SURVEY OF NETWORKED CONTROL SYSTEMS AND THEIR POTENTIAL APPLICATIONS IN NUCLEAR POWER PLANTS

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ABSTRACT

This paper provides an overview of networked control systems (NCSs) and their industrial applications. Most widely used NCSs based on fieldbus technologies; namely, ControlNet, Profibus (DP/PA), and Foundation Fieldbus have been discussed. The objectives and benefits of using such networks are presented and factors influencing their design and implementation are examined. Then, some of the special requirements in controlling nuclear power plant (NPP) have been considered. The potential of applying networked control systems in such installations has been discussed. Finally, the concept of wireless networked control systems is also described.

I. INTRODUCTION

Recent advances in computer networks and computer technologies have made networked control systems (NCSs) a viable solution in some practical applications. Generally speaking, an NCS is a control system that connects field devices such as sensors and actuators through a network to form a closed-loop system to regulate the process being controlled. NCSs are different from data networks in several important ways [1]; first of all, the traffic in an NCS has frequent and small packets whereas the traffic in a data network has infrequent and bursty large packets. Secondly, an NCS has hard real-time constraints whereas data networks in most applications have soft real-time constraints. Finally, the limited bandwidth in NCSs makes their design more challenging as compared to that of data networks.

In a typical control system, there can be multiple control loops. Therefore, if NCSs are used, multiple communications have to be carried out over the network. Often, these systems have to provide real-time communications among various physical components that might be spatially distributed over a certain area. Therefore, the interference among different channels and the delays in signal transmission have to be considered. The benefits of replacing the traditional point-to-point wiring with a communication link using an NCS are numerous. The most notable ones are (i) reduce maintenance, (ii) lower construction cost, (iii) increase flexibility, (iv) reduce weight, and (v) improve reliability with easily added redundancies. A typical NCS is illustrated in Fig.1, in which there are N actuators, M sensors and a multiplexing controller.

The paper is divided into four sections. Section II introduces the concept of NCS and discusses some important factors when designing such networks for different applications. Section III focuses on networked control protocols, which is often called *Fieldbuses*. Applications of Fieldbuses are discussed in Section IV. Issues on potential applications of NCS in nuclear power plants (NPPs) are addressed in Section V, in which the idea of using wireless networks is also considered. The conclusion is drawn in Section VI.

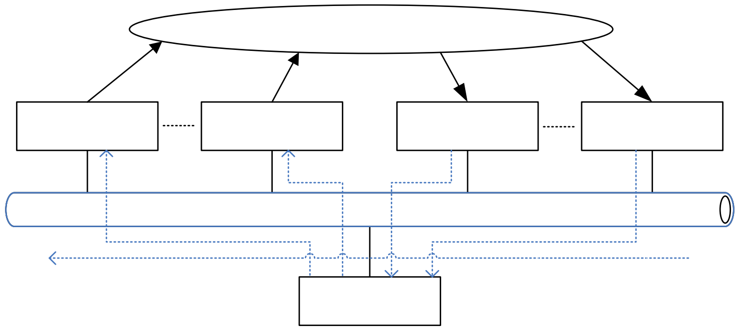

Fig.1 A Typical Networked Control System

II. OVERVIEW OF NCS

The flexibility offered by NCSs has motivated industries and research institutions to spend tremendous amount of resources to carry out research in this area. In general, NCS can be found in several different fields [2]; teleoperation, supervisory control, and feedback control. This paper focuses on feedback control systems. In a feedback control system, all the sensors, actuators, and the controllers are connected through a communication media. The control loop is closed via a communication media, rather than by physical wires. Generally speaking, an NCS can have two structures: direct and hierarchal [3]. In the former, the physical plant along with the sensors and actuators may be located at different locations from the controller and they are connected through a communication network. In the hierarchal structure, the main control system is connected to a number of remote controllers, sensors, and actuators. The choice of one structure over the other depends on the specific needs of the application. Extensive research has been done in applying NCS to control systems in industries. Many networked control protocols have been developed and implemented in practice; for example, Controller Area Network (CAN) for industrial and automotive applications [4], BACnet for building automation [5], and Fieldbus for process control applications [6]. These networks are currently being used in a wide range of industrial applications, such as manufacturing plants, chemical and petrochemical plants, to name a few.

On the other hand, the presence of the communication network adds additional challenges when designing and analyzing NCSs [7]. Some of them do not exist in traditional control systems. The first one is the network-induced delays. Signals from sensors to the controller and from the controller to actuators may suffer from network-induced delay. Such delay could be constant or time-varying depending on the situation. Severe degradation in performance and even system instability could happen if this delay is not taken into account when designing such NCSs. The second issue is that, not only are packets subject to delay, but also they can get lost or corrupted during transmission which results in more delay for retransmission or worse performance if these packets are discarded. Finally, some of control networks have limits on the packet size [1] which leads to multiple-packet transmission. In this case, the signal from a sensor to a controller may become fragmented which produces different arrival times for different fragments. This phenomenon will certainly cause delays in control signal synthesis which can consequently lead to performance degradation such as end-to-end delay and jitter.

III. FIELDBUS TECHNOLOGY

In the previous section, the concept of networked control systems has been covered. This section will focus more on the most widely used Fieldbus technologies, namely, ControlNet, Profibus, and Foundation Fieldbus that have been described in the international fieldbus standard IEC 61158. In general, all fieldbus protocols have only three layers of Open System Interconnection (OSI) model; physical, medium access control (MAC) and logical link control (LLC), and application layers that are required for real-time networks [8].

1. *ControlNet*

ControlNet [10] is a networked control protocol based on token-passing bus method. Therefore, it is a deterministic network that guarantees a maximum waiting time before sending messages. The node that holds the token keeps sending its data till it runs out of data or the timer of holding the token expires. There is no data collision in such networks as there is only one node that can send data at any instant of time. Furthermore, ControlNet uses common industrial protocol (CIP) as its upper layer protocol. Also, it uses producer/consumer model [6] which allows all nodes in the network to get access to the same data from one source. This has many advantages such as better performance, increased efficiency, and precise synchronization.
The bus speed of ControlNet network is 5Mbps and the data size is 504 bytes. The maximum number of nodes can be as high as 99 nodes. The advantage of using ControlNet in an industrial network is its determinism because of token-passing method and this is suitable for both time-critical and non-critical applications. On the other hand, ControlNet has poor performance when employed in networks with low traffic [1], because when there are many nodes in the same ring, a lot of time will be spent for passing the token without sending real data.

2. *Profibus (DP/PA)*

Profibus is a universal, open industrial communication protocol that has widely been used in manufacturing automation and process control. There are two compatible versions of Profibus fieldbus [6]: decentralized peripherals (DP), and process automation (PA). In addition, Fieldbus Message Services (FMS) is used as the application layer protocol. Profibus DP is designed for data rates from 9.6 Kbps to 1.5 Mbps with short time response (up to 1 ms). Profibus DP uses a simple and cost-effective transmission technology called RS-485, which forms either a bus or a tree topology, Fig2. It is widely used for direct control for intelligent field devices and distributed I/Os. One of the nice features of Profibus DP is its deterministic bus communication that results from using master/slave messaging model.

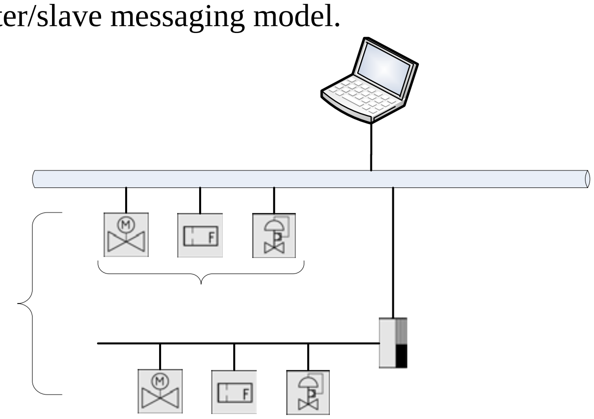

Fig.2 A Profibus Network with Bus/Tree Structure

Moreover, Profibus DP can be used in redundant architectures, the feature that makes it very suitable in applications where high level of reliability is required. There are two transmission techniques in Profibus: cyclic transmission for process data and acyclic transmission for configuration, alarm and diagnostic information. On the other hand, Profibus PA uses a synchronous transmission with a rate of 31.25 Kbps with time response up to 10 ms. It is widely used in process industry to connect devices such as actuators, valves, and sensors. Profibus PA, also, forms either bus or tree topology. Both Profibus DP and PA can accommodate up to 32 participants in one segment and 126 participants per network.

3. Foundation Fieldbus

Foundation Fieldbus (FF) provides an open, integrated fieldbus architecture suitable for both industrial and process control applications. FF has two profiles: H1 and High Speed Ethernet (HSE) [11]. The deployment of either profile depends on the application requirements. FF H1 is also used to connect field devices such as sensors and actuators to field controllers. It operates at 31.25 Kbps and uses a single twisted pair wire that can be as long as 1900 m without using signal boosters. The media used can form either a bus or a tree topology. One of the featuring characteristics of FF H1 is that devices on the network can be powered directly from the FF cable. Moreover, up to 32 devices can be connected onto one segment, if repeaters are used, the network can accommodate 240 fieldbus devices. FF HSE, on the other hand, is used as a backbone to interconnect multiple FF H1 fieldbuses together. It operates at 100 Mbps or 1 Gbps. It forms star topology and uses either standard twisted-pair Ethernet cables with 100 m or fiber optic cables with 2000 m in length. One important feature of HSE is its ability to form a redundant network for fault tolerant applications.

The benefits of using FF in industrial and process control applications are numerous. The control strategy uses different flexible function blocks (FFBs), such as Analog Input (AI), Analog Output (AO), and PID blocks. These blocks can be implemented in the field devices to reduce the amount of computations performed by the controller. Using FF reduces wiring and decreases the overall cost of maintenance by using a single wire that carries the signals from multiple field devices. In addition, FF allows adding additional field devices online. This feature is very useful for network expansion and avoids process shutdown. Another advantage of FF H1 is its data quality. FF H1 uses digital signals. This provides better loop performance and reliability. Furthermore, FF H1 is able to connect different devices from different vendors, which makes FF H1 interoperable.

Table 1 Summary of Some Existing Industrial NCSs

Fieldbus Type	Network Topology	Physical Media	Maximum Devices (nodes)	Maximum Distance
ControlNet	Linear, Tree, Star, or Combination	Coax or Fiber	99 nodes	1000 m (coax) 3000 m (Fiber)
Profibus DP/PA	Line, Star, and Ring	Twisted pair or Fiber	127 nodes	DP: 10 Km PA: 1900 m
Foundation Fieldbus H1	Star or Bus	Twisted pair or Fiber	240 nodes per segment	1900 m

Table 2 Characteristics of Three Industrial NCSs

Fieldbus Types	Communication Methods	Transmission Properties	Data Transfer Size	Arbitration Methods
ControlNet	Producer/ Consumer	5 Mbps	0-510 bytes	CTDMA
Profibus DP/PA	Master/slave peer to peer	DP: 9.6 Kbps - 12 Mbps PA: 31.25 kbps	0-244 bytes	Token passing
Foundation Fieldbus H1	Client/server publisher/ subscriber, Event notification	31.25 kbps	128 octets	Scheduler, multiple backup

Tables 1 and 2 show a summary and some characteristics of the three explained fieldbuses.

IV. APPLICATIONS OF FIELDBUSES

Due to their inherent advantages, fieldbuses are widely used in industry. Each application requires specific type of fieldbus with certain features [6]. For example, process control industry, such as chemical processes and energy production, requires a fieldbus that can handle real-time traffic among network's devices (sensors, actuators, and controllers). Delay in such environment can lead to closed-loop system instability that could result in disastrous consequences. Other fault-tolerant applications that implement redundancy require fieldbuses with redundant capabilities.

In other applications, fieldbuses are used to handle spatially distributed devices and controllers. An example of this is controlling utilities networks where fieldbuses are required to perform remote monitoring and station control. In these applications, data synchronization becomes a very important issue as the order of the received information is critical. Another issue is the distance compensation. Data traveled long distances suffer from network-induced delays which can degrade network performance. In other non-industrial applications, such as building automation, the fieldbus is required to perform supervisory and data acquisition services instead of traditional control services. Services provided by fieldbuses must be reliable, available, and safe and secure. Also, reliability and availability play a vital role when it comes to remote monitoring for medical applications.

V. POTENTIAL APPLICATIONS IN NUCLEAR POWER PLANTS

Nuclear power plants have wide range of control systems that monitor and control the operation of the plant. Typically, nuclear power plants use between 2000 and 4000 signals from field devices, such as sensors and actuators, in their control systems. In the existing nuclear power plant, the connections between all field devices and field controllers are done by using dedicated wire for each sensor and each actuator. These wires carry analog signals and run over long distances to connect into the Main Control Room (MCR).

It is interesting to point out that the concept of fieldbus comes originally from nuclear instrumentation and control (I&C). A Computer Automated Measurement and Control (CAMAC) network [12] was developed in early 1970s. It is the first instrumentation system that provides a data highway as a backbone channel for communication between modules, computers, and computers peripherals. Advanced digital control systems have been developed and implemented in nuclear power plants to meet nuclear standards of safety and reliability. For example, in Canadian Deuterium Uranium (CANDU) 6 digital control systems are used for controlling the reactor and the balance of plant (BOP). In many pressurized water reactor (PWR) plants, the analog control systems of standby generators, turbine governors, and steam generator level control have been replaced with digital computer systems. However, none of the fieldbus technologies have been used in existing plants.

1. *Potential application of fieldbus in NPP*

Fieldbuses have the potential to be used in nuclear power plants in safety and non-safety systems. The advantages are numerous including: low installation cost, interoperability, improved information accuracy, remote access to measurement data, reduction of maintenance cost, and employ of more advanced control strategies. The installation cost is drastically reduced when fieldbuses are used where the cost of specialized wiring of one foot for harsh environment can cost as much as $2000. In addition, the cost of inspecting, testing, troubleshooting, and repairing will significantly reduced if one fieldbus communication link is used instead of tens or even hundreds of cables. Furthermore, nuclear power plants are vulnerable to equipments and devices obsolescence. The vendor-independent plug-and-play approach for configuring the fieldbus devices will help in solving obsolescence problems down the road.

When used in nuclear power plants, fieldbuses must meet rigorous requirements [13] such as high reliability and availability, and redundancy capabilities. In addition, when used in safety applications, additional design considerations should be taken into account, such as using isolated safety channels to place fieldbus devices in different communication buses, the process which will provide protection against random failures. Two concerns of using fieldbus in nuclear industry are (i) design errors leading to common mode failure, and (ii) the ability of fieldbus to guarantee deterministic responses. One scenario of using fieldbus technology in NPP would be as a simple data acquisition system. Every fieldbus serves as a separate safety channel. Two or more channels could be used to deliver plant signals to a central safety computer. Another scenario is when safety channels exchange trip-related information. In this case, each channel receives information from the other channel and decides if a trip is required.

One drawback of using fieldbus in large scale industrial and nuclear applications is its limited number of control devices that can be connected onto one fieldbus. To solve this scalability problem, two or more fieldbuses need to be connected together using either bridges or backbone links [14]. Using bridges introduces additional delay when information is transferred from one fieldbus to another. This network-induced delay is unacceptable in most time-critical applications in NPPs. When using a backbone, all fieldbuses share the backbone and use it to exchange information, and therefore the network-induced delay is drastically reduced. Fiber distributed data interface (FDDI) could be used as a backbone and it has many advantages: high bandwidth, short delay times, high level of reliability, and high level of immunity to noise. Unfortunately, using a wired backbone in existing plants is extremely difficult where cable laying would be unfeasible. In such environments, using a wireless backbone would be a reasonable solution due to its several advantages.

2. *Wireless fieldbuses in NPP*

Using wireless, one can avoid the limitations of wired networks and offer competitive advantages such as: lower installation and maintenance cost, ease of replacement and upgrading, reduced connector failure, greater physical mobility, and faster commissioning. However, to be used in industrial fieldbus control systems, wireless networks must have a sufficiently large bandwidth to integrate the traffic generated by different sources. Also, wireless fieldbuses must withstand the industrial harsh environment and meet strict requirements on reliability and timing.

Exploiting wireless technology in control and monitoring systems in nuclear power plant applications, one has to consider (i) the transmission of safety-related signals must be reliable and bounded; (ii) message priorities must be supported; and (iii) small size for stringent timing messages. Strictly speaking, safety-related messages must be transferred reliably and timely with a percentage as high as possible (e.g. >99.x %) [16]. Furthermore, wireless fieldbus should provide the same services of wired fieldbus in addition to mobility and flexibility.

Finally, deploying wireless networks in nuclear power plants is associated with many important issues such as [15] network safety, loss of data, radio frequency (RF) coverage, electromagnetic interference (EMI), security, and reliable implementation. Security in nuclear plants is very vital in order to protect vital data and ensure continuity of operations. Generally speaking, implementing a secure wireless network is much harder than implementing a wired one. Three potential security threats are sniffing, denial of service, and man-in-the-middle and traffic redirection. Other important issues include adaptability, scalability, low-power, low-cost, and security all of which are being addressed for continual research. There are many applications of using wireless technology in nuclear power plants; it can be used for voice over internet protocol (VoIP), video, or data such as controlling and monitoring data.

VI. CONCLUSION

This paper has presented the concept of networked control systems (NCSs) and the advantages of applying this type of networks in industrial applications. Some of well known NCSs protocols, fieldbuses, have been briefly described and the pros and cons of using each protocol are discussed. Potential application of fieldbuses in the nuclear power plants is discussed and the option of using a wireless network to connect the field devices together has been proposed.

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