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Abstract

A demonstration system, designed for testing and developing fault diagnostic methods in a real building and HVAC process, places a designer close to technical problems that do not exist in a simulation environment. This paper presents such a demonstration system, and finds new solutions to a few practical problems confronted in developing the system into a fault diagnostic product. The demonstration system consists of a building energy management system interfaced to an air handling process, modified by an embedded computer program executing the diagnostic procedures. Although not yet a prototype, the demonstration system already contains a lot of typical features of a diagnostic product. In order to evaluate such features an assessment method is proposed. It points out possible problems of the system and gives new viewpoints for further developing the prototype and finishing the actual diagnostic product.

Fault detection and isolation is based on an on-line diagnostic test (ODT), which is a series of control and monitoring actions applied to a process. Performing an on-line diagnostic test means exciting the automated process by means of prescribed input signals, disturbances or loads, supervising responses and comparing results with a process model. The ODT is an uncomplicated diagnostic method for finding distinct and abrupt changes in a process but not for detection of slow degradations and gradual faults. This paper presents a new and straightforward procedure for fault isolation, in which learning algorithms of fault patterns are not necessary.

Vocabulary

The terminology applied in the field of fault diagnostics is not consistent. Many authors use concepts that are not compatible or included in the IEC 50(191) standard (1990). New or rarely applied expressions usually cause no problems but different definitions of a commonly used expression may confuse the reader. The following list clarifies some expressions utilized in this paper.

Analytical redundancy
A procedure of using model information to generate additional signals, to be compared with the original measured quantities (Patton 1994).

Artificial fault
An intentional man-made fault, typically implemented by a change in process conditions, replacement of a system component with a faulty one or manual introduction of a faulty setting, which tries to reproduce the same symptoms as a natural fault (Yoshida & Pakanen, 2001).

Assessment method
A procedure for testing the properties and performance of a diagnostic method, tool or system according to set criteria.

Complete failure
A failure which results in the complete inability of an item to perform all required functions (IEC 50(191) 1990).

Degradation failure
A failure, which is both a gradual failure and a partial failure (IEC 50(191) 1990).

Degradation fault
The state of an item after a degradation failure has occurred.

Diagnostic method
A procedure, designed for either fault detection or fault isolation or both.

Diagnostic tool
A computer program, designed to implement a diagnostic method, executable in a computer, a computer-controlled process automation system or computer-based equipment containing necessary instrumentation to be interfaced to a process.

Diagnostic system
A computer-controlled automation system interfaced to a process, and which contains at least one diagnostic tool.

Disabled state
A state of an item characterized by its inability to perform a required function (IEC 50(191) 1990).

Failure
The termination of the ability of an item to perform a required function (IEC 50(191) 1990).

Fault
The state of an item characterized by inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources (IEC 50(191) 1990). Some authors use the words fault and failure as synonyms (Gertler 1988).

Fault detection
The event of a fault being recognized (IEC 50(191) 1990).

Fault diagnosis
Actions taken for fault detection, fault localization and cause identification (IEC 50(191) 1990). Isermann (1984, 1994) has presented a different definition for the expression.

Fault isolation
Used as a synonym for fault localization. Another interpretation of the fault isolation has been given by Gertler (1988).

Fault localization
Actions taken to identify the faulty sub-item or sub-items at the appropriate identure level (IEC 50(191) 1990).

Fault signature
An effect or a characteristic pattern of a fault in a residual signal.

Gradual failure
A failure due to a gradual change with time of given characteristics of an item (IEC 50(191) 1990).

Natural fault
A fault that occurs in a real process and results from natural wearing, deterioration, human errors in design, operation or maintenance (Yoshida & Pakanen, 2001).

On-line diagnostic test
A series of control and monitoring actions applied to a process, designed to reveal possible faults of the process. The test is executed on-line, i.e., normal process operation is interrupted for a short time and continued right after finishing the test procedure. A different definition for a diagnostic test is presented by Pau (1981).

Partial failure
A failure which results in the ability of an item to perform some, but not all, required functions (IEC 50(191) 1990).

Pragmatic aspect
A restriction that must be considered when a diagnostic method is implemented in practice. Practical aspects specify limits for instance for available knowledge, tools and process environment.

Simulated fault
An artificial fault, usually implemented by software to circumvent the physical limitations of artificial or natural fault implementation, useful in early stages of diagnostic method or tool development (Yoshida & Pakanen, 2001).

Up state
A state of an item characterized by the fact that it can perform a required function, assuming that the external resources, if required, are provided (IEC 50(191) 1990).

Nomenclature

A_j	Set: time points of signal j at landmarks; qualitative model
$\underline{A}_j$	Set: time points of signal j at landmarks; quantitative model
B_j	Set: landmarks of signal j; qualitative model
$\underline{\mathrm{B}}_j$	Set: landmarks of signal j; quantitative model
G_j	Set: Sampled values of signal j
H_j	Set: Stochastic landmarks and their stochastic time points
H_0	Null hypothesis
H_1	Alternate hypothesis
M	Integrated qualitative and quantitative model
S	Sum
f	Function
h	Sampling time
l_n	Landmark n
t	Time variable, test parameter
$\underline{s}$	Sample variance
t_k	Discrete time -point k
u_a	Outdoor temperature
u_c	Channel temperature after the preheating coil
u_e	Entering water temperature of the preheating coil
u_m	Humidity of the return air
u_p	Leaving water temperature of the preheating coil
u_r	Return air temperature
u_s	Supply air temperature
v_p	Valve position feedback
z_c	Control signal of the cooling coil
z_d	Control signal of the mixing dampers
z_f	Control signal of the fan
z_h	Control signal of the heating coil
z_m	Control signal of the humidifier
z_p	Control signal of the valve in the preheating process
μ	Expected value
σ	Standard deviation
i,j,k,n,m	Subscript variables
{ }	Set

AHU	Air handling unit
BEMS	Building energy management system
FDI	Fault detection and isolation
HVAC	Heating, ventilating and air conditioning
ODT	On-line diagnostic test

Preface

This paper presents a demonstration system to be applied in fault diagnosis of air-handling units. The objective was to develop a practical diagnostic method and tool, which hopefully leads to a commercial diagnostic product. The main part of the research was done during the year 1998. Dr. Jouko Pakanen is a senior research scientist from VTT Building and Transport. Computer programs needed in the demonstration system was programmed by Mr. Jouni Broman. At the time of the research he was an engineering student and working for VTT.

The research is part of the Finnish contribution in Annex 34, coordinated by IEA's Executive Committee of the Energy Conservation in Buildings and Community Systems. The Annex focused on computer-aided fault detection and diagnosis.

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Contents

1. Introduction

Research on fault detection and isolation in automated processes has been active over several decades. The HVAC process has also been a subject of interest during the last ten years. IEA Annex 25 was a leading forum in this field in the 1990's. A number of methodologies and procedures for optimizing real-time performance, automated fault detection and fault isolation were developed in the Annex (Hyvärinen & Kohonen 1993). Many of these diagnostic methods were later demonstrated in real buildings in IEA Annex 34, which concentrated on computer-aided fault detection and diagnosis (Dexter & Pakanen 2001).

Research on diagnostic methods, especially in their early stages of development is usually based on computer simulations and data gathered from laboratory HVAC plants. However, many of these methods are not applicable in practice. That is why there are only a few diagnostic products in real process environments, when compared to the considerable amount of research done during the last decades. Demonstrating fault detection and isolation (FDI) methods in a real building and HVAC process, places the system designer close to technical problems that do not exist in a simulation environment. In addition, implementing the FDI method in an automated, computer-controlled process is one step in developing the method into a commercial FDI product. Even if such a step is successful, many problems are not yet encountered. However, the demonstration phase may reveal some crucial shortcomings helping the designer further develop his/her FDI tool or system.

1. 1 Principles of on-line diagnostic tests

An on-line diagnostic test (ODT) is a series of control and monitoring actions applied to a process, which try to reveal possible faults of the process. Performing an on-line diagnostic test means exciting an automated process by means of prescribed input signals, disturbances or loads, supervising responses and comparing results with a process model. If abnormal responses are generated, the process is faulty (Figure 1). An ODT is focused on one process at a time. When the entire process consists of several subprocesses, faults are better isolated by testing each of them separately.

The ability of the on-line diagnostic test to detect and locate faults is based on a comparison between the behaviour of a faulty and a normally operating process. An ODT is repeated similarly every time, in similar process conditions. The approach is simple and robust because process models are necessary only for responses to specific input signals, making modelling an uncomplicated task. On the other hand, one must carefully utilise all the information generated by the test in order to ensure fault detectability and isolatability. Thus, on-line diagnostic tests share mainly model-based diagnosis and analytical redundancy, but they may also utilise features of other FDI methods.

An on-line diagnostic test comprises of three different parts: identification, fault detection and fault isolation. Data gathered during the identification period represents characteristic operation of the process in normal condition. Later, this data is compared with data collected during the fault detection period. Fault location is a result of reasoning based on a comparison of the data of current and earlier periods. One test may refer to several possible faults. By combining the results of earlier tests and the tests of other subprocesses, redundant fault alternatives are excluded.

A diagnostic test is performed on-line, during the normal up state of the process and controlled by an automation system. However, the execution time of the test is selected so that disturbances, load or environmental conditions are similar to those of earlier tests. Achievement of the right process conditions is taken care of by an automation system, with good control over the process.

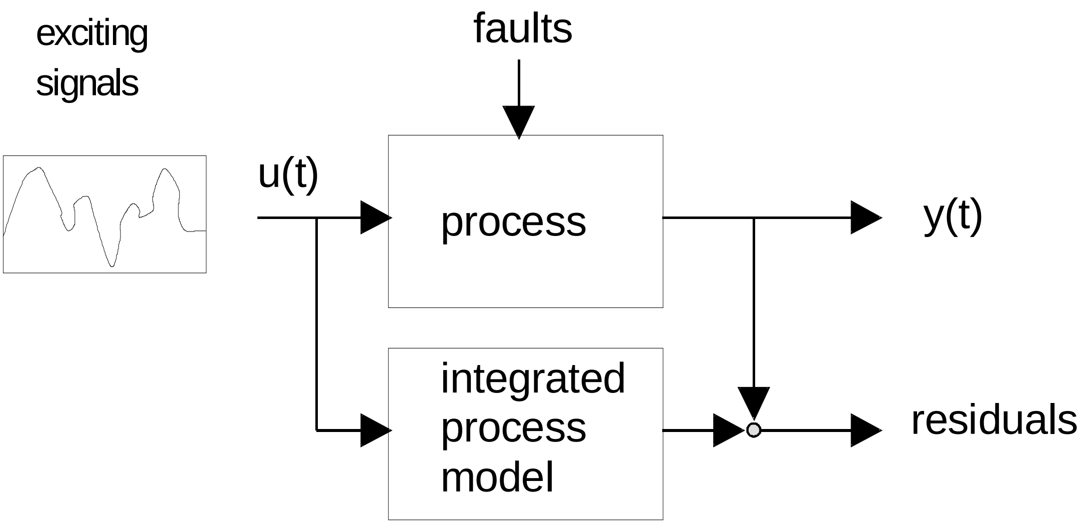

Figure 1. Principle of fault diagnosis using on-line diagnostic tests.

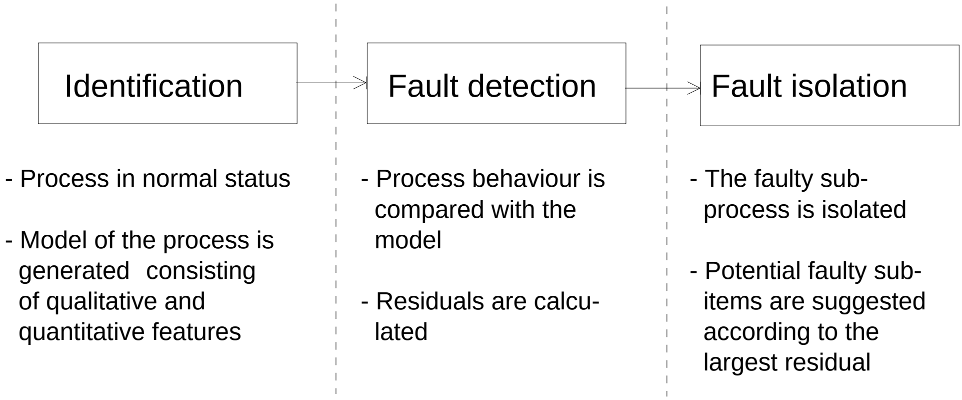

Figure 2. Decomposition of on-line diagnostic tests into identification, fault detection and fault isolation.

1. 2 Selected approach

An on-line diagnostic test is not a new diagnostic method. Pakanen (1996) described the basic principles and presented some results of its implementation. In this paper the method is developed further. The objective is to test the diagnostic approach in a real AHU by means of a demonstration system. The system consists of a building energy management system (BEMS) interfaced to an air handling process, modified by an embedded computer program performing the on-line diagnostic tests.

The major differences compared to the solutions of Pakanen (1996) concern fault isolation. The original paper presents a procedure that makes it possible not only to isolate a fault in a subprocess but also to evaluate the detected fault using fault signatures, specific to each fault. The new procedure does the same, but in a more straightforward way. The primary objective is to isolate the faulty subprocess and after that the faulty sub-items inside the process, but without any learning algorithms (Figure 2).

Performing an ODT requires comprehensive control of the process and its environment. So, besides algorithms for fault detection and isolation the demonstration system must be provided with control actions for steering the process equipment, recording sensor data and maintaining stable environmental conditions during the test. Moreover, the system must be prepared to manage unusual or unexpected situations that come up as a result of a fault or disabled state of the process. The necessary control actions are one of the subjects discussed in the following pages.

The demonstration system is capable of running an ODT in four subprocesses of an AHU: preheating, cooling, humidifying and heating. Only the results from the preheating process are presented here. Results from other subprocesses are presented by Broman (1998). The faults needed to test the diagnostic procedures are not natural faults occurring in HVAC systems. This is due to difficulties in setting up natural faults. Instead, only artificial faults are introduced.

The demonstration system is closer to a final product than a purely diagnostic method. It is already physically and electrically tied to the HVAC process and its environment. Although not yet a prototype, the demonstration system already has many typical features of a diagnostic product. Assessment of the demonstration system points out possible problems and gives new viewpoints for developing a prototype and after that finishing the actual product. The following pages propose a simple assessment procedure, which is applied in the ODT system.

2. Identification and fault detection

2.1 Qualitative approach

A qualitative approach is one choice for model identification of the ODT. In FDI applications, qualitative information is often a supplement of the whole process model (Purna & Yamaguchi 1995, Isermann 1994, Kurki 1995). A purely qualitative process model is usually not enough for extensive diagnosis. But, integrated models based on both qualitative and quantitative knowledge seem to be rare (De Kleer 1993). Jorgensen & Hangos (1995) present one, which they call a grey box model, but their definition of a qualitative model is not conventional.

The FDI method presented by Pakanen (1996) enables integration of qualitative and quantitative knowledge in the same process model. The basic difference between a conventional qualitative approach and the Pakanen's method is that the operating procedure of the on-line diagnostic test is always the same and the tests are always excited by the same known signals producing the same envisionment every time, without any abnormal transitions. Neither is there need to solve qualitative differential equations, but only to learn the quantity spaces, directions and landmarks of the qualitative variables. The approach also eliminates the possibility of extraneous solutions.

A qualitative model of an HVAC process is created by examining the behaviour of the exciting and response signals of one ODT. Each signal j represents a function f_j, which has a finite set of distinguished time -points:

$$A_j = \{ t_0, t_1, t_2, \ldots, t_m \,|\, t_0 = a, t_m = b, t_i < t_{i+1} \} \tag{1}$$

and a corresponding, finite set of landmark values:

$$B_j = \{ l_1, l_2, \ldots, l_k \,|\, l_i < l_{i+1} \}, \tag{2}$$

which represent some characteristic points of the signals. The landmarks are points, where

$$f_j(a) = l_1 \ , \ f_j(b) = l_k \tag{3}$$

or

$$f_j(t_n) = l_i \ , f_j'(t_n) = 0, n \in \{ 0,1,2,\ldots,m \}, i \in \{ 1,2,3,\ldots,k \}. \tag{4}$$

Landmarks defined by Equation 3 are maximum and minimum points of the signal. When a response signal gets its landmark point, the corresponding points of all other response signals reach values specified as intervals between two adjacent landmarks. Either a landmark or an interval is described as the qualitative magnitude of the variable. In addition to the interval, the direction of change of the signal can also be identified. These definitions allow the setting of logical constraints, which both describe and restrict signal and process dynamics. By comparing the dynamics of a complete model and the real process, possible faults are detected.

2.2 Quantitative approach

A quantitative approach is another choice. The quantitative part of the model utilizes available measured signals of the process input and output. For one signal, *j*, this means the sampled values:

$$G_j = \{ \ u_i = u(t_i) \,|\, t_i = a + i\,h, i = 0,\ldots,n \,;\ a + n\,h = b \}, \tag{5}$$

where *h* denotes sampling time, and *a* and *b* are starting and ending time points. Repeating an ODT a number of times reveals that measured points u_i can be described by a stochastic variable $\underline{u}_i$. One may utilise all the variables $\underline{u}_i$, $i \in (a,b)$ of the model or only those points that correspond to the landmarks of the qualitative model. Due to the stochastic character of the process, the actual landmark points of repeated ODTs do not occur at the same time instants. Thus, the time points of these landmarks $\underline{t}_j$ are also stochastic variables. For one signal, j, all the previous points are defined as

$$H_j = \{ \underline{u}_j, \underline{t}_j \mid \underline{u}_j \propto \phi_{uj}(u_j), \underline{t}_j \propto \phi_{tj}(t_j), u_j \in \underline{B}_j, t_j \in \underline{A}_j, t_j \neq a,b \}, \tag{6}$$

where Φ_{ui} and Φ_{ti} refer to probability density functions. Notation $\underline{B}_j$ refers to the landmarks corresponding to the set B_j, but its elements are chosen from the set G_j. A similar definition concerns the set $\underline{A}_j$. It is assumed that arbitrary sample points $\underline{u}_i$, $\underline{t}_i$ $i=0,1,2,...$ are normally distributed stochastic variables, $\underline{u}_i \sim N(\mu_u, \sigma_u^2)$ and $\underline{t}_i \sim N(\mu_t, \sigma_t^2)$, where unknown parameters μ_u, μ_t and σ_u, σ_t are approximated from the data.

2.3 An integrated model

By combining the constraints S_i, an integrated model M is produced:

$$M = \{ S_i, i=1,\ldots,n,\ S_i = \{ x \mid x \in A_j, B_j, G_j, H_j, j=1,\ldots,m \} \}, \tag{7}$$

where the letter m equals the number of signals. So, the model is a collection of constraints which tie up qualitative time -points A_j, the corresponding landmarks B_j, quantitative sampled values of the signal G_j and the points defined by the probability density functions in H_j. Model M enables the prediction of process dynamics during an ODT. A fault is detected by comparing predicted and real behaviour.

The integrated model is generic in character, providing an outline but not details for utilizing the model in fault diagnosis. The best combination of the constrains A_j, B_j, G_j, and H_j and their detailed content depends on the implementation of the ODT. As noted before, an ODT can be realized in many ways. Exciting the process may be accomplished by means of input signals, disturbances or loads. The form of the exciting signal may also vary. Therefore, the details of the contraints must be chosen according to the designed ODT.

2.4 Statistical approach in fault detection

The results in chapter 5 are based on a procedure that utilises stochastic features of the integrated model for fault detection. This is only one choice provided by the model. The applied ODT procedure probably would support some other constraints as well. However, the results were encouraging. Thus, all test runs applied the same procedure.

Consider a response signal $\underline{u}_j$ during an identification period p. A sum S_p is produced from m measurements as

$$S_p = \sum_{j=1}^{m} \underline{u}_j \tag{8}$$

The identification is repeated n times. If $\underline{u}_j$ is characterized as a normally distributed stochastic variable, the sums S_1, S_2, S_3,..., S_n, must also be samples from a stochastic distribution $N(\mu_s,\sigma_s^2)$, where parameters μ_s and σ_s are unknown. The corresponding sum of the measurements recorded during the reference period produces a numerical mean value, denoted as μ_0. A statistical test can be set up to analyze if μ_0 has changed enough to be intepreted as a fault. According to the null hypothesis of the test, the unknown mean value μ_s is identical to μ_0:

$$H_0 : \mu_s = \mu_0 \; . \tag{9}$$

According to the alternative hypothesis:

$$H_1 : \mu_s \neq \mu_0 \; . \tag{10}$$

Since variance σ^2 is unknown in practice, it is estimated by using a sample variance:

$$\underline{s}^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(S_i - \bar{S}\right)^2 \tag{11}$$

where $\bar{S}$ is the arithmetic mean value of the sums S_1, S_2, S_3,..., S_n . The actual test parameter t is thus

$$t = \frac{\bar{S} - \mu_0}{\frac{s}{\sqrt{n}}} , \qquad (12)$$

which is distributed approximately as t-distribution. If H_0 is not valid, $| t | > t_p$, where t_p is the significance level. The procedure is applied to all the response signals of the ODT.

3. Fault isolation

The original fault isolation procedure (Pakanen 1996) classified fault patterns generated by each test. Such an approach makes it possible to specify the cause of a failure inside each subprocess. On the other hand, it requires that the fault pattern created by each fault is known. This means that somehow the system has to learn the pattern. The procedure applied in this paper is a simplified version of the original. The primary objective is to isolate the faulty subprocess. Yet, available fault patterns are utilised to isolate faulty sub-items inside the process, but without any learning algorithms. In addition, the fault patterns are created, not by detailed analysis of quantitative and qualitative features of the response signals, but simply by choosing the response signal causing the largest residual during the ODT. The isolation procedure consists of the following phases.

1) An ODT is performed in each subprocess, one by one. Basically, the faulty subprocess is isolated in this phase. If the procedure is successful this may be a sufficient result. Exceptions are faults that come up in several subprocesses or if the faulty sub-item needs to be isolated. In such cases one must go on further with the isolation procedure.

2) If only one subprocess is found to be faulty, then the responses of the measured signals are examined. The results presented in chapter 5 clearly indicate that sensitivity to the fault is different for each response signal. The response signals together generate a pattern, which is

characteristic for each fault. A simple isolation procedure is to relate the largest residual signal to potential faults. An example is presented in Figure 3, where the residual suggests several possible faults. A closer look will then reveal what the actual cause of failure is. Because just one subprocess is found to be faulty the fault itself must be typical only for the observed subprocess. This restricts the number of possible faults.

3) If two subprocesses are found to be faulty, the AHU contains either several faults or one fault that is common to both. Again, one can make a list of possible faults. Now, the number of faults is larger, consisting of potential faults in both processes. However, if the AHU contains only one fault, the actual fault must be on the both lists. So, the common faults should be checked first.

4) A corresponding procedure is applicable in a case, where several subprocesses are faulty. However, there is an increasing risk that the whole process has fallen into a disabled state and none of the ODT procedures are successful. This may result from a complete failure of the AHU or from several partial failures.

Actually learning from old solutions cannot be totally avoided. It is difficult for a user to name possible faults, related to the largest residuals but not for an expert (Hyvärinen & Kohonen 1993). So, a list of potential faults in a standard AHU as a function of the largest residuals and subprocesses could be provided by the BEMS manufacturer. By means of the list the user, perhaps a professional serviceman can quickly check a few possible causes of failures. However, the list is only a suggestion of possible faults. Due to the differences and characteristic features of AHUs and their equipment, such a listing is not exhaustive. So, the user may need to amend the list according his/her experiences.

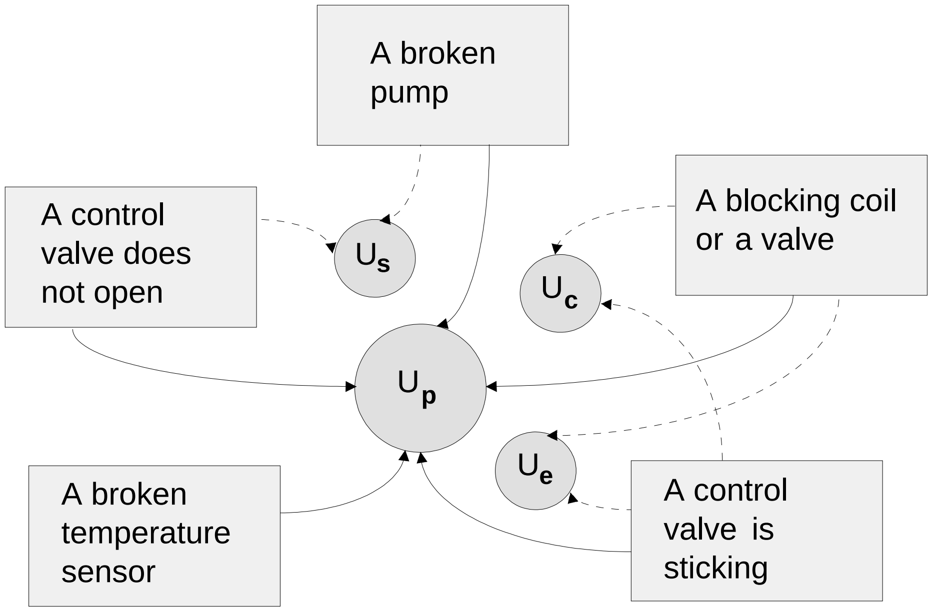

Figure 3. A diagram showing a few possible faults in a preheating process and four measurements (u_s, u_c, u_e and u_p) monitored during an ODT. Most of the faults have an effect on more than one measured signal. Yet, the presented faults generate the largest residual signal in the leaving water temperature of the heating coil (u_p).

4. Driving to the operating point

Before the exciting signal is activated, the air-handling process must be driven to an operating point, at which the water and channel temperatures, moisture and fan speeds are close to the initial conditions (Table 1). A prerequisite to achieve the required operating point is overall control of the HVAC system and the surrounding processes. The latter expression means HVAC controls of the neighbouring rooms or zones. Usually they are physically separated but they may share the same hot water supply and hot water temperature control. Abrupt changes in hot water pressure or air velocity caused by another HVAC process must be prevented. Usually, one BEMS can handle all the essential processes of the building.

Table 1. ODT procedure for fault detection. The procedure for the identification phase is similar except the "comparison", which is not included (Pakanen,1996).

Operation	**Description**
Initialisation	Examination of time and environmental conditions for execution of the on-line diagnostic test. Normal operation of the AHU is terminated if the requirements are satisfied.
Preparation	The process is steered to a specified operating point. If the operating point is not attained, a branch to an external reasoning procedure follows.
Control	Activation of exciting signals and monitoring of their response during the test procedure.
Comparison	A comparison is made between the process and model behaviour and permission for a reasoning phase is generated if the constraints are not satisfied.
Restoration	Test command mode is terminated and normal operation of the observed process and AHU is reestablished.
Reporting	A message about the detected fault is sent to the user and the symptoms of the fault are presented.

Outdoor temperature and humidity represent uncontrolled physical quantities that cannot be stabilised. That is why the ODT procedure must be designed and implemented so that these physical quantities have a small or negligible effect on the on-line diagnostic test. This is accomplished by opening the mixing dampers for full circulation during the test, thus extracting their effect on the preheating, cooling, humidifying and heating processes (Figure 4). The duration of one test is a few minutes, which is a short time compared to the time constants of the building envelope. When the dampers are examined, the air temperature for the mixing dampers can be kept stable by means of a heat recovery unit.

Sometimes a fault, environmental conditions, an untuned control etc. prevent driving directly to the operating point. Then special arrangements are necessary. If the heating process is in a disabled state, the required increase in temperature can be obtained by the preheating process and vice versa. If the cooling process is out of control, test conditions are attained by means of the heat recovery unit and cool outdoor air. Cooling, as well as heating, is also possible using the mixing dampers, if the outdoor temperature is appropriate. If the humidifier cannot be used, an increase in the moisture content may be difficult to achieve, unless the indoor temperature needs to be lowered.

The pseudo-code procedure of Appendix 1 illustrates some alternatives for achieving the operating point when some subprocesses are in a disabled state. The procedure is not exhaustive, but it presents the main approaches. Some feed back loops in control are omitted. For example a new heating phase is needed after humidifying or humidifying, and heating must be controlled at the same time. Fan control has also been dropped out.

5. Creating artificial faults[1]

5.1 Classification of faults

Fault implementation is a central issue when FDI methods are developed into practical systems. But introducing faults in an AHU is a problem. Basically faults can be classified into three different types by considering their nature: natural, artificial and simulated faults. A natural fault occurs in a real process and results from natural wearing and/or deterioration and human errors in design, operation and maintenance. An artificial fault is an intentional man-made fault, typically implemented by a change in process conditions, replacement of a

[1] Yoshida & Pakanen, 2001

system component with a faulty one or manual introduction of a faulty setting that tries to reproduce the same symptoms as a natural fault. An artificial fault is usually introduced in a real or emulated process. A simulated fault is also artificial, implemented to circumvent the physical limitations of artificial fault implementation. Simulated faults are useful when more expensive and thorough field tests are not necessary or available.

5.2 Artificial fault – a practical choice for FDI tool testing

The best choice for testing an FDI tool would be to use natural faults occurring in real HVAC systems, but this is difficult to do in practice. Natural faults do not occur in a manner and at a time suitable for the developer. If natural faults are introduced, their number should be enormous in order to test all "typical cases". This is due to the fact that every natural fault in a real process is unique, causing unique symptoms. So, symptoms caused by faults that seem to be identical are similar only statistically. Ultimately this means that even though all the symptoms are clearly measurable, an FDI tool designed to detect and diagnose one specific fault is not always successful. In addition, some HVAC system faults occur gradually. They are defined as degradation faults. It is obvious that implementation of realistic degradation faults is even more difficult. Due to these limitations and difficulties, introducing artificial faults is a practical and in some cases the only solution for testing an FDI tool in a real environment.

5.3 How to introduce artificial faults

FDI methods and tools need to be tested before they are finished into practical and commercial products. This is a central issue in developing FDI tools. Ultimately, it means that the FDI tool must be verified by applying all the faults the tool is designed for. This should be done in a real process environment.

Due to the great number of components and sub-systems in HVAC systems, there are so many fault alternatives that it is impossible to test them all. This means selection and prioritizing of the most important faults is essential. This issue is covered by Hyvärinen & Kohonen (1993), who describe typical faults in HVAC systems. The paper presents heating systems, chillers and heat pumps, VAV air handling units and thermal storage systems. Some important faults may be omitted in specific systems, and the importance of faults may differ slightly from country to country due to local workmanship or other engineering conditions.

Basically, there are two ways to introduce artificial faults. One is to replace a test component with a faulty one, and the other is to create process conditions that give symptoms similar to the specific fault. The first method is not usually chosen because it is difficult to find or make an appropriate faulty component or to do so requires substantial work, cost and time.

Some faults can be simulated by making minor artificial modifications in an existing component. Examples include a faulty PID parameter setting, a stuck valve, and an unusual supply of chilled water fed into an AHU coil. Examples of artificial faults, which are difficult to introduce into an existing component, include coil fouling, unstable data transfer behaviour through communication wiring, and vibration caused by ball bearing wear. In general, degradation faults are difficult to implement and need some specific means for implementation.

5.4 Created faults

The demonstration system was constructed so that it is capable of testing different subprocesses of the AHU and their typical faults. All the faults of the AHU were artificial. The following table explains how the faults were introduced.

Table 2. Examples of fault introduction into an AHU of a college building.

Fault type	**How the fault was introduced**
Sticking control valve	Manually hindering control valve opening or closing
Faulty sensor	Loosening a wire connector
Blocked coil or control valve	Partially shutting a manually controlled valve installed close to the coil or valve
Only partially opening valve	Manually hindering valve opening

According to Table 2 and Yoshida & Pakanen (2001), a typical artificial HVAC fault is an abrupt or large abnormal change in equipment or process operation, like a temporarily installed mechanical hindrance, a manual deviation of process parameters, a manual control action of process equipment, a change in electrical installations or a temporary modification of software parameters.

6. Assessment of the FDI system

6.1 Assessment criteria

Assessment of the FDI method, tool or the whole system is one milestone in the research and development of a commercial FDI product. The subject is covered by several authors in the final report of Annex 34. The objective was to find proper performance criteria (House et. al 2001) and to compare FDI tools (Dexter & House 2001, Isakson & Carling 2001). Both problems are interesting but rather difficult to solve. This is due to the fact that performance criteria inevitably concern, besides the diagnostic method or tool itself also the environment: the automation system, process and instrumentation. The same is true for a comparison of diagnostic methods and tools.

Consequently, instead of defining criteria for assessing diagnostic methods and tools, one should preferably assess the whole fault diagnostic system. Such a system consists of the building automation system interfaced to a process, in addition to the instrumentation and the embedded fault diagnostic tool. The diagnostic system is closely tied to the HVAC process and its environment. This means that the assessment criteria must also be practical, closely tied to the operating environment. Hence, the assessment criteria are related to the pragmatic aspects of FDI systems (Steels 1990, Leitch & Gallanti 1992, Kurki 1995). Commercial requirements are also closely related (Gruber 2001). In any case, the pragmatic aspects specify the available domain knowledge and limits for ideal solutions. They are seen as constraints that are set for the diagnostic system. These constraints may come from the application environment or they may be general requirements. Assessing the whole diagnostic system does not remove the original problems but gives the right perpective for solving them.

6.2 Qualitative evaluation

The following assessment method is based on qualitative evaluation. It is not exhaustive for the FDI system evaluation. An in-depth method would compare FDI systems in the same process environment and use a test platform giving fair, numerical results. As noted before, such a comparison is difficult to arrange. It is also hard is to find a metrics that gives fair numerical results for qualitative features that inevitably will be met. Yet, qualitative evaluation does not replace or exclude the need for practical testing of the FDI system. Such a test is an essential part of the total evaluation of the system.

The proposed qualitative evaluation method is simply a checklist. The left side of the list presents properties of an ideal FDI system, consisting of commercial, user and technical requirements etc. (Pakanen et al. 1996). On the right side the FDI system designer and/or evaluator writes down corresponding properties of his own system. So, the real and ideal systems are compared. Obviously, the comparison is not fair. However, the point is that the designer pays attention to the essential features that are not yet included in his FDI system. A practical FDI system is always a compromise of those properties. But, if too many features differ from the ideal or good properties the designer should reconsider how to change his system or consider whether it is even reasonable to continue the development any more. Table 3 presents a short qualitative evaluation of the ODT system. The list of properties is not complete. Depending on the operating environment one can change or add new viewpoints.

7. The demonstration system

7.1 The building

The demonstration system is installed in a college building in Oulu, Finland. The three-storey building was constructed during the seventies. The total building volume is 60000 cubic meters, but it is only partly controlled by the demonstration system. The zones under control of the demonstration system consists of laboratories, and facilities for the staff. Two thousand students and officials occupy the building in the daytime between 08:00 and 20:00 five days a week.

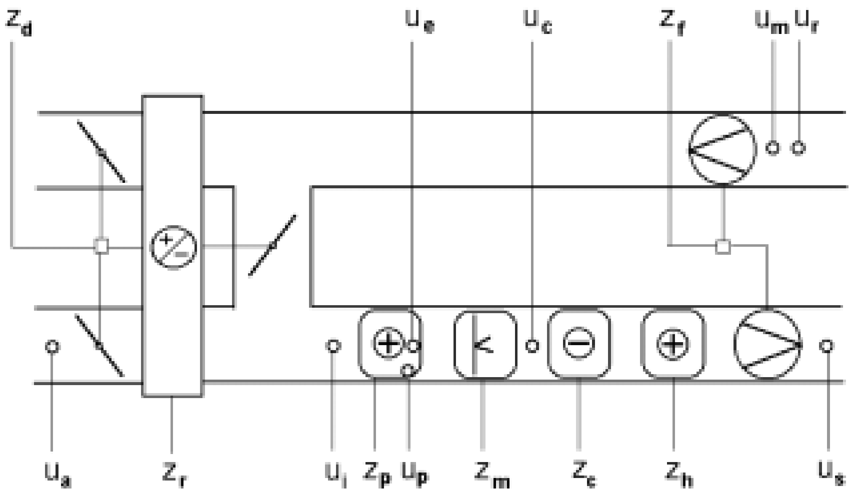

Figure 4. Simplified schematic of the air-handling unit.

7.2 The HVAC-system

The demonstration system consists of a BEMS interfaced to an air handling process. Figure 4 presents a schematic of the AHU and Figure 5 the real AHU. It contains a heat recovery unit, mixing dampers, and preheating, humidifying, cooling and heating processes. The heat recovery unit, dampers, heating and cooling need continuous control signals (z_r,z_d,z_p,z_h,z_c), but the humidifier is controlled by an on-off signal (z_m). The dampers are connected to a single control signal z_d. Supply and return fans can be driven at two different speeds, controlled by signal z_f. In addition, there are temperature measurements of the outdoor air (u_a), mixed air (u_i), supply air (u_s), return air (u_r), leaving (u_p) and entering (u_e) water of the preheating coil, and channel air after the preheating coil (u_c). The humidity of the return air (u_m) is also measured. Usually, the set point temperature of the zone is maintained using a cascade control algorithm, but during the ODTs each subprocess is controlled separately.

Figure 5. Overview of the demonstration system. The air-handling unit is on the left and the BEMS is on the right.

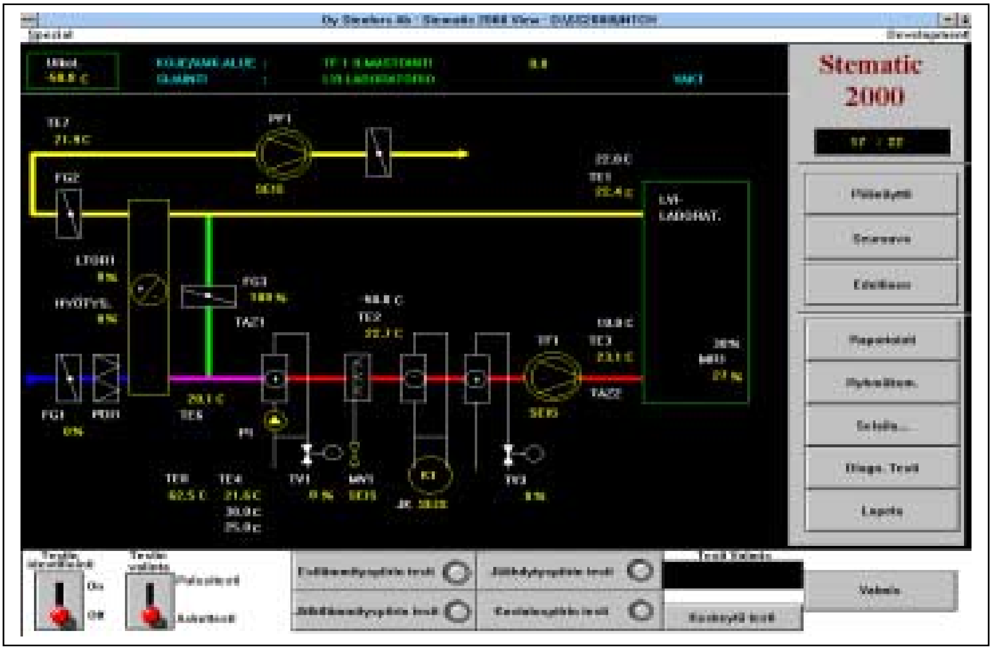

Figure 6. Graphical user interface of the BEMS, created using tools of an InTouch-operating system. The buttons below the process diagram are designed for controlling the ODTs of preheating, cooling, humidifying and heating.

7.3 The automation system

A commercial building energy management system (BEMS) controls the AHU. The BEMS supervises and controls only one air-handling unit although its capacity is enough for several AHUs and zones. The reason is that the AHU and the BEMS comprises a teaching system. By means of the system, students at the college study the operation of automation equipment and air handling processes. The AHU and the BEMS are also designed for continuous air handling of a few laboratories, and facilities for the staff. The rest of the building and its zones are controlled by another building energy management system.

The user interface is based on an Intouch -real time operating system (Figure 6). InTouch controls all the operations of the air handling process through a separate sub-control unit, interfaced to the process. The operating system enables the user to add new features into the original process control by writing special script language programs. All the extra operations needed for controlling the on-line diagnostic tests were programmed using the script language, but analysis of the results needed other programming tools, also.

7.4 Measurements and control

The BEMS provides the on-line diagnostic tests with the following controls and measurements.

- Outdoor air temperature (u_a)
- Supply air temperature (u_s)
- Return air temperature (u_r)
- Channel air temperature after preheating coil (u_c)
- Leaving water temperature of the preheating coil (u_p)
- Water temperature entering the heating processes (u_e)
- Mixed air temperature (u_i)
- Return air humidity (u_m)
- Preheating valve control (z_p)
- Heating valve control (z_h)
- On-off cooling control (z_c)
- On-off humidity control (z_m)
- Mixing damper control (z_d)
- Heat recovery control (z_r)
- Two-stage supply fan control (z_f)

8. Results

8.1 The test procedure

The following pages illustrate ODTs applied in the preheating process of the AHU. The process is excited by opening and closing the preheating control valve. The test procedure is almost similar for both identification and fault detection. First, the normal operation of the AHU is terminated. Then, the preparation phase follows; the fans are started and the whole AHU is steered to the operating point. The room and duct temperatures are maintained stable for a few (4 - 5) minutes. At this point the coil valve is near to its closed position, automatic control of the leaving air temperature is disconnected and the mixing air dampers are set to full circulation.

When the control phase of the test begins, the valve is first driven fully open and kept there for a few (4 - 5) minutes, and then driven to a closed position. The exact magnitude and duration of the opening depends on the characteristics of the process, but the leaving water temperature of the heating coil should get about ten to fifteen degrees higher than the steady-state level. The response signals are monitored continuously until the stationary condition or the prescribed time limit of the test is achieved. Control actions of the other subprocesses are similar and they all follow the general procedure presented in Table 1.

All the faults were artificial and introduced according to chapter 5. The created faults were the following: blocking of a pipe or valve, temporary or permanent sticking of a valve, a partly opening valve, and a broken sensor. The process was excited by the control signal of the coil valve. All the figures consist of two curves, a mean-valued signal during normal operation and a corresponding signal of faulty operation. The mean valued signal is obtained from three identification test runs. So, at a 5 % significance level and n = 3, t_p = 4.303. A test parameter value of each figure indicates if the fault is detected. Symptoms are measured and collected from several sensors.

8.2 A blocking coil or valve

Figures 7, 8 and 9 present a case where the coil and/or pipes in the preheating process are partly blocked causing 30 % decrease in water flow. The fault is artificial and made by partly shutting a manually controlled valve. According to the statistical test, a fault is detected if the test parameter $| t | > 4.303$. The figures illustrate how the fault is detected by monitoring different measurement signals of the AHU process.

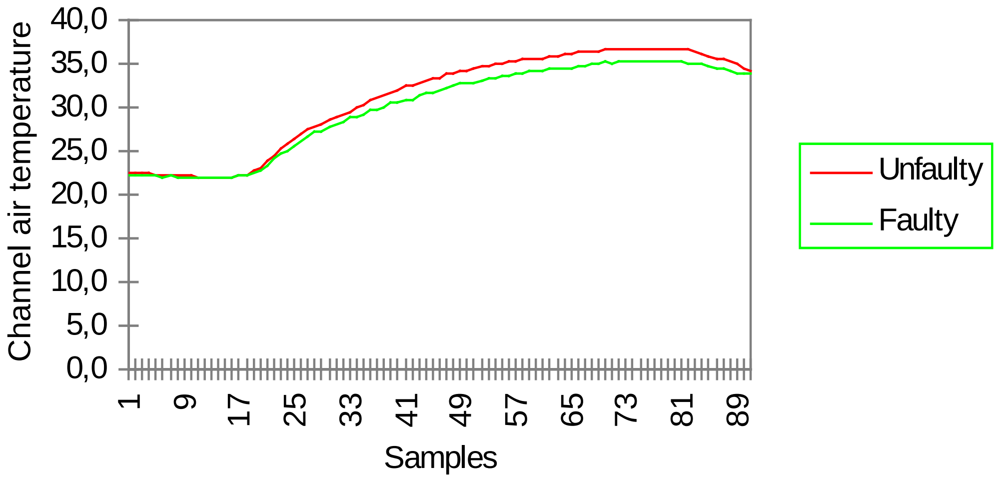

Figure 7. Response signal of the channel air temperature when the coil and/or pipes of the preheating coil are partly blocked. The test parameter value is t = 1.70, which indicates no fault.

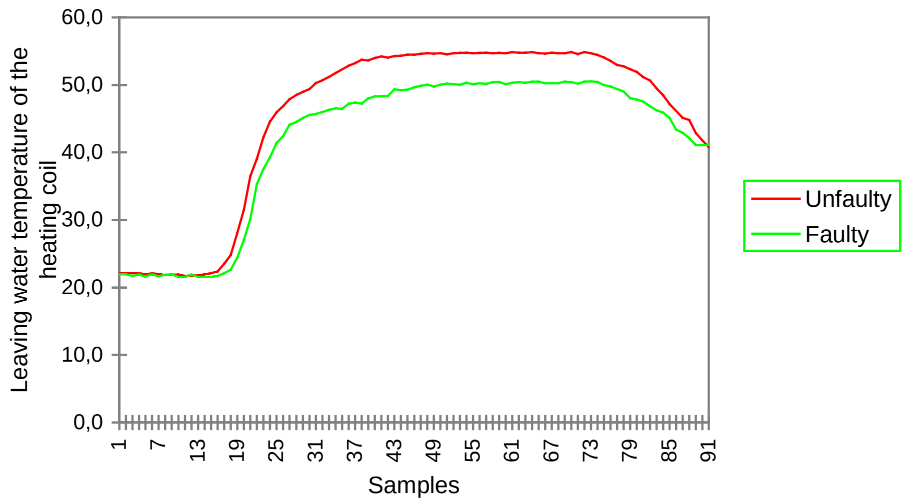

Figure 8. Response signal of the leaving water temperature in the preheating coil when the coil and/or pipes of the preheating coil are partly blocked. The test parameter value is t = 12.74, which means that the fault is detected.

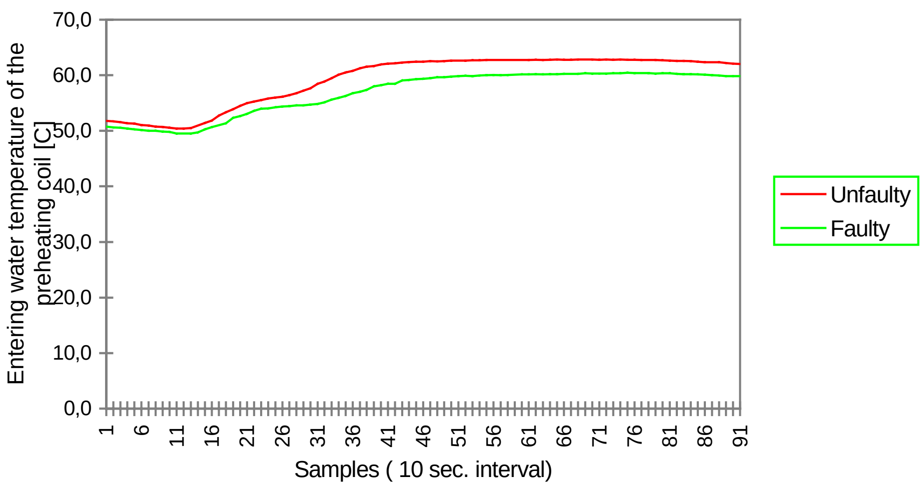

Figure 9. Response signal of the entering water temperature in the preheating coil when the coil and/or pipes of the preheating coil are partly blocked. The test parameter value is $t = 2.69$. The test parameter value is not exceeding t_p = 4.303 and the fault is not detected.

8.3 A sticking valve

Figures 10, 11 and 12 represent a case where the control valve of the heating coil is sticking in the opening phase. The controller is finally able to steer the valve to a fully open position but the opening is delayed when compared to a case, where no fault is present. The fault is artificial and made by mechanically hindering the valve's opening.

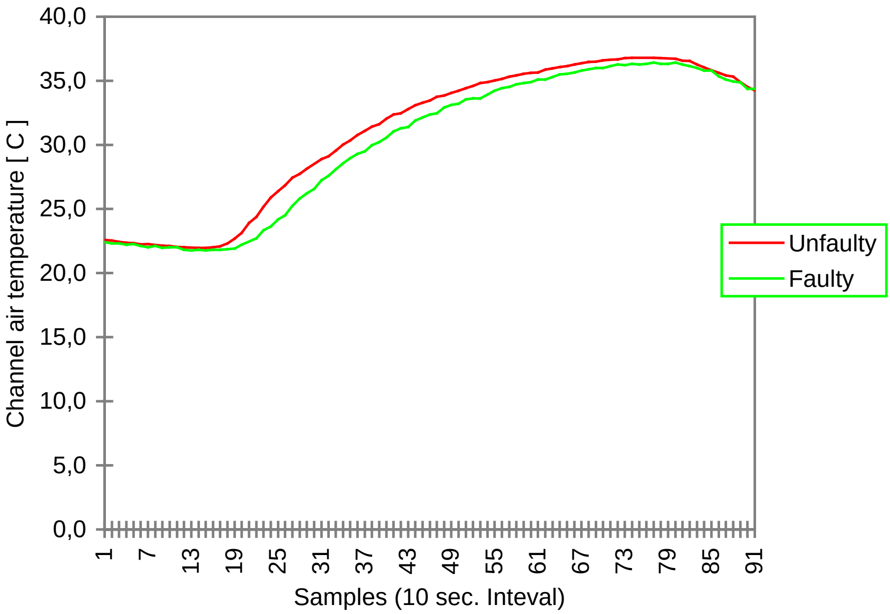

Figure 10. Response signal of the channel air temperature when the control valve of the heating coil is sticking. The test parameter value is t = 1.33, which indicates no fault.

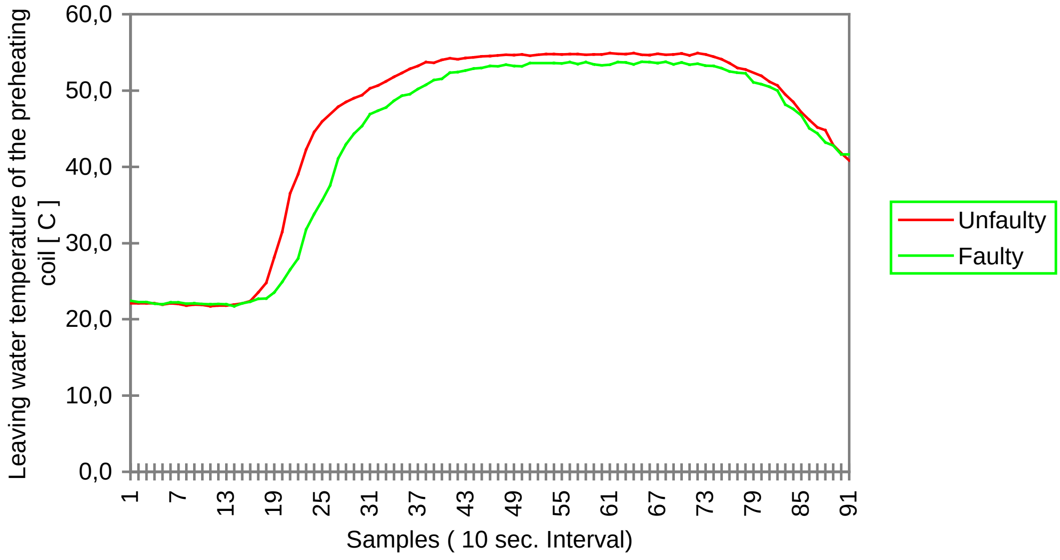

Figure 11. Response signal of the leaving water temperature in the heating coil when the control valve of the heating coil is sticking. The test parameter value is t = 7.24. The fault is detected.

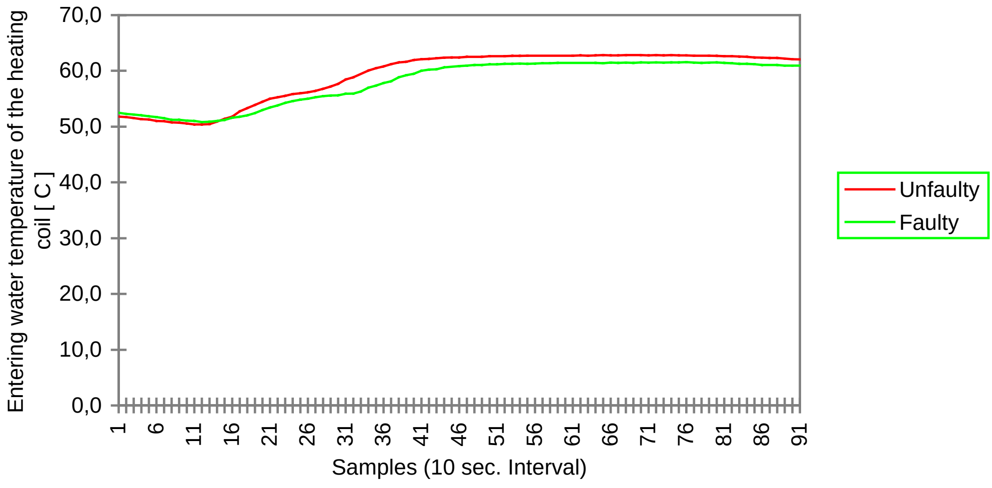

Figure 12. Response signal of the entering water temperature in the heating coil when the control valve of the heating coil is sticking. The test parameter value is t = 1.38, which indicates no fault.

8.4 A valve, which opens only partly

Figure 13 represent a case where the control valve of the heating coil is only partly opening. The valve does not reach the fully open position. The fault is made by mechanically hindering the valve's opening. The fault is detected by monitoring the supply air temperature.

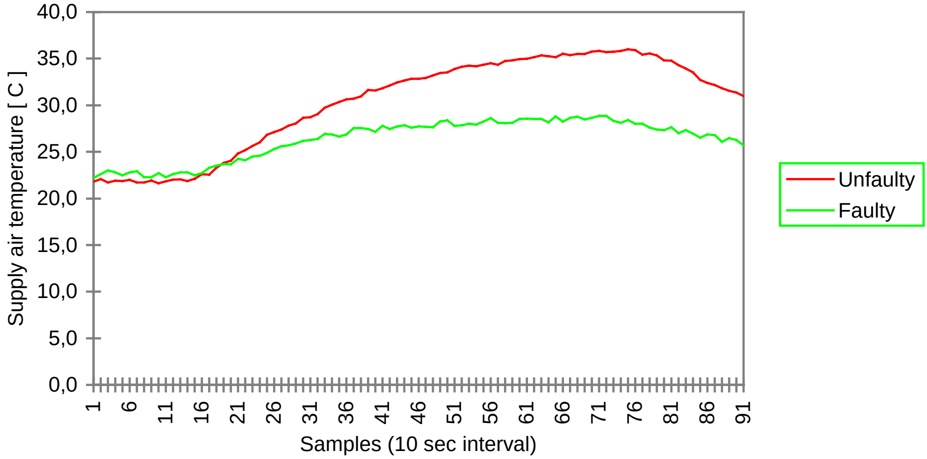

Figure 13. The control valve of the heating coil does not attain a fully open position. The test parameter value is t = 7.97.

8.5 A broken sensor

Figures 14 and 15 represent a case where the electrical cable connecting a temperature sensor to a controller is broken. The fault is artificial and made by loosening a wire connector.

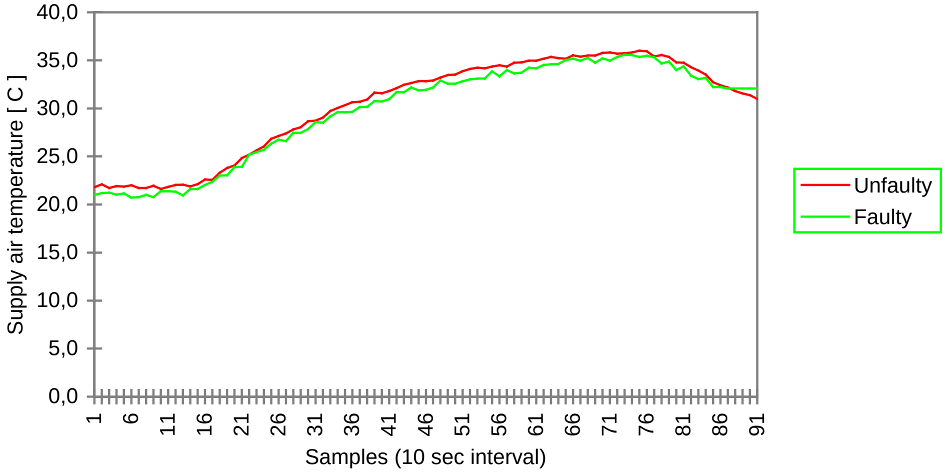

Figure 14. An electrical cable connecting a temperature sensor to a controller is broken. The figure presents the effect of the fault on the supply air tempreature. The test parameter value is $t = 1.15$, which indicates no fault.

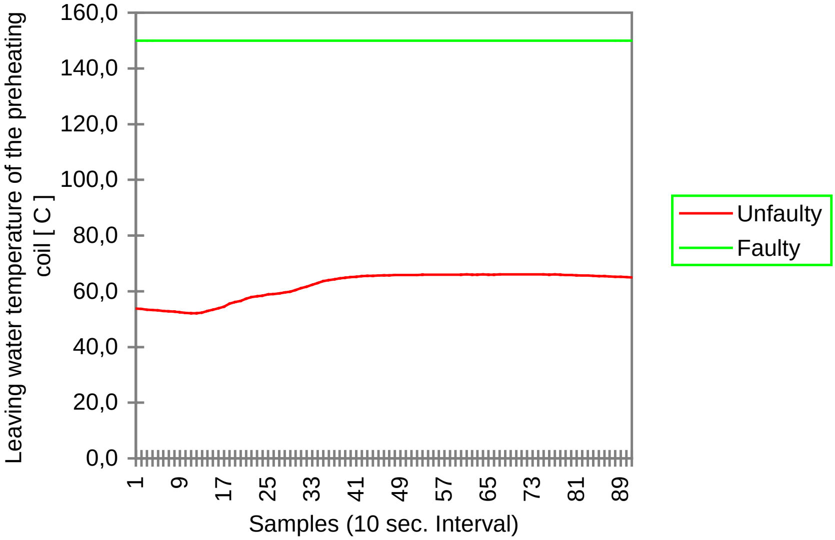

Figure 15. An electrical cable connecting a temperature sensor to a controller is broken. The figure presents the effects on the measurement signal of the faulty sensor. The test parameter value is t =-483.8. So, $|t| > t_p$ and the fault is detected.

9. Discussion

The demonstration system was constructed in order to test ODTs in a real building, using a BEMS interfaced to a real AHU. Although the process, the control systems and the environment were real, it was necessary to resort to artificial faults in testing the methods. However, by careful design the artificial faults and their symptoms can be made close to natural, especially for abrupt faults. The above test runs showed that ODTs are successful in detecting abrupt faults.

All the introduced faults were distinct and/or abrupt changes in normal operation of the process. As pointed out earlier, degradation faults are difficult to create artificially. Thus, no test runs were performed using degradation faults. However, the test runs give a feeling that degradation faults will be difficult to detect by means of an ODT. This is due to the fact that the larger tolerances of the process control and changing environmental conditions increase variance and set a limit on the detected fault size.

Although the introduced faults could be detected, the trials pointed out some possible problems in practical applications. The BEMS must be able to control all the HVAC processes of the building that have influence on the ODT and the test environment. The conditions must be the same throughout the identification and fault detection periods. This is a requirement that may need special arrangements in the HVAC system. In any case, the test environment must be carefully checked out in order to guarantee uncorrupted results. In addition, process controls must be in good condition and well tuned. Large fluctuation in the controlled physical quantity or difficulties in achieving the targeted operating point may cause problems in performing on-line diagnostic tests or at least degrade the results.

Fault detection and isolation is largely based on instrumentation. Instrumentation is usually designed for process control, not for diagnostics. The above results clearly show how instrumentation has an influence on both fault detection and isolation. If the leaving water temperature of the preheating coil is dropped out from ordinary measurements, detection of a sticking valve is hardly successful by means of the ODT. The reason is that the effect on the other responses (Figures 10 and 12) is not large enough to exceed the test parameter limit value.

So, the sensitivity of the response signal is different for each fault. This phenomenon is utilized in fault isolation, as presented in Figure 3.

Assessment of the ODT system using qualitative evaluation (Table 3) clearly reveals the benefits and drawbacks of the ODT system. In principle, the ODT is an uncomplicated diagnostic procedure, which is generic over faults and processes. The system requires no additional instrumentation, needs only few input data and no more than domain knowledge for initiation. But, the on-line diagnostic test is not a transparent operation. The process must be stopped and the whole HVAC system must be steered to a special state before running the test. Integrating ODT procedures in a BEMS is a rather tedious process and will have an effect on developing costs. In addition, fault isolation sometimes needs supporting diagnostic procedures or even human assistance for successful operation. However, the drawbacks are not serious. The ODT still has potential for a practical diagnostic method in a BEMS or in an automation system.

Table 3. Qualitative evaluation of the ODT system.

Properties of an "ideal" FDI system	Properties of the ODT system
Needs only a few input data submitted by the user.	The user must input a few data values before the ODT method is ready for use.
Needs only domain knowledge for initiation or updating.	Only domain knowledge is necessary for initiation or updating.
Adapts easily to new faults.	Basically, adapts easily to new faults. The algorithm is not designed to detect any specific fault(s).
Does not disturb normal operation of the process.	Disturbs normal operation of the process. Normal operation of the HVAC-process must be terminated before an ODT is executed. After execution of the ODT normal operation of the process and AHU is re-established.
Needs no human assistance during detection or isolation.	Sometimes human assistance is needed during fault isolation. The ODT method isolates the fault only in a subprocess. The user has to localize the fault in the subprocess.
Causes no additional energy/fuel consumption.	Causes no additional energy/fuel consumption if designed properly.
Requires only a short training period/a few training data.	Requires a few identification periods before the method is ready for fault detection. The exact number of training periods depend on the required significance level of statistical test.
Applies to many kinds of HVAC processes; generic over processes.	The ODT method is applicable to several HVAC processes but the procedure is different in each process and needs a proprietary design.
Applies to many kinds of faults; generic over faults.	Applies to several fault types.
Supports both fault detection and isolation.	Supports both fault detection and isolation. Primarily, the faulty equipment is not isolated, only the subprocess containing the fault.
Needs only an uncomplicated process model.	Needs only an uncomplicated process model.
Is easy to configure to new applications.	Is easy to configure to new AHU applications. the number of conceivable subprocesses operating under the ODT depends on each AHU.
Is technically easy to embed and integrate in building automation systems.	Technically easy but rather tedious to embed in a BEMS. ODTs are based on existing control and monitoring algorithms, typically available in a building automation systems.
Requires only a minimum or moderate amount of work/costs for development and implementation.	Work/costs for development and implementation of ODTs are probably moderate. Costs depend on existing software solutions of the BEMS and software tools to be applied in implementation.
Requires no additional instrumentation.	Basically, requires no additional instrumentation

10. Summary

A demonstration system, designed for testing fault detection and isolation methods in a real building and HVAC process, places the system designer close to technical problems that do not exist in a simulation environment. Installation of the FDI method in an automation system is one step in developing the method into a commercial FDI product. Even if such a step is successful, many problems are not yet encountered. However, the demonstration phase may reveal some crucial shortcomings in the FDI method and help the designer further develop his/her FDI method, tool or system.

The ODT is an appropriate diagnostic method for finding distinct and abrupt changes in a process, but not for detecting slow degradations and gradual faults. The size of the detected faults depends partly on the control capability of the automation system. The system must be able to manage the process and its environment and to drive the process repeatedly to the same operating point. Disturbances and deviations from the targeted operating point increase variances and decrease residuals, which in turn determine the size of the detectable fault.

An ODT is an uncomplicated diagnostic approach. But implementation of the method as an embedded system, which exploits the resources and algorithms of the BEMS and takes care of the user interface, needs some efforts. Some of the required control and monitoring operations in the demonstration system were implemented using the programming capabilities of the operating system. Still, there are many details and procedures that must be created at the application program level if the demonstration system is further developed.

An FDI system is closely tied to the process and its operating environment. Hence, the assessment method and criteria also must be related to the pragmatic aspects of the FDI system. The proposed assessment method is based on qualitative evaluation. The assessment method did not reveal any fundamental shortcomings that could prevent development of the ODT system into a commercial FDI product.

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APPENDIX 1

DRIVING TO THE OPERATING POINT - A PSEUDO CODE PROCEDURE

```
Start: Set the operating point as a set point
       IF targeted temperature is at the set point GOTO Testi
       IF targeted temperature is high*) THEN
           GOTO Cool
       ELSE ! Comment: Targeted temperature is low
           Turn on temperature control of the preheating process
           Pass a delay
           IF targeted temperature is still low*) THEN
               OUTPUT Temperature control of the preheating process failed
               Turn off temperature control of the preheating process
               Turn on temperature control of the heating process
               Pass a delay
               IF targeted temperature is still low*) THEN
                   OUTPUT Temperature control of the heating process failed
                   Turn off temperature control of the heating process
                   IF Outdoor temperature is higher than indoor temperature
                   THEN
                       Turn on mixing damper control
                       Pass a delay
                       IF targeted temperature is within specified limits THEN
                           GOTO Moist
                       ELSE
                           OUTPUT  temperature control of the mixing dampers
                           failed
                           OUTPUT Diagnostic testing of the preheating
                           process failed
                       ENDIF
                   ENDIF
               ELSE
                   OUTPUT Diagnostic testing of the preheating process
                   failed
               ENDIF
           ENDIF
       ENDIF
       GOTO Moist
Cool:  Turn on the cooling control
```

```
        Pass a delay
        IF targeted temperature is still high*) THEN
            OUTPUT Temperature control of the cooling process failed
            GOTO Out
        ELSE
            GOTO Moist
        ENDIF
Out:    IF Outdoor temperature is lower than targeted temperature THEN
            Turn on mixing damper control
            Turn on heat recovery control
            Pass a delay
            IF (targeted temperature - set point temperature) is within limits
            THEN
                Turn off mixing damper control
                Turn off heat recovery control
                Close the damper (back to full circulation)
                GOTO Testi
            ELSE
                OUTPUT Temperature control of mixing dampers and heat
                recovery failed
                OUTPUT Diagnostic test failed
            ENDIF
        ENDIF
Moist:  IF Humidity of the zone is low*) THEN
            Turn on humidity control
            Pass a delay
            IF Targeted moisture is still low*) THEN
                OUTPUT Humidity control failed
                OUTPUT Diagnostic test of the humidifier failed.
            ELSE GOTO Testi
        ENDIF
```

High*) and low*) means higher or lower than the operating point including tolerances.

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Title

Demonstrating a fault diagnostic method in an automated, computer-controlled HVAC process

Abstract

A demonstration system, designed for testing and developing fault diagnostic methods in a real building and HVAC process, places a designer close to technical problems that do not exist in a simulation environment. This paper presents such a demonstration system, and finds new solutions to a few practical problems confronted in developing the system into a fault diagnostic product. The demonstration system consists of a building energy management system interfaced to an air handling process, modified by an embedded computer program executing the diagnostic procedures. Although not yet a prototype, the demonstration system already contains a lot of typical features of a diagnostic product. In order to evaluate such features an assessment method is proposed. It points out possible problems of the system and gives new viewpoints for further developing the prototype and finishing the actual diagnostic product.

Fault detection and isolation is based on an on-line diagnostic test (ODT), which is a series of control and monitoring actions applied to a process. Performing an on-line diagnostic test means exciting the automated process by means of prescribed input signals, disturbances or loads, supervising responses and comparing results with a process model. The ODT is an uncomplicated diagnostic method for finding distinct and abrupt changes in a process but not for detection of slow degradations and gradual faults. This paper presents a new and straightforward procedure for fault isolation, in which learning algorithms of fault patterns are not necessary.

Keywords

fault diagnostics, fault detection, test methods, buildings, HVAC, simulation, energy economy, air handling, assessment, air conditioning, monitoring, heating, computer programs

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