Benchmark Definition

WUT Team
with cooperation with UPC

Preliminary, ver. 1.0

March 17, 2002

1. Version Info

version #	Remarks	Date
draft		02-March-2002
1.0 preliminary	• Changes in performance indexes definitions • Introduction of new performance indexes • Updates in glossary • Changes in the forms due to the changes in performance indexes	17-March-2002

2. Introduction

Benchmark scope

The benchmark concerns on actuator consisting of: control valve, pneumatic linear servo motor and positioner.

The general description of actuator is given in Appendix VIII. More detailed description can be found in document ***"Specification of Actuators Intended to Use for Benchmark Definition"***. This document can be downloaded from DAMADICS Information Website, section ***Benchmark / Introduction***.

Objectives

Comparing the properties of fault detection and isolation methods intended to be applied for actuator diagnosis in industrial environment.

Assumptions

1. Benchmark is based on:
   - actuator Simulink-Matlab model,
   - real process data files with artificial generated faults.
2. Analytical model of actuator is not available. This is typical situation when considering industrial implementation. Available are real process data files.
3. Due to unlimited number of possible fault scenarios the important limitations were introduced:
   - number of considered actuator faults is equal to 19,
   - two fault simulation scenarios are assumed: abrupt and incipient,
   - only single fault scenarios are considered and simulated.
4. Benchmark structure:
   - **Step I**. Benchmark basing on Simulink model. Step I is suited for ***evaluation*** a features of FDI methods. Fault scenarios are well defined to allow evaluation.
   - **Step II**. Benchmark basing on Simulink model. Step II is suited for ***testing*** a features of FDI methods. Data files will be generated with hidden faults. Fault scenarios will be defined by project coordinator.
   - **Step III**. Benchmark basing on real process data. Step III is suited for ***approving*** applicability of FDI methods.
5. Benchmark is designed to ensure comparability of the results achieved by applying different FDI approaches.

3. Step I

The aim of this benchmark part is investigating of partners FDI methods. Step I is based on the data generated by data generator.

Every project partner has to show FDI results for ***all*** fault scenarios considered in Step I. In every scenario they are defined: kind of fault (fault number) and failure mode.

In Step I:

- Only two failure modes are available: abrupt and incipient. Modes are defined in document ***Using Damadics Actuator Benchmark Library (DABLib)"*** ; in section ***'DGen' functional block*** / ***Failure modes***.
- Total of 44 fault scenarios must be investigated. Scenarios are given in document: ***Using Damadics Actuator Benchmark Library (DABLib)"*** in section ***'DGen' functional block*** / ***Fault scenarios***.

Step I in details

For all scenarios three time zones were fixed:

- First zone, Set-up zone, was set to avoid taking into account false FDI decisions which can occur at the beginning, *e.g., some FDI methods need to be tuned properly before starting*. This zone is limited by the time t_{on} (see Figure 1)
- Second zone is a Benchmark zone. All results (figures, performance indexes, etc.) are referring to this zone. This zone is limited by the time horizon t_{hor}:

$$t_{hor} = t_{from} + t_{fd} + t_{ov}$$

  where t_{ov} is a preset period of time form the moment where the fault strength reaches its maximum value.

- Third zone, Out of interest zone, is outside of the scope of the benchmark.

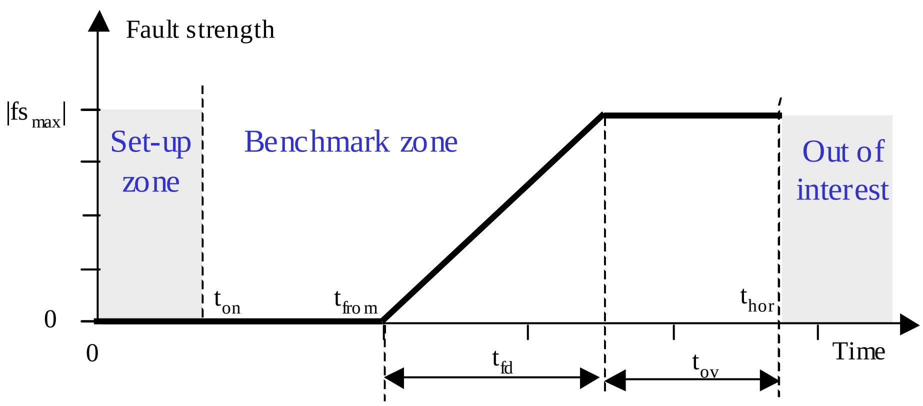

Figure 1. Definition of time parameters of a benchmark – step I scenarios.

Table 1 presents values time parameters of benchmark – step I scenarios.

Table 1. Parameters of failure modes

<table>
<tr><th rowspan="2" colspan="2">Parameter</th><th colspan="2">Fault type</th></tr>
<tr><th>Abrupt</th><th>Incipient</th></tr>
<tr><td colspan="2">$|fs_{max}|$</td><td colspan="2">according to Scenario</td></tr>
<tr><td colspan="2">t_{on}</td><td colspan="2">300 s</td></tr>
<tr><td colspan="2">t_{from}</td><td colspan="2">900 s</td></tr>
<tr><td rowspan="3">t_{fd}</td><td>short</td><td rowspan="3">0 s</td><td>900 s</td></tr>
<tr><td>medium</td><td>3600 s</td></tr>
<tr><td>long</td><td>84000 s</td></tr>
<tr><td colspan="2">t_{ov}</td><td colspan="2">600 s</td></tr>
<tr><td rowspan="3">t_{hor}</td><td>short</td><td rowspan="3">1500 s</td><td>2400 s</td></tr>
<tr><td>medium</td><td>5100 s</td></tr>
<tr><td>long</td><td>85500 s</td></tr>
</table>

For evaluating of benchmark – Step I results a set of performance indexes was given (see Appendix II). The calculated indexes should be presented on proper form.

<u>Reporting results</u>

To make easier the comparison of achieved results, the special booklet of forms was designed. There are two kinds of forms:

- Form presenting features of applied FDI method. This form will be further called as S1-MF form (see Appendix III)

- Forms presenting results of FDI method applied for fault scenarios foreseen in Step I. This forms will be further called as S1-FF-fxx forms (where xx denotes fault number, see Appendix IV)

Results of benchmark **-** Step I will be collected together. The results achieved will be a good base for DAMADICS partners common paper.

4. <u>Step II</u>

Step II of benchmark is suited for ***testing*** FDI methods.

Four fault scenarios are foreseen, one per each fault group (see fault definitions in ***Using Damadics Actuator Benchmark Library (DABLib)"*** ; in section ***'Act' block*** / ***Simulation of faults***). These fault scenarios will be set by project coordinator. Fault scenarios will be unknown for all partners taking part in the benchmark. Basing on the chosen scenarios data files will be generated using Simulink data generator block. Data files will be spread among project partners using internet.

<u>Reporting results</u>

To make easier the comparison of achieved results, the special form was designed. This form will be further called as S2-SF-x forms (where x denotes scenario number, see Appendix VI).

These scenarios will be published after sending results from all partners to project coordinator. Common evaluation of results will be made.

5. Step III

Step III of benchmark is suited for ***approving*** applicability of FDI methods.

Step III is based on data from three real actuators installed in the Lublin Sugar Factory. A general view of actuator placement in technological installation is given in Appendix IX. More detailed can be found in document ***"Specification of Sugar Production Process Connected to the Actuators Intended to Use for Benchmark Definition"***. This document can be downloaded from DAMADICS Information Website, section ***Benchmark*** / ***Introduction***.

Five fault scenarios will be chosen from those that were simulated in Lublin Sugar Factory. These fault scenarios will be chosen by project coordinator. Fault scenarios will be unknown for all partners taking part in the benchmark. Proper data files will be prepared and spread among project partners using internet.

Reporting results

To make easier the comparison of achieved results, the special form was designed. This form will be further called as S3-SF-x forms (where x denotes scenario number, see).

These scenarios will be published after sending results from all partners to project coordinator. Common evaluation of results will be made.

Appendix I Glossary

Abrupt fault. A fault where the effect develops rapidly (IFAC definition).

Incipient fault. A fault where the effect develops slowly (IFAC definition).

Detection threshold. Limit value of a residual's deviation from zero, so if exceeded, a fault is declared as detected (based of IFAC Threshold definition).

Isolation threshold. Limit value of a FI decision deviation from zero, so if exceeded, the fault is declared as isolated (based of IFAC Threshold definition).

Elementary diagnosis. An elementary diagnosis is a set of faults that are defined in FDI algorithm as unisolable. The FDI diagnosis decision pointing out fault free state and undetectable faults is treated also as elementary diagnosis. Such a elementary diagnosis is denoted as DGN_0.

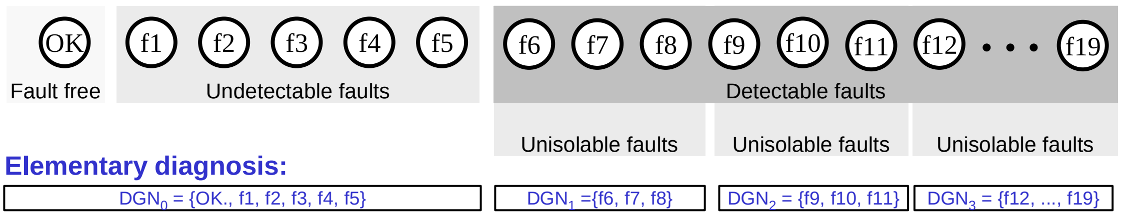

Figure 2. Explanation of elementary diagnosis definition.

Primary Diagnosis The elementary diagnosis which includes fault that where simulated or was marked as simulated (for hidden faults).

Complementary Diagnosis All elementary diagnosis except of primary one and DGN_0.

Fault Free Diagnosis The elementary diagnosis which points out fault free state and undetectable faults.

Detection Decision DD The binary signal that indicates the existence of a fault in the system.

Isolation Decision ID. The isolation decision is a set of elementary diagnosis, *e.g., FDI decision:* $\{DGN_2, DGN_3\}$.

Primary Isolation Decision PID The binary signal that indicates primary diagnosis.

Complementary Isolation Decision CID The signal that indicates complementary diagnosis. Its value equals the number of elementary diagnosis pointed in the complementary diagnosis, *i.e., 0...N-2 where N is the number of elementary diagnosis.*

Fault Free Isolation Decision FFID The binary signal that indicates fault free diagnosis.

Appendix II Performance indexes

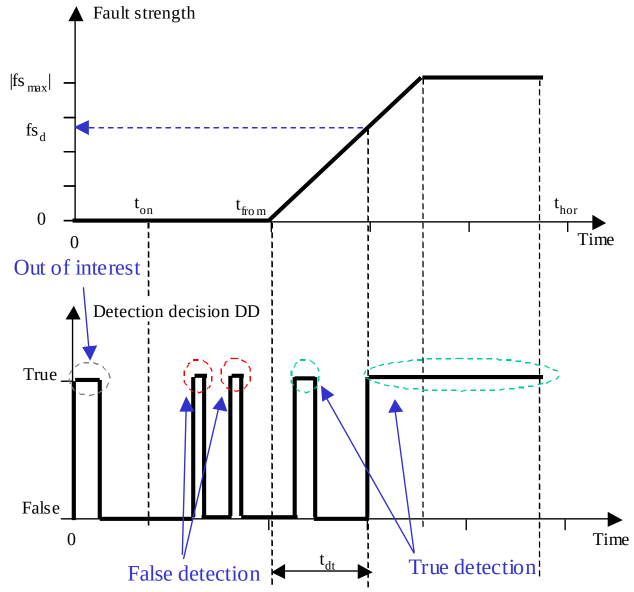

Figure 3. Explanation of parameters used in performance indexes for FD.

Detection time t_{dt}. Period of time from the begin of fault start-up t_{from} up to the moment of the last leading edge of DD signal.

Detection recovery time t_{drt}. Period of time from the end of fault simulation t_{to} up to the moment of the last falling edge of DD signal (used in case of data files with hidden faults in Step II and III).

Detection moment t_{dm}. Time of the last leading edge of DD signal, starting from the beginning of benchmark file (used in case of data files with hidden faults in Step II and III).

Detection recovery moment – t_{drm}. Time of the last falling edge of DD signal, starting from the beginning of benchmark file (used in case of data files with hidden faults in Step II and III).

False detection rate r_{fd}.

$$r_{fd} = \frac{\sum_i t_{fd}^{i,DD}}{t_{from} - t_{on}}$$

where $t_{fd}^{i,DD}$ is a i[th] period of high DD signal value between t_{on} to t_{from} (see red circles on Figure 3)

True detection rate r_{td}.

$$r_{td} = \frac{\sum_i t_{td}^{i,DD}}{t_{hor} - t_{from}}$$

where $t_{td}^{i,DD}$ is a i[th] period of high DD signal value between t_{from} to t_{hor} (see green circles on Figure 3)

Fault detection sensitivity factor $\boxed{fs_d}$. The value of fault strength in the moment of the last leading edge of DD signal (see Figure 3).

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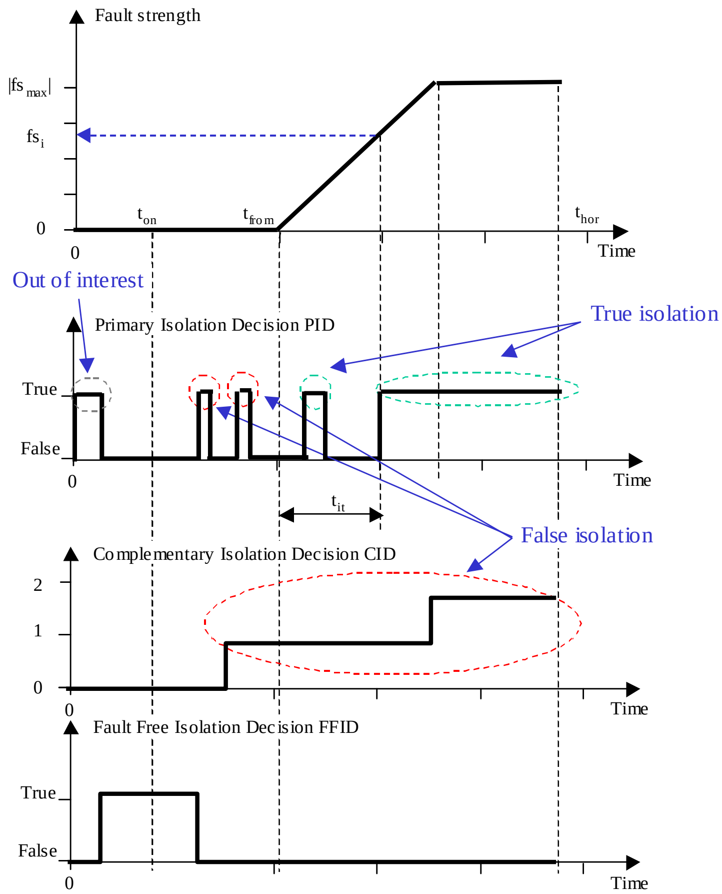


Figure 4. Explanation of parameters used in performance indexes for FD.

Isolation time $\boxed{t_{it}}$. Period of time from the begin of fault start-up t_{from} up to the moment of the last leading edge of PID signal.

Isolation recovery time $\boxed{t_{irt}}$. Period of time from the end of fault simulation t_{to} up to the moment of the last falling edge of PID signal (used in case of data files with hidden faults in Step II and III).

Isolation moment $\boxed{t_{im}}$. Time of the last leading edge of PID signal, starting from the beginning of benchmark file (used in case of data files with hidden faults in Step II and III).

Isolation recovery moment – $\boxed{t_{irm}}$. Time of the last falling edge of PID signal, starting from the beginning of benchmark file (used in case of data files with hidden faults in Step II and III).

False isolation rate $\boxed{r_{fi}}$.

$$r_{fi} = \frac{\sum_i t_{fi}^{i,PID}}{t_{from} - t_{on}}$$

where $t_{fi}^{i,PID}$ is a i[th] period of high PID signal value between t_{on} to t_{from} (see red circles on Figure 4).

True isolation rate $\boxed{r_{ti}}$.

$$r_{ti} = \frac{\sum_i t_{ti}^{i,PID}}{t_{hor} - t_{from}}$$

where $t_{ti}^{i,PID}$ is a i[th] period of high PID signal value between t_{from} to t_{hor} (see green circles on Figure 4)

Mismatch isolation rate $\boxed{r_{mi}}$.

$$r_{mi} = \frac{\int_{t_{on}}^{t_{hor}} CID \cdot dt}{t_{hor} - t_{on}}$$

Fault isolation sensitivity factor $\boxed{fs_i}$. The value of fault strength in the moment of the last leading edge of PID signal (see Figure 4).

****

Theoretical diagnosis accuracy $\boxed{dacc_t^i}$.

$$dacc_t^i = \frac{1}{L}$$

where: i – the number of elementary diagnosis, method dependent,

L - the number of faults indicated in i[st] elementary diagnosis, for DGN_0 the fault free state (OK) is also counted.

Theoretical mean diagnosis accuracy $\boxed{dacc_{tm}}$.

$$dacc_{tm} = \frac{1}{N} \sum_{i=0}^{N-1} \Delta dgn_t^i$$

where N is a number of elementary diagnosis.

Diagnosis accuracy $\boxed{dacc}$.

$$dacc = \frac{1}{L}$$

where L is a number of faults indicated in FDI decision when the permanent true detection / isolation is achieved.

Appendix III FDI method form … *S1-MF*

Form:	Partner:	Method name:
S1-MF	**WUT**	**FDI based of partial FNN for FI and F-DTS for FD**

General method description:

The method is based on application of fuzzy neural networks model for residual generation purpose. The isolation of faults is based on F-DTS method of reasoning. For more details please refer to:

- Smith J. (2001), My revolutionary FDI method, UNSAFEPROCESS 2001, pp. 234-235
- Appendix S1-MF_A1 – If any appendix considered please construct the name according to example.

Questionnaire:

Set of considered faults:	f1, f2, f3, f4, f10, f13 and f18
Does the method base on models? *If YES then what kind of model and used for what?*	Yes FNN are used to build partial models
Does the method need training data with faults?	No
…	
…	

Elementary diagnosis and indexes:

Elementary diagnosis	Component faults	Δdgn_t^i	Comments
DGN_0	OK	1/1	denotes the fault free state
DGN_1	f1, f2, f3, f10	1/4	
…	…	…	…
DGN_N	f13, f15, f19	1/3	
Index	**Value**	**Comments**	
$dacc_{tm}$	0.38		

Detection

Methodology description:

Six residuals are designed. Five of then are based on five partial models (five different FNN).

please include necessary tables, figures, etc., e.g. set of residuals in a table

Fuzzy residual evaluation is used. Two achieve crisp FI decision, a detection threshold equal to 0.5 was used.

A fault is detected in any of the residuals exceeds defined threshold.

Analysis of detectability:

Seven faults are detectable: f1, f2, f3, f4, f10, f13 and f18.

Isolation

Methodology description:

Isolation is based on analysis of symptoms. The symptoms are expressed is a fuzzy terms.

please include necessary tables, figures, etc., e.g. diagnostic matrix

To elaborate FI decision a F-DTS method is used. See reference xxx.

Analysis of isolability:

Faults (f2, f3, f4) and (f13, f18) are not isolable.

Appendix IV Fault test form … *S1-FF-fxx*

Form:	Partner:	Failure mode	Method name:
S1-FF-f13	**WUT**	**Incipient**	**FDI based of partial FNN for FI and F-DTS for FD**

Fault type:

f13 – Rod displacement sensor fault

Group of not isolable faults:

f13, f18

Performance indexes

Index	Value	Comments
t_{dt}	250 s	the moment where the permanent detection was achieved
r_{fd}	33 %	
r_{td}	80 %	
fs_d	0.45	
t_{it}	500 s	the moment where the permanent isolation was achieved, even if other groups of faults were distinguished
r_{fi}	25 %	
r_{ti}	45 %	
r_{mi}	5%	
fs_i	0.8	
dacc	0.5	for 1800 s

Questionnaire:

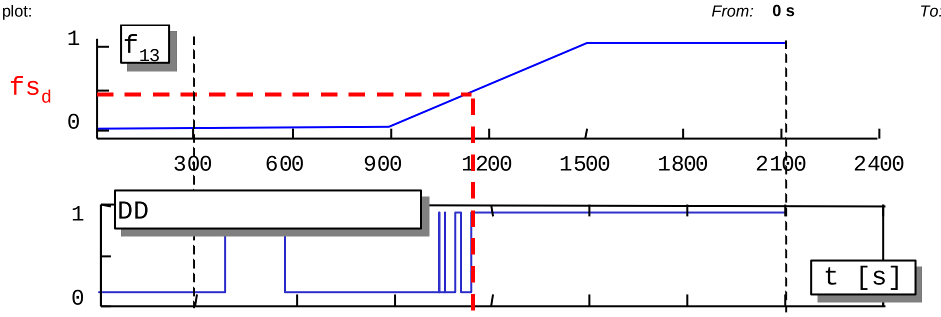
to be defined in future.	
...	

Notes:

It is the best result that we had ever achieved in the history of WUT.

Detection

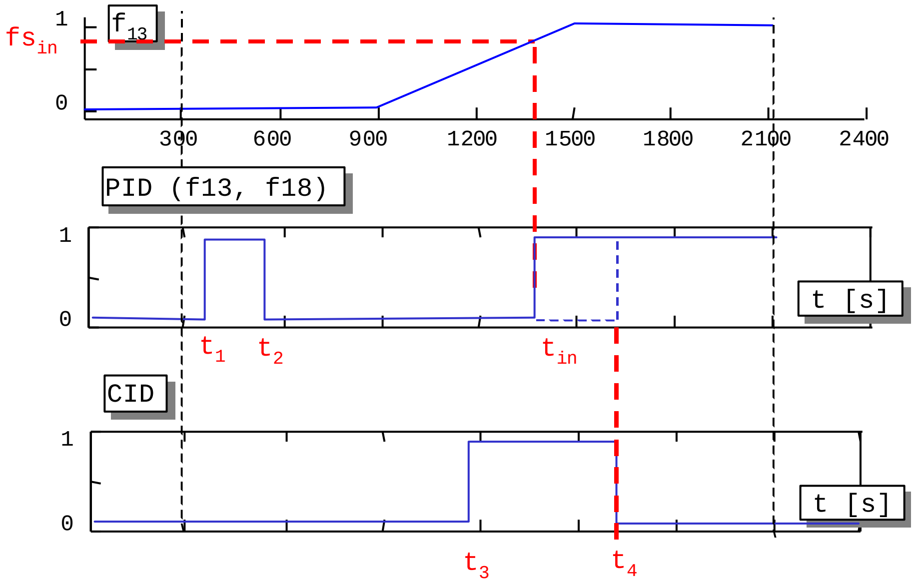
Fault detection signal plot: *From:* **0 s** *To:* 2400 s



Comments:

No comments

Isolation			
Fault isolation signal plot:		*From:* **0 s**	*To:* 2400 s

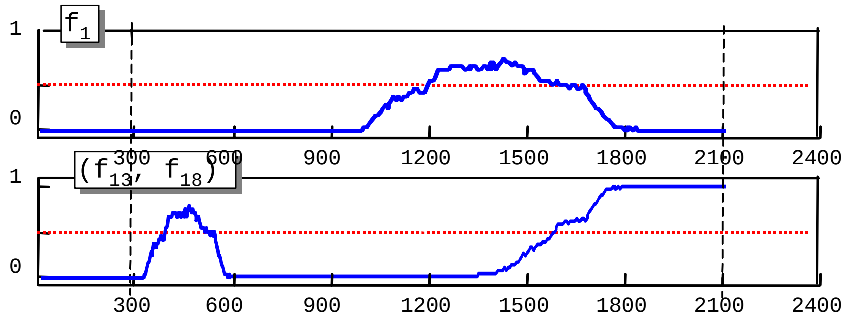


Comments:

see Appendix S1-FF-f13_A1 – If any appendix considered please construct the name according to example.

Appendix V Example of additional appendix for S1-FF-fxx form

Appendix S1-FF-f13_A1



Used FI algorithm generates fault certainty factors. To achieve crisp FI decision a isolation threshold equal to 0.5 was chosen.

True value of “Isolation Decision for all the other groups“ in period (t_3, t_4) was caused by false isolation of f_1.

etc ...

etc ...

Appendix VI Scenario form of Step II ... *S2-SF-x*

Form:	Partner:	Method name:
S2-SF-1	**WUT**	**FDI based of partial FNN for FI and F-DTS for FD**

Overall FDI results:

We found that f13 or f18 was simulated.

Only one fault (or a group of not isolable faults) must be declared as a result of FDI. All other results of FDI are treated as false and must be reported.

Performance indexes

Index	Value	Comments
t_{dm}	2300 s	-
t_{drm}	-	No fault decay was detected
t_{im}	2400 s	-
t_{irm}	-	No fault decay was detected
...		

Questionnaire:

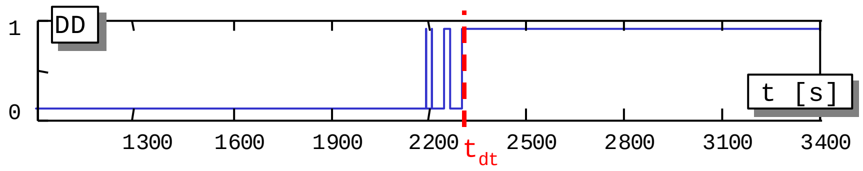
to be defined in future.	
...	

Notes:

None.

Detection

Fault detection signal plot: *From:* **0 s** *To:* 3400 s



The plot should cover the whole time horizon of data file.

Comments:

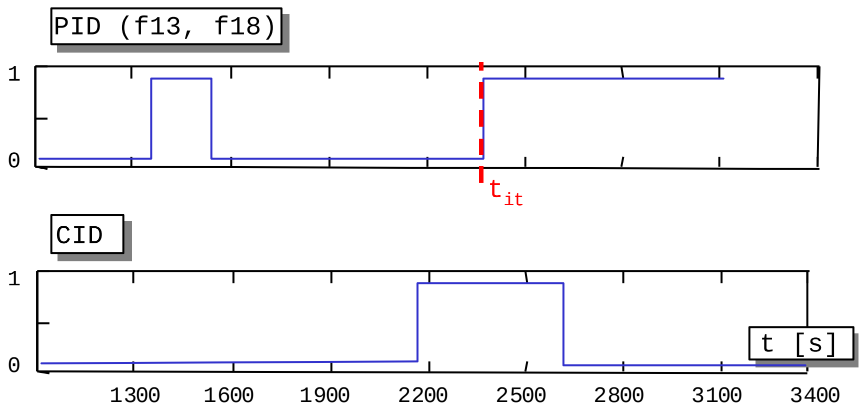
No comments

Isolation

FI results:

Please give all the faults(or group of faults) that were isolated for the whole time horizon.

Fault isolation signal plot: *From:* **0 s** *To:* 3400 s



The plot should cover the whole time horizon of data file.

Comments:

No comments

Appendix VII Scenario form of Step III ... *S3-SF-x*

Form:	Partner:	Method name:
S3-SF-1	**WUT**	**FDI based of partial FNN for FI and F-DTS for FD**

Overall FDI results:

We found that f13 or f18 was simulated.

Only one fault (or a group of not isolable faults) must be declared as a result of FDI. All other results of FDI are treated as false and must be reported.

Performance indexes

Index	Value	Comments
t_{dm}	2001 s	-
t_{drm}	3020 s	-
t_{im}	2201 s	-
t_{irm}	2612 s	-
...		

Questionnaire:

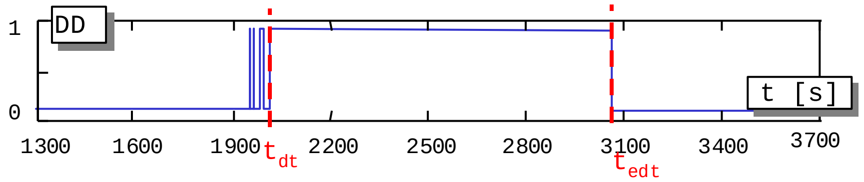
to be defined in future.	
...	

Notes:

None.

Detection

Fault detection signal plot: *From:* **0 s** *To:* 2400 s



The plot should cover the time:

- 600 s before the fault was permanent detected and / or isolated
- 600 s after the fault was removed (if such a moment was detected)
- the time units should be calculated form the beginning of data file.

Comments:

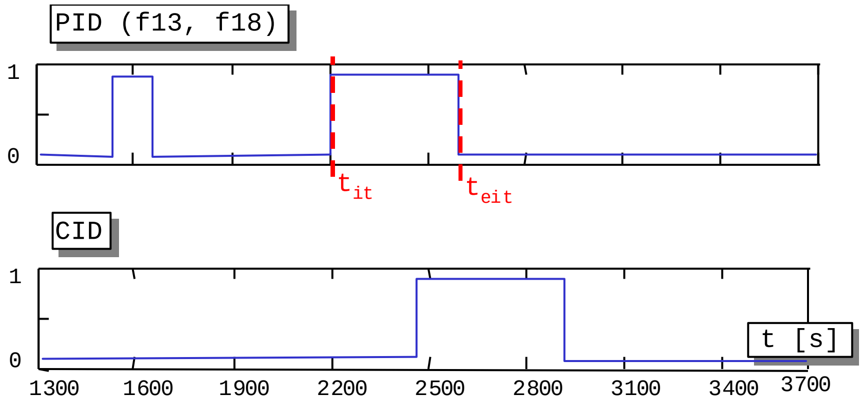
No comments

Isolation

FI results:

Please give all the faults(or group of faults) that were isolated for the whole time horizon.

Fault isolation signal plot: *From:* **0 s** *To:* 400 s



The plot should cover the time:

- 600 s before the fault was permanent detected and / or isolated
- 600 s after the fault was removed (if such a moment was detected)
- the time units should be calculated form the beginning of data file.

Comments:

No comments

Appendix VIII Actuator description

General description

The benchmark actuator selected is a final control element or simply named *actuator*, which interacts with the controlled process. The input of the actuator is the output of the process controller (flow or level controller) and the actuator modifies the position of the valve allowing a direct effect on the primary variable in order to follow the flow or level set-point (Figure 5).

Figure 5. View of the typical industrial control valve actuator.

The actuator consists in three main components (Figure 6):

- control valve,
- spring-and-diaphragm pneumatic servo-motor,
- positioner.

Control valve is the mean used to prevent and/or limit the flow of fluids. Changing the state of the control valve is accomplished by a servomotor.

A spring-and-diaphragm ***pneumatic servomotor*** can be defined as a compressible (air) fluid powered device in which the fluid acts upon the flexible diaphragm, to provide linear motion of the servomotor stem.

Positioner is a device applied to eliminate the control-valve-stem miss-positions produced by the external or internal sources such as friction, pressure unbalance, hydrodynamic forces etc. It consists in a inner loop with a P controller of a cascade control structure, including the output signal of the outer loop of the flow or level controller and the inner loop of the position controller.

The components available in this actuator are:

- Pneumatic servo-motor S
- Control valve V
- Positioner P

ZC	- position P controller (internal loop)
C	- flow or pressure PI controller (external loop)
E/P	- electro-pneumatic transmitter
ZT	- rod position transmitter
D/A	- digital to analogue transducer

Additional external components:

V1, V2	- cut-off valves
V3	- by-pass valve
PSP	- positioner supply pressure
PT	- pressure transmitter
FT	- volume flow rate transmitter
TT	- temperature transmitter

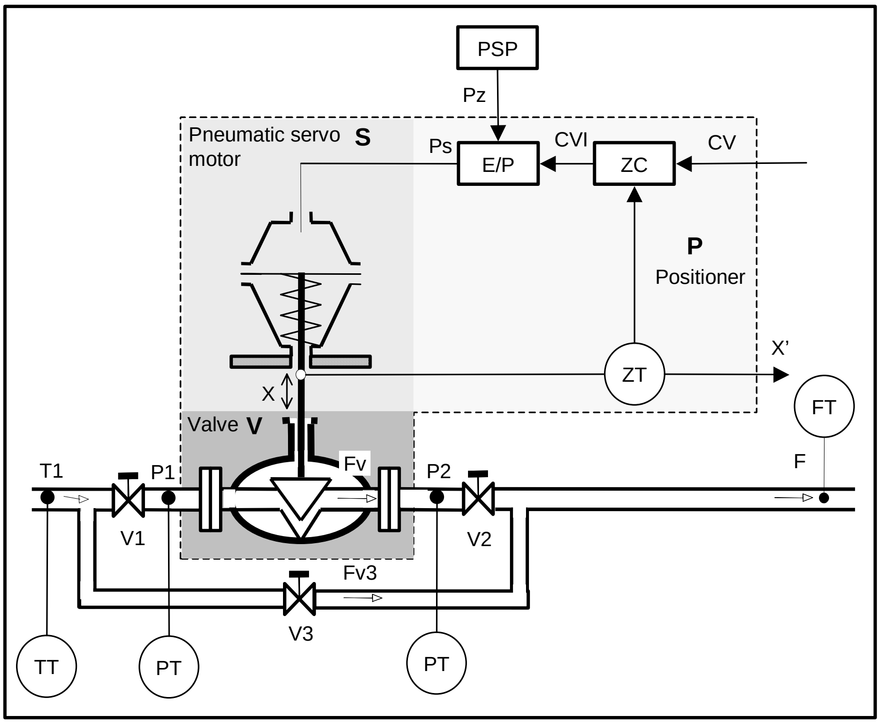


Figure 6. The actuator scheme.

Set of basic measured physical values:

- external (flow or level) controller output **- *CV***
- flow sensor measurement - ***F***
- valve input pressure – ***P1***
- valve output pressure – ***P2***
- liquid temperature – ***T1***
- rod displacement – ***X***

Set of additional physical values that are realistic to measure:

- positioner supply pressure - ***Pz***
- pneumatic servo-motor chamber pressure - ***Ps***
- position P controller output - ***CVI***

Additional variables are not available for benchmark. These variables are available in **'EXTACT'** block in ***DABLib*** Simulink actuator library. **'EXTACT'** block is not used in a benchmark steps, however can be applied for additional FDI research.

Additional set of unmeasurable physical values that are used in structural analysis:

- flow through the valve V - ***Fv***
- flow through the valve V3 - ***Fv3***
- Vena-contracta force – ***Fvc***
- By-pass valve opening ratio – ***X3***

Additional unmeasurable physical values can not be used as an inputs of FDI algorithms, unless they are reconstructed basing on measured variables.

All above mentioned variables are called main variables. The selection of main variables corresponds to physical variables appearing when entering first level of Simulink actuator model structure.

Structural Analysis

The structural analysis allows to define the relation between variables.

Table 2 summarizes the relations of the actuator main variables.

Table 2. Components and variables relations

Component	Relations
Pneumatic servo-motor, S	$X = r_1(Ps, Fvc)$
Control valve, V	$Fv = r_2(X, P1, P2, T1)$ $Fvc = r_3(P1, P2, X, T1)$
Bypass valve, V3	$Fv3=r_4(P1, P2, T1, X3)$
P position controller, ZC	$CVI=r_5(CV, X)$
Electro-pneumatic transducer, E/P	$Ps=r_6(CVI, Pz, X)$
Other – external	$F=r_7(Fv,Fv3)$

The Table 3 shows the structural matrix and Figure 7 is the resulting causal graph.

Table 3. Components and variables relations

	CV	P1	P2	T1	Pz	X3	CVI	Ps	Fv	Fv3	Fvc	X	F
r_1								x			x	x	
r_2		x	x	x					x			x	
r_3		x	x	x							x	x	
r_4		x	x	x		x				x			
r_5	x						x					x	
r_6					x		x	x				x	
r_7									x	x			x

Legend: - measured variables
x – variables in relations

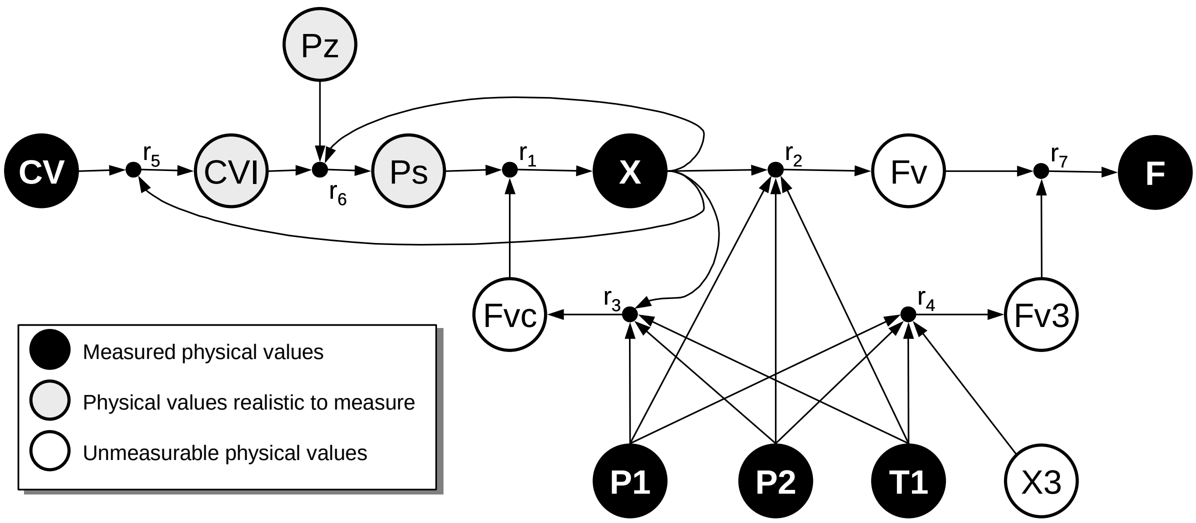


Figure 7. Causal graph of the benchmark main variables.

Appendix IX Examples of actuators in real processes

The actuators chosen for Benchmark – Step III are installed in Lublin Sugar Factory (Poland). Three valves have been selected. Two of them are installed at Evaporation Station (see Figure 8):

- actuator controlling thin juice level in the 1st stage of evaporation station,
- actuator controlling thick juice outflow from the 5th stage of evaporation station.

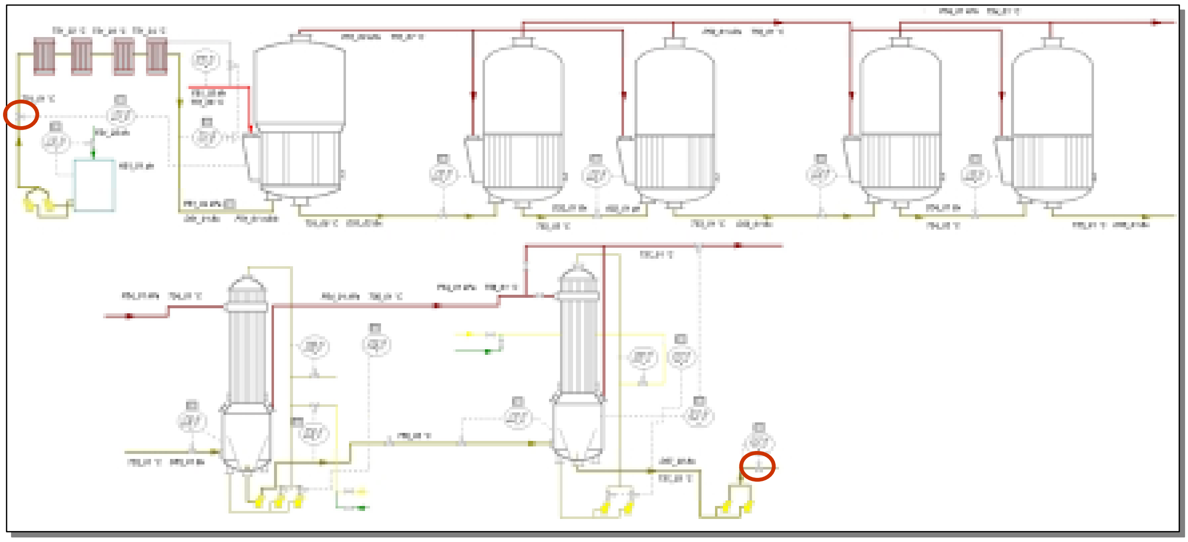


Figure 8. Schematic Diagram of Evaporation Station.

The third one is installed at steam boiler (see Figure 9):

- actuator controlling water level in the 4th boiler station.

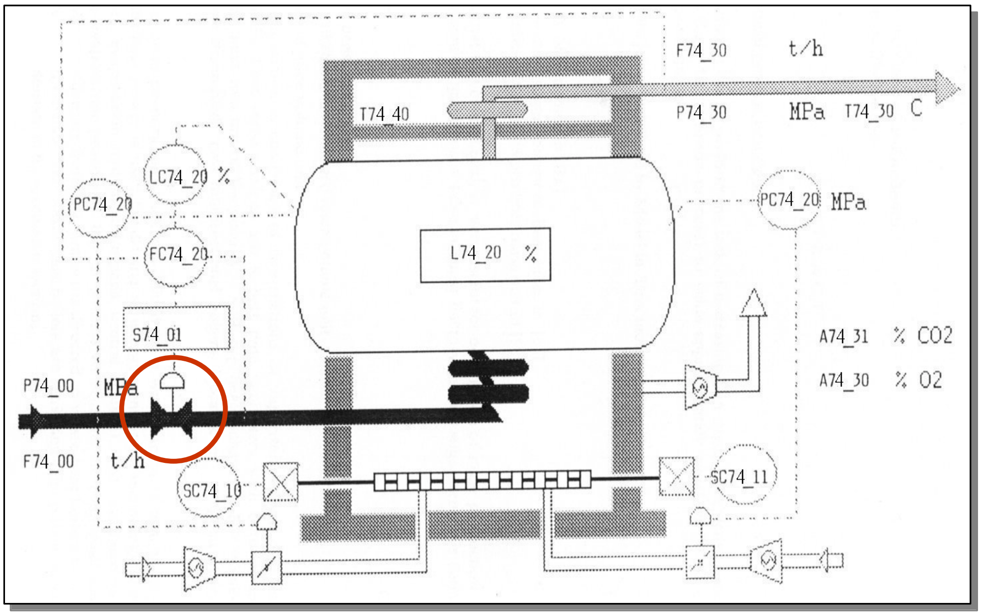


Figure 9. Schematic Diagram of Boiler Station.