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AVAILABILITY THROUGH FIELD DEVICE DIAGNOSIS IN FEEDFORWARD CONTROL: A CASE STUDY OF FOUNDATION FIELDBUS-BASED TEMPERATURE CONTROL

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Abstract. *For endusers, requiring an action to enable a fieldbus-based process control that is not hazardous to continue its operation in the event of transmitter failures, it is essential to understand how diagnostic capability of field instruments is helpful in availability enhancement. In order to effectively implement a feedforward control strategy with increased availability, this article presents a control configuration method when utilizing a Foundation Fieldbus (FF)-based temperature feedforward control as an illustrative case study. Four function block assignment options for configuring the studied control strategy during engineering phase are described. The 'Uncertain' measurement status provided by temperature transmitters is treated as 'Good' measurement status in all control configuration options for availability goal by reducing process downtime. In addition, based on experimental results, a simplified Petri net model for logical behavior representation of the interested FF-based feedforward is also proposed.*

Keywords: Availability, Device diagnosis, Foundation Fieldbus, Feedforward control, Field instrument, Function block, Measurement status

1. **Introduction.** An installation of digital sensor/instrument networks at the field level of automation systems to provide reliable measurements is the first step in a phased approach for implementing 'Industrial Internet of Things' architecture for plant modernization in the era of digitalization [1-3]. Based on features of network-enabled assess management to expand an operator's view to a plant floor, all field device data including measurement validity statuses can be remotely accessed from a host system at a central control room for commissioning, operating, and maintenance tasks [4-6]. A digital data transmission enables software applications to directly operate with smart field devices throughout the plant for data collection, processing, and analysis to manage assets effectively [7-9]. Nowadays, device diagnostic information becomes a natural part of process monitoring tasks and predictive maintenance practices [10,11]. Typically, key operating issues of smart field instruments provided with diagnostic functions can be determined that an intermediate repair task is needed to prevent process upsets, or it can be delayed until scheduled maintenance period. Plant personnel are always kept informed, if field device operations are questionable, so they can take necessary actions for locating and resolving problems to maintain production. The self-diagnostic capabilities of field instruments using Foundation Fieldbus (FF) H1 with fixed data transfer rate of 31.25 kbps also provide considerable opportunities of process control improvement in terms of safety and

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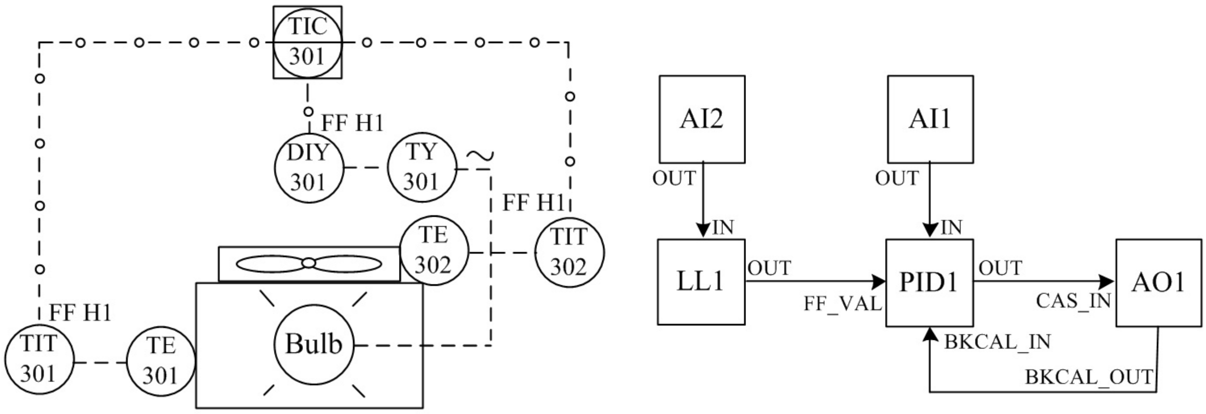
availability [12,13]. With a loop-by-loop basis, it is possible to choose the desired loop actions to be taken in the presence of transmitter failures, which are aimed at either plant safety or production availability. To achieve the safe action in the presence of invalid measurements, the affected control loops should be automatically shut down and brought to their predefined safe state without operator intervention. On the other hand, to achieve the good availability in the event of uncertain measurements, the affected control loops should be continued their functions. Acting on diagnostic and validity information provided by FF H1 transmitters for two basic control strategies, proportional-integral-derivative (PID) and cascade, by utilizing the 'Control in the Field' approach has been introduced [12]. Moreover, possible safety and availability improvements when utilizing the 'Control in the Host' approach to build the PID and cascade loops have been described [13]. A configuration technique during engineering phase for enhancing process safety of an FF-based feedforward control loop in hybrid architecture has been recently proposed [14]. Logical behaviors of the studied loop with increased safety in different levels from five possible cases to configure the interested parameters of function blocks used have been discussed. In order to gain relevant advantages of field device diagnosis for enhancing availability of the FF-based feedfoward control loop with dynamic compensation by using a lead-lag (LL) function block, effects of different measurement statuses as well as effects of different function block assignments on control actions in case of transmitter failures are addressed in this article. The loop actions from experimental tests in the event of 'Good', 'Uncertain', and 'Bad' measurement statuses provided by the transmitters used in a case study of temperature feedforward control are illustrated, when assigning the function blocks for control strategy configuration in four different cases. Additionally, logical behaviors of the interested control loop with increased availability are represented by a simplified Petri net model.

The remainder of this article is structured as follows. Section 2 describes the FF-based temperature feedforward control, which is employed as the case study. Section 3 details the proposed control configuration method to provide the availability enhancement of feedforward control. Section 4 shows the experimental results and discussion. Lastly, Section 5 gives the conclusions and possible future work.

2. **Case Study on Temperature Feedforward Control.**

To demonstrate the proposed configuration method feasibility, the FF-based temperature feedforward control in Figure 1 is utilized as the case study [15]. The system includes three FF H1 field instruments (TIT_301, TIT_302, and DIY_301), one 4-20 mA device (TY_301), and an integrated host with H1 interface, which is the DeltaV distribution control system (DCS) for doing control and monitoring. The interface module modeled M-series Serial Interface is used to connect the FF H1 field devices to the DCS host. The temperature measured by the TIT_301 transmitter connected with TE_301 sensing element is the controlled parameter, while the temperature measured by the TIT_302 transmitter connected with TE_302 sensing element is the measured disturbance input. The controlled parameter and disturbance input are in range of 40°C-60°C and 20°C-60°C, respectively. The TIC_301 controller can be performed by the PID function block running on the FF H1 devices, DCS host, or H1 interface module. Tables 1 and 2 summarize major details of the devices used in Figure 1(a) and the function blocks used in Figure 1(b), respectively [15]. The feedforward control with lead-lag compensation is applied to improving the response time of the basic feedback control under disturbance due to cooling fan operation [16]. The output (OUT) parameter of the AI1 analog input block is linked to the input (IN) parameter of the PID1 control block. The received value is then stated as the process variable, which is employed in conjunction with the setpoint in the PID feedback algorithm. The OUT parameter of the AI2 analog input block is connected to the IN parameter of the LL1 lead-lag function block, and the OUT parameter of this block is also linked to the feedforward value (FF_VAL) parameter of the PID1 block, which supports the feedforward algorithm. The AO1 analog output block receives its cascaded 'set point' input (CAS_IN) from the OUT parameter of the PID1 block. The link between the back-calculation output (BKCAL_OUT) parameter of the AO1 block and the back-calculation input (BKCAL_IN) parameter of the PID1 block is used for providing anti-reset windup protection and bumpless transfer of closed loop control [17].



(a) Piping and instrumentation diagram (b) Function block diagram

FIGURE 1. Studied temperature feedforward control using FF technology [15]

TABLE 1. Tags, models, and functions of the devices used in Figure 1(a) [15]

Tag	Device model	Function
TE_301	–	Temperature sensing element of TIT_301 for measuring the controlled parameter, which is generated by a light bulb power.
TIT_301	Rosemount 3144P (FF H1)	Temperature transmitter with local indication, which contains the AI function blocks.
TE_302	–	Temperature sensing element of TIT_302 for measuring the disturbance input, which is caused by a cooling fan operation.
TIT_302	Yokogawa YTA320 (FF H1)	Temperature transmitter with local indication, which contains the AI function blocks.
TIC_301	–	PID controller supporting feedforward input and algorithm to combine with feedback output.
DIY_301	Smar FI302 (FF H1)	Signal converter with local indication, which contains the PID and AO function blocks.
TY_301	Sangi Electric SCR-1A030	Power regulator for adjusting the bulb supply.

Table 2. Details of the function blocks used in Figure 1(b) [15]

Block	Description
AI1	To condition the measured data of the controlled parameter from the transducer block and to output the processed data to the downstream PID1 function block.
AI2	To condition the measured data of the disturbance input from the transducer block and to output the processed data to the downstream LL1 function block.
PID1	To support the feedforward control in combination with feedback control algorithms that use proportional, integral, and derivative terms.
AO1	To process the value received from the upstream PID1 function block to output the executed data to the downstream transducer block.
LL1	To provide dynamic compensation of the input parameter by utilizing lead time function, lag time function, or combination of both two lead and lag functions.

3. **Control Strategy Configuration Method.** The control strategy configuration during engineering phase includes linking and configuring the function blocks, which offer a number of parameters to be configured in accordance with the user's requirements. The proposed configuration method for the control loop that is not hazardous is based on reducing shutdown actions caused by minor transmitter problems such as 'out-of-range' measured value to provide the higher degree of availability. With diagnostic capabilities, the FF H1 transmitters indicate 'Bad' or 'Uncertain' validity of their measurement result when detecting severe failures or less severe failures, respectively. These measurement statuses provide the user the ability to balance between process safety and production availability with respect to failures for each individual control loop [4,5]. It is possible that two control loops using the same measurement value accompanied by its status act differently when configuring the different option parameters [12,13]. Based on the DetlaV DCS host, the engineering software called 'Control Studio' was utilized for implementing and configuring the desired temperature feedforward control. In order to examine effects of different function block assignments on the control loop actions in the presence of transmitter failures, Table 3 shows four specified options for locating the function blocks in the diagram of Figure 1(b) to implement the hybrid architecture-based control loop [15]. The AI1 and AI2 analog input blocks are placed in the TIT_301 and TIT_302 temperature transmitters, respectively, while the AO1 analog output block is assigned in the DIY_301 converter. The LL1 block can be located in either the H1 interface module (for 'OPT1' and 'OPT2' options) or the DCS host controller (for 'OPT3' and 'OPT4' options). The PID1 control block can be located in the H1 interface module (for 'OPT1' option), the DIY_301 converter (for 'OPT2' and 'OPT3' options), or the DCS host controller (for 'OPT4' option). The 'Normal' mode of the function block is usually utilized in the host to

Table 3. Function block assignment options for control configuration of Figure 1(b) [15]

OPT	AI1	AI2	LL1	PID1	AO1
1	TIT_301	TIT_302	H1 interface module	H1 interface module	DIY_301
2	TIT_301	TIT_302	H1 interface module	DIY_301	DIY_301
3	TIT_301	TIT_302	DCS host controller	DIY_301	DIY_301
4	TIT_301	TIT_302	DCS host controller	DCS host controller	DIY_301

remind the operator or user which mode should be for setting the ‘Target’ mode required for normal operations. The ‘Normal’ mode of the AI1, AI2, LL1, and PID1 blocks is the automatic (Auto) mode, whereas the ‘Normal’ mode of the AO1 block is the cascade (Cas) mode. Commonly, the ‘Target’ mode is selected only one from set ‘Permitted’ modes, which are varied according to the type and function of the block. For the AI1, AI2, LL1, and PID1 blocks, their ‘Permitted’ modes consist of out-of-service (OOS), manual (Man), and Auto. The ‘Permitted’ modes configured for the AO1 block are OOS, Man, Auto, and Cas. If the abnormal or error operating conditions cause the ‘Target’ mode to be unable to achieve, then the ‘Actual’ mode of function blocks will be automatically changed to the next higher priority ‘Permitted’ mode by their operating mode shedding mechanism without operator intervention [4]. Among four defined ‘Permitted’ modes, the OOS mode has the highest priority, and the Cas mode has the lowest priority. Besides, the priority of the Man mode is higher than that of the Auto mode. Table 4 shows the major parameters and their values for configuring the function blocks of Figure 1(b). The AI1, AI2, and AO1 blocks have transducer scale (XD_SCALE) parameter for their value on the input/output hardware channel, which is set by the CHANNEL parameter. With setting the linearization type (L_TYPE) parameter of the AI1 and AI2 blocks to be ‘Indirect’, the measurement value obtained from the transducer block is re-scaled via the

Table 4. Major parameters and their values for control configuration of Figure 1(b)

Block	Parameter/option parameter	Value
AI1	CHANNEL	1
	L_TYPE	Indirect
	XD_SCALE	40°C-60°C
	OUT_SCALE	0%-100%
AI2	CHANNEL	1
	L_TYPE	Indirect
	XD_SCALE	20°C-60°C
	OUT_SCALE	0%-100%
PID1	FF_GAIN	0.3
	FF_SCALE	0%-100%
	PV_SCALE	0%-100%
	OUT_SCALE	0%-100%
	GAIN	1.40
	RESET	99.2 s
	RATE	18.5 s
	Use Uncertain as Good	Enabled
	Initiate Fault State if Bad IN	Disabled
	Target to Man if Bad IN	Disabled
AO1	CHANNEL	1
	PV_SCALE	0%-100%
	XD_SCALE	4-20 mA
	Fault State to value	Disabled
	Target to Man if Fault State activated	Disabled
LL1	LEAD_TIME	616 s
	LAG_TIME	198 s
	GAIN	0.92

XD_SCALE to the output scale (OUT_SCALE) parameter. Therefore, the measurement values of 40°C and 60°C for the AI1 OUT parameter are converted into the percent values of 0% and 100%, respectively. Similarly, the measurement values of 20°C and 60°C for the AI2 OUT parameter are converted into the percent values of 0% and 100%, respectively. The lead time constant, lag time constant, and gain factor of the LL1 block are set by the LEAD_TIME, LAG_TIME, and GAIN parameters, respectively. The PID1 and AO1 blocks have the process variable scale (PV_SCALE) parameter for their input. Within the PID1 block, the feedforward gain (FF_GAIN) and feedforward scale (FF_SCALE) parameters are used for feedforward algorithm, and the GAIN, RESET, and RATE parameters are employed for PID algorithm. Based on the XD_SCALE and PV_SCALE of the AO1 block, the percent values of 0% and 100% are converted into the analog output signals of 4 mA and 20 mA, respectively, which are sent to the TY_301 power regulator for adjusting the bulb supply. For improving availability, the control loop should be shut down in the event of 'Bad' measurement status, whereas the control loop should be continuously able to function in the event of the 'Uncertain' measurement status. The 'Use Uncertain as Good' option parameter in the PID1 control block is enabled to treat the 'Uncertain' status as the 'Good' status for avoiding unnecessary shutdown. Otherwise, this option parameter should be disabled for shutting the control loop that is hazardous down for safety reasons. Moreover, the 'Initiate Fault State if Bad IN' and 'Fault State to value' option parameters of the PID1 and AO1 blocks, respectively, are disabled to hold the AO1 OUT parameter at the last usable value in the presence of invalid measurement of the transmitter. To provide the PID1 and AO1 blocks to instantly return to their normal operating 'Target' modes after the 'Bad' AI1 OUT status disappears for maximizing availability, the 'Target to Man if Bad IN' option parameter of the PID1 block as well as the 'Target to Man if Fault State activated' option parameter of the AO1 block is disabled.

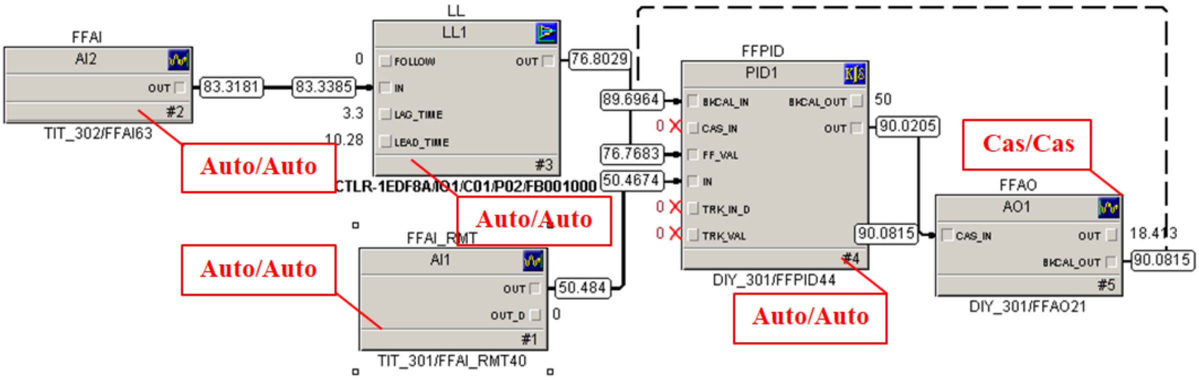
4. **Results and Discussion.** To verify the workability of the proposed method, experiments were performed by configuring and running the studied feedforward control loop with increased availability in four different options for function block assignments by using the DeltaV host system. The transmitter failures were emulated to cause the uncertain and invalid measurements. The 'Good', 'Uncertain', and 'Bad' validities of measurement values of the TIT_301 and TIT_302 transmitters are indicated by the AI1 OUT and AI2 OUT statuses, respectively. From experimental results for all specified function block assignments, Table 5 summarizes the 'Target' and 'Actual' modes of the PID1 block when detecting the failure and after resolving the failure. It is seen that the automatic changes

Table 5. 'Target' and 'Actual' modes of the PID1 block from experiment results

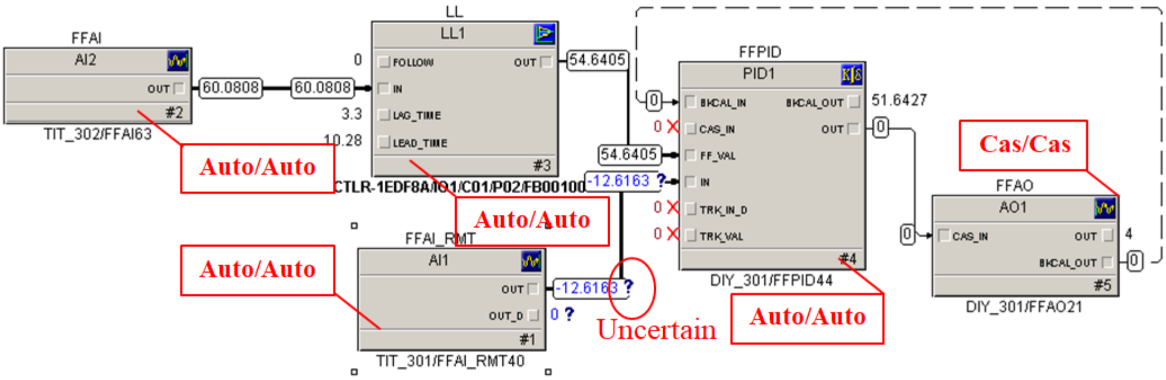
AI1 OUT status	AI2 OUT status	When detecting the failure		After resolving the failure	
		'Target'	'Actual'	'Target'	'Actual'
Good	Uncertain	Auto	Auto	Auto	Auto
	Bad	Auto	Auto	Auto	Auto
Uncertain	Good	Auto	Auto	Auto	Auto
	Uncertain	Auto	Auto	Auto	Auto
	Bad	Auto	Auto	Auto	Auto
Bad	Good	Auto	Man	Auto	Auto
	Uncertain	Auto	Man	Auto	Auto
	Bad	Auto	Man	Auto	Auto

of the ‘Actual’ mode of the PID block from Auto mode into Man mode are caused by the ‘Bad’ AI1 OUT status only. The ‘Uncertain’ and ‘Bad’ AI2 OUT statuses have no impact on the operations of the PID block. Due to disabling the ‘Target to Man if Bad IN’ option, the ‘Target’ mode of the PID block is not changed when detecting the ‘Bad’ AI1 OUT status. In addition, the ‘Uncertain’ AI1 OUT status also has no effect on the ‘Target’ and ‘Actual’ modes of the PID1 block because of enabling the ‘Use Uncertain as Good’ option.

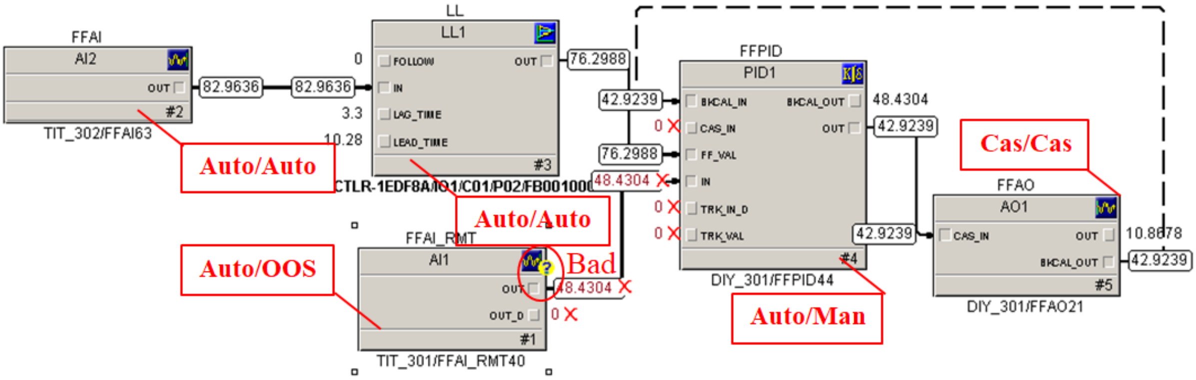
After the failure has been resolved, the feedforward loop with increased availability can immediately continue its automatic control function. Moreover, different LL1 and PID1



(a) ‘Target’ and ‘Actual’ modes of the blocks in case of ‘Good’ AI1 OUT status



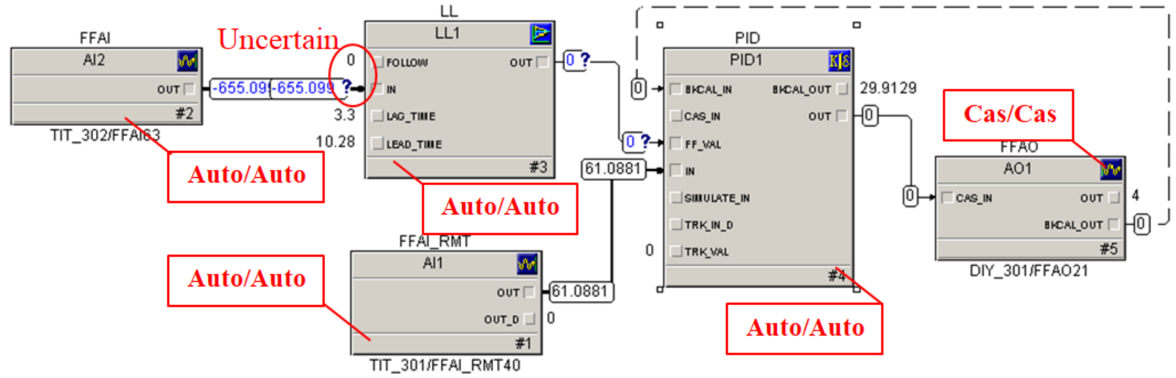
(b) ‘Target’ and ‘Actual’ modes of the blocks in case of ‘Uncertain’ AI1 OUT status



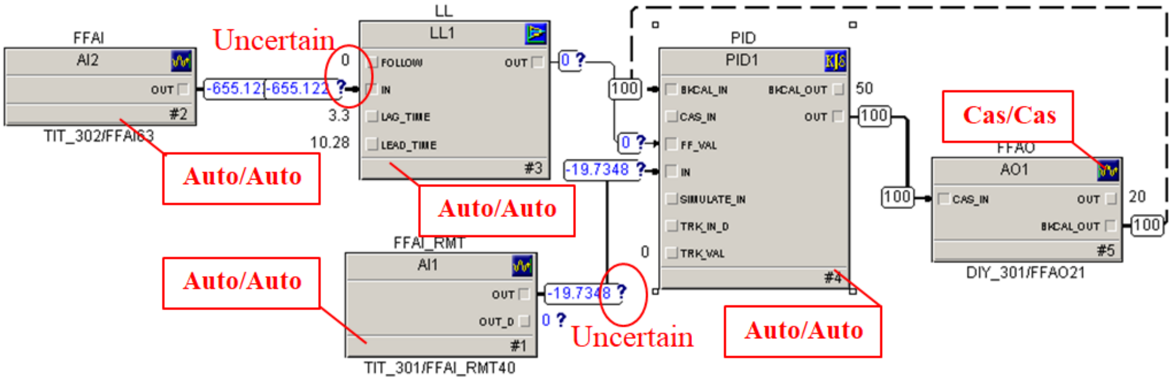
(c) ‘Target’ and ‘Actual’ modes of the blocks in case of ‘Bad’ AI1 OUT status

FIGURE 2. Results for ‘OPT2’ option in case of ‘Good’ for the AI2 OUT status

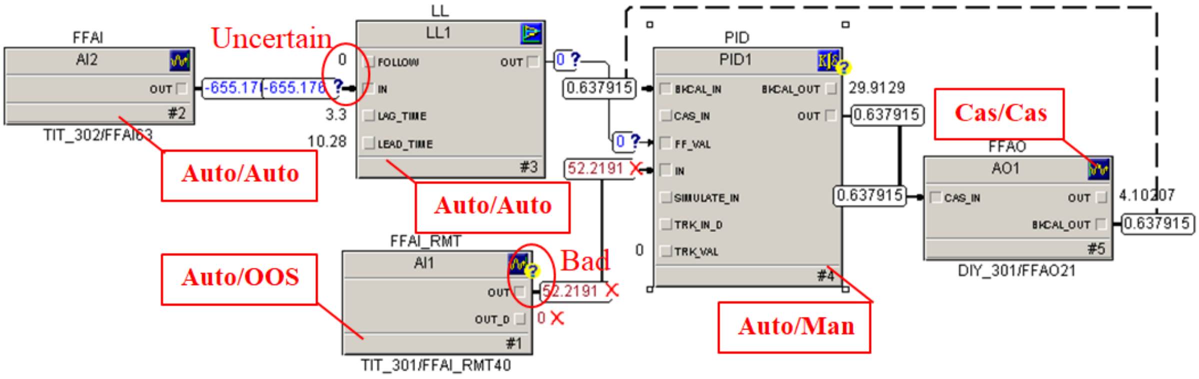
block placements have no impact on the operating mode shedding in response to the 'Bad' AI1 OUT status. In order to be examples for examining the feedforward loop actions under normal and abnormal operating conditions, only the results from the 'OPT2' and 'OPT4' options are displayed in Figures 2 and 3, respectively. They are screenshots of the DeltaV Control Studio program in online mode during experiments. In the event of 'Good' status for both AI1 OUT and AI2 OUT of Figure 2(a) as well as in the event of 'Uncertain' AI1 OUT and 'Good' AI2 OUT of Figure 2(b), all function blocks are executed in their normal operations. Similarly, in case of 'Good' AI1 OUT and 'Uncertain' AI2 OUT of Figure 3(a) as well as in case of 'Uncertain' status for both AI1 OUT and AI2 OUT of Figure 3(b), all function blocks are also processed in their normal operations. However, in



(a) 'Target' and 'Actual' modes of the blocks in case of 'Good' AI1 OUT status



(b) 'Target' and 'Actual' modes of the blocks in case of 'Uncertain' AI1 OUT status



(c) 'Target' and 'Actual' modes of the blocks in case of 'Bad' AI1 OUT status

FIGURE 3. Results for 'OPT4' option in case of the 'Uncertain' AI2 OUT status

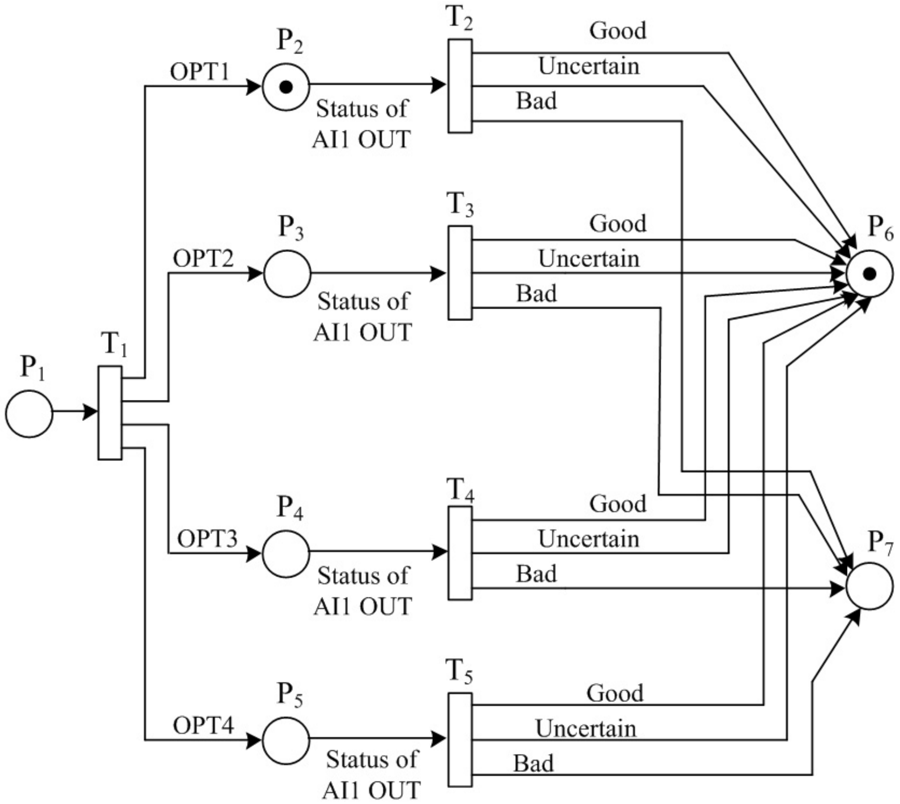


FIGURE 4. Model representation of the behaviors in different control configuration options

the presence of 'Bad' AI1 OUT and 'Good' AI2 OUT of Figure 2(c) as well as the event of 'Bad' AI1 OUT and 'Uncertain' AI2 OUT of Figure 3(c), the 'Actual' modes of the AI1 and PID1 blocks are changed to OOS mode and Man mode, respectively. The LL1 block in Auto mode propagates the AI2 OUT status from its input to its output. If the FF_VAL status is 'Bad', the last usable value will be utilized for feedforward contribution to the execution of the PID1 control block. To represent the logical behaviors of the feedforward control with increased availability in response to the transmitter failures for four different function block placements, the simplified Petri model and its place (P) and transition (T) descriptions are shown in Figure 4 and Table 6, respectively, where the input place 'P_1' is the initial state of the studied feedforward control, and only one of two final output places 'P_6' and 'P_7' will occur. The transition 'T_1' is let by choosing one of four specified options to assign the function blocks for control strategy configuration, which are 'OPT1', 'OPT2', 'OPT3', and 'OPT4' options for causing 'P_2', 'P_3', 'P_4', and 'P_5' output places, respectively. It should be noted that these output places of the transition 'T_1' do not occur simultaneously, and then only output place 'P_2', 'P_3', 'P_4', or 'P_5' can happen. The transitions 'T_2', 'T_3', 'T_4', and 'T_5' are let by the statuses of the AI1 OUT parameter, which are 'Good', 'Uncertain', and 'Bad'. The transitions 'T_2', 'T_3', 'T_4', and 'T_5' provide the same final output places 'P_6' and 'P_7', which do not happen concurrently. The output place 'P_6' occurs in the presence of 'Good' or 'Uncertain' measurement status provided by the TIT_301 transmitter for maintaining the automatic control. On the other hand, the output place 'P_7' occurs in the presence of 'Bad' measurement status provided by the TIT_301 transmitter for bringing the control loop to be manual operation. It is evident that setting the 'Uncertain' to be treated as 'Good' status is helpful for the feedforward control loop that requires high availability.

Table 6. Descriptions of the model places and transitions in Figure 4

Item	Description
P_1	The function block diagram of Figure 1(b) is created for the feedforward loop.
P_2	The control loop is configured by utilizing the 'OPT1' block assignment.
P_3	The control loop is configured by utilizing the 'OPT2' block assignment.
P_4	The control loop is configured by utilizing the 'OPT3' block assignment.
P_5	The control loop is configured by utilizing the 'OPT4' block assignment.
P_6	'Target' and 'Actual' modes of the PID block are Auto.
P_7	'Target' and 'Actual' modes of the PID block are Auto and Man, respectively.
T_1	If the control loop is configured by utilizing the 'OPT1' assignment then P_2. If the control loop is configured by utilizing the 'OPT2' assignment then P_3. If the control loop is configured by utilizing the 'OPT3' assignment then P_4. If the control loop is configured by utilizing the 'OPT4' assignment then P_5.
T_2, T_3, T_4, T_5	If the AI2 OUT status is 'Good', 'Uncertain', or 'Bad' and the AI1 OUT status is 'Good' then P_6. If the AI2 OUT status is 'Good', 'Uncertain', or 'Bad' and the AI1 OUT status is 'Uncertain' then P_6. If the AI2 OUT status is 'Good', 'Uncertain', or 'Bad' and the AI1 OUT status is 'Bad' then P_7.

5. **Conclusions.** In this article, an improving availability through device diagnosis for the feedforward control using Foundation Fieldbus technology has been proposed. The temperature control loop configured and operated on the DeltaV DCS host has been employed as the case study. The control strategy configuration based on reducing shutdown actions caused by minor transmitter failures for availability enhancement has been described. The simplified Petri net model for illustrating the logical behaviors of the studied feedforward control with increased availability in response to the event of transmitter failures has been introduced. Comparative analysis between the studied FF-based feedforward control and its alternative control strategy implementations in terms of availability and/or safety improvement is possible future work.

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