A Fault-Tolerant Computing Architecture in a Distributed Control System

Hong-ju Moon, Myung-Hyun Yoon, and Yong-Kwan Lee
Nuclear Instr. and Control Group,
Nuclear Power Generation Research Lab., Korea Electric Power Research Institute
103-16 Munji-dong, Yusong-ku Taejon 305-380, Korea
Tel: +82-42-865-5642, Fax: +82-42-865-5504, Email: hjmoon@kepri.re.kr

Abstract— **The faults in a digital system usually make discrete and abrupt changes in its output, which are hard to be expected exactly in advance. To cope with these situations, the fault-tolerance is an inevitable property of a distributed control system.**

A distributed digital control system consists of many equipments, and each equipment can be implemented by many different technologies. The fault-tolerance has to be implemented depending on the overall architecture and how each equipment is implemented. The paper analyzes and compares the strategies and tactics to add the fault-tolerances in a distributed digital control system, and studies how they can be combined appropriately.

Key Words: fault-tolerance, computing architecture, distributed control system

I. Introduction

Many traditional process control systems and manufacturing systems have been replaced by a distributed digital control system. The role of the distributed digital control system has been increased constantly and most of the plant operation relies on it.

Many traditional control systems consist of module type analog controllers. In such a system, the control loops are separated and many functions are replicated throughout the system. As they evolve to a modern digital integrated control systems, the control loops are concentrated and functions are distributed efficiently. This evolution makes the fault-tolerance of a control system more important than before.

The distributed digital control system has many shared common components and a single fault in the system may have effects on not a single function. Not as in an analog system, the faults in a digital system usually make discrete and abrupt changes in its output, which are hard to be expected. To cope with these situations, the fault-tolerance is an inevitable property of a distributed control system.

A distributed digital control system consists of many equipments, and each equipment can be implemented by many different technologies. The fault-tolerance has to be implemented depending on the overall architecture and how each equipment is implemented. In a distributed control system, the fault-tolerance is considered in many respects: I/O points, control modules, control functions, and communication networks. Different techniques are applied to each part of a distributed control system, and the relation between the parts and the overall operation have to be considered to obtain the fault-tolerance of the distributed control system.

This study proposes a fault-tolerant computing architecture in a distributed control system. This study analyzes the techniques for each part of a distributed control system to get the fault-tolerance, and propose a fault-tolerant computing architecture in a distributed control system by combining them appropriately.

II. Architecture of a distributed digital control system

In this section, an architecture of a distributed digital control system is presented and each component of the system is discussed on its characteristics.

The paper assumes the overall structure of a distributed digital control system as shown in Figure 1.

The architecture consists of several major components which will be discussed as follows. In the figure, three types of controllers are connected to the control network.

Input/Output modules An input/ouput module converts a signal from a sensor or a transmitter to the digital data which the digital controller can handle, or converts the data generated by the controller to the signal for the actuators.

Local controllers A local controller executes the major control functions which usually require fast operations. The functions provided by the local controller are simple but play key roles in controlling the processes. A single or not many control loops are treated in a local controller.

Group controllers A group controller supervises and coordinates the local controllers. It can also execute the major control functions.

Communication networks The communication network has the hierarchy which consists of three types of networks. The field network connects local controllers and a group controller. The control network connects group controllers and the data gateways. The operator interface stations can be connected to the control network. The information network connects the data gateway, the operator interface station, and the engineer interface station.

Data gateways The data gateway is defined in the considered architecture of the distributed digital control system to exchange data between the control network

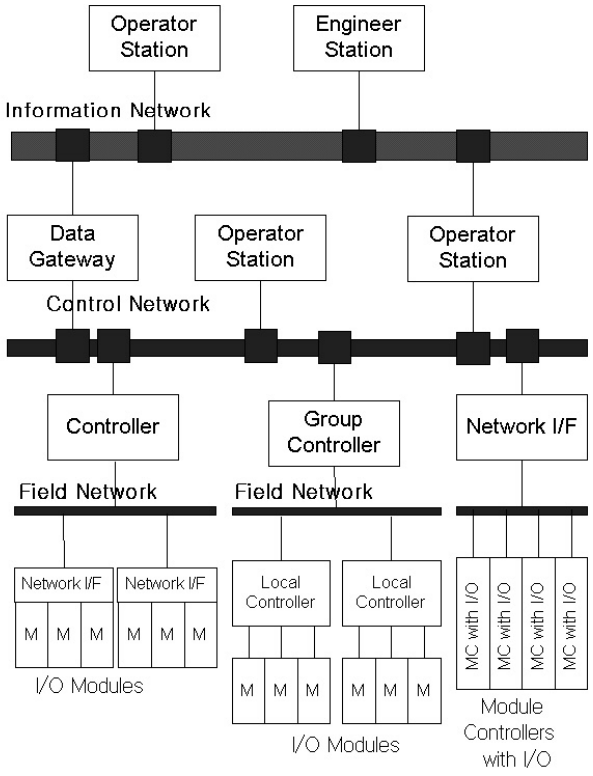


Fig. 1. Architecture of a distributed digital control system

and the information. In the paper, a data gateway for two different networks is defined with the following properties. 1) A data gateway exchanges the data between the two communication networks. 2) A data gateway does not allow a direct connection between the two nodes in different networks. 3) A data can be controlled to be passed in bi-direction or uni-direction, and not to be passed.

Operator interface stations An operator interface station provides various operator functions. They include alarm management, process management, data logging, historical data store, and system management.

Engineer interface stations An engineer interface station provides various engineering function. They include graphic builder, control loop and logic builder, data point configuration, logging and historical data configuration, and system configuration.

This paper defines three types of controller architectures, which are depicted in Figure 1.

The first one consists of one powerful controller and many input/output modules. The second one consists of a group controller and multiple local controllers, which has been presented above. And, the third one consists of many modular controllers which have embedded input/output functions.

Module based control systems make it possible to isolate each control loop, and usually have a simple structure. They enhance the independency to achieve safety features at the expense of costs. Many modern digital control systems consist of powerful control units which may handle many control loops in a single unit. They provide various functionalities and save costs.

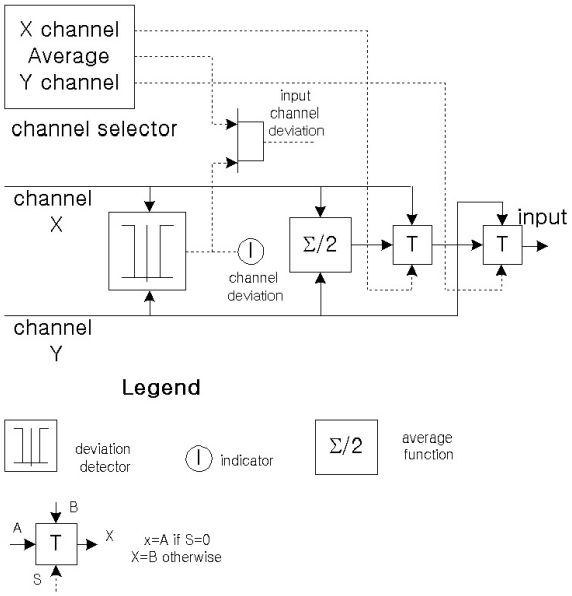


Fig. 2. Example of using the average calculation.

III. Analysis of fault-tolerant architecture

This section analyzes the fault-tolerant architecture for each components of the distributed digital control system. The fault-tolerance is implemented by redundancy for each component.

The analysis can be done by the analytic approach, or quantitative way. In doing so, many practical values are necessary for the system characteristics such as failure rates and the depedability of the redundancy logic. In addition, the method usually has to make some assumptions. Therefore, this paper focuses on the qualitative approach in analyzing the fault-tolerant architecture.

A. Sensors and Actuators

The redundancy of sensors and actuators must precede the redundancy of controllers when high reliability is required.

The input value can be determined from the duplicated inputs from multiple sensors by an appropriate calculation or exclusive selection. The calculation may take the average, the maximum, or the minimum (in case of analog inputs) depending on the system characteristics. The selection logic has to determine which is the valid input. It may be done by detecting the invalid range or by using the voting logic. Figure 2 shows an example of using the average calculation.

The redundant actuators can be used in parallel or selective manner. The parallel actuators can be implemented in an additive way or prohibitive way depending on their usage.

TABLE I
INPUT REDUNDANCY.

Input usage	calculation	selection
Appropriate signal type	analog (digital)	analog/digital
Advantage	simple implementation	accurate value
Disadvantage	deviation	dependable selection logic

TABLE II
ACTUATOR REDUNDANCY.

Actuator usage	parallel	selection
Appropriate type	control of continuous value	action
Advantage	simple implementation	accurate
Disadvantage	deviation	selection logic

B. Input/Output modules

The redundancy of the I/O modules usually goes with the redundancy of the sensors and the actuators. In most cases, the input module alone is not duplicated. Instead, it is duplicated according to the duplication of input signals or sensors. The input modules are also duplicated when the control systems are duplicated. If the input sources are from the same sensor, a splitter circuit is required. The output modules may be duplicated to drive duplicated actuators separately. The output modules are also duplicated when the control systems are duplicated. If the actuators are not duplicated in this case, the single output generation logic is required.

C. Control modules

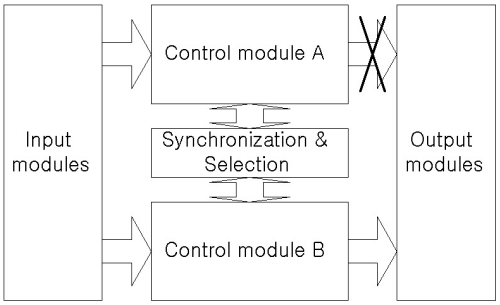
The redundancy of control modules is implemented depending on the controller types and the communication network architecture.

Redundant control modules can be implemented to operate in a selective manner or in parallel. The selection logic has to be operate to activate a control module selectively. To operate in parallel, either the selection logic is implemented for the output of the control modules or the component module to use the output from the control modules must have a selection function.

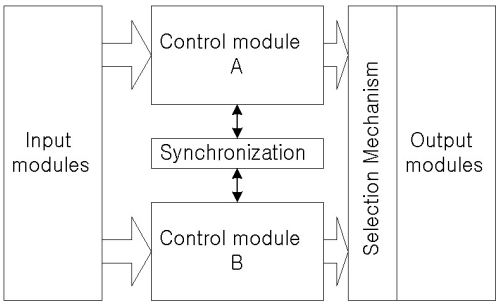
Whether they operate in parallel or in a selective manner, a synchronization mechanism is required to narrow the difference in the operation phase between the redundant control modules. The synchronization can be achieved in two ways. One is the communication among the redundant modules to keep track of others' operation phase while they are running. The other is to restore the status information by memory dump when a module takes over the control function. When the redundant modules operate in parallel mode, the synchronization can be minimized. If the output phase is mainly determined by the input phase, the synchronization mechanism can be eliminated given the phase difference is within a bound small enough.

TABLE III
CONTROL MODULE REDUNDANCY.

Redundancy mode	parallel	selection
Advantage	simple structure, minimized backup latency	stable operation in normal condition
Disadvantage	selection logic in output modules, possibility of continual jitters in output	complexity in the selection and synchronization logic, backup latency



(a) selective operation



(b) parallel operation

Fig. 3. Control module redundancy with a selective operation mode.

Figure 3 (a) shows the architecture with a selective operation mode and Figure 3 (b) shows that with a parallel operation mode. The selection logic could be a voting logic or a selection logic with a checkup code.

D. Communication networks

For the redundancy, the communication network is considered respectively on the cable with connecting devices and the network interface module. The network cable and

TABLE IV
COMMUNICATION NETWORK REDUNDANCY.

Transmit	Receive	Feature
selection	receive all	data loss during switching process with detection latency, complex transmit control, sequence data in order, no global synchronization in selection logic
parallel	channel selection	data loss only during switching process, complex receive control, possible violation of sequence order, no global synchronization in selection logic
parallel	consumer's choice	simple, selection mechanism for the consumer
selection	selection	complex selection logics, possible inconsistency of selections over the network

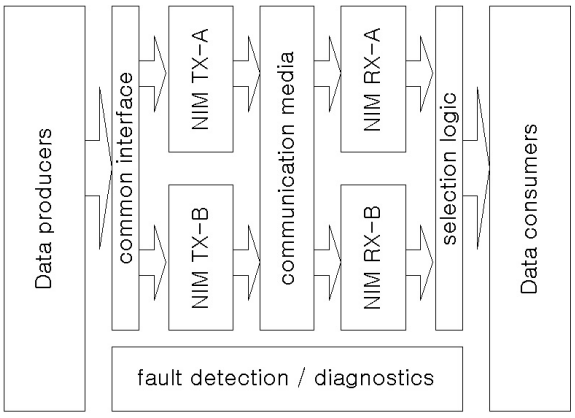


Fig. 4. A redundancy architecture of a communication network.

connecting devices are prone to noise and fault. They have to be implemented, installed, and maintained with special attention. For the most of all the distributed digital control systems, the network cables are duplicated.

For the fault-tolerance of the whole distributed digital control system, the localization of a fault has to be reflected in designing the system with more importance than the other parts of the system. The fault may have not only a passive effect but also an active effect on the system. An active fault propagates the fault state throughout the system. The communication network connects the distributed controllers and the possibility of the fault propagation is greater than other parts.

Figure 4 shows a redundancy architecture of a communication network in a distributed control system. The figure shows the example of the redundant communication architecture with two network interface modules. The data producer passes the data to the two network interface modules at once or to one of the two selectively by the common interface. The data selection can be done in the way that the selection logic selects one of the two network interface module for the receiving channel or that the data consumer selects a dependable data actively from the duplicated data. The methods for transmit control and receive control can be combined in various ways. The choice of the methods may depend on the communication protocol, the implemented architecture, and the characteristics of the data traffic.

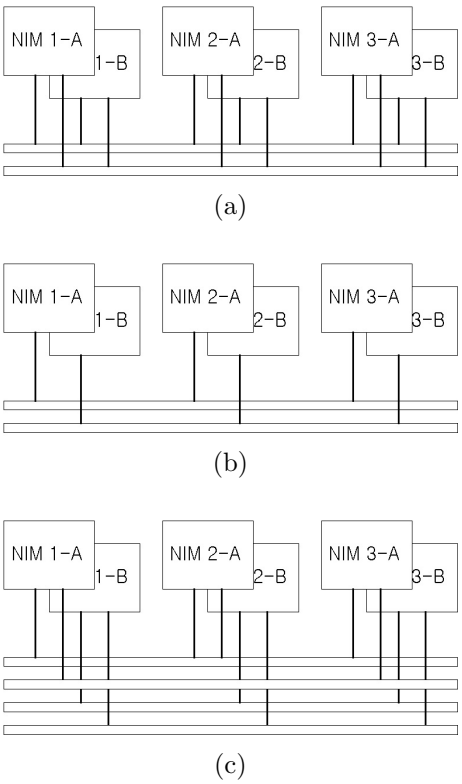


Fig. 5. Combination of redundant media and redundant NIMs.

The redundancy of the communication media can be combined with the redundant network interface module in various ways. Figure 5 shows the possible combinations. The combination may depend on the system requirements and the redundancy method for the network interface modules (NIMs).

E. Operator interface stations

Most distributed control systems allow multiple operator interface stations, and they can define their function separately. Therefore, the redundancy of the operator interface station can be implemented rather freely. The operation interface station may manage a database, and a backup mechanism is required.

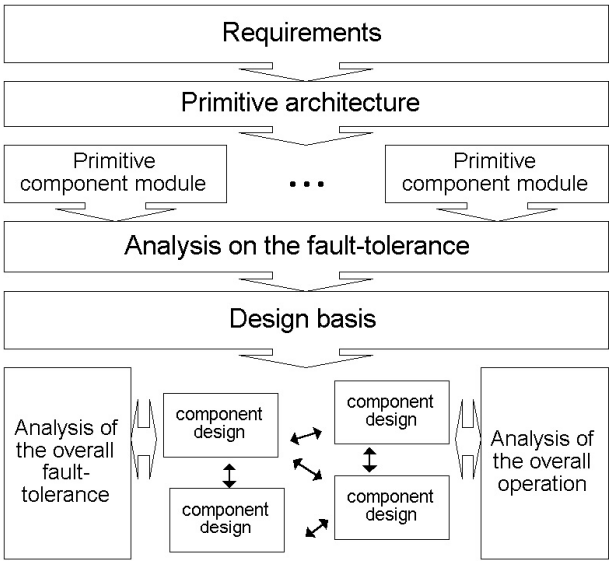


Fig. 6. Procedure to design the redundant architecture

F. Overall architecture

The whole structure and redundancy mechanism of each component have to be analyzed and determined by considering the whole architecture and implementation of all the components in a redundant distributed digital control system.

The procedure shown in Figure 6 may be a possible way to design the overall architecture.

IV. Conclusion

The paper analyzed and compared the redundancy strategies for the components of a distributed digital control system, and studied how they can be combined appropriately.

The fault-tolerance has to be implemented depending on the overall architecture and how each equipment is implemented.

The redundancy architecture includes fault detection mechanism and backup or selection mechanism. The redundant modules can be used in a selective way or a parallel operation. The selection usually needs a complex and dependable selection mechanism and is accompanied with an abrupt change in the states. The parallel operation may be implemented with a simple mechanism, and is desirable in many cases.

The fault-tolerance of a distributed digital control system could be considered at two phases. When the distributed digital control system is designed and implemented, it has to be considered first. Then, when the system is applied to a plant, the fault-tolerance has to be considered again. At this phase, the requirements and the characteristics of the plants have to be considered.

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