Modeling Of Effects Of A Foundation Fieldbus H1 Network In A Network-Based Control System

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Abstract

This paper reports some theoretical analysis and experimental studies on the effects of a Foundation Fieldbus (FF) H1 network in a network-based control system (NCS). The tests verify that only a portion of the additional delays introduced by substituting the FF H1 network for hardwires are communication delays. The tests also investigate the relationship between the network's effects and their influencing factors including the control mode, the control program scan rate, and the FF H1 macrocycle. Furthermore, models of the FF H1 network's effects are developed based on the test results, and some suggestions to reduce delays are provided.

1. Introduction

It has long been realized that the applications of data networks in control systems can bring many benefits, such as lower costs and higher flexibility. However, networks also introduce side effects, such as additional delays, possible data loss, and quantization [1]. Therefore, many studies have been conducted to understand networks' effects in network-based control systems (NCS). Among these studies, most are devoted to the investigation of network-induced delays, which may have big influences on NCS control performance. Network-induced delays are largely dependent on which network is used. Therefore, studies have been carried out to investigate the network-induced delays of almost all major industrial networks, including Foundation Fieldbus (FF) H1 [2, 3], CAN [4-7], Profibus [4-6, 8-10], Modbus [6], and Industrial Ethernet [11-13]. Various models have been developed to estimate network-induced delays based on these studies.

Previous studies have considered delays within control loops including network communication delays. However, the studies assume that only communication causes additional delays within control loops and that all other delays are equivalent when networks are used to substitute for hardwires. In fact, additional delays may also be introduced into control loops because filters, Analog-to-Digital Converters (ADC), Digital-to-Analog Converters (DAC), and some computing functions are moved to field devices in a NCS. Since filters, ADC/DAC, and processors at field devices are of lower performance specifications than those at controllers and I/O modules some additional delays will be introduced. The estimation given by the existing models, which only considers communication delays, may therefore be shorter than the actual additional delays introduced by substituting networks for hardwires.

As far as FF H1 is concerned, to the best of our knowledge, no previous study in the open literature experimentally investigates the relationship between its effects in a NCS and the configuration of parameters. Pang and Nishitani have measured FF H1 communication delays, but no attempt has been made to develop models [2]. Wang *et al* present delay models obtained through analyzing FF H1 protocols, but the models only estimate communication delays [3].

In this paper, theoretical analysis and experimental tests are carried out to investigate the effects of a FF H1 network in a NCS, and new models are developed. Section II of this paper introduces the test-bench including the Distributed Control System (DCS) under study. Section III evaluates the DCS using hardwires for communicating with field devices. Section IV evaluates the same DCS, but using a FF H1 network. In Section V, new models of networks' effects are developed based on the tests results. The results of this paper are summarized in Section VI.

2. Description of test-bench

The DCS included in the test-bench is a DeltaV DCS from Emerson Process Management, as shown in Figure 1. One redundant MD Plus controller, one redundant FF H1 card, one 4-20mA analog input (AI) card, and one 4-20mA analog output (AO) card are used in this study. The DCS is able to communicate with field devices using either hardwires or the FF H1 network.

When the FF H1 network is used, there are three devices on the network: DeltaV FF H1 card, a SMAR IF302 converter, and a SMAR FI302 converter. The IF302 is used to convert industrial standard 4-20mA signal to FF H1 signal, while the FI302 is used to convert FF H1 signal back to 4-20mA signal. A Relcom power hub is used to connect the three devices to the FF H1 network. A network-based control loop is formed when the IF302 is connected to a sensor with 4-20mA output, and the FI302 is connected to an actuator which accepts 4-20mA signal.

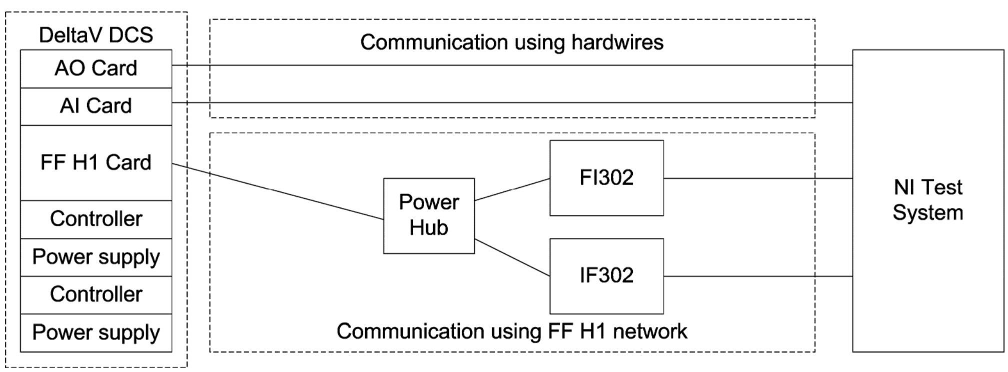


Figure 1 Framework of test-bench

A test system from National Instrument (NI) is adopted to perform loop-back tests on the DCS using either hardwires or FF H1 network. During the tests, the NI test system generates a square current signal between 10mA and 14mA. The DeltaV DCS reads the signal, and immediately sends it back to the test system. The NI test system records the signals at both DeltaV AI card and AO card or IF302 and FI302 at a sampling rate of 100Hz. Test results can be obtained by comparing the two signals.

Since it is critical to ensure the timing of the test signals is precise, a NI PCI-6071E card with Direct Memory Access (DMA) mode is used. When DMA mode is used, data are exchanged between PCI-6071E and the memory of NI workstation directly, while the CPU of the workstation is not involved. In addition, a Tektronix TDS 210 oscilloscope is used to verify the accuracy of the timing of the test signals.

3. Analysis and Tests on DCS using hardwires

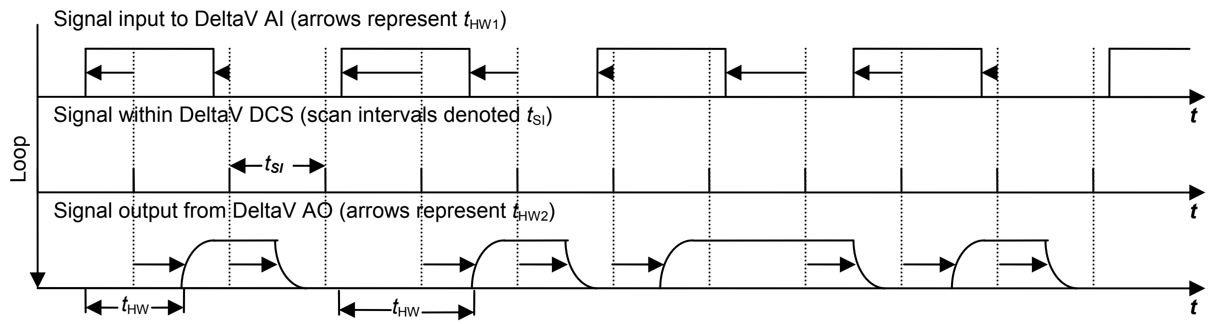


Figure 2   Timing diagram of the DeltaV DCS using hardwires

Figure 2 is the timing diagram of the DeltaV DCS using hardwires. The loop-back time t_{HW}, which is defined as the difference between the time that the step change of DeltaV AI signal occurs and the time that DeltaV AO signal completes the initial 10% of the overall rise/fall, can be divided into t_{HW1} and t_{HW2}. The time t_{HW1} is a time slice between the time that the step change of DeltaV AI signal occurs and the time that DeltaV AI card start sampling the signal, while t_{HW2} is the time spent within the DeltaV AI card, the AO card, and the controller.

In Figure 2, scan interval t_{SI} is equivalent to sampling interval. It is determined by the scan rate of the DeltaV control program, which is denoted by t_{SR}, as the scan rate determines how often control programs at the DeltaV controller execute. However, t_{SI} has a small variance as the DeltaV controller needs to scan its I/O cards in addition to execute programs and the two tasks are performed asynchronously [14].

The duration of t_{HW1} is assumed to follow uniform distribution between 0 and one scan interval. That is because the test signals are completely independent of the DeltaV DCS, thus the probability for a rise/fall to occur anywhere within a scan interval is the same. The duration of t_{HW2} is not influenced by the configuration of the scan rate.

The loop-back tests are performed when the scan rate is set to be 100ms, 200ms, and 500ms respectively. The frequency of the test signal is configured to be 0.5 Hz when the scan rate is 100ms and 200ms, and 0.25Hz when the scan rate is 500ms. Considering that t_{HW1} is unpredictable during the tests, the test signals are time shifted each instance over one scan interval. The time shift step is 10ms when the scan rate is 100ms or 200ms, and 20ms when the scan rate is 500ms. The tests are performed by time shifting over the entire scan interval allowing 5 cycles for each time shift position; therefore 10 rises/falls are completed for the test at each time shift position.

Figure 3 presents typical signals at the DeltaV AI card and the AO card when the scan rate is set to be 200ms, while Table 1 presents the measured loop-back time relative to different scan rates. The DeltaV AI signal is the signal fed into the DeltaV AI card and the DeltaV AO signal represents the output signal from the DeltaV AO card.

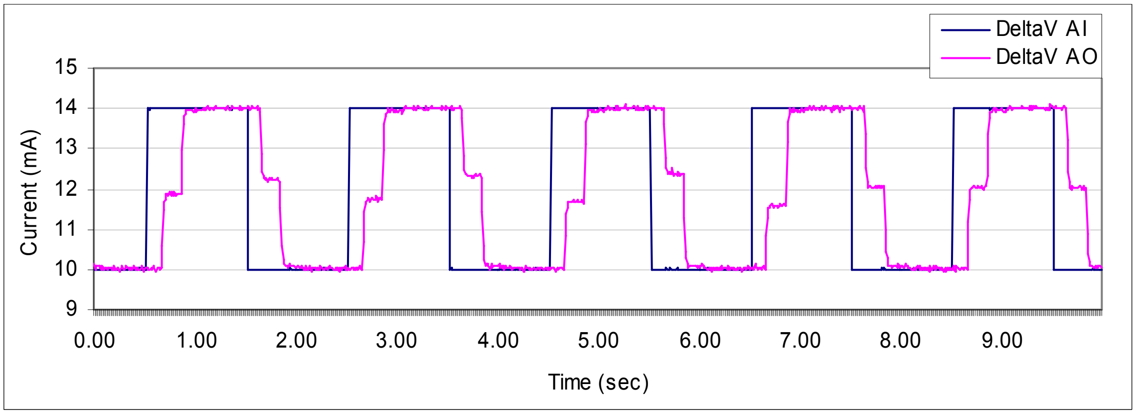


Figure 3 Test results when the scan rate is set to be 200ms

Table 1 Measured loop-back time with hardwires

Scan Rate (ms)	Measured Loop-back Time				
	Mean (ms)	Std. Dev. (ms)	Min (ms)	Median (ms)	Max (ms)
100	149	31	80	150	220
200	197	58	100	200	310
500	351	145	100	360	620

Figure 3 shows that, though the DeltaV AI signals are perfect square signals, the DeltaV AO signals may contain some glitches, i.e., they may take several steps to complete a rise/fall. These glitches are due to the dynamics introduced by the low pass filter within the DeltaV AI card, as square signals contain high frequency components. To be more specific, when a square signal passes through a low pass filter, it will no longer be a square wave. If the signal samples are taken by the ADC before a complete rise/fall cycle of the signal, such glitches will appear.

The measured loop-back time and its variance listed in Table 1 represent the delays with respect to control applications. When the DeltaV DCS is used to control a physical process, these delays are likely to influence control system performance if the dynamics of applications is small. In addition, the test results demonstrate that both the measured loop-back time and its variance increase as the scan rate increases. This is because a major part of the loop-back time is t_{HW1}, which follows a uniform distribution between 0 and one scan interval.

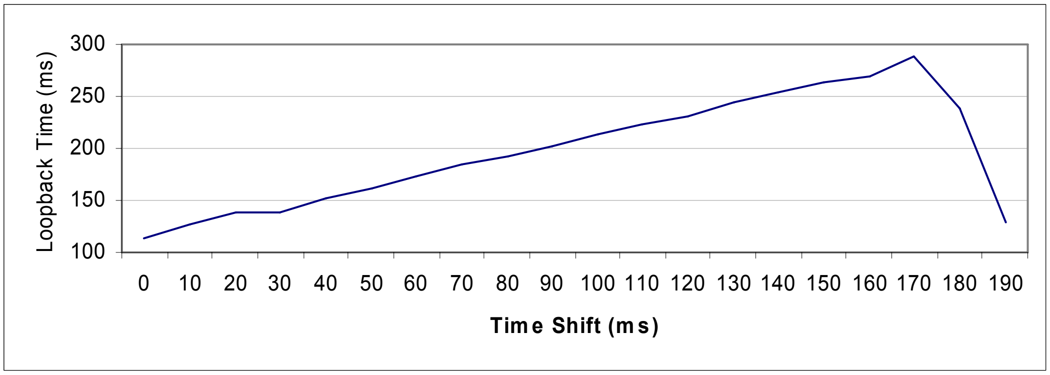


Figure 4 Average loop-back time relative to the time shifts at the scan rate of 200ms

Figure 4 shows the average loop-back time relative to the time shifts at the scan rate of 200ms. The time shift where the loop-back time is the smallest is the time shift where t_{HW1} is closest to 0ms. Note that the time shift 0ms as indicated should be considered as relatively close to 0ms prior to the scan, not exactly at 0ms. The region beyond 170ms is considered to be unpredictable, as there is no deterministic response time within this range and therefore extremely high and low values are present. The given curve is an accurate representation of the averaging of these unpredictable high and low values which occur in the direct proximity of 0ms of the scan.

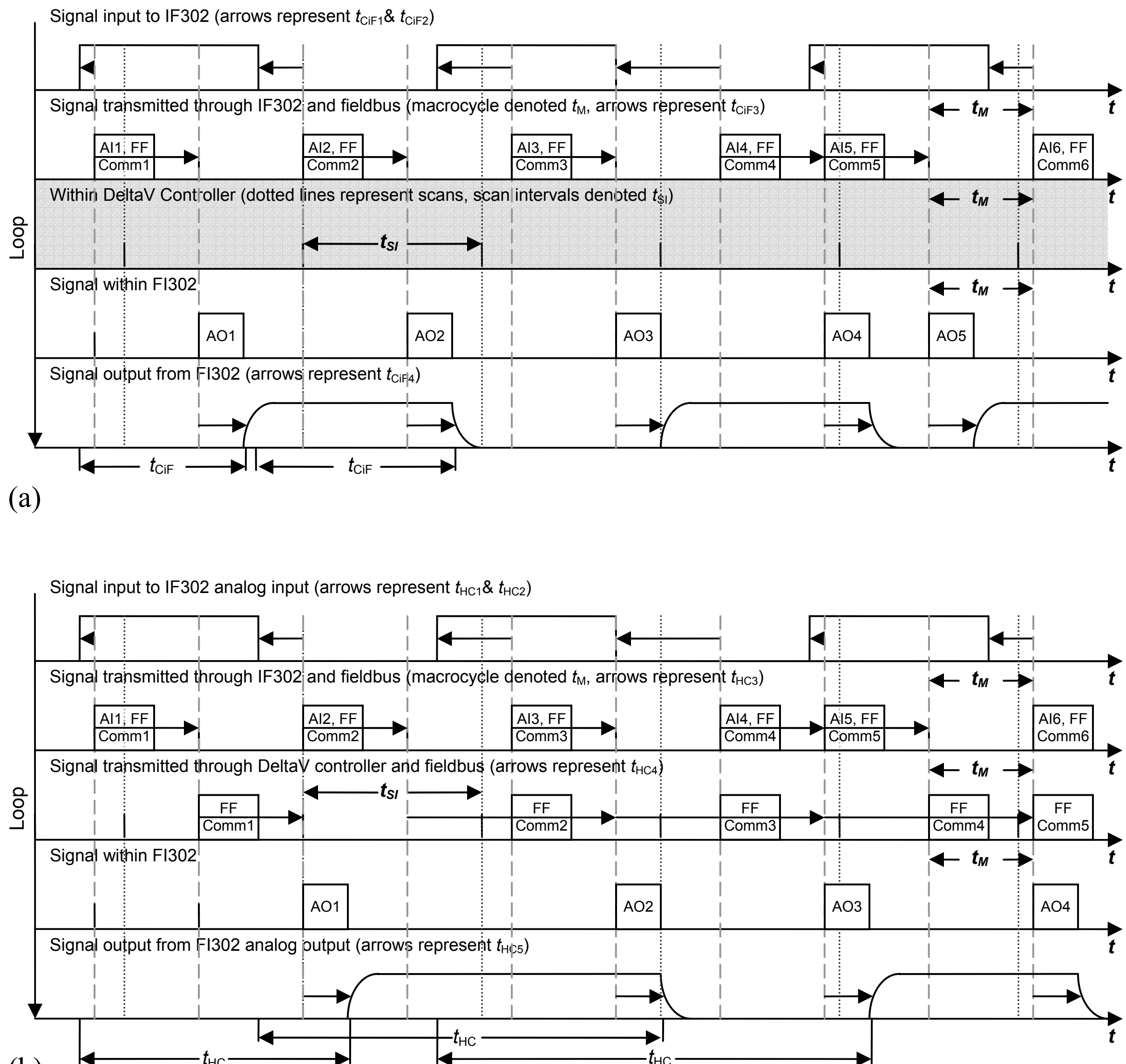
The test results in this section will be used as a benchmark for investigating the effects of the FF H1 network in the next section.

4. Analysis and Tests on DCS using FF H1 network

When a FF H1 network is used, the macrocycle of the FF H1 network, which is denoted by t_M, determines how often the input signals are sampled and transmitted over the network. The smallest possible macrocycle is dependent on communication configurations, such as the number of FF H1 devices on the network. The macrocycle must be shorter than the scan rate to ensure that the DeltaV controller always has the latest data to process [14].

In addition to the scan rate and the macrocycle, control mode is also an important configurable parameter. Control mode can be either control in the field or hybrid control. If all functions blocks are downloaded to the field devices, the control mode is called control in the field; otherwise the control mode is called hybrid control. The control in the field mode can reduce network load, thus a shorter macrocycle can be implemented; while the hybrid control mode can implement more advanced control algorithms, but a longer macrocycle is required. The test results will not be influenced by the scan rate when the control in the field mode is used, because no communication between field devices and the DeltaV controller is required in this control mode [14].

Figure 5 shows the timing diagram of the DeltaV DCS using the FF H1 network. Note that the AI function block, the AO function block, and the FF H1 communication are performed at every macrocycle, but only those involved in the transmission of the rises/falls of the signals are presented.



(a)

(b)

Figure 5 Timing diagram of the DeltaV DCS using FF H1 network with (a) the control in the field mode and (b) the hybrid control mode

When the FF H1 network is used with the control in the field mode, the loop-back time t_{CiF} can be divided into 4 components, as show in Figure 5.

1) t_{CiF1} is the time slice between the time that the step change of the FF AI signal occurs and the time that the IF302 starts to process the step change. This time slice is assumed to follow a uniform distribution between 0 and one macrocycle.
2) t_{CiF2} is the time that the IF302 processes the step change so that the information is ready for its AI block to use. The time is independent of the macrocycle.
3) t_{CiF3} is one macrocycle that is needed to transmit the data from the IF302 to the FI302. That is because in the FF H1 network, the AI and AO blocks are scheduled to run before the transmission of data. As a result, when the FI302 receives the new data from the IF302, the

AO block has already been executed, and an additional macrocycle is needed for the FI302 to output the updated signal. The execution of the IF302's AI block and the communication between the IF302 and the FI302 are nested within this macrocycle.

4) t_{CiF4} is the time slice between the time that the FI302's AO block is executed and the time that the FF AO signals complete 10% of the overall rise/fall. This component is independent of the macrocycle.

If the communication between the IF302 and the FI302 can be arranged between the execution of the AI block and the AO block, all the three will be performed within one macrocycle instead of two macrocycles. As a result, the loop-back time can be significantly reduced.

When the FF H1 network is used with the hybrid control mode, the loop-back time t_{HC} can be divided into 5 components, as show in Figure 5. Among the 5 components, t_{HC1} corresponds to t_{CiF1}, t_{HC2} corresponds to t_{CiF2}, t_{HC4} corresponds to t_{CiF3}, and t_{HC5} corresponds to t_{CiF4}. The time t_{HC3} is the time that the DeltaV controller has to wait to retrieve new data from DeltaV FF H1 card, and send the data to the FI302. Since the DeltaV controller only retrieves the data once every scan interval, this will take one or more macrocycles depending on how big the scan rate is. Therefore, t_{HC} is dependent on both the macrocycle and the scan rate.

In addition to the loop-back time, rise/fall time and additional delay are also needed to investigate the effects of the FF H1 network. Rise/fall time is defined as the difference between the time that the FF AO signals complete the initial 10% of the overall rise/fall and the time that the FF AO signals completes 90% of the overall rise/fall. Additional delay is defined as the difference between the measured average loop-back time when hardwires and FF H1 network are used respectively with the same scan rate.

Next, the relationships between the three indexes and their influence factors are investigated. The control mode, the scan rate, and the macrocycle are varied throughout the tests to examine their influences.

The control in the field mode is used in the first batch of tests. During the tests, the AI and AO function blocks are downloaded to the field devices; and the data are configured to be sent from the IF302 to the FI302 directly. The frequency of the square test signal is set to 0.25Hz. The test signals are time shifted each instance to cover one macrocycle; and the tests last 5 cycles for each time shift position.

Figure 6 shows typical test results, which are obtained when the scan rate is 200ms and the macrocycle is 150ms. In the figure, the FF AI signal is the signal sent into the IF302 and the FF AO signal represents the output signal from the FI302. The figure demonstrates that the FF H1 network introduces some first-order dynamics in addition to pure delays. The measured average rise/fall time of FF AO signals is 640ms, which changes little for different combinations of the scan rate and the macrocycle. That is because the first-order dynamics are mainly due to the low pass filter within the FI302.

Table 2 presents measured loop-back time for each combination of the macrocycle and the scan rate. The table shows that raising the macrocycle increases the loop-back time and its variance. It also confirms that raising the scan rate does not influence the test results.

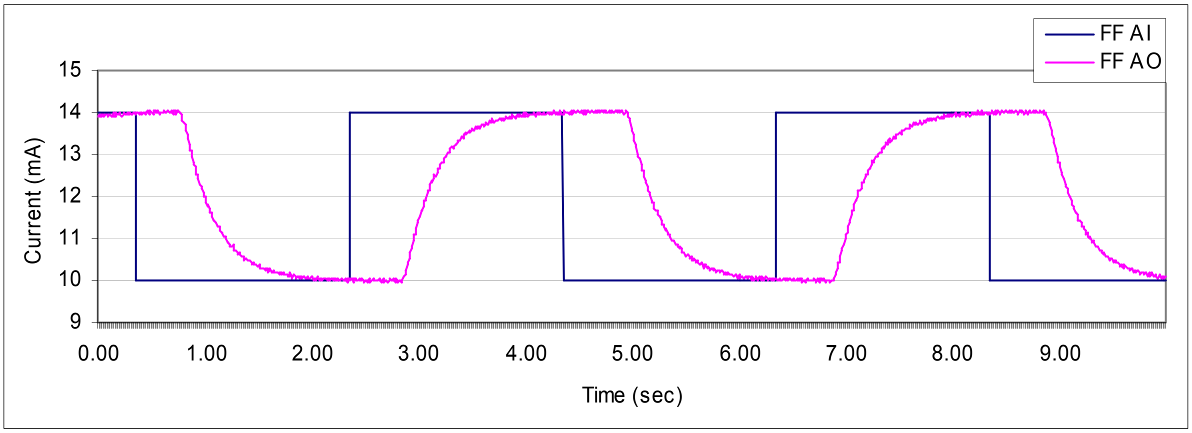


Figure 6 Typical test results when the FF H1 network is used

Table 2 Measured loop-back time with the control in the field mode

Macrocycle (ms)	Scan Rate (ms)	Measured Loop-back Time				
		Mean (ms)	Std. Dev. (ms)	Min (ms)	Median (ms)	Max (ms)
150	200	574	94	300	570	770
150	1000	575	93	320	570	780
250	1000	730	106	470	730	990
500	1000	1096	167	680	1090	1470

The hybrid control mode is used in the second batch of tests. The AI and AO function blocks are downloaded to the field devices, and a simple calculation block is downloaded to the DeltaV controller. The calculation block is the simplest function block, which receives the data from the AI block and sends the data to the AO block without any processing. During the tests, the frequency of the square test signal remains 0.25Hz; the time shifts of the test signals are able to cover one macrocycle plus one scan interval; and the tests are performed over 5 cycles for each time shift position. The test results are presented in Table 3.

Table 3 Measured loop-back time with the hybrid control mode

Macrocycle (ms)	Scan Rate (ms)	Measured Loop-back Time				
		Mean (ms)	Std. Dev. (ms)	Min (ms)	Median (ms)	Max (ms)
165	200	874	124	520	870	1270
165	500	1017	159	580	1010	1450
250	500	1323	224	800	1310	1910

Table 3 demonstrates that raising the scan rate and/or the macrocycle increases the loop-back time and its variance. However, it does not affect the rise/fall time of the FF AO signals, as it remains about 640ms and is apparently independent of the scan rate and the macrocycle.

Comparisons between Table 2 and Table 3 demonstrate that the loop-back time can be significantly influenced by the control mode, as the control in the field mode has introduced much shorter delays than the hybrid control mode. However, the rise/fall time of the FF AO signals is not affected by the control mode. In addition, comparisons between Table 1, Table 2 and Table 3 demonstrate that the loop-back time is significantly longer when the FF H1 network is used to substitute for the hardwires.

5. Modelling of network's effects

According to the above test results, the effects of substituting a FF H1 network for hardwires can be modeled as a pure delay together with first-order dynamics.

$$F(s) = \frac{e^{-\tau s}}{\tau' s + 1} \tag{1}$$

where τ is a pure delay dependent on several factors, while the time constant τ' is 290ms, as the average rise/fall time of FF AO signals is 640ms. In the model, τ can be estimated when the control mode, the macrocycle and the scan rate are given.

When hardwires are used, t_{HW1} is a random variable which follows uniform distribution between 0 and one scan interval, while t_{HW2} is a constant. Therefore, the average t_{HW1} is $0.5t_{SR}$, and t_{HW2} is determined to be 99ms using the measured average loop-time when the scan rate is set to be 100ms. As a result, the following equation can be used to estimate the average loop-back time:

$$\overline{t}_{HW} = 0.5t_{SR} + 99 \tag{2}$$

where $\overline{t}_{HW}$ is the average loop-back time when hardwires are used.

According to the analysis of t_{CiF} in Section 4, the average of t_{CiF1} is equal to $0.5t_M$, and t_{CiF3} is equal to t_M. The sum of t_{CiF2} and t_{CiF4} is determined to be 350ms using the measured average loop-time when the macrocycle is set to be 150ms. Therefore, the following equation can be used to estimate the average loop-back time:

$$\overline{t}_{CiF} = 1.5t_M + 350 \tag{3}$$

where $\overline{t}_{CiF}$ is the average loop-back time when the FF H1 network is used with the control in the field mode.

If the control in the field mode is used, the following equation can estimate the additional delay that is beyond the benchmark loop-back time when hardwires are used:

$$\overline{\tau}_{\mathrm{CiF}} = 1.5t_{\mathrm{M}} - 0.5t_{\mathrm{SR}} + 251 \tag{4}$$

where $\overline{\tau}_{\mathrm{CiF}}$ is the average additional delay when the FF H1 network is used with the control in the field mode.

According to the analysis of t_{HC} in Section 4, the key is to estimate t_{HC3} when the hybrid control mode is used. If $t_{\mathrm{M}} \le t_{\mathrm{SR}} \le 2t_{\mathrm{M}}$, the probability for the execution of the calculation block to occur within one macrocycle is $t_{\mathrm{M}}/t_{\mathrm{SR}}$, while the probability for the execution of the calculation block to occur not within one macrocycle but within the next macrocycle is $(t_{\mathrm{SR}}-t_{\mathrm{M}})/t_{\mathrm{SR}}$. In the former case, t_{HC3} is one macrocycle; in the latter case, t_{HC3} is two macrocycles.

If $t_{\mathrm{M}} \le t_{\mathrm{SR}} \le 2t_{\mathrm{M}}$, the following equation can be derived to estimate the average loop-back time:

$$\overline{t}_{\mathrm{HC}} = \frac{2.5{t_{\mathrm{M}}}^2}{t_{\mathrm{SR}}} + \frac{3.5(t_{\mathrm{SR}} - t_{\mathrm{M}})t_{\mathrm{M}}}{t_{\mathrm{SR}}} + t_{\mathrm{HCF}} \tag{5}$$

where $\overline{t}_{\mathrm{HC}}$ is the average loop-back time when the FF H1 network is used with the hybrid control mode, and t_{HCF} is the sum of t_{HC2} and t_{HC5}.

If $2t_{\mathrm{M}} \le t_{\mathrm{SR}} \le 3t_{\mathrm{M}}$,

$$\overline{t}_{\mathrm{HC}} = \frac{2.5{t_{\mathrm{M}}}^2}{t_{\mathrm{SR}}} + \frac{3.5{t_{\mathrm{M}}}^2}{t_{\mathrm{SR}}} + \frac{4.5(t_{\mathrm{SR}} - 2t_{\mathrm{M}})t_{\mathrm{M}}}{t_{\mathrm{SR}}} + t_{\mathrm{HCF}} \tag{6}$$

In Equations 5 and 6, t_{HCF} is determined to be 433ms using the measured average loop-back time when the macrocycle is 165ms and the scan rate is 250ms.

If the hybrid control mode is used and $t_{\mathrm{M}} \le t_{\mathrm{SR}} \le 2t_{\mathrm{M}}$, the following equation can estimate the additional delay that is beyond the benchmark loop-back time when hardwires are used:

$$\overline{\tau}_{\mathrm{HC}} = \frac{2.5{t_{\mathrm{M}}}^2}{t_{\mathrm{SR}}} + \frac{3.5(t_{\mathrm{SR}} - t_{\mathrm{M}})t_{\mathrm{M}}}{t_{\mathrm{SR}}} - 0.5t_{\mathrm{SR}} + 334 \tag{7}$$

where $\overline{\tau}_{\mathrm{HC}}$ is the average additional delay when the FF H1 network is used with the hybrid control mode.

Table 4 presents the comparisons between the estimations by the above equations and the measurements. All the estimations are accurate except the estimation when the hybrid control mode is used, the macrocycle is 250ms and the scan rate is 500ms. That is because both the macrocycles and the scan intervals are not deterministic. As a result, when the scan rate is equal to two macrocycles, t_{HC3} could be equal to three or more macrocycles.

Table 4 Comparisons between estimated and measured loop-back time

Communication Option and Control Mode	Macrocycle (ms)	Scan Rate (ms)	Estimated Average Loop-back Time (ms)	Measured Average Loop-back Time (ms)
Hardwires	-	200	199	197
	-	500	349	351
FF H1 network with Control in the Field	250	-	725	730
	500	-	1100	1096
FF H1 network with Hybrid Control	165	500	1014	1017
	250	500	1183	1323

In Equations 4 and 7, the constant terms stand for the additional delays not due to communication. Therefore, if the scan rate is 200ms and the macrocycle is 150ms (or 165ms in the case of the hybrid control mode), only 126ms of the 377ms additional delays are communications delays if the control in the field mode is used, and 343ms of the 677ms additional delays are communications delays if the hybrid control mode is used.

6. Conclusions

In this paper, a FF H1 network's effects in a NCS are systematically investigated. Compared with the benchmark results of tests on the DeltaV DCS using the hardwires, the results of the tests on the DCS using the FF H1 network demonstrate that only some of the additional delays introduced by substituting the FF H1 network for the hardwires are communication delays. The tests also indicate that in the NCS, delays are mainly dependent on the control mode adopted, the scan rate of the control program in the DeltaV controller, and the macrocycle of the FF H1 network.

New models of networks' effects in NCS are developed based on the test results. The new models consider the influences of the control mode, the macrocycle and the scan rate directly, and are easier and more practical to use in real-world applications. Moreover, the new models consider not only communication delays, but also the additional delays due to processors, ADC/DAC, and filters of lower performance specifications present in the field devices.

Though the models are developed using the results of the tests on the specific NCS consisting of the DeltaV DCS and the SMAR converters, they can be used to estimate networks' effects in other NCSs using FF H1 networks as well. However, the constant terms of the equations will need to be recalibrated.

The study also suggests several ways to reduce delays. First, it confirms that the control in the field mode should be used whenever possible, and both the scan rate and the macrocycle should be set to be smallest possible. Second, if the hybrid control mode is used, the scan rate should be longer than one macrocycle, but shorter than or equal to two macrocycles. Third, delays can be significantly reduced if the FF H1 communication can be scheduled between the execution of the AI and the AO function blocks.

7. References

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