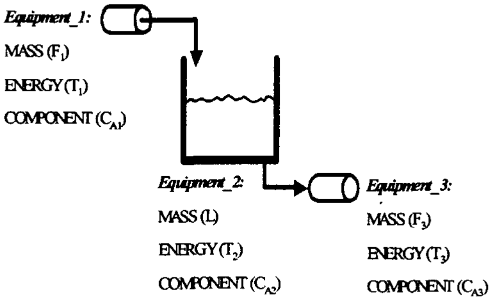

Fig. 2. A simple process for the explanation of diagnostic agenthood.

The process topology-based model and the activities and role of DA are explained using a simple process, shown in Fig. 2. This system consists of three process units: the input is fed into a tank unit through a pipe unit and the output comes out through another pipe unit. DA infers causal relationships through communication with neighboring DAs and fundamental self-reasoning. The detecting module of DA is always active, and DAs perform diagnosis by sending and receiving messages when events leading to faults occur.

DAs of Equipment 1, 2, and 3 are named DA1, DA2, and DA3, respectively. Let us assume a leak occurs at Equipment_2, a tank. This event causes a symptom of low flow of Equipment_3 (F3) and low level of Equipment_2 (L). The symptom is expressed in the language of function-behavior model as follows: *keyword status* low of keyword MASS(MASS[LOW]) is detected in DA2, and MASS[LOW] is detected in DA3. Triggered by an event leading to a fault, DA3 sends a query to DA2 in order to verify if this symptom is propagated or intermittent. Triggered by the event of receiving a query message, DA2 replies to the query of DA3, and DA3 performs a local diagnosis upon receiving the reply. In this case, it can be concluded that the fault was propagated to the unit itself based on the fact that MASS[LOW] was received and the status of itself is MASS[LOW]

3.2. Inference Reasoning

Reasoning is started when a fault is detected and replies of queries to other DAs are received. If a reply telling that the fault was detected in an input stream DA (cause-DA) is received, the DA concludes that the fault was propagated from the input stream and sends a 'tell' message reminder to the cause-DA of being faulty. Message 'reply' is a response to a query, and the reasoning also starts when a DA receives a 'reply' message from other DAs.

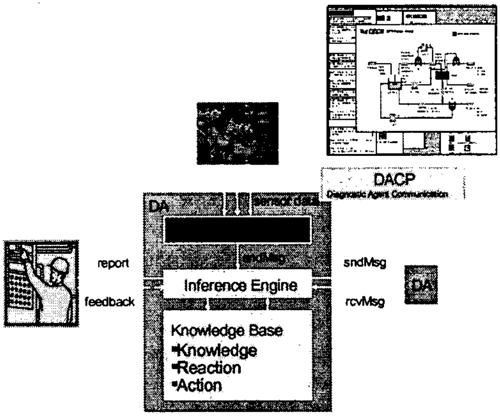

Fig. 3. A prototype implementation of the proposed architecture. The upper right window shows the flow diagram of the testbed process.

3.3. Certainty Factor (CF)

Distributed fault diagnosis shows good performance in portability, expandability, and speed. However, conflicting diagnostic results may exist and should be resolved [12,16,20]; local fault diagnoses and communications among agents are inherent in this system [4]. In our proposed framework, the possibility of the occurrence of a certain fault is quantified by introducing certainty factor (CF), and the conflicting diagnostic results are resolved for the improved overall diagnosis. For the weighting factor used in calculating CF, Gaussian distribution is assumed in the time domain, from the start of the diagnosis up to the current time. This approach is suitable considering the characteristics of fault diagnosis as the latest diagnostic results take priority over the past results, even though old results are not ignored completely. An improved scheme of enhanced knowledge sharing and conflict resolution among heterogeneous DAs is being designed using the adaptive agency concept.

4. Implementation and Case Study

The testbed process used in the case

study, a CSTR+heat exchanger process (see Fig. 3 for the flow diagram of the process), is a classic example for fault diagnosis and has been used in many researches, including the work of Kramer and Palowitch [11]. The mathematical modeling result of Sorsa and Koivo [22] was used for this study. There are three feedback control loops in the process, and PI controllers are used. They control the level of reactor, recycle flowrate of product, and reactor temperature, respectively. The level control of reactor is direct and no keyword change occurs; recycle flowrate control is reverse and no keyword change occurs; and the temperature control of reactor is direct and keyword change occurs. Therefore, different function-behavior models were required for each controller.

We implemented a prototype of the proposed architecture as a fault diagnosis system development tool for chemical processes. Fig. 3 shows a multi-agent fault diagnosis system constructed by applying it for the CSTR process. As process units are DAs, process topology of the real process is preserved in the diagnosis system. The global fault diagnosis is carried out and improved through unit-wise local diagnoses and continuing cooperation of agents. The system and user interfaces are very user-friendly and easy to understand.

Case Study: Heat Exchanger Fouling

Because of a fouling, the overall heat transfer coefficient of the heat exchanger is decreased. In early stage of the fault, the temperature of recycled product flow increased (see Fig. 4), so the temperature of reactor (T_r) and the flow rate of cooling water (F_w) increased. Temperature of reactor could be controlled, and T_r went to the normal range. As the system settled down onto a new steady state, the remaining symptom was the increasing F_w. As a result, PIPE-DA-11 suggested the high need of coolant, and the state of HX-DA-5 was out-stream energy-high. This suggests that the fault was occurred in the heat exchanger. The final results of diagnosis obtained from the collection of local diagnoses and the CFs of involved DAs are summarized in Table 1.

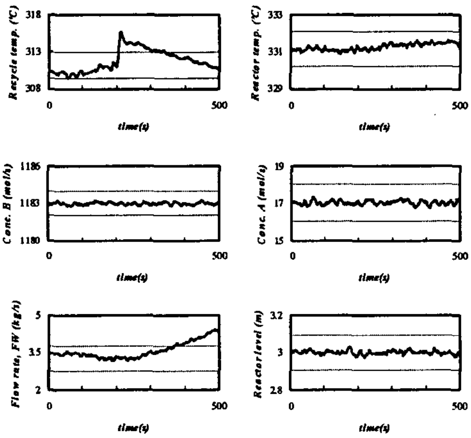

Fig. 4. Sensor readings simulated for the heat exchanger fouling.

5. Conclusions

Due to its benefits of enabling the systematic design of cooperative problem-solving

Table 1. Diagnostic results for the heat exchanger fouling

ID of DAs	Keyword status	Diagnosis	CF
PIPE-DA-11	MASS_HIGH	HIGH_NEED_COOLANT	0.9
HX-DA-5	HOT_STREAM_OUT_ENERGY_HIGH	Need further reasoning	-
PIPE-DA-6	ENERGY_LOW	Physically impossible	0.1
CSTR-DA-2	ENERGY_HIGH	HIGH_REACTANT	0.1

systems, the multi-agent technology offers a powerful alternative for diagnostic problem solving in a lot of engineering applications, especially for reconfigurable systems like holonic manufacturing systems. In this paper, we suggested a multimodel-based, distributed multi-agent diagnostic system for chemical processes where diagnostic agents of different expertise communicate by exchanging messages in parallel and try to cooperatively solve the global fault diagnosis problem by collaborative constraint satisfaction. The validity and usefulness of the suggested approach was demonstrated by implementing a prototype system for various test cases, and its framework is being extended as a general framework of coordinating the cooperative problem solving in a group of various decision-supporting systems being used distributely in process operations.

Acknowledgements

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