EVALUATION OF A DISTRIBUTED CONTROL SYSTEM FOR POTENTIAL APPLICATIONS IN NUCLEAR POWER PLANTS

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Abstract: There are a wide variety of requirements for control systems to be used in a nuclear power plant (NPP). Distributed Control Systems (DCSs) have become an obvious choice. Even though they have many attractive features over their analog counterparts, however, to meet the reliability and safety requirements, it is important that the functionalities of commercial DCSs be evaluated. In this paper, a novel framework for evaluating DCSs for use in a nuclear power plant is presented. The evaluation can be divided into (a) static evaluations and (b) dynamic evaluations. Further, the dynamic evaluations will include generic and application-specific tests. For dynamic evaluation, a flexible test-bench has been constructed. Evaluations are carried out against the requirements of a typical NPP. The communication diversity, controller throughput, latency, and jitter of hard-wired digital, hard-wired analog, Modbus, and Ethernet connectivity are investigated. The generic tests are performed on an Emerson Process DeltaV DCS. Steam Generator Level Control (SGLC) is used in the application-specific tests.

Keywords: performance evaluations, nuclear power plants, distributed control systems, steam generator level control.

I. Introduction

Nuclear power plants (NPPs) have a wide variety of processes that need to be controlled, such as reactor, pumps, steam generators, to name a few. At present, most of the existing NPPs still rely on specialized hard-wired controllers. However, Distributed Control Systems (DCSs) have many attractive features [1-4], which make them a suitable choice for control applications in NPP. DCSs can easily accommodate built-in redundancy, reliable Fieldbus networks, modular and simpler design, and are usually less expensive to setup and to maintain. Many such control systems also meet the international standards (e.g. IEC-61513) on safety.

Before DCSs can be widely accepted in NPP applications, they have to be evaluated against the requirements for specific applications. Yan *et al* discussed DCSs use in future nuclear power plants [1]. Manduchi presented DCS evaluations for the control of fusion processes [5]. Lindgren *et al* treated the evaluation of real-time DCSs [6]. Kopetz provided simple guidelines for partitioning centralized systems into distributed components, and examined some benefits of distributed systems, including how elementary interfaces between components lead to simpler testing procedures [7].

This paper mainly presents a framework for evaluating DCS for their applications in NPPs. Note that this paper does not intend to present a complete test report on DCSs; instead, it presents a methodology and a test-bench for such evaluations.

This paper contains seven sections. Section II divides DCS evaluations into static and dynamic parts. Further, the tests for dynamic evaluations are sub-divided into generic and application-specific tests. Section III presents static evaluations on the communication diversity. Section IV describes the test-bench used in performing the dynamic evaluations. Section V discusses generic tests and the results. Using a Steam Generator Level Control (SGLC) as an application example, Section VI presents test procedures and some test results. Finally, conclusions are drawn in Section VII.

II. Categories of DCS Evaluations

Based on whether or not a test-bench is needed for evaluation, evaluations of DCS can be divided into (a) static evaluations, and (b) dynamic evaluations.

Static evaluations can be performed mainly by analyzing the DCS specifications. The evaluations are for those attributes that are system inherent. One example can be the communication diversity.

Dynamic evaluations have to be performed on a physical test-bench. The evaluation criteria represent those attributes that can change over time as the controller carries out its control functions. One example is the I/O latency. The strategy of hardware in the loop (HIL) simulation is adopted in dynamic evaluations. There are many examples of HIL simulations, such as the design of traffic signal controllers [8] and engine controllers [9]. HIL has been adopted in a number of scenarios, namely when a model of the controller is not fully developed, or when doing so would cause state space explosion in the simulation.

Depending on how the tests are performed, the dynamic evaluations can further be divided into (a) generic tests; and (b) application-specific tests.

Generic tests are performed without having a specific application in mind. Examples include measuring DCS read and write latency, jitter, throughput, utilization percentage of the network, processor, and memory. The results of these tests are very useful in the early stage of DCS selection process, as they can help to eliminate a number of unqualified DCSs.

In addition to generic tests, it is also necessary and important to conduct application-specific tests to ensure that the selected DCS can indeed meet the operational requirements of the process. In this paper, Steam Generator Level Control (SGLC) [10] is chosen as the process against which DCSs are evaluated in the application-specific tests.

To ensure that a DCS is viable choice; many aspects of the system performance should be evaluated, including control performance, reliability, fault-tolerance capabilities, and upgradeability. Usually both static and dynamic evaluations should be performed to evaluate a DCS thoroughly.

III. Static Evaluations on DCS Communication Diversity

In the static evaluation, various aspects of DCSs are examined, including communication diversity and existence of redundancy. In this paper, more focus is made to investigate the communication diversity.

Communication diversity is the ability of the DCS to communicate across a high percentage of the available commercial communication protocols. In other words, it is the ability of the controller to connect to other networks or devices. The high diversity means that the likelihood of meeting a particular communication design is greater. Therefore, communication diversity is a useful index for considering current DCS upgrades and required interface protocols. It should be noted that the gateways and protocol adapters have not been considered in this paper. Normally, adapters are not under the direct control or monitoring of any DCS.

A number of protocols have been considered. Some protocols are quite simple, for example digital binary I/O can have two values, one encodes logical zero and the other encodes logical one. Other protocols can be quite complicated, such as a network layered on top of a TCP/IP running on wireless Ethernet. Most of the listed protocols and media are mature technologies; some are only gaining acceptance now.

A number of industrial protocols and media have been summarized in Table 1. Note that, while some protocols are only for supported media, other protocols can run on various media. For example, Ethernet can communicate over copper, fibre, and wireless, albeit at differing rates. Any protocol that is capable of running on top of Ethernet can run on those media. They are included in Table 1 to show the media diversity. Nuclear power plants rely on defense-in-depth. If a DCS supports both fibre and copper natively, the copper could be used in low EMI areas, while the fibre can provide as a backup, or as an alternative in high EMI areas.

Static evaluations have been carried out on several DCSs and Programmable Logic Controllers (PLCs) as shown in Fig. 1. The reason to include PLC is because PLCs are becoming more and more powerful, the difference between PLC and DCS is getting smaller. Many PLCs are becoming more intelligent and increasingly network friendly. On the other hand, even though existing DCSs are not designed for safety applications, their ever-improved reliability record makes them also a potential replacement for PLCs.

Table 1. Supported protocols and media of DCSs/PLCs

DCS/PLC	Analog I/O	Digital I/O	Profibus DP	Profibus PA	HART I/O	Foundation Fieldbus	Modbus RTU/ASCII	Profinet CB, RT, IRT	OPC Client/Server	Ethernet/IP	Ethernet (Copper)	Ethernet (Fiber)	Ethernet (Wireless)	AS-i	CANBus/CANOpen	DH/DH+/DH-485	DeviceNet	ControlNet
Siemens S7-300	•	•	•	•	•	×	•	•	•	×	•	•	×	•	×	×	×	×
Emerson Process DeltaV M3	•	•	•	×	•	•	•	×	•	×	•	•	×	•	×	×	•	×
Honeywell C200	•	•	•	×	•	•	•	×	•	×	•	×	×	×	×	×	×	•
Triconex Tricon	•	•	×	×	×	×	•	×	•	×	•	×	×	×	×	•	×	×
Foxboro IA A^2 T940	•	•	•	×	×	×	•	×	•	×	•	×	×	×	×	×	•	×
ANP Teleperm XP	•	•	•	×	•	×	•	×	•	×	•	•	×	×	×	×	×	×
Yokogawa CS3000	•	•	•	•	•	•	•	×	•	×	•	•	×	×	×	×	•	×

In Table 1, the entry with "•" represents that the associated DCS can natively communicate using the corresponding protocol. The entry with "×" means that the protocol is not supported natively. However, this does not mean that it cannot be used. An unsupported protocol could often be used through a gateway. An unsupported medium can be added through an additional communication module.

From Table 1, some measures of the communication diversity can be derived. Communication diversity provides a convenient way to implement defense-in-depth, i.e. multiply different controllers using different protocols and media. A system with a higher safety integrity level requires a risk reduction through the removal of possibly common mode failures. Common mode failure is less likely if different media and different protocols are employed. In addition, communication diversity is also important for future control system upgrade.

Note that the supported protocols and media of DCSs will change when manufacturers change their product lines. The table is based on the information to date.

IV. Descriptions of the Test-bench for Dynamic Evaluations

For proper dynamic evaluations of DCS, it is necessary to have a test-bench. The test-bench presented in Figure 1 was initially proposed in [11] and it can provide a basis for more advanced measurements. This test-bench is used both in generic and application-specific tests.

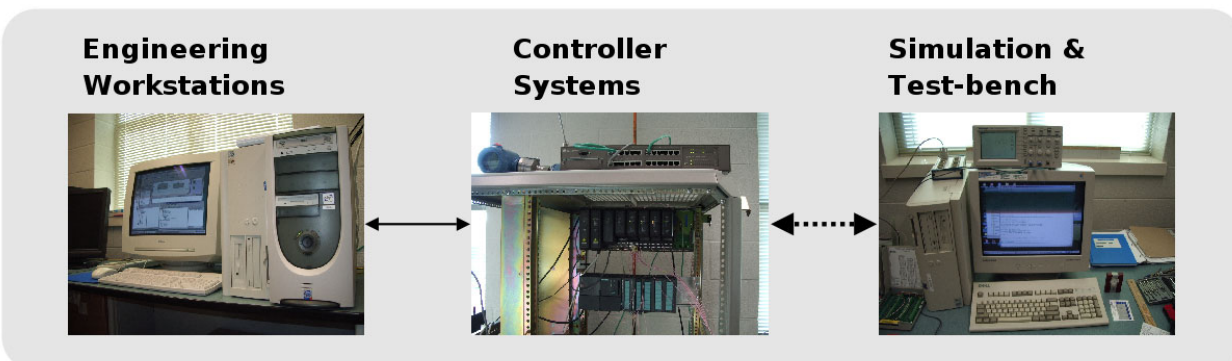

Figure 1. Test-bench Components

The protocols used in the test-bench and the measured indices for the generic tests are summarized in Table 2. The "Type" column defines communication protocols. For example Modbus can communicate on the same physical layer using ASCII or RTU protocols. The RTU version is preferred for high-speed communication since it represents an encoded ASCII data that takes up fewer bytes.

Table 2. Communication protocols investigated and indices measured

Protocols	Type	Measured Indices
Analog I/O	4-20mA control signals	Latency, throughput, jitter
Digital I/O	Binary states 0V DC and 25V DC	Latency, throughput, jitter
Modbus	RTU Master-slave protocol over RS-232	Latency, throughput, jitter
Ethernet	OPC client/server	Latency, throughput

The definitions of latency, throughput, and jitter are important for interpreting the results of dynamic evaluation and drawing conclusions. Read latency refers to the duration of time between issuing a read command and receiving the result. Write latency is similar and refers to the duration of time between issuing a write command and receiving the result. Read and write throughputs are the maximum rate at which the DCS can process either a parameter 'read' or a parameter 'write'. Read and write jitters refer to the variance in the collected values of either latency or throughput. A deterministic communication protocol will tend to have a near zero variance in latency and throughput. In practice, the variance may not be zero due to the time taken by DCS to process the data. It should be noted that the inverse of the latency should be proportional to the maximum throughput.

The indices considered for the dynamic evaluations are derived from the online plant performance requirements. A DCS that is a part of a process control may need to sample an input within a specified period. The DCS may be a part of a voting scheme, redundant controller, or part of a controller network. A DCS involved in a voting scheme must be able to respond at some fixed time intervals, with hard real-time requirements. The ability to vote at a fixed time interval relates directly to dynamic performance, in particular, low jitter in the input and the output, and the processing latency.

In order to measure the indices listed in Table 2, the test-bench must have an interface to the physical communication layer, and a software interface to the higher level protocols. For communication using analog or digital signals, the test-bench requires both types of inputs and outputs. The test-bench is equipped with analog and digital sampling cards. For communication over the Modbus, the test-bench requires an RS-232 interface, and the OSI layer 7 software that can communicate as either a slave or a master. OPC defines communication over higher OSI layers, with the lower layers being independently selectable. In this paper, OPC is tested using TCP/IP and Ethernet for the lower layers.

The data acquisition and processing system of the test-bench is made of hardware and software components. The hardware is based on National Instruments DAQ components. The software uses LabWindows/CVI to gather and process information from the DAQ hardware. LabWindows/CVI can interface directly with Matlab through Windows based DDE. The LabWindoes/CVI code can be interfaced with SCLC simulation implemented using Matlab. Similar data acquisition and processing systems have been used in automotive and transportation industry to test safety-critical control systems [8, 9, 12].

During the dynamic evaluation process, the physical controllers are connected, configured, and programmed through computer networks on the test-bench. To perform generic tests, the test-bench simulates different plant conditions by applying different inputs and observing the system responses. Application-specific tests are done by running a SGLC simulator on a workstation, and connecting the simulator to the controller through selected communication system on the test-bench. The data acquisition and processing system analyzes the collected data off-line. Similar evaluation methods have also been used in the past [12, 13].

V. Generic Tests and Results

In latency measurements, read and write latencies are assumed to be equal. Without internal device probes, read and write latencies cannot be measured independently. For example, to determine the time at which a read is completed requires timing the result. This returning result is a write on some other communication channel which has not yet been measured. Therefore a single read and write are always measured together. Therefore, the latencies associated with read and write commands are assumed to be equal.

In order to measure read/write latency, a parameter is written to the communication channel on the test-bench. The DCS must read the parameter, process the value, and immediately write the parameter back. The test-bench reads the parameter that is written back and calculates the time difference Δt between the read and the write. The latency is modeled by three parameters: transmission time, read/write latency, and processing time. Equations (1) and (2) can be used to calculate the latency.

$$\Delta t = 2t_{tran} + (t_{wirte} + t_{read}) + t_{cpu} \tag{1}$$

$$t_{read} = t_{write} = \frac{\Delta t - 2t_{tran} - t_{cpu}}{2} \tag{2}$$

where t_{tran} is the transmission time, t_{read} is the read latency, t_{write} is the write latency, t_{cpu} is the processing time on DCS.

The physical layers used for the channel transmission are the same for both the outbound and the inbound signals. The transmission time is assumed to be symmetric, because the physical layer is the same. Without internal measurements the read and write latencies have to be assumed equal.

The test-bench can measure and eliminate the effects of transmission time by using a loop-back test. The test-bench reads and writes its own parameters on the communication network. This measurement creates an estimate of the test-bench overhead, and transmission time. The test-bench overhead and transmission times are subtracted from all the tests. As a baseline for t_{cpu} the DCS is programmed to copy the input parameter to the output without changing it. The final t_{read} and t_{write} represent the latency in parameter reads and writes for the chosen communication network.

While measuring throughput, throughput equals the maximum frequency of change in the parameter that is recordable by the DCS. In order to measure the throughput, a secondary channel of a higher throughput is required. The output of the secondary channel output is a copy of the test channel input. A comparison of the two channels reveals that if the DCS is able to record the change in the parameter value.

In the process of jitter measurement, the jitter of latency equals the standard deviation of the measured latency, and the jitter of throughput equals the standard deviation of measured throughput.

Table 3 presents the results of generic tests on DeltaV DCS. The throughput, jitter of throughput, latency, and jitter of latency of hard-wired digital, hard-wired analog, serial Modbus are presented respectively.

Table 3. Results of generic tests on DeltaV DCS

Type of I/O	Throughput (Hz)	Jitter of throughput (Hz)	Latency (ms)	Jitter of latency (ms)
Hard-wired Digital	5.0	0.1	69.3	29.5
Hard-wired Analog	5.1	0.3	227.9	25.9
Serial Modbus	10.1	0.9	99.7	8.6

The results of tests on OPC Ethernet are not included in Table 3. DeltaV OPC server coerces the update value to 500ms every time while testing OPC Ethernet. The OPC server cannot update faster than this value. The set test rate that is normally 5Hz, but it appears as 2.5Hz from the analysis. Thus it is under-sampled.

VI. Application-specific Tests

In a CANDU nuclear power plant, the power is generated through the use of a steam turbine which drives a generator to produce electric power. The steam is created using the heat generated from the reactor. A specialized steam generator is used for steam generation. Even though control of steam generators in a nuclear power plant is a very complex problem, in this paper a simplified model is used to provide a test environment for DCS.

When the temperature and pressure of the steam begins to drop, due to disturbances, the steam generator must issue a control signal to the reactor to increase its power output. A full steam generator model can be used to represent the steam generator in operation while maintaining the steady-state pressure and also during warm-up or cool-down cycles. A one-dimensional SGLC model based on [14] is used for the dynamic performance evaluation of DeltaV DCS. The model involves a mass, volume, and energy balance. Recirculation is assumed constant between the feed-water liquid, down-comer and sub-cooled water. Equations (3)–(6) describes the model:

$$\frac{d}{dt}(M_f + M_{sc} + M_g) = \dot{m}_w - \dot{m}_s \tag{3}$$

$$v_f(M_f + M_{sc}) + M_g v_g = V \tag{4}$$

$$\frac{d}{dt}[M_f h_f + M_{sc}(\frac{h_f + h_r'}{2}) + M_g h_g] = \dot{Q}_w + \dot{m}_r(h_r' - h_f) + \dot{m}_w h_f - \dot{m}_s h_g \tag{5}$$

$$h_r = \frac{(\dot{m}_r - \dot{m}_w)h_f + \dot{m}_w h_{fw}}{\dot{m}_r} \tag{6}$$

where M_f is the mass of the saturated liquid (kg), M_{sc} is the mass of subcooled water (kg), M_g is the mass of the saturated steam (kg), $\dot{m}_w$ is the feedwater input flow rate (kg/s), $\dot{m}_s$ is the steam output flow rate (kg/s), v_f is the specific volume of the saturated water (m^3/kg), v_g is the specific volume of the saturated steam (m^3/kg), V is the volume of the steam generator (m^3), h_f is the enthalpy of the saturated water (J/kg), h_r' is the enthalpy of the recirculating water (J/kg), h_g is the enthalpy of the saturated steam (J/kg), $\dot{Q}_w$ is the heat transferred from the primary (J/s), $\dot{m}_r$ is the recirculation rate (kg/s), and h_{fw} is the enthalpy of the feedwater (J/kg).

Equation (3) represents conservation of mass. Equation (4) is based on the conservation of volume. Equation (5) can be derived based on the conservation of energy. The three fundamental conservation equations dictate the behavior of the one-dimensional model. In addition to the one-dimensional model, presented is the concept of recirculation. Equation (6) describes the behavior of liquid recirculation in the steam generator. The variable h_r' is the delayed value of h_r and provides a mixing mechanism for the arriving feedwater.

The physical parameters of the steam generator are taken from a CANDU 6 design, and the operating levels are assumed to be at the full power steady state. The parameters include reactor output in joules, SG water level, steam flow rate, and feed-water flow rate at full power. These parameters are used to stabilize the non-linear SG equations at the full power. Reactor power and steam load are the inputs to the SG model. The feed-water valve is the controller output. The generator water level and pressure are the outputs of the model.

The steam generator is simulated in real-time with Matlab. A communication link between Matlab and the controller is established using a Modbus link. During the tests, a PID controller is used for the level control of the steam generator. The PID loop is tuned using the DeltaV M3 "tune" software based on a gain/phase margin method. The controller provides a phase margin of 45 degrees and a gain margin of 2. However, nonlinearities, such as feed-water input valve saturation, have not been taken into consideration in the simulation.

Similar tests as in [15] have been used with some modifications to the control variables. The first three tests involve step changes in the level set-point. These types of changes are required for maneuvering the reactor from zero to full power. The next three tests simulate increases in steam generator load. These two scenarios, both set-point change and changes in load, are the required procedures in the overall operation of any power reactor.

Table 4. Results of application-specific tests on DeltaV DCS

Parameters	**Tests**	**Time to Stabilize (s)**	**Overshoot (m)**	**Lowest Level (m)**
Gain = 1.12 Reset = 83.64 (s) Rate = 13.34 (s)	Water level set-point change by 10%	323	0.09	5.00
	Water level set-point change by 20%	324	0.18	5.00
	Water level set-point change by 30%	326	0.27	5.00
Gain = 2.14 Reset = 29.17 (s) Rate = 4.67 (s)	Steam flow rate change by 10%, Reactor step 10%	172	0.003	4.89
	Steam flow rate change by 20%, Reactor step 15%	173	0.006	4.78
	Steam flow rate change by 30%, Reactor step 15%	162	0.01	4.68

All tests are performed at 100% reactor power level. The initial set-point for the water level is 5m above the riser. The tests and the test results are presented in Table 4. By comparing the test results against the requirements of SGLC, one will be able to determine whether the DeltaV DCS can meet the performance requirements. Such information is crucial to select right DCS for SGLC.

VII. Conclusions

A novel framework for evaluating DCSs and their applications in NPPs is presented. The framework includes both static evaluations and dynamic evaluations. Under this framework, a flexible test-bench has been constructed for dynamic evaluations, including both generic tests and application-specific tests.

Indices investigated are derived from NPP process requirements. DCS communication diversity is investigated during the static evaluations. The controller throughput, latency, and jitter of digital, analog, Modbus, and Ethernet connectivity of Emerson Process DeltaV DCS are investigated in the generic tests. SGLC in a CANDU plant is selected as the process for application-specific tests.

The results of such DCS evaluation can provide useful information in selection of control systems in the upgrade. In addition, the evaluation results could also be used to examine the strength of DCSs in relation to the requirements of NPP, leading to future improvements in design. It is believed that the framework and the evaluation results reported are useful to engineers in the process industry. Furthermore, the test-bench is flexible enough to be enhanced to measure additional qualities, thus to investigate other aspects of DCSs.

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