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David KLIMÁNEK*, Bohumil ŠULC**

AUTO-DETECTION OF SENSOR DISCREDIBILITY IN A CONTROL LOOP VIA EVOLUTIONARY ALGORITHMS

AUTODETEKCE DISKREDIBILITY SENZORU V REGULAČNÍM OBVODU EVOLUČNÍMI ALGORITMY

Abstract

When operating control loops, we can encounter hidden malfunctions, usually caused by the sensors used for measuring the controlled variables. These sensors often do not stop operating completely (which would be easy to recognize); they only start to provide slightly wrong measurements of the controlled variables. If the differences between the measured values and real values are not extreme, there is only a very small chance that the operator will recognize any malfunction of the sensor, assuming that there are no additional sensors available in the control loop for performing a hardware check. The problem is as follows: although the control loop seems to work properly, the consequences of such a small sensor malfunction (sensor discredibility) can become substantial and expensive (for example, we can imagine a combustion ratio control where some deviations from an optimal ratio value have no principal influence on the operation of the device, but late discovery of an increase in harmful emissions may be very costly).

This paper concentrates on two new ideas: detection of sensor discredibility as a way that replaces usual hardware redundancy and saves the costs of additional measurements; and the use of sensor detection as a means of improving the function of a controlled system by avoiding hidden impreciseness in the control loop operation.

Abstrakt

Při řízení procesů se můžeme setkat s problémem tzv. malých chyb regulace, které jsou obvykle zapříčiněny změnami parametrů senzorů použitých pro měření řízených veličin. Senzory nepřestávají zcela vykonávat svou činnost, ale poskytují zkreslené informace o řízené veličině. Pokud rozdíl mezi změřenou a skutečnou hodnotou řízené veličiny není velký, je pro operátora obtížné rozlišit jakoukoli zhoršující se funkci čidla, zvláště pak nejsou-li k dispozici žádná přídavná měření, nebo duplicitní senzory, pomocí kterých je možno určit, zda čidlo poskytuje správné informace. Z hlediska vnějšího pozorování regulace probíhá bezchybně, ale při zhoršené funkci čidla, např. při řízení procesů spalování, může dojít k zvýšení emisí, což může představovat finanční postihy.

Cílem příspěvku je prezentovat pokus o detekci diskredibility senzoru, jinou než obvyklou hardwarovou redundancí, tzv. softwarovou redundancí. Softwarové řešení poskytuje výhodu ušetření nákladů na redundantní čidla a umožňuje vylepšení funkce regulačního obvodu.

* Ing., Department of Instrumentation and Control Engineering, Faculty of Mechanical Engineering, Czech Technical University in Prague, Technicka 4, Prague, tel. (+420) 59 732 4380, e-mail David.Klimanek@fs.cvut.cz

** doc., Ing., CSc., Department of Instrumentation and Control Engineering, Faculty of Mechanical Engineering, Czech Technical University in Prague, Technicka 4, Prague, tel. (+420) 59 732 2531, e-mail Bohumil.Sulc@fs.cvut.cz

1 INTRODUCTION

The notion of “sensor discredibility” refers to a type of sensor faults that do not involve a total sensor failure, but only a small deviation from its correct function. These changes are not very apparent from the behavior of the control loop. To the outside observer, the control loop seems to be working properly, because the fact that the sensor provides a biased measurement of the controlled variable, implying an inaccurate control process, cannot be detected without some additional measuring.

This paper attempts to find new ways toward detection of discredibility that differs from the usual utilization of redundant measuring equipment, i.e. hardware redundancy. Although, such hardware redundancy may involve additional costs, it is needed to control dangerous processes. To avoid unnecessary costs, we are working on how to detect sensor discredibility with the use of software tools. Software detection, or software redundancy, can substitute one or two redundant pieces of measuring equipment. Evolutionary algorithms seem to be a very suitable tool for this task. The main advantage of such a solution is that necessary information about changes in sensor properties can be obtained from standard operation data. The data is in any case acquired from the controlled process.

Simulated annealing, together with the other evolutionary algorithms such as genetic algorithms, evolution strategies and genetic programming are derivate–free methods with a heuristic approach, i.e. they contain a random component [5].

2 SIMULATED ANNEALING ALGORITHM FOR SENSOR DISCREDIBILITY DETECTION

Simulated annealing (SA) is an evolutionary algorithm technique. It is an effective optimization algorithm suitable for solving this problem. The idea of SA appeared in a paper published by Metropolis et al. in 1953 [7]. The SA technique is based on the principles of thermodynamics, according to which solids are heated and cooled gradually to a crystalline state with minimum energy. This process is known as annealing. If a solid is heated above the melting point and then cooled down, the structural properties of the solid will depend on the speed of cooling. If the liquid is cooled slowly enough, large crystals will be formed. However, if the liquid is cooled quickly (quenched), the crystals will contain imperfections. Metropolis’s algorithm simulated the material as a system of particles. The algorithm simulates the cooling process by gradually lowering the temperature of the system until it converges to a steady, frozen state [5].

2.1 Presentation of the algorithm

Fig. 1 shows the pseudo–code of the simulated annealing algorithm. This algorithm represents the content of the block “Simulated Annealing Algorithm Subsystem” in Fig. 5. The pseudo–code can be denoted as follows:

In order to solve the optimization problem via simulated annealing in Fig. 1, the following steps are required:

1. an initial temperature and a final temperature t_{cur} respectively t_{final} are set. The temperatures are used to test the stop criterion and to evaluate the Boltzmann criterion (1), which affects the acceptance of the new solutions in step 4,
2. a random vector of the potential values of the sensor coefficients k and q is selected and quality criterion z_1 is obtained. In the case of sensor auto–detection, the criterion is a deviation between the transmitted and the estimated water level. The estimated water level is evaluated from a set of recorded or computed steady-state characteristics. The constants k and q are the sensor coefficients according to equation (2),

Initialization()
set initial and final temperature t_{cur} respectively t_{final}
randomly select vector of initial solution *(k, q)*
obtain quality index z_1 for initial solution
set index of iteration $i=1$
initialize weighting coefficient λ
if $t_{cur} > t_{final}$
randomly select vector of potential solution *(k, q)*
obtain quality index z
evaluate Boltzmann criterion $p = \exp(-(z - z_i) / t_{cur})$
if decide whether to accept or reject new solution $z < z_i$ or random $< p$
set the quality index equal to the new value $z_{i+1=}z$
accept current vector of solutions *(k, q)*
else
keep old solution of quality index $z_{i+1} = z_i$
end
decrease simulated temperature $t_{cur}= \lambda\, t_{cur}$;
save solutions *(k, q)* into vector x_{i+1}
increment iteration index
end

Fig. 1 Schematic Simulated Annealing algorithm

3. a new solution vector is selected. Using a stochastic strategy, the vector of solutions k and q is randomly generated and the corresponding quality criterion value z is evaluated,
4. the difference $z - z_i$ between the current value z_i of the quality criterion and the value z from the previous iteration step is evaluated. If $z - z_i < 0$, then the solution vector (k,q) is accepted (Fig. 2). If $z - z_i > 0$ the algorithm may accept the solution vector according to the probability defined by the formula (Boltzmann criterion)

$$p = e^{-\frac{z - z_i}{t_{cur}}}, \qquad (1)$$

5. the current simulated temperature t_{cur} is weighted with a coefficient λ, where $0 < \lambda < 1$,
6. if t_{cur} is lower or equal to the final temperature t_{final}, then the current solution vector is accepted as a vector of changed coefficients, otherwise a return to step 3 repeats the process.

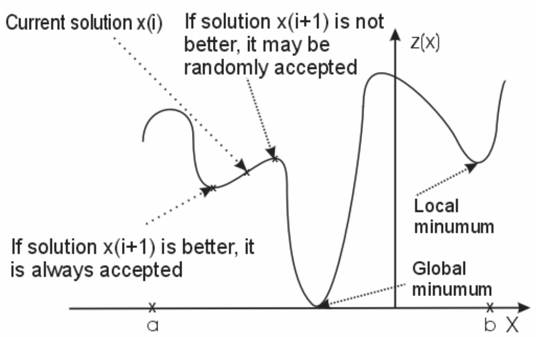

Fig. 2 Principle of finding the global minimum of a quality index via the simulated annealing algorithm, where x represents vector of solution $(k\,,q)$

2.2 Realization of Sensor Discredibility Auto–Detection in Matlab/Simulink Software

Fig. 3 presents a block scheme of the program in Simulink by means of which the influence of the sensor coefficient changes *k, q* has been tested. Until a sensor discredibility occurs, the sensor provides exact data for further processing in the controller. However, after we have simulated a change in the sensor coefficients, the sensor model starts to provide biased information. As has already been mentioned, the simulated changes of sensor properties (2) should not represent a total failure of the sensor, but only a deviation from the expected features. The simplified model of a sensor credibility loss can be based on a linear model of the sensor characteristic expressed by the equation

$$h_{transmitted} = kh_2 + q, \tag{2}$$

where:

k, q – changing sensor parameters,

h_2 – the real value of the controlled water level.

During the simulation process, the block called "Simulated Annealing Algorithm Subsystem" in Fig. 4 attempts to minimize the deviation between the water level values (the controlled variable) $h_{transmitted}$ that are transmitted by the sensor with the changed coefficients, and the water level expected from characteristic $h_{estimated}$. The estimated water level is obtained from the graphs in Fig. 6 based on the measurement of the actuating signal and the volume rate of flow. In this presented case, this steady–state characteristic was obtained with the support of MS Excel via computing a balance of the volume rate of flow [5].

If the steady-state characteristics of the controlled system are known, it is not a problem to employ them for finding the estimated water level. In a more complex structure, it would be necessary to obtain such steady–state characteristics by a measurement performed at a time when the sensors are providing correct data.

The suggested solution is reasonable when the additional experiments do not impose excessively high extra costs in comparison to the cost of the added sensors for hardware redundancy.

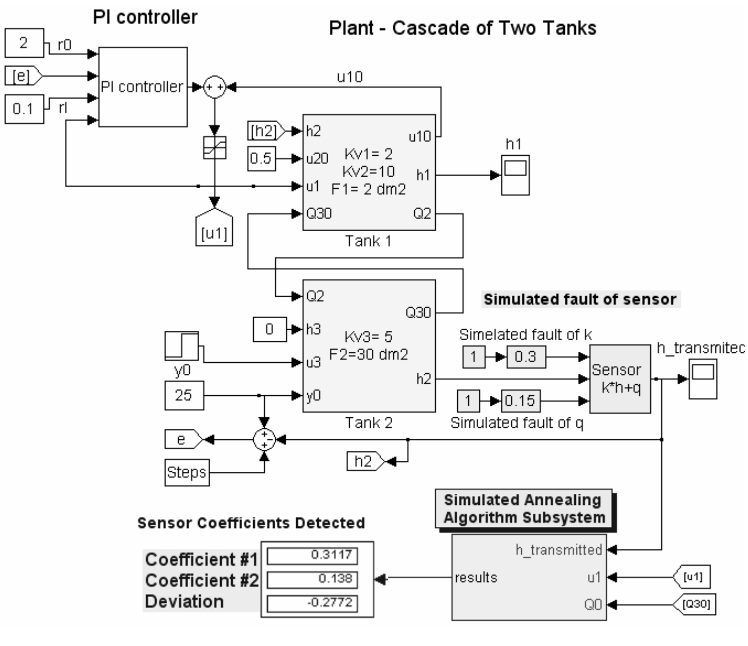

Fig. 3 Simulation scheme for auto–detection of sensor discredibility in Matlab/Simulink software

The simulation process runs with the original coefficients $k = 0.285$, $q = 0.2$ (i.e. with the values reported by the producer) as long as some simulated changes of the sensor parameters are carried out. The parameters representing a sensor discredibility are characterized by the values, e.g., $q = 0.3$, $k = 0.15$. The SA algorithm block tries to evaluate these changed coefficients (those coefficients that are currently used by the model of the real cascade). In each iteration, the algorithm compares deviations between the current and the previous iteration, and evaluates a new set of potential parameters. The progress in the sensor parameter development is shown in Table 1. In this simulation run, the values 0.312 and 0.138, respectively, have been assigned to the newly evaluated coefficients k and q. The evaluated parameters are different from the expected ones. Now the operator is informed via visualization screens that some changes in the sensor properties may have occurred. No other actions are needed, because the difference between the values of the coefficients obtained by means of SA and those reported by the producer do not exceed 10 %.

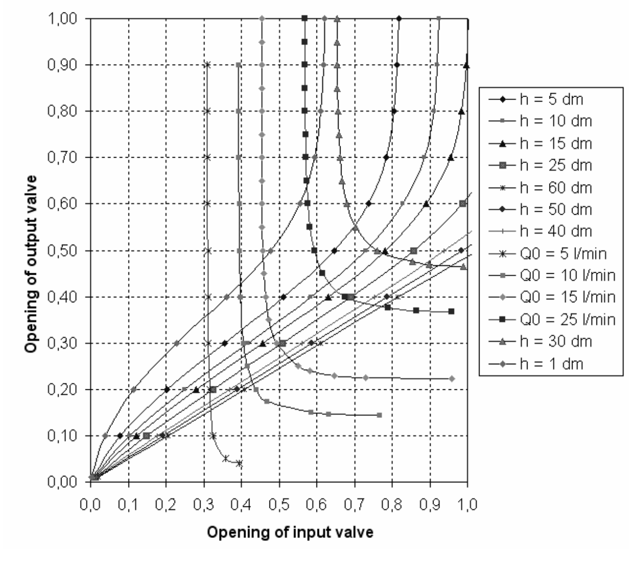

Fig. 4 Steady-state characteristic of a two-water-tank cascade, where h, Q0 corresponds to the estimated water level, respectively to the volume rate of flow

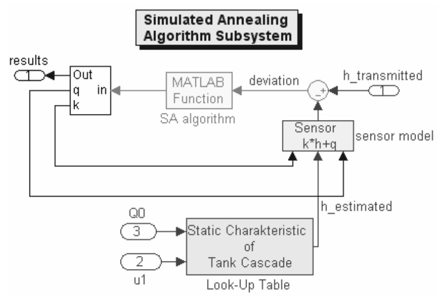

Fig. 5 Simulated annealing algorithm subsystem

The settings of the subsystem in Fig. 5 are as follows: initial annealing temperature t_{init}=100, final simulated annealing temperature t_{final}=0.001, temperature decrement factor Lambda=0.95.

Tab. 1 Progress of the sensor parameter development

Number of iteration	*Coefficients*		*Deviation*
	k	*q*	
150	0.217	0.109	2.8
250	0.251	0.125	1.5
350	0.311	0.152	0.1
540	0.312	0.138	0.3

3 CONCLUSIONS

The described software detection of sensor discredibility via the simulated annealing algorithm has proved a suitable tool for detecting simulated changes of sensor properties. The simulated annealing algorithm found the solution in hundreds of iterations. It is obvious that in a more complex structure it would be necessary to carry out more iterations and this would consume more evaluation time. However, in the case of the application used here, this disadvantage does not matter, because small malfunctions do not lead to fatal errors in the control loop operation. However, by early detection we can avoid some harmful effects that may result from sensor discredibility.

Comparing our results with [3], which attempted detection via the genetic algorithm, both algorithms have proved to be useful utilities. There is no significant difference between the algorithms; their good convergence depends mainly on the algorithm settings. Our attempt focuses on detecting discredibility for a single sensor. In more complex devices with more controlled loops it will be necessary to design discredibility evaluation from the viewpoint of the whole unit function.

For future development of the described sensor discredibility detection, we plan to make use of agent based systems, mainly their ability to achieve mutual cooperation and coordination. In the nearest future it is expected that further research will aim to optimize the combustion process of a small stoker–fired boiler for burning biomass for central heating. It is planned that an oxygen probe will be applied to optimize the combustion process. The aim will be to verify whether the probe is providing correct data. This experiment should discover possibilities of probe credibility verification.

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