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COMPARATIVE ANALYSIS BETWEEN CONTROL IN THE HOST AND CONTROL IN THE FIELD IN TERMS OF SAFETY AND AVAILABILITY FOR FOUNDATION FIELDBUS-BASED PROCESS CONTROL

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Abstract. *Design work of process control to provide necessary performance requirements must be based on capabilities and limitations of the technology used. This paper aims at analyzing possible safety and availability enhancements of basic process control based on Foundation Fieldbus (FF) technology in which the control function blocks can be assigned either in the host system controller, called 'Control in the Host' (CIH), or in the field devices, called 'Control in the Field' (CIF). Implementing the control loops with CIH and CIF strategies for water tank process is utilized as a case study to demonstrate the proposed analysis. The major configuration details of field devices, control strategies, and function blocks are described. Experimental results were analyzed for examining the parameter options as well as the control loop actions in response to invalid measurements to compare the safety and availability improvements between the CIH and the CIF. The proposed analysis can be useful to enable economical solutions for design phase of the FF-based control loops.*
Keywords: Foundation Fieldbus, Process control, Safety, Availability, Control in the host, Control in the field, Function block

1. **Introduction.** Foundation Fieldbus (FF) specially designed for process control applications is one of industrial automation technologies in the IEC 61158 standard, which can be the starting point for digital transformation of field device networks in plant modernization. The FF function block specification is also compliant with the IEC 61804 standard, which can be the basis for interoperability between various field devices and host system from different suppliers [1]. Compared to traditional analog instrumentation and control, the FF not only reduces the hardware components of system architecture but also provides a wide range of new capabilities [2,3]. Some examples of these capabilities include more powerful instruments, more process and device data available, and more advanced diagnostics. Inevitably, the FF necessitates some new engineering and design practices [4-7]. In addition, the FF specification is uniquely different from other digital fieldbuses for process industry sector in that it has the ability to perform control function, which is distributed into field devices. This control strategy based on field device capability is referred as 'Control in the Field' (CIF). It is an alternative to traditional control

strategy using a host system controller, which is called 'Control in the Host' (CIH). The CIF shall be employed for Proportional-Integral-Derivative (PID) and cascade control strategies when installing all associated field instruments within the same FF H1 network [8]. Based on the FF technology, end users then have flexibility in designing their plant automation infrastructure. Although the FF can provide a broad range of benefits, there are still obstacles to the technology adoption for end users to actually achieve its advantages. One of major impediments to effective use of this technology is the underutilization of device information available such as measurement validations and detailed diagnostics. In order to perform the required functionalities, a number of parameter options of function blocks within FF field devices must be configured in engineering phase. The correctness of device and control strategy configurations is crucial for achieving the FF advantages. It is therefore important that stakeholders of a revamping or new plant project should truly understand both capabilities and limitations of the FF technology for control system design and implementation to meet maximized benefits.

The self-diagnostic and self-validation capabilities of FF field instruments can be used to increase the safety and availability of basic process control systems in the event of a fault beyond that found in basic control systems using conventional analog signal transmission [9-12]. A suggestion on how to use a failure-safe mechanism based on FF function blocks for increasing the safety of PID control loop has been introduced [9]. However, there are no experimental results verifying the effectiveness of this proposed suggestion. A method on how to fully benefit from FF function blocks for enhancing the safety of cascade control loop has been presented [10]. This proposed method describes how different configurations of function block options affect the actions of cascade control loop in the event of abnormal conditions. However, the operating mode shedding of function blocks and the fault recovery of control loop are not discussed. A technique on how to configure the FF function blocks within field devices for balancing between safety and availability of the PID and cascade control loops has been reported [11]. This proposed technique introduces how different configuration options affect the control loop behaviors concerned with the function block mode shedding in response to measurement validations and the fault recovery after correcting device failures. Nevertheless, these useful techniques presented in [9-11] focus on improving the safety and availability of PID and cascade control loops based on CIF only. The right balance between safety and availability for control loops based on CIH is not examined. Recently, the Petri net modeling of the PID and cascade control loops based on CIH and CIF to represent the control loop behaviors in terms of safety and availability enhancement has been presented [12]. However, only the experimental results confirming the correctness of the proposed model for the PID control loop with CIH are shown in the article. The purpose of this paper therefore is to compare and analyze the behaviors of the PID and cascade control loops with CIH and CIF for improving the safety and availability to provide the proven guideline. An FF-based water tank process for liquid level control that is essential in most process industries such as oil and gas, food and beverage, and chemical processing is used as a case study for realizing the interested control loops. Based on experimental results, the options of function block parameters and the actions of CIH-based and CIF-based control loops were intensively investigated for possible improvements of the safety and availability.

This paper is organized into five sections. After the Introduction, Section 2 introduces the process control using FF technology. Section 3 details the case study on water tank process operated by the DeltaV host system. Section 4 describes the experimental results and discussion for balancing the interests of safety versus availability when realizing the PID and cascade loops using CIH and CIF. Finally, Section 5 gives the conclusions.

2. **FF-Based Process Control.** The FF-based control loop is a group of software function blocks connected by links to perform the monitoring and control functions for the process. Figures 1(a) and 1(b) show the function block diagrams for executing control strategies of the PID loop and cascade loop, respectively [13]. The PID loop consists of three function blocks and three links, while the cascade loop consists of five function blocks and six links. The analog input (AI) and analog output (AO) blocks are placed in the measuring and actuating devices, respectively. The PID function blocks are located in the host controller for creating the CIH-based control loops, whereas they can be assigned to either the measuring device or the actuating device for creating the CIF-based control loops. To minimize the scheduled communications over the FF H1 network, the PID function blocks are preferably located in the actuating device [14,15]. Table 1 summarizes the normal operating mode and operational description of the function blocks used to build the PID and cascade control loops of Figure 1.

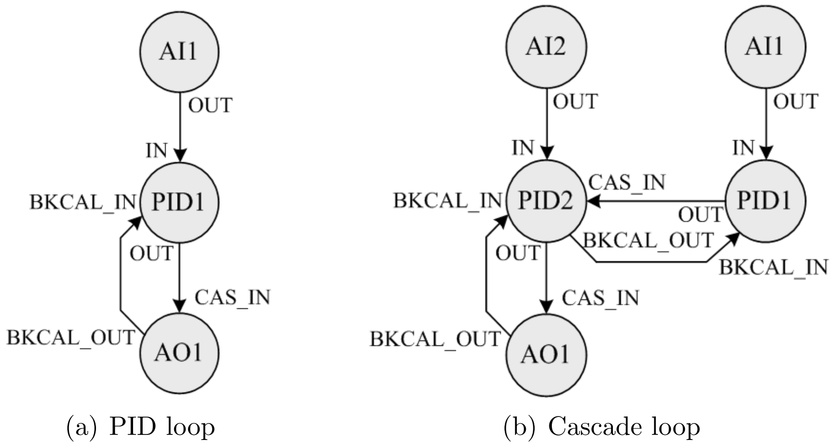

FIGURE 1. Function block diagrams for FF-based basic process control [13]

TABLE 1. FF function blocks used for configuring PID and cascade loops of Figure 1

Block	Control Loop	Normal Mode	Operational Description
AI1	PID, Cascade	Automatic	Processing primary measurement value and status from the I/O channel parameter to be available for the PID1.
AI2	Cascade	Automatic	Processing secondary measurement value and status from the I/O channel to be available for the PID2.
PID1	PID, Cascade	Automatic	Receiving the AI1 output and the operator-entered setpoint in determining the block output.
PID2	Cascade	Cascade	Receiving its cascade setpoint from the PID1 output as well as the secondary measurement value and status from the AI2 output, and calculating the block output.
AO1	PID, Cascade	Cascade	Fetching and scaling the upstream block output and passing to the I/O channel for manipulating the process.

3. **Case Study on Water Tank Process.** The water tank process is a good process to use as an illustrative case study for investigating the control loop actions in response to the event of field device failure because its dynamic behavior is reasonably intuitive. Moreover, this process is an example of combined level and flow control. The water level in a tank and the inlet flow rate in a pipeline can be controlled individually or together; thus the PID or cascade control strategy can be created easily in the water tank process. In level-to-flow cascade architecture, the water level is the primary process variable, while the inlet flow rate is the secondary process variable. Figure 2 illustrates a schematic diagram of the water tank process integrated into the DeltaV Distributed Control System (DCS), which is utilized as the case study for analyzing possible safety and availability improvements of the FF-based process control. Three FF field devices installed in the studied process on the H1 network are the LIT_101 level transmitter for measuring the water level in the tank, the FIT_101 flow transmitter for measuring the inlet flow rate of water to the tank, and the FCV_101 control valve positioner for regulating the water flow rate. Table 2 gives major details of the FF field instruments in Figure 2. The DeltaV DCS was used as the host system for configuring control strategies and device function blocks as well as for commissioning and operating the water tank process in experiments. From Figure 1, the function block placements for building the PID and cascade control loops with CIH and CIF strategies are shown in Table 3 for our case study, where the PID function blocks are located in the DCS host controller and the FCV_101 valve positioner for the CIH and the CIF, respectively. For configuring the PID loop, the AI1 and AO1 blocks are located in the LIT_101 and the FCV_101 for tank level measurement and inlet flow manipulation, respectively. For creating the cascade loop, the primary AI1 and

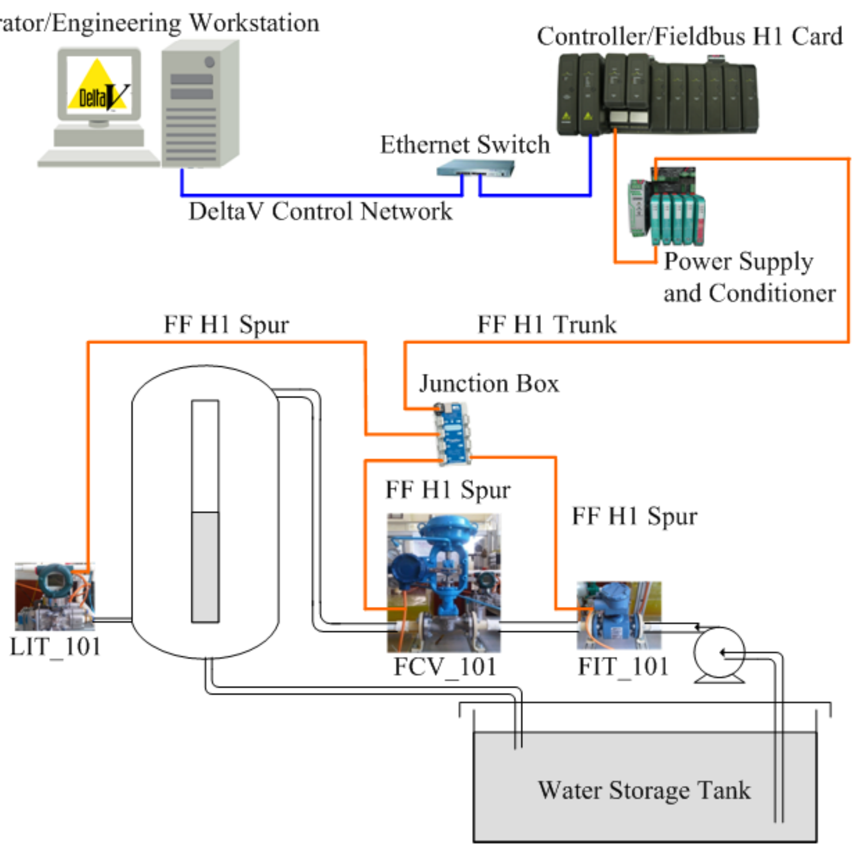

FIGURE 2. Diagram of the water tank process integrated into the DeltaV host system

Table 2. Major details of FF H1 instruments installed in the studied water tank process

Item	LIT_101	FIT_101	FCV_101
Manufacturer	Yokogawa	Emerson Process Management	Azbil
Device Model	EJX110A	Rosemount 8732E	AVP303
Device Revision	3	2	2
H1 Device Class	Link Master	Link Master	Basic
Number of AI blocks	3	1	N/A
Number of PID blocks	1	1	2
Number of AO blocks	N/A	N/A	1

Table 3. Placements of function blocks for building the control loops in Figure 1

Control Loop	Function Block	CIH Strategy	CIF Strategy
PID	AI1	LIT_101	LIT_101
	PID1	DCS Controller	FCV_101
	AO1	FCV_101	FCV_101
Cascade	AI1	LIT_101	LIT_101
	AI2	FIT_101	FIT_101
	PID1	DCS Controller	FCV_101
	PID2	DCS Controller	FCV_101
	AO1	FCV_101	FCV_101

Table 4. Options in the AI and AO blocks to improve the safety and availability [12]

Parameter	Option	Description	Safety	Availability
STATUS_OPTS	Uncertain if Limited	Set the output status of the block to 'Uncertain', if the measured value is limited.	Enable	Disable
	Bad if Limited	Set the output status of the block to 'Bad', if the sensor is at a high or low limit.	Enable	Disable
	Uncertain if Man mode	Set the output status of the block to 'Uncertain', if the actual mode of the block is in manual mode.	Enable	Disable
IO_OPTS	Fault State to value	Determine the output action to take when a fault occurs	Enable	Disable
	Use Fault State value on restart	Use the FSTATE_VAL as the initial output value on restart.	Enable	Disable

secondary AI2 blocks are assigned to the LIT_101 and FIT_101 for tank level and inlet flow measurements, respectively, and the AO1 block is located in the FCV_101 for fluid flow regulation.

In order to improve the safety and availability of the FF-based control loops, the key parameter options in the AI and AO blocks to be enabled or disabled are shown in Table 4

[12]. If the AI block operation is in automatic (Auto) mode, the OUT parameter reflects the value and status quality of the PV. The measurement validity of the OUT is indicated by its status attribute (Good, Uncertain, or Bad), where the 'Good' status can assume that the OUT is valid and can be used for further processing, the 'Uncertain' status can suppose that the OUT can only be used for further processing to a limited extent, and the 'Bad' status can deduce that the OUT is invalid. If the AO block operation is in cascade (Cas) mode, the CAS_IN parameter provides the analog setpoint value, and the back calculation output (BKCAL_OUT) parameter is linked to the back calculation input (BKCAL_IN) of the upstream block that provides CAS_IN to offer the bumpless transfer on operating mode changes and the windup protection in the upstream block. Table 5 gives the interested valid options of the STATUS_OPTS and CONTROL_OPTS parameters in the PID blocks located in the DeltaV host system controller and the FCV_101 control valve positioner. It is seen that the 'IFS if BAD IN' and 'IFS if BAD CAS_IN' options are not available in the PID block when assigning it in the host system controller.

Table 5. Valid options in the PID blocks assigned in the host controller and the H1 device

Parameter	Option	Description	Host	H1 Device
STATUS_OPTS	IFS if BAD IN	Set 'Initiate Fault State' status in the OUT, if the IN parameter status is BAD.	N/A	√
	IFS if BAD CAS_IN	Set 'Initiate Fault State' status in the OUT, if the CAS_IN parameter status is BAD.	N/A	√
	Target to Manual if BAD IN	Set the target mode to Man, if the IN parameter status is BAD.	√	√
	Use Uncertain as Good	Consider the IN parameter status as GOOD when the status is actually Uncertain.	√	√
CONTROL_OPTS	Bypass Enable	Enable the 'BYPASS'.	√	√

4. **Experimental Results and Discussion.** The safety and availability are normally two conflicting purposes for basic process control system [3]. In the event of failure, the control loop must be shut down for safety goal. On the other hand, the control loop must be able to perform for availability goal. In order to examine the possible improvements of safety and availability of the PID and cascade control loops using CIH and CIF strategies, how different configurations in the status and control options in the PID function blocks located in the host system controller and the control valve positioner as given in Table 5 affect the control loop actions in the case of invalid measurements were intensively investigated, and many experiments with different configurations in parameter options were conducted to control the water level in the tank of Figure 2 under the mimic failures to cause the 'Uncertain' and 'Bad' statuses of the AI1 and AI2 blocks for verifying the enabled function block options. Table 6 summarizes the parameter options in the PID function blocks of the studied control loops to be enabled or disabled for balancing the interests of safety versus availability when implementing the control loops using CIH and CIF strategies.

The actions of the PID and cascade control loops with increased safety in response to invalid measurements are shown in Tables 7 and 8, respectively. Similarly, in case of

TABLE 6. Options in the PID blocks for improving the safety and availability of the loops

Block	Control Loop	Parameter Option	Safety		Availability	
			CIH	CIF	CIH	CIF
PID1	PID, Cascade	IFS if BAD IN	N/A	Enable	N/A	Disable
		Target to Manual if BAD IN	Enable	Enable	Disable	Disable
		Use Uncertain as Good	Disable	Disable	Enable	Enable
PID2	Cascade	IFS if BAD IN	N/A	Enable	N/A	Disable
		IFS if BAD CAS_IN	N/A	Enable	N/A	Disable
		Target to Manual if BAD IN	Enable	Enable	Disable	Disable
		Use Uncertain as Good	Disable	Disable	Enable	Enable
		Bypass Enable	Disable	Disable	Enable	Enable

TABLE 7. Actions of the PID control loop with increased safety

<table>
<tr><th rowspan="2">AI1 OUT Status</th><th colspan="2">Actions for Safety Goal</th></tr>
<tr><th>CIH Strategy</th><th>CIF Strategy</th></tr>
<tr><td>Uncertain</td><td rowspan="2">Switch the PID1 from Auto to Man mode by freezing the OUT of AO1 in the last value. After the failure has been solved, the PID1 remains the 'failed' state in Man mode of operation.</td><td>Switch the PID1 from Auto to Man mode by freezing the OUT of AO1 in the last value. After the problem has been fixed, the control loop can resume the control immediately.</td></tr>
<tr><td>Bad</td><td>Change the target mode of the PID1 to Man, and switch the AO1 to local override (LO) mode by setting its OUT to the Fault State (predefined safe) value. After the failure has been fixed, the PID1 remains the 'failed' state in Man mode.</td></tr>
</table>

availability enhancement, the actions of the studied control loops with increased availability in response to invalid measurements are given in Table 9. It can be seen that the CIF-based control loops provide higher level of process safety especially in response to the status quality of 'Bad'. The fail-safe shutdown can be achieved by setting the control valve positioner to be the preset 'fail-safe' position, which is defined by enabling the 'IFS if Bad IN' and 'IFS if BAD CAS_IN' options (in the PID function block located in the field device only) and enabling the 'Fault State to value' option (in the AO function block). In addition, by enabling 'Target to Manual if BAD IN' option in the PID block (located in the field device or the host system controller) for deciding the fault recovery, the affected loop can continue the 'failed' state in Man mode until the operator switches to Auto mode (or Cas mode) to achieve higher safety. Otherwise, the affected loop can continue its operation immediately after the failure has been solved to obtain higher availability. Moreover, the FF H1 field instruments with the capabilities of self-validation and self-diagnostic can also differentiate between the serious failures and less serious failures by indicating 'Bad' status and 'Uncertain' status, respectively. The 'Uncertain' status can be configured to be treated either as 'Good' status to continue the control function of the loop for availability goal or as 'Bad' status to shut the process down or to fetch the control to manual operation for safety goal. The results from the proposed comparative analysis can be applied not only in choosing between CIH and CIF during project design phase but also in shortening the time for project engineering phase.

Table 8. Actions of the cascade control loop with increased safety

<table>
<tr><th rowspan="2">Block</th><th rowspan="2">OUT Status</th><th colspan="2">Actions for Safety Goal</th></tr>
<tr><th>CIH Strategy</th><th>CIF Strategy</th></tr>
<tr><td rowspan="2">AI1</td><td>Uncertain</td><td rowspan="2">Switch the PID1 from Auto to Man mode by freezing the OUT, the PID2 setpoint, in the last value. The secondary flow loop can be performed. After the problem has been solved, the PID1 remains its operation in Man mode.</td><td>Switch the PID1 from Auto to Man mode by freezing the OUT, the PID2 setpoint, in the last value. The secondary flow loop can be performed. After the problem has been fixed, the PID1 can return to operate in Auto mode instantly.</td></tr>
<tr><td>Bad</td><td>Switch the PID1 from Auto to Man mode by freezing the OUT in the last value. The secondary flow loop can be performed. After the problem has been fixed, the PID1 remains its operation in Man mode.</td></tr>
<tr><td rowspan="2">AI2</td><td>Uncertain</td><td rowspan="2">Change the target mode of the PID2 to Man by freezing the OUT in the last value. After the failure has been solved, the PID2 remains in Man mode by using the last value for restarting the valve positioner.</td><td>Switch the PID2 from Cas to Man mode by freezing the OUT in the last value. After the failure has been fixed, the flow loop can continue its operation instantly.</td></tr>
<tr><td>Bad</td><td>Change the target mode of the PID2 to Man, and switch the AO1 to LO mode by setting its OUT to the Fault State value. After the failure has been fixed, the PID2 remains its operation in Man mode by setting the Fault State value as the initial position for restarting the positioner.</td></tr>
</table>

Table 9. Actions of the studied PID and cascade loops with increased availability

<table>
<tr><th rowspan="2">Control Loop</th><th rowspan="2">Block</th><th rowspan="2">OUT Status</th><th colspan="2">Actions for Availability Goal</th></tr>
<tr><th>CIH Strategy</th><th>CIF Strategy</th></tr>
<tr><td rowspan="2">PID</td><td rowspan="2">AI1</td><td>Uncertain</td><td colspan="2">The ‘Uncertain’ status is treated as ‘Good’. The loop is operated in Auto mode.</td></tr>
<tr><td>Bad</td><td colspan="2">Actions are similar with that of the CIF-based PID loop with increased safety in response to ‘Uncertain’.</td></tr>
<tr><td rowspan="4">Cascade</td><td rowspan="2">AI1</td><td>Uncertain</td><td colspan="2">The ‘Uncertain’ status is treated as ‘Good’. The PID1 is operated in Auto mode.</td></tr>
<tr><td>Bad</td><td colspan="2">Actions are similar with that of the CIF-based cascade loop with increased safety in response to the OUT status of AI1 of ‘Uncertain’.</td></tr>
<tr><td rowspan="2">AI2</td><td>Uncertain</td><td colspan="2">The ‘Uncertain’ status is treated as ‘Good’. The PID2 is operated in Cas mode.</td></tr>
<tr><td>Bad</td><td colspan="2">Actions are similar with that of the CIF-based cascade loop with increased safety in response to the OUT status of AI2 of ‘Uncertain’.</td></tr>
</table>

5. **Conclusions.** In this paper, the experimental analysis for comparing the safety and availability improvements of the FF-based PID and cascade control loops using CIH and CIF has been described. The results obtained from experiments in the case study verify that the function block options for handling measurement status and deciding the fault

recovery as well as the capabilities for detecting field device failures and reporting diagnostic and measurement validity data provide the user the ability to increase the process safety or availability for each individual control loop. The CIH-based process control is traditionally targeted toward high availability, whereas the CIF-based process control is more selective strategy to offer the high level of safety or the high degree of availability. Further modeling of the analysis results for ease of understanding of the system behaviors will be needed. In addition, a reliability analysis of the studied control loops is also the future work.

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