Interactive Education of Engineers in the Field of Fault Diagnosis and Fault-Tolerant Control

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Abstract: The main purpose of this paper is to present how the new information technologies can be used to aid engineering education in the area of fault diagnosis and fault-tolerant control. A 3D virtual reality model of the second stage of a water filtration system together with its simulation model are pointed out as a useful learning mean for stimulating education in the domain of advanced control theory at the university level. Some applications of the elaborated tool for presenting either fault diagnosis or fault-tolerant control issues are given and the most important merits and limits of the proposed approach in the education process discussed.

Keywords: fault diagnosis, fault-tolerant control, information technologies, virtual reality, interactive education tools

1. Introduction

Nowadays, it is well understood that technical systems and processes must be safely and reliably operated due to requirements of a human life and a health protection, an environment quality management, as well as of economic interests. From this point of view, such objects require advanced control rules taking into account these three factors simultaneously. It leads to development of more and more useful and effective methods, which can be used in real world applications. Recent achievements in control theory and its industrial usage are included into three closely related parts: robust control, fault diagnosis and fault-tolerant control [2, 10, 12]. The sufficient knowledge and skill sets are also needed for scientists and engineers in order to be able to read and understand international publications in this field. Technical universities and colleges in the whole world offer a number of programs for students containing courses on subjects such as robust control, fault diagnosis and fault-tolerant control design. On the other hand, there are publicly available benchmark projects that can be employed for either learning or research purposes in this domain.

There are available a number of courses connected with diagnostics, robust control, fault-tolerant control, e.g. “Vibration analysis training” delivered by Mobius Institute [21]. It consists of vibration analysis, balancing, shaft alignment, condition monitoring and reliability trainings. The course follows the ISO 18436-2:2003 standard specifying the training requirements and certification process resulting in a vibration analyst certificate.

Currently, following the rapid achievements in computer science, software and hardware development, a growing number of applications of virtual and augmented reality technologies in development of training mobile systems are noticed. Such systems aid the user carrying-out maintenance or diagnostics tasks on real objects [6, 13], e.g. during the building a noise map generated by a machine (device) [17], maintenance of an armored personnel carrier turret [7]. Furthermore, there are also available other augmented reality training systems applied in machinery design [11], medical diagnostics [15], as well as education and entertainment [8].

A second comprehensive source of knowledge and diagnostic data are the benchmarks being some kind of training and test platforms, known for many years. For example, in the early ’90s there was developed a numerical model (Tennessee Eastman plant simulator) of an industrial chemical process [5]. This is the model of gas-liquid exothermic reactions and incorporates models of a reactor, separator and recycle arrangement. The model of the process was shared as the FORTRAN subroutines. The purpose of sharing was to develop study and evaluate process control technology [18]. The benchmark DAMADICS [1] is a set of on-line diagnostic tools applicable for the power, food processing and chemical industries.

The training concerns development and integration of many diagnostic methods applied in a real sugar factory, mainly for valves plant actuators. The next example [20] concerns a simulation of continuous stirred tank heater (CSTH) pilot plant. The model takes into account volumetric and heat balances, and measured (not simulated) nonlinearities of the actuator and process. The benchmark contains the Simulink model, experimental data, and some suggestions for system identification, fault detection and diagnostics. There is also available the benchmark model for the fault-tolerant control of wind turbines [16]. The model incorporates actuators, sensors and system faults in the drive train, pitch system, generator and converter system. Also DiaSter [4] – Intelligent System for Diagnostics and Automatic Control Support deserves attention.

Fig. 1. A 3D virtual reality model of the power plant
Rys. 1. Trójwymiarowy wirtualny model elektrowni

This system implements advanced methods of modeling, diagnostics and control of industrial processes. DiaSter system is composed of a core software platform and specialized packages. It provides the following functionalities: process simulation and modeling, fault detection, fault diagnosis, process parameters processing, virtual sensors and analyzers, knowledge discovery in databases, advanced control and optimization, etc.

The paper presents some results of the project entitled „Interactive education of engineer" – exercise 21: "Maintenance and diagnostics of a selected object". The object under test is an exemplary power plant. The project resulted in a 3D interactive software containing a virtual model of the power plant (fig. 1). It allows realizing a virtual visit of the user on the power plant, familiarizing the user with the basic diagnostic knowledge, carrying out many on-line and of-line diagnostic tests of the power plan equipment, like a turbo set, a pump, a thrust fan, a coal mill or a conveyor belt. This paper focuses on fault diagnosis and fault-tolerant control of the water filtration system of the power plant.

2. 3D virtual reality and simulation models

From 2010 to 2012, Faculty of Mechanical Engineering at Silesian University of Technology carried out a project called InterEdu (http://www.interedu3d.pl). The main purpose of this project was to elaborate interactive didactic materials applying the 3D technology developed by the i3D company (http://www.i3D.pl). This technology allows to create 3D virtual scenes taking advantage of the dynamics occurring between objects. A user can move freely inside the 3D virtual reality and modify the virtual reality scene by previously defined rules and principles.

One of the tasks of the InterEdu project was to develop an interactive application presenting selected issues of maintenance and diagnostics of a complex technical system. A fossil-fuel power station was chosen as an example [14]. The application consists of three logical parts. The first is a virtual walk through a power station (see fig. 1). It allows to observe stages of electric power generation. Consequently, the user can understand the principle of operation of the power station. In the second part, the application presents selected issues of machines maintenance, particularly shafts alignment of the turbo generator, rotor balancing and others. The third part of the application is diagnostics of machines and industrial processes [3]. It is where the user can inspect the turbine blades, bondage and wheels using the endoscopic technology. It is also possible to diagnose a condition of a turbo generator, a coal mill and a coal conveyor using vibro-acoustic measurements. A second stage of the water filtration system (fig. 2, 3) was selected to present the main issues of fault diagnosis and fault-tolerant control. This system was chosen due to the similarity to the classic three tanks system [12].

In thermal power stations, a high degree of water cleanliness is required due to the requirements of the steam production process [19]. For this reason, the thermal power stations have multi-stages systems of the water filtration. The first few steps in the water filtration process are performed using the mechanical filtration. Unfortunately, detailed information about such systems is not generally available in the technical literature. For this reason, an individual proposition of the water filtration system

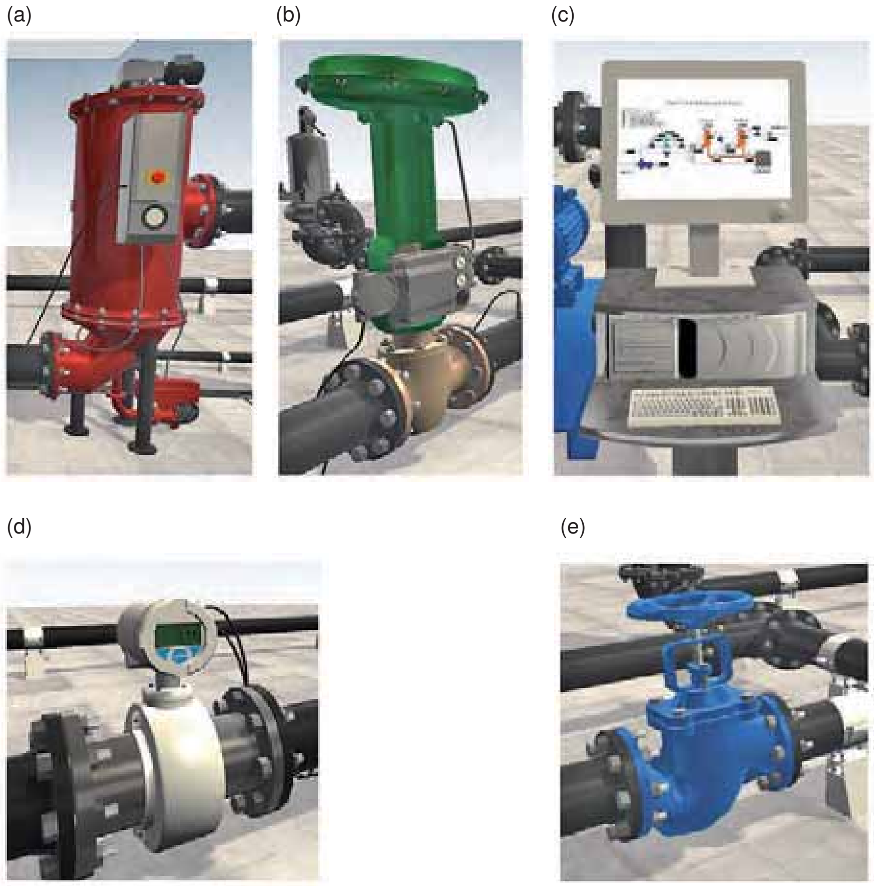

Fig. 2. Selected components of the water filtration system: (a) an automatic self-cleaning water filter, (b) a control valve, (c) a control panel, (d) a flow meter, (e) a globe valve

Rys. 2. Wybrane komponenty układu filtracji wody: (a) filtr samoczyszczący, (b) zawór regulacyjny, (c) panel sterowania, (d) przepływomierz, (e) zawór ręczny

was developed at the Faculty. It is based on two automatic and self-cleaning filters made by the HYDAC company [9]. Details of the proposition are shown in fig. 3(a). The remaining components are: a pump unit with a 3-phase asynchronous motor, a control valve and a digital valve controller (fig. 2(b)), globe valves (fig. 2(e)), a safety valve, flow meters (fig. 2(d)), pressure sensors, a temperature sensor, an operator control panel with an interface to SCADA system (fig. 2(c)), pipes, pipe joints and pipe supports.

A setting point of our system is defined by the values of pressure and water flow at the outlet of the second filter. The developed system enables control of these two parameters. The water flow is controlled by the control valve and the pressure by the pump. An additional element that was introduced in the presented filtration system includes a bypass of the control valve (fig. 3(a)). This solution allows to replace the valve without the necessity to shut down the filtration system.

Fig. 3(b) illustrates the MATLAB/Simulink model created using the concept and ideas proposed in the frame of the DAMADICS project [1]. Elements like an electro-pneumatic valve actuator (1) and fault simulation blocks were directly used from the DABLIB library. Moreover, the simulation model was extended to other elements of the water filtration system such as the pump (2), two self-cleaning filter systems (3, 4) and the pipes (5–7) connecting them to the other components in the power plant. Simulink models of these elements have also the possibility to simulate the faults affecting the functional behavior of the whole system. In this way, it was possible to obtain a wide range of actuator, sensor as well as plant component faults. There are also two fault-tolerant regulators, embedded in the feedback loops, for automatic and systematic control the water pressure (8) of the water flow (9) in the pipeline despite faults that might affect the performance of this plant.

As seen in fig. 3(b), for diagnostic and fault tolerant control purposes, only selected process variables are available, such as the temperature TIP1 [°C], pressures PIP1-6 [bar], main pipeline flow rates FIP1-3 [m^3/h], the estimated pomp efficiency PE [%], the valve plug displacement RV1 [%] and reference signal values like the water flow set-point CV1 [m^3/h], the pressure set-point CV2 [bar] and the position set-point CVRV1 [%]. This model is released for students and can be completed and modified in different ways during laboratory classes or homework exercises. The 3D model of the water filtration system was designed in such a way, that the dynamic behavior of the system operating under steady state and fault conditions was emulated with the use of the simulation model. Therefore, it can be applied by lecturers to create the on-line interactive animations which can be presented during lectures and other classroom activities to clearly explain the most important issues in designing fault diagnosis and fault-tolerant control systems.

3. Case studies

In the section, some results of using the elaborated learning means are briefly described. Inserted examples show how the new information technologies can be employed to aid the engineering education in a domain of the paper subject. The first one is concentrated on the problem of fault detection and isolation for the water filtration sys-

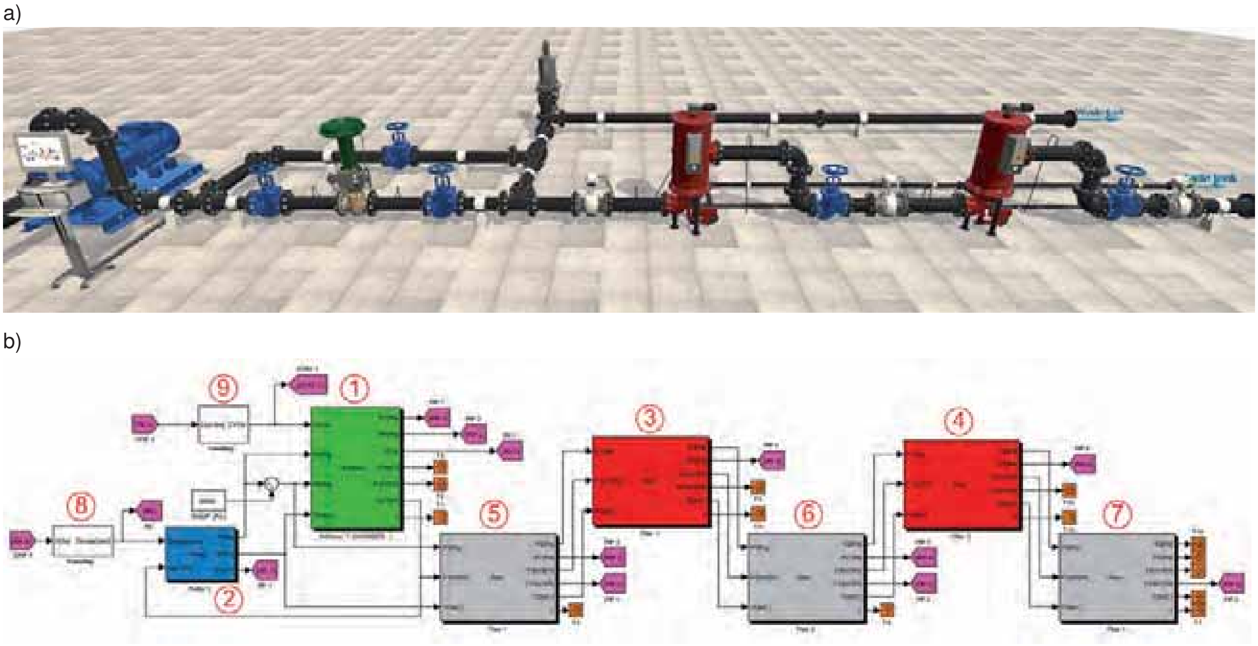

Fig. 3. 3D virtual reality scene (a) and simulation models (b) of the water filtration system

Rys. 3. Wirtualny model 3D (a) i model symulacyjny (b) układu filtracji wody

tem, whereas the second focused on fault-tolerant control of the plant. In order to present some aspects more clearly only three faults presented in tab. 1 are investigated.

Tab. 1. The set of the considered faults

Tab. 1. Zbiór rozważanych uszkodzeń

f_0	Faultless
f_1	Pipeline clogging
f_2	Flow rate sensor fault (FIP3)
f_3	Servomotor’s diaphragm perforation

Model-based fault detection is realized herein using a well-known diagnostic scheme where a model of the process is created for fault-free conditions [12]. Eleven different relationships between process variables were discovered using autoregressive with exogenous input models (ARX). The Akaike information criterion was used for determining the structure of each model. The least-squares method was applied to estimate parameters of ARX models. The mean absolute percentage error calculated for every model during the identification procedure was smaller than 5 % and the histogram of the error signal (residual) had normal distribution. All the residuals are obtained in the same manner presented in fig. 4. After input/output signal pre-processing, the output of

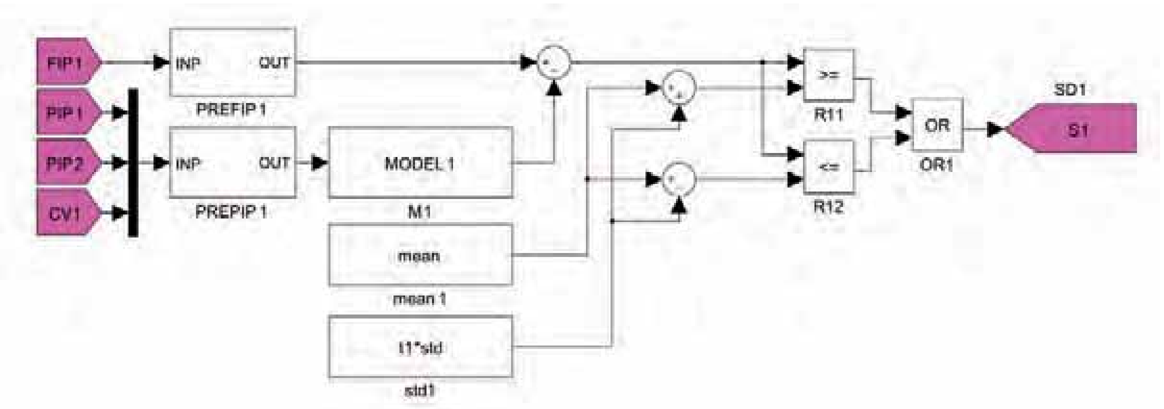

Fig. 4. Model-based fault detection scheme

Rys. 4. Schemat detekcji uszkodzeń oparty na modelu

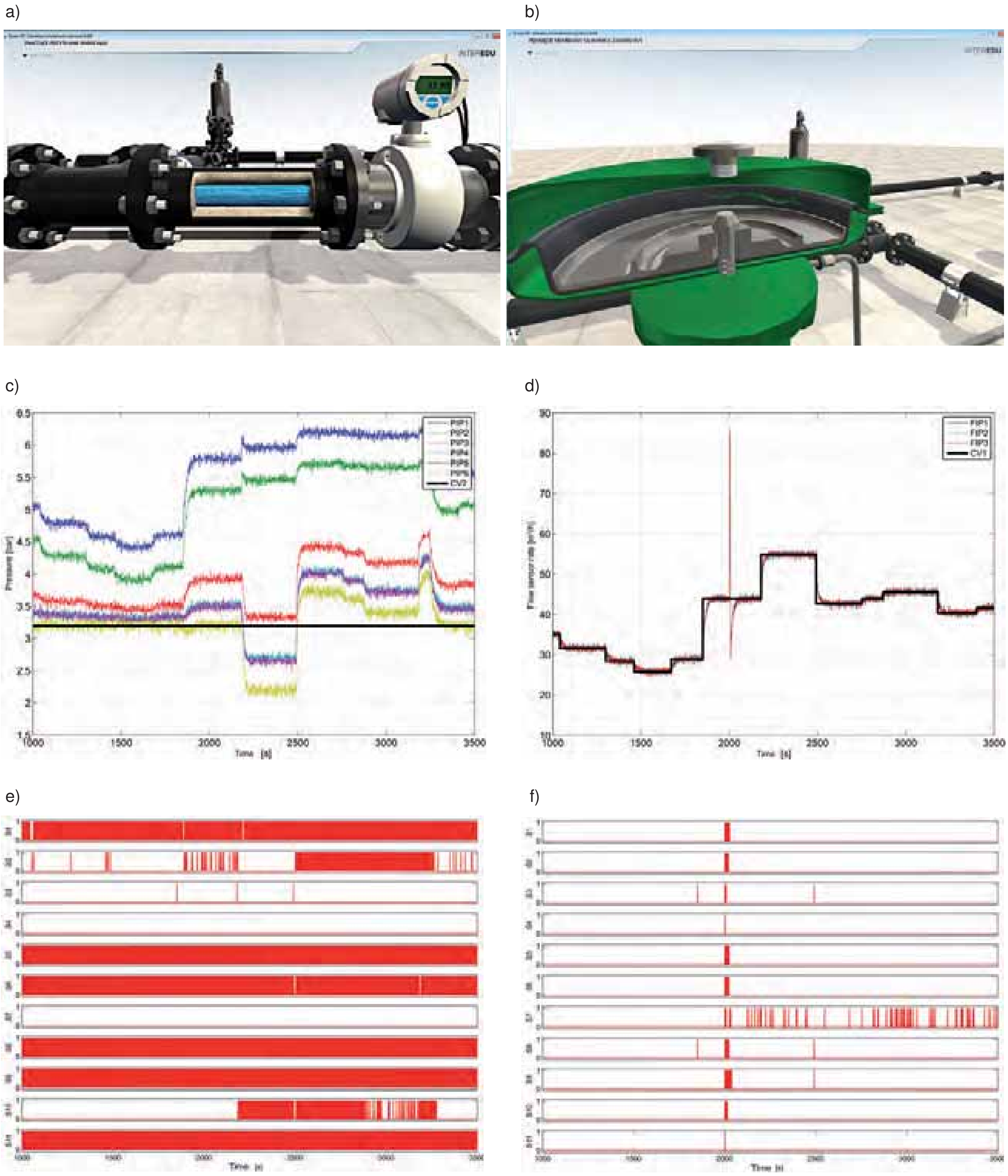

Fig. 5. Selected examples of actuator and plant component faults of the water filtration system

Rys. 5. Wybrane przykłady uszkodzeń układów wykonawczych i komponentów instalacji filtracji wody

the ARX model of the relation FIP1 = (PIP1, PIP2, CV1) is compared with the measured signal FIP1. The decision thresholds are calculated with the use of the mean and standard deviation of the residual obtained in the testing procedure and the diagnostic signal is generated when the lower or upper threshold is exceeded.

Diagnostic signals from residual generation and evaluation blocks are passed to the input of the fault isolation module. This part of the diagnosis process is carried out using the binary diagnostic matrix that represents the relation existing between the values of bi-state signals (diagnostic signals) and faults [12]. In this paper it was

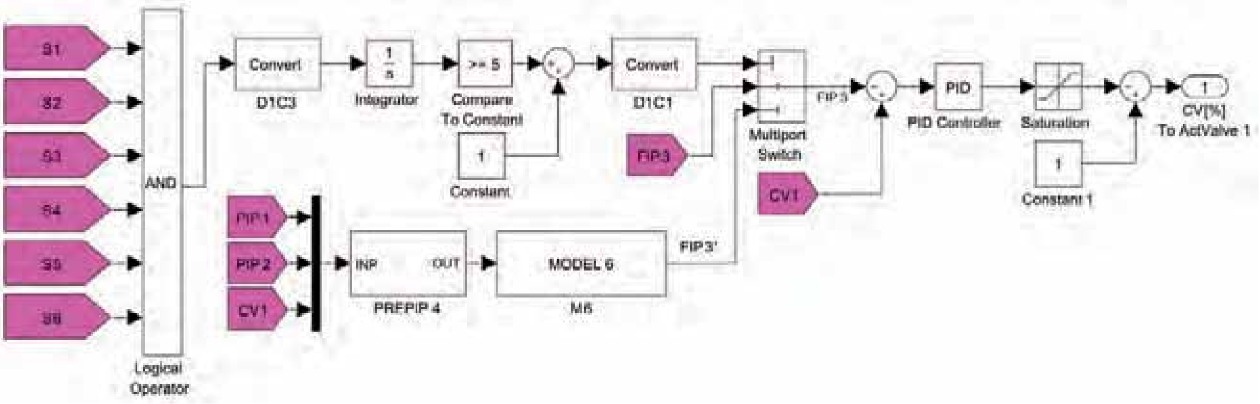

Fig. 6. Active fault-tolerant control scheme
Rys. 6. Schemat aktywnego sterowania odpornego

designed using system equations taking into account the effect of faults.

Fig. 5 shows the example slides obtained by means of the interactive learning tool. These pictures deal with two scenarios with faults f_1 and f_3 (tab. 1). The fault f_1 is an incipient change in the process, but it is assumed that the final stage of its propagation is observed. The second fault is an abrupt event in the structure of the actuator valve and it appears after 2000 s. Fig. 5(a) and (b) present screens from the interactive animations with 3D model representations of the plant's components that can be used to visualize physical defects associated with faults f_1 and f_3. It can be seen in fig. 5(a), that the pipe clogging fault is caused by limescale build-up due to water quality. It is well known that pressure drop in the pipe is proportional to the square of the velocity and the length of the pipe, whereas is inversely proportional to the pipe diameter. It is valid for all fluids in both laminar and turbulent flow. As a result it leads to a strong nonlinear behavior of the system working under pipeline clogging fault. It can be observed in fig. 5(c) that water pressure drops (differences of values of PIP1-6) in pipes strongly depend on the velocity of the medium. If the velocity of the water is low (1000–1800 s) there is no problem with the feedback control of the pressure in the pipe network even though the fault f_1 occurs in the process. In contrary, if the velocity of the water is high (1800–3600 s) the pressure set-point CV2 is not achieved. Such nonlinear behavior not only can be observed in process variables but also has a significant influence on the values of the diagnostic signals. The results of fault detection are presented in fig. 5(e). As is shown, diagnostic signals S1, S5, S6, S8, S9, S11 point out the fault f_1 over the whole time period, while signals S2 and S10 react on this fault after 2200 s and 2500 s respectively.

The effect of the fault f_3 is presented in fig. 5(b). Servomotor's diaphragm perforation of the actuator valve is caused by e.g. fatigue and ageing processes. It has a significant impact on the stability of the water flow control loop. Fig. 5(d) shows how the water flow control device responds to the fault occurred at 2000 s. It can be seen that the control system of the actuator valve is in the unstable state for a few seconds. and the water flow in the pipeline grows up dangerously to the unacceptable

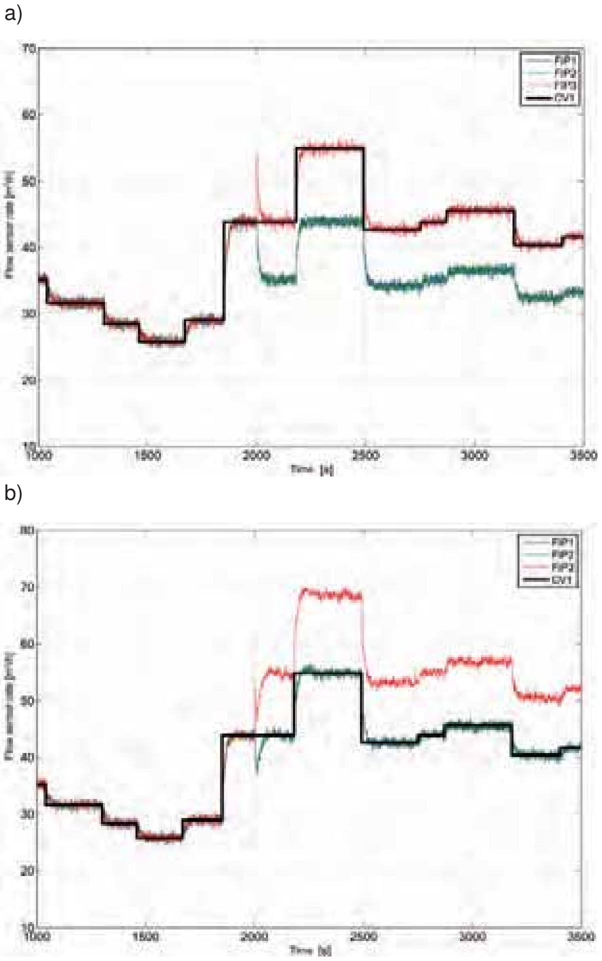

Fig. 7. Examples of classic and fault-tolerant control using the virtual flow sensor
Rys. 7. Przykłady sterowania klasycznego i odpornego z użyciem wirtualnego czujnika przepływu

level. After that, the flow returns to the set-point value CV1. It should be noted that, in this case, there were neither active nor passive fault-tolerant control rules designed. The typical PID controller of the actuator valve worked in such a way that the fault f_3 was masked. It is well seen in fig. 5(f) that almost all the diagnostic signals indicate the fault for a short period of time, instead of the signal S7 changing its state from the moment when the fault occurred to the end of the simulation.

The last regarded example is focused on the problem of fault tolerant control of the process subjects to constraints and the fault f_2 in the flow rate sensor FIP3. In this case, control rules were designed with the use of an active fault-tolerant control strategy. The scheme of the elaborated controller is shown in fig. 6. It is based on the PID controller that regulates the variable FIP3 at the set-point CV1. Fault-tolerance is achieved by switching the signal from the flow meter sensor FIP3 to the signal from the virtual one. This virtual sensor is modeled in the same way as it was mentioned in the case of the fault detection example. The output signal from the ARX model of the relation FIP3 = (PIP1, PIP2, CV1) is used as a reference signal in the feedback loop. The decision about the time of the switching event is dependant on the values of the diagnostic signals coming from the fault detection and isolation modules.

Fig. 7 presents the difference between classic and fault-tolerant control due to the abrupt fault f_2 that occurs at 2000 s. The first plot (fig. 7(a)) shows the fault-free case. It can be observed that the real water flow rate (measured by FIP1 − 2) in the pipeline is smaller than the other measured by the fault sensor FIP3. The second one (fig. 7(b)) illustrates how the set-point flow rate is achieved when the virtual sensor signal is employed in the feedback control loop.

4. Conclusions

In the paper, the authors have presented the complete tool to aid engineering education in the area of fault diagnosis and fault-tolerant control currently applied at Silesian University of Technology. Lecturers can use it to create the on-line interactive three-dimensional animations that can be shown during lectures and other classroom activities. On the other hand, students can apply it during laboratory classes or homework exercises to acquire knowledge and technical skills in practical aspects of the advanced control system design. The main merit of the described application is that the students can develop and test fault diagnosis and fault-tolerant control algorithms without using the real world plant. Moreover, they can see the physical effects of the faults that might occur in the process. The limit of the elaborated solution is the problem with the implementation of other types of faults for the reason that new 3D models and animations must be prepared. It is planned by the authors to develop this framework in order to have much more realistic behavior of the system and much more interactive user interface.

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Interaktywne kształcenie inżynierów w zakresie diagnostyki procesów i sterowania odpornego na błędy

Streszczenie: Głównym celem artykułu jest zaprezentowanie nowych technologii informacyjnych do wspomagania nauczania w zakresie diagnostyki procesów i sterowania odpornego na błędy i uszkodzenia. Zaproponowano trójwymiarowy wirtualny model układu filtracji wody stanowiący jeden ze stopni systemu przygotowania wody w elektrowni. Model ten połączono z jego modelem symulacyjnym, otrzymując narzędzie przydatne do stymulacji procesu nauczania akademickiego w zakresie zaawansowanych systemów sterowania. W artykule pokazano przykłady zastosowania opracowanego systemu informatycznego do prezentacji zagadnień z diagnostyki uszkodzeń oraz sterowania odpornego. Artykuł kończy dyskusja na temat zalet i ograniczeń proponowanego podejścia w zakresie procesu kształcenia.

Słowa kluczowe: diagnostyka uszkodzeń, sterowanie odporne na błędy, technologie informacyjne, rzeczywistość wirtualna, narzędzia interaktywne w kształceniu

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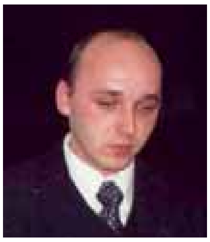

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