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Single acting electro-pneumatic positioner

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Zajmuje się zagadnieniami związanymi z teorią i praktyką systemów sterowania procesów, detekcji i lokalizacji uszkodzeń, systemami tolerującymi uszkodzenia, systemami sieci przemysłowych, zastosowaniami logiki rozmytej oraz rozwojem inteligentnych urządzeń pomiarowych i wykonawczych automatyki. Jest współautorem 3 monografii naukowych oraz 3 podręczników, autorem 96 artykułów i referatów konferencyjnych, współautorem bądź autorem 4 patentów oraz autorem 59 konstrukcji urządzeń mechatronicznych.

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Abstract

The selected problems of the development of a single acting electro-pneumatic positioner intended for the use with the linear and rotary final control elements have been presented in this paper. The structure of a developed positioner has been briefly described. Particular attention was paid to the concept of development of applicable feedback fault tolerant electro-pneumatic actuator. Example of industrial implementation of the presented positioner has been presented.

Keywords: actuators, final control elements, fault tolerant systems, fault detection and isolation.

Ustawnik elektropneumatyczny do siłowników jednostronnego działania

Streszczenie

W artykule przedstawiono wybrane aspekty konstrukcji ustawnika elektropneumatycznego przeznaczonego do stosowania w urządzeniach wykonawczych automatyki wyposażonych w siłownik pneumatyczny jednostronnego działania o ruchu liniowym lub obrotowym tłoczyska. Przedstawiono ogólną strukturę ustawnika. Następnie zaprezentowano koncepcję realizacji układu tolerującego uszkodzenia toru sprzężenia zwrotnego ustawnika. Przedstawiono również przykład wdrożenia przemysłowego ustawnika.

Słowa kluczowe: elementy wykonawcze automatyki, systemy tolerujące uszkodzenia, detekcja uszkodzeń.

1. Introduction

Control tasks of technological processes can be generally defined in terms of acting on the energy and mass flows. Actuators (final control elements) are applied for acting on these flows. The actuators are installed mainly in harsh environments, e.g., in: high temperature, high pressure, high humidity, and typically are surrounded by dusty pollutants, chemical solvents, aggressive media, etc. (Fig. 1). This has the crucial influence on the final control element predicted lifetime. As examples from industrial practice show, the mean lifetime of actuators may be as short as approximately 8 weeks.

Malfunction or failures of actuators cause long-term process disturbances or even sometimes force us to shut the installation down. Moreover, final control elements faults may lower the final product quality and cause reasonable economic losses. Approximately 40% of faults in industrial installations and control systems are caused by faults of final control elements. Hence arises the need of development and application of more robust and fault tolerant devices. The on-line diagnostics of final control elements is applied in the industrial practice to ensure a proper fault prevention at a sufficiently early stage. Permanent or occasionally performed diagnosis of actuators significantly cuts the installation maintenance costs.

Fig. 1. High temperature (up to 75˚C) and dusty environment significantly cut down the actuator lifetime applied in the boiler section of a power station. Snap was taken after two months of putting a new positioner for the operation
Rys. 1. Wysoka temperatura pracy (do 75˚C) oraz duże zapylenie są istotnymi czynnikami ograniczającymi żywotność elementów wykonawczych. Fotografia przedstawia ustawnik zainstalowany w układzie sterowania dysz OFFA w kotle w zawodowej elektrowni węglowej. Zdjęcie wykonano po dwóch miesiącach od dnia zainstalowania ustawnika

On-line diagnosis of actuators can be accomplished either by the application of a remote supervisory diagnostic systems, or autonomously by the actuators themselves. This, however, needs make use from local intelligence [6, 11, 12]. These intelligent techniques and condition monitoring are popular in applied control engineering research and development, and there are now many real applications. However, they do not provide means of monitoring and diagnosis of the overall plant at both local and global levels, as required for the reliable operation of complex and highly interconnected process systems. What is in fact required, is a combination of the local intelligence with a more advanced diagnostic capability (combining fault monitoring and diagnosis at both local and global levels) to perform FDI functions on as many process plant components as possible [8]. On-line diagnosis of actuator components provides a valuable high-level information for the process operators. This information is fundamental for the decision making process about the actions to be undertaken for the adjustment of losses caused by the failure or failures. These actions, however, require us to have time. Prolongation of the faulty state of the installation or its part typically brings additional losses. Fault tolerant control [3, 7] may help us to solve the problem and minimize loses.

2. The actuator

The actuator typically plays the role of the power booster in the control system structures [1]. It is placed typically between the controller and the controlled system (Fig. 2). Here, CV signal plays the role of the actuator reference signal, and F plays the role of the actuator process value. Generally, an actuator may be considered as a closed loop autonomous subsystem.

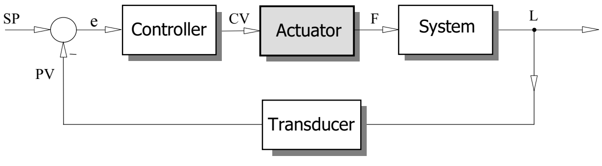

Fig. 2. The placement of the actuator in the control system. Notions: SP- setpoint; PV-process value; e-control error; CV-control value, F, L - physical values depending on the controlled system
Fig. 2. Miejsce elementu wykonawczego w układzie automatyki. Oznaczenia: SP- wartość zadana; PV- wielkość mierzona ; e- odchyłka regulacji; CV- sygnał sterujący, F, L – strumień objętościowy i poziom medium: symbole wielkości przykładowych zmiennych procesowych zależnych od konkretnej realizacji systemu sterowania

In the simplest case, if one neglects the dynamics, the actuator may be considered as the follow up system described by the unity transfer function. Actuators need to be powered. This power is delivered in the mechanical or electrical form, and is converted into the actuator output power. In this paper we will be dealing with air supplied actuators. These devices belong to a wide subclass of actuators commonly used in the industrial practice.

The actuator is considered here as an assembly consisting of the following components:

- control valve,
- single action spring-and-diaphragm pneumatic servomotor,
- positioner.

The control valve acts on the flow of the fluid passing through the pipeline installation. A servomotor carries out a change in the position of the control valve plug, thus acting on the fluid flow rate. A spring-and-diaphragm pneumatic servomotor is a compressible fluid powered device in which the fluid acts upon the flexible diaphragm to provide a linear motion of the servomotor stem. The positioner is a device applied to eliminate the control-valve-stem miss-positions produced by the external or internal sources such as: friction, clearances in mechanical assemblies, supply pressure variations, hydrostatic and hydrodynamic forces acting on the valve's plug, etc.

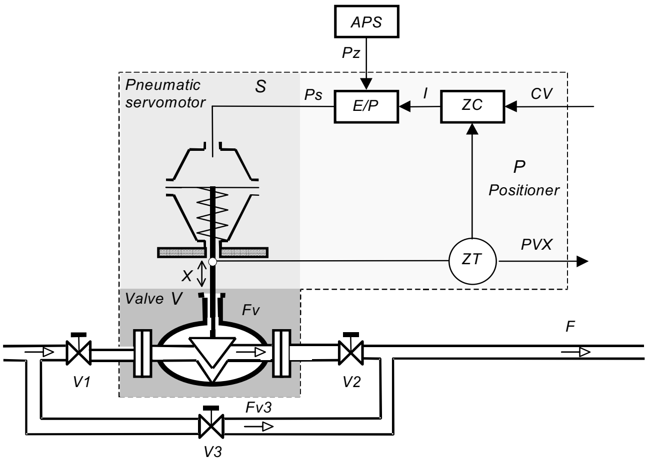

Fig. 3. Simplified structure of an electro-pneumatic actuator
Notions:
APS - positioner air supply system
CV - process control value
I - internal signal acting on the electro-pneumatic transducer
E/P - electro-pneumatic transducer
F - flow rate of the fluid in the main pipeline
Fv - flow rate of the fluid in the control valve
Fv3 - flow rate of the fluid in the actuator by-pass pipeline
P - positioner
Ps - E/P transducer output pressure
PVX - stem position process value
S - pneumatic servomotor
V - control valve
V1,V1,V3- cut-off valves
X - stem position
ZC - autonomous positioner controller
ZT - stem position transmitter

Rys. 3. Uproszczona struktura elektropneumatycznego elementu wykonawczego
Oznaczenia:
APS - system zasilania pneumatycznego ustawnika
CV - wielkość sterująca
I - sygnał sterujący przetwornik elektropneumatyczny
E/P - przetwornik elektropneumatyczny
F - strumień objętościowy medium w rurociągu
Fv - strumień objętościowy medium w zaworze sterującym
Fv3 - strumień objętościowy medium w rurociągu obejściowym
P - ustawnik pozycyjny
Ps - ciśnienie na wyjściu przetwornika E/P
PVX - zmienna procesowa – przemieszczenie tłoczyska siłownika
S - siłownik pneumatyczny
V - zawór sterujący
V1,V1,V3- zawory odcinające sterowane ręcznie
X - przemieszczenie tłoczyska siłownika
ZC - regulator wewnętrzny ustawnika
ZT - nadajnik położenia tłoczyska

An actuator may be considered as a set of two subsystems (Fig. 4). The first subsystem is the closed-loop system that transforms the external control value signal *CV* into the physical position *X* of the stem of the pneumatic servomotor. This subsystem consists of the positioner *P* and the pneumatic servomotor *S*. The second subsystem is the feed-forward subsystem that transforms the servomotor's stem displacement *X* into the fluid flow rate *F* according to the specific flow characteristics of the control valve *V*. Cut-off valves *V1, V2, V3* make easier installing, dismounting, diagnostics and maintenance of the control valve.

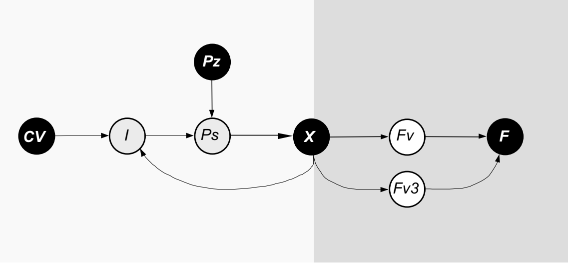

Fig. 4. Simplified causal graph of the electro-pneumatic actuator
Rys. 4. Uproszczony graf przyczynowo-skutkowy elektropneumatycznego elementu wykonawczego

Stem position *X* provides the feedback signal for the positioner controller *ZC*. Feedback should be considered as a system consisting of mechanical and electrical parts. Mechanical part of the feedback is very often prone to failures.

The feedback fault, regardless on where it has originated, either in a mechanical or an electric part, may cause spurious behaviour of the servomotor stem position. In general, this fault cannot be compensated by the external control loop shown in Fig. 2. If the positioner feedback fault will be recognized by the external or internal diagnostic system, then the proper actions should be undertaken immediately. During the repair or replacement of the positioner, the system should be controlled manually by means of cut-off hand-driven valves.

3. Concept of the feedback fault tolerant positioner

Taking into account the above presented considerations, a novel feedback fault tolerant actuator (FFTA) concept has been proposed [2]. This concept assumes that the positioner should not lose its control functions in the case of the feedback fault. However, an intermediate setback or lowering of the control quality factors may take place. The block structure of the FFTA has been presented in Fig. 5. Generally it was assumed that the positioner may use the local intelligence. This gives us the opportunity to apply these positioners in systems that are supervised or not by external diagnostic and monitoring systems [10]. Moreover, the application of this concept is possible in positioners with either analogue or digital signalling. The concept of FFTA is based principally on the application of the hardware and software redundancy. Electro-pneumatic transducer (4) controls the air pressure in the chamber of a spring-and-diaphragm pneumatic servomotor (6). The change of the air pressure in the chamber is transformed into the displacement of the pneumatic servomotor stem (7) which changes the control valve (8) cross-section. The displacement of the pneumatic servomotor stem (7) is measured by the stem position transducer (9) of the positioner. The feedback consists of mechanical and electric parts. The displacement signal is fed to the controller (1). The controller (1) generates a control value on its output X based on process setpoint (11) and feedback signal (13). In the fault free state, this output is fed to the input of the electro-pneumatic transducer (4) by switch which is normally closed (3). This allows us to close the positioner control loop.

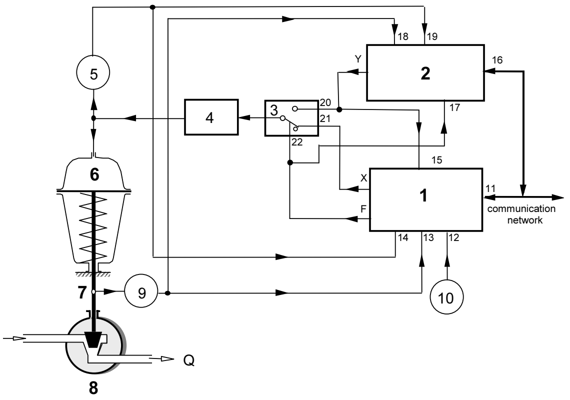

Fig. 5. Structure of the feedback fault tolerant actuator
Rys. 5. Struktura ustawnika tolerującego uszkodzenia toru sprzężenia zwrotnego

Depending on the position of the switch (3), the electro-pneumatic transducer (4) may be controlled alternatively by the signal *Y* generated by the redundant controller (2). The switch (3) connects the control signal Y with the input of the transducer (4) for the time periods in which the feedback fault certainty is relatively high. Feedback fault detection and isolation algorithm is carried out as the separate thread in the control unit (1). This algorithm makes use the measurements of the stem displacement (13), chamber pressure (14), external setpoint value (11) as well as the knowledge of *X* and *Y* signals. The binary signal *F* switches the input of the transducer (4) to the output of controller (1) in the fault-free case, and to the output of the controller (2) in the case of the feedback fault. Controller (2) provides the control functions similar to the ones of the controller (1) with the exception that the feedback signal is the pressure signal measured by the pressure transducer (5), instead of the displacement signal from the displacement transducer (9).

4. FDI considerations

Development of the appropriate feedback fault detection and isolation algorithms allows us to implement the FFTA concept presented in Section 2. The switching between the outputs of the controllers (1) and (2) in Fig. 8 may cause transients in the stem displacement, may lower control quality factors figures, or introduce the steady state control error.

Hopefully, the false switching between outputs of both controllers in the case of normal (typical) state does not cancel the positioner controllability. Hence, the positioner depicted in Fig. 5 is tolerant not only to feedback faults but also to the false feedback fault isolation. False fault isolation takes place in circumstances in which uncertain or imprecise models are used for the fault detection. This may happen due to the measurement noise, in the case of the lack of sufficient knowledge about the fault-symptom relation, insufficient number of possible diagnostic tests, etc.

Taking into account practical aspects of the implementation and the above discussed robustness to false diagnoses in the FFTA, it is reasonable to consider a problem of necessity of the fault isolation. The probability of the positioner feedback fault is roughly comparable with the probability of the fault of the electro-pneumatic transducer. For simplicity of reasoning, let us assume that the pressure transducer has also comparable fault probability, and the probability of a failure of the electronic part is at least one order lower. In the case of the failure of electro-pneumatic transducer, distinguishing between the feedback fault, the electronic part fault and the pressure sensor fault does not make sense. The positioner will stay inoperable. In this case, a false or true switching of the controllers (1) and (2) outputs in Fig. 5 does not improve or deteriorate the positioner action. The same situation takes place in the case of the electronic part fault.

In the case of the pressure transducer fault, the positioner feedback fault tolerant mode is not possible, because in this mode, the pressure feedback replaces the displacement feedback. In this case, switching the outputs of the controllers (1) and (2) (Fig. 5) does not improve or deteriorate the positioner action.

Hence, the positioner control structure given in Fig. 5 may be tolerant exclusively to the feedback fault. Remaining faults are not tolerated. From these considerations one has to gain a very important conclusion that the fault isolation phase of the FDI algorithm here is not necessary at all. In other words, switching the control outputs between the controller (1) and (2) takes place in the case of detection of any fault. This simplifies the implementation of the FFTA and significantly saves the computational power of the internal microprocessor of the positioner.

5. Fault detection models

Model based fault detection approaches have been examined experimentally. Model based algorithms allow us a sufficiently early and accurate detection of the faults. The models investigated should be relatively simple and easy to be implemented in the positioner, keeping in mind limitations in the computational power and memory resources. Several modelling techniques and approaches may be considered here; among others: static and dynamic behavioural models, heuristic, neural, fuzzy or neuro-fuzzy models [4, 5, 8, 9].

Models may be based on the following set of available signals:

- external control value (*CV*),
- pneumatic servomotor stem displacement (*PVX*),
- air pressure in the chamber of the servomotor (*Ps*),
- internal control signal of the electro-pneumatic transducer (*I*).

Dynamic and static neural models have been tested during the search for applicable suboptimal models. The final decision about the choice of the best model was based on the criterion of the maximum model sensitivity to the faults. Very poor sensitivity to the feedback fault has been observed by means of the dynamic model (1).

$$PVX=f(PVX(t-30),\ PVX(t-20),\ PVX(t-10),\ CV). \tag{1}$$

Therefore, this model was not further considered, despite of its accuracy. Fig. 6 shows an example of validation of a very simple static neural model of the pneumatic servomotor stem displacement in the form:

$$PVX=f(Ps). \tag{2}$$

The accuracy of this model is worse compared to the one achieved in model (1). This model has a moderate or poor accuracy in the normal conditions (Fig. 6), as well as in the faulty conditions. But this model is really sensitive to the feedback fault. In that sense, this model is practical. Diagnostic signals achieved from this model should be, however, evaluated very carefully. If a simplest constant threshold technique is used, then threshold value should not be lower than 10%.

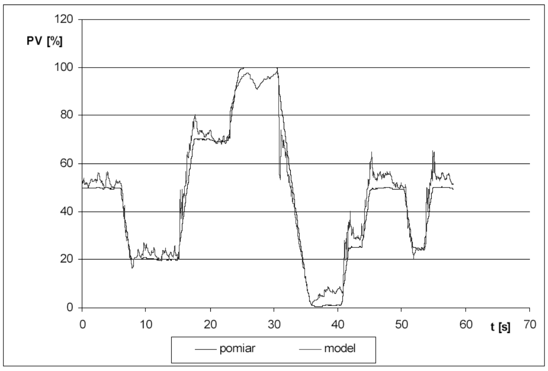

Fig. 6. Illustration of the accuracy of the neural static model (2) of the stem displacement
Rys. 6. Ilustracja dokładności modelowania przemieszczenia tłoczyska siłownika przy użyciu neuronowego modelu statycznego o postaci (2)

6. Industrial implementation

A prototype positioner intended for investigations and experimental verification of the FFTA algorithms have been developed in the Institute of Automatic Control and Robotics of the Warsaw University of Technology. Positioner internal controllers were build up by an application of the idea of the state space controllers. Electro-pneumatic actuator has been placed in the special laboratory test bed intended for the evaluation of final control elements. The positioner was equipped with the serial digital communication facility making possible the fast exchange of data with the external control and data acquisition system by means of the MODBUS RTU protocol. Satisfactory laboratory results obtained give an impetus towards industrial implementation.

The above presented positioner has been set in to production by the one of the Polish manufactures operating in the field of automatic control elements. The *"mature"* form of the positioner is shown in Fig. 7. Positioner has passed appropriate laboratory and industrial tests. Currently it has found applications in power and food industries. An example of industrial test of the final control assembled with the above presented positioner has been depicted in Fig. 8. A test was conducted in the manual control mode. The final control element was applied here for acting on OFFA nozzles in the power boiler of a power station. OFFA nozzles are playing important role in the control of the level of NO_x emissions.

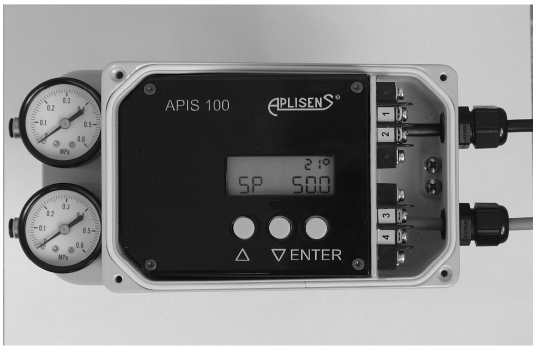

Fig. 7. Front view ot the industrial version of the implemented positioner
Rys. 7. Widok przemysłowej wersji ustawnika od strony czołowej

The application of the positioner allows us among others:

- obtaining low steady state positioning errors,
- masking internal hysteresis,
- improving system stiffness
- shaping the dynamic properties of the final control element
- suppressing the effects of the air pressure supply variations on the pneumatic stem displacement,
- suppressing the influence of the hydrodynamic and friction forces acting on the positioner stem,
- improving the actuator robustness.

7. Summary

The concept of an intelligent electro-pneumatic actuator tolerant to the feedback faults has been presented in this paper. This concept goes towards easy implementation, assurance of better safety, reliability and efficiency of the industrial control systems.

The concept relies on the application of a redundant controller with the pressure feedback instead of the position feedback. Switching on the redundant controller output is driven by the model based fault detection algorithm. Appropriate models have been developed and tested. Considerations about the necessity of the fault isolation implementation have been presented.

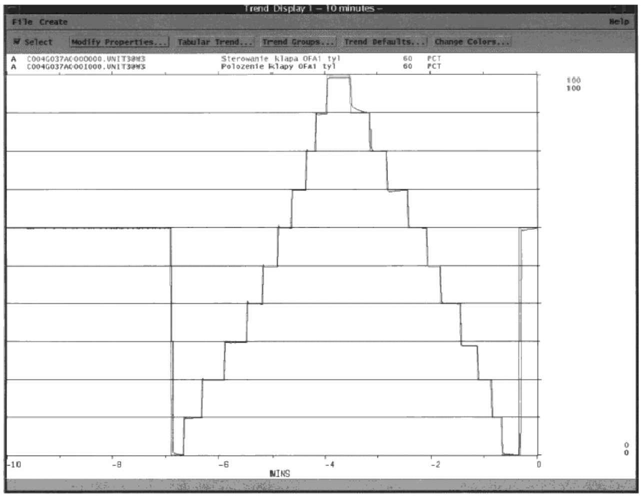

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Fig. 8. An example of the industrial test of the final control element equipped with the developed positioner
Rys. 8. Przykład testu przemysłowego elementu wykonawczego wyposażonego w prezentowany ustawnik

The presented feedback fault tolerant procedure can be summarised in the procedure consisting form the following steps:

1º continuous searching for actuator steady states in fault free states,
2º updating of mapping of the displacement setpoint value into the pressure setpoint values space,
3º on-line model based fault detection,
4º switching from the displacement feedback mode to the pressure feedback mode in the case of fault detection,
5º in the case of fault recovery, switching back from the pressure feedback mode to the position feedback mode.

8. References

[1] Bartyś M., Patton R., Syfert M., de las Heras S., Quevedo J.: Introduction to the DAMADICS actuator FDI benchmark study. Control Engineering Practice, vol. 14, no. 6, 2006, 577-596.

[2] Bartyś M.: Electropneumatic positioner. Application PL385695, 2008. Patent Office of the Republic Poland.

[3] Blanke M., Kinnaert M., Lunze J., Staroswiecki M.: Diagnosis and Fault-Tolerant Control, Springer-Verlag, 2004.

[4] Chen J., Patton R.: Robust model based fault diagnosis for dynamic systems, Kluwer Akademic Publishers, Boston, 1999.

[5] Gertler J.: Fault Detection and Diagnosis in Engineering Systems. Marcel Dekker, Inc. New York - Basel - Hong Kong, 1998.

[6] Henry M.P.: Plant assessment management via intelligent sensors: digital, distributed and for free. Computing & Control Engineering Journal, vol. 11, no. 5, 2000, 211-213.

[7] Isermann R.: Fault Diagnosis Systems. An Introduction from Fault Detection to Fault Tolerance, Springer-Verlag, New York, 2006.

[8] Korbicz J., Kościelny J. M., Kowalczuk Z. Cholewa W.: Fault Diagnosis: Models, artificial intelligence methods, applications, Springer-Verlag, 2004.

[9] Kościelny J.M., Bartyś M., Rzepiejewski P. Sá da Costa J.:Actuator fault distinguishability study for the DAMADICS benchmark problem. Control Engineering Practice, vol. 14, no. 6, 2006, 645-652.

[10] Kościelny J.M., Syfert M., Wnuk P.: Advanced monitoring and diagnostic system 'AMandD', 6th IFAC Symposium on Fault Detection, Supervision and Safety of Technical Processes, Beijing, P.R. China, 2006, vol. 1, 635-640.

[11] Tombs M.: Intelligent and self-validating sensors and actuators. Computing & Control Engineering Journal, vol. 13, no.5, 2002, 218-220.

[12] Yang J.C., Clarke D.W.: The Self-Validating Actuator. Control Engineering Practice, vol. 7, 1999, 249-260.

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