NONLINEAR CONTROL IN CHANGING OPERATING CONDITIONS

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Abstract: Operating conditions are often changing so strongly that the changes in nonlinearities must be taken into account. A practical solution comprises several intelligent systems: intelligent analysers make the adaptation easier by providing informative measurements for the controller, and high-level control supervises the adaptation procedure. Linguistic equation (LE) controllers combine various control strategies, and their compact matrix-based implementation is essential in building multilevel control systems including adaptation, prediction and several control strategies. Dynamic simulation with LE models is a very fast and reliable method for controller tuning. Applications provide good examples of a smart adaptive application consisting of practical and interactive small-scale intelligent systems.

Keywords: adaptive control, nonlinear control, predictive control, intelligent control, model-based control, fuzzy set systems, multivariable systems.

1. INTRODUCTION

In industrial applications, operating conditions are often changing so strongly that the changes in nonlinearities must be taken into account. Pulp and paper industry has been in the pioneering role in the development of process automation: various intelligent applications have been developed for fibre line, chemical recovery, bleaching, paper mill, and water treatment (Juuso, 2004*a*). Efficient integration of subprocesses is important in pulp and paper industry.

Internal water circulation is essential for an integrated pulp and paper mill as washing is done in many stages of the process. The water can be kept in the circulation if the treatment is capable to clean it. All disturbance of the purification result will later cause new disturbances in the pulping or paper making processes (Juuso, 2004*a*).

Energy production is another area where adaptation to changing operating conditions is necessary. Different Control methodologies have been tested in the *Acurex Solar Collectors Field* of the *Plataforma Solar de Almeria (PSA)* located in the desert of Tabernas (Almeria), in the south of Spain (Juuso, 1999*a*). Waste handling has similar requirements but the measurements do not always give the correct information, which leads to wrong control actions, and eventually to switch-off of the automatic control strategy. As operators have lots of additional information, the control strategy should be designed for working with inputs from the operator. (Oestergaard, 2004)

Linguistic equations have been used in three control applications: a solar collector field, a lime kiln in a pulp mill and a flotation unit in internal water circulation of a pulp mill. Lime kilns are used in the chemical recovery of the chemical pulping process. Development of control strategies has been increased in recent years mainly due to tightened environmental requirements and decreasing water consumption in pulp and paper mills (Joensuu *et al.*, 2004).

Application areas have similar requirements, e.g. lime kilns can use bio fuels generated from biomass (Järvensivu *et al.*, 2001). Efficient use of chemicals, water and energy requires adaptation of the nonlinear multivariable processes into ever changing operating environments.

This paper summarises different approaches for adapting control systems to changing operating conditions from industrial experiences. Adaptive linguistic equation controllers are taken as an example of integration of different control strategies in these application areas.

2. PROCESS CONTROL

Various approaches exist for coping with nonlinearities in changing operating environment:

- *Nonlinear* control extends the operating area of the control systems, especially intelligent methods provide new tools for this.
- *Adaptation*, first for linear controllers and later for nonlinear controllers, is primarily devoted to new operating conditions but recent progress in modelling have improved possibilities for predefined adaptation. Also new adaptation mechanisms have been introduced.
- *Model-based* control was already used in the very beginning of automatic process control. Model-based predictive control has recently become increasingly popular research topic. Various modelling approaches have been used in these applications.
- *Human* operators can control successfully processes which are very difficult for classical automatic control. The tradition of rule-based control has been extended by fuzzy control.
- *Multivariable* control should take into account a very large number of variables. This could be done technically but the complexity of these systems has introduced a need for software sensors or intelligent analysers.

These approaches, which extend the use of normal *feedback (FB)* and *feedforward (FF)* controllers to changing operating conditions, have been during the years used mostly separated but practical industrial applications require combining these approaches in a hybrid control system. The resulting huge variety of features means that the tuning of the control system must be done with modelling and simulation. The overall structure combines ideas from classical and advanced approaches (Fig. 1).

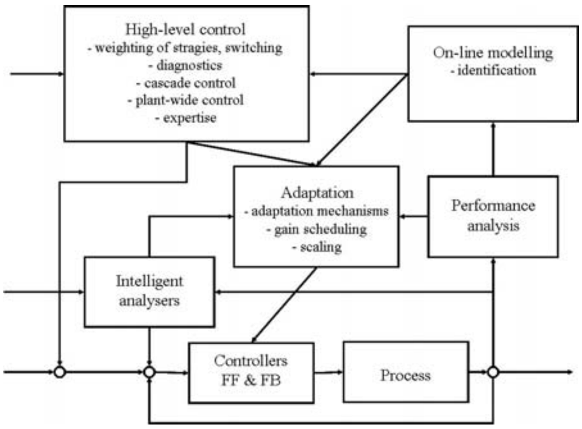

Fig. 1. Modules of adaptive control.

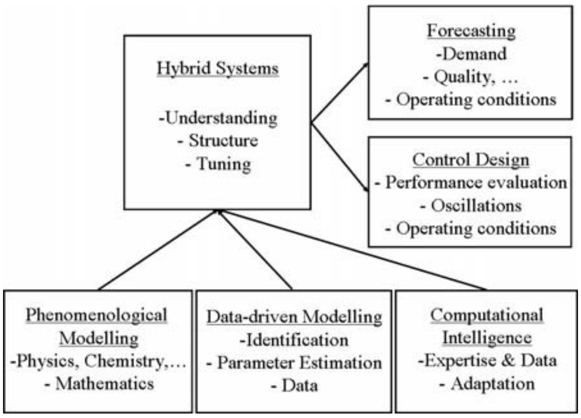

Fig. 2. Alternatives of modelling and simulation for adaptive control applications.

Intelligent methods provide a good basis for handling *nonlinear* multivariable systems. The first industrial *fuzzy logic controller (FLC)* was realised in 1978 (Holmblad and Oestergaard, 1982) (1982). For the solar plant, a PI type conventional fuzzy logic controller presented in (Rubio *et al.*, 1995) was designed manually on the basis of the experience of the previous experiments. An automatic genetic design technique was later developed (Gordillo *et al.*, 1997) since the trial and error methodology make the improving task hard and difficult.

Classical adaptive schemes do not cope easily with strong and fast changes unless the adaptation rate is made very high. This is not always possible: some a priori knowledge about the plant dynamic behaviour should be used. One alternative for these cases is a switching control scheme which selects a controller from a finite set of predefined fixed controllers. An important difference to the gain scheduling scheme is that each controller can have a completely different structure. The switching strategy can be based on heuristic rules or predictions with models.

Model-based control is widely applied to industrial applications (Camacho and Bordons, 1995). Since the identification is on a practical level only for linear systems, a lot of work with local linear models is needed. The models should be designed for forecasting (Fig. 2). *Feedforward control (FF)* can be based on models, e.g. most of controllers tested in the solar collector field at PSA use model-based feedforward control (Camacho *et al.*, 1992). *Generalized predictive control (GPC)* based on a gain scheduling algorithm was able to handle different operating conditions and sudden perturbations caused by clouds (Camacho and Berenguel, 1994). A combination of a switching algorithm and predictive control (MPC) is presented in (Lemos *et al.*, 2002)

High-level control is a natural area for intelligent control (Oestergaard, 1996; Juuso, 1999*a*). Weighting of several control strategies should be based on operating conditions. In this way even several control loops can operate consistently in changing operating conditions (Juuso, 2004*b*). On this level, automatic control is interacting with operator actions (Oestergaard, 2003).

The control performance can be enhanced by linking it with *software sensors* and *fault diagnosis*. Adaptive control uses these new measurements to improve performance of the operation. Modelling is essential in software sensors, diagnostics, and model predictive control. In this classification, modelling includes dynamic modelling and simulation (Juuso, 2004*b*).

On-line adaptation based on identification or on adaptation mechanism is sometimes too slow. Also reliable switching between models is not always robust enough. The trade-off between the necessary accuracy and resulting complexity becomes increasingly important when the nonlinear and multivariable behaviour must be taken into account. Modelling is used for predicting in a long horizon, especially in batch processes, and control design (Fig. 2).

Lime kiln control has been based on almost all the methodologies presented above: starting from phenomenological and data-driven modelling integrated with linear control approaches to intelligent modelling integrated with expert control. A comparison of in lime kiln applications has been presented in (Juuso, 2004*a*). More references of nonlinear control approaches can be found in (Juuso, 2004*c*). Intelligent methods have been used in various industrial areas (Juuso, 2004*d*).

The history of solar plant applications is quite similar starting from feedforward control, adaptive and model-based methodologies. In this application the model-based predefined adaptation can be partly developed from physical principles. Self-organising controllers have problems in water treatment control but a combination of an intelligent analyser and an adaptation model provide good results.

3. ADAPTIVE LE CONTROLLERS

Linguistic equation (LE) approach, which originates from fuzzy logic, has been applied in several applications as it provides a good basis for integration of several process units (Juuso, 1999*a*; Juuso, 2004*a*).

The linguistic equation (LE) consists of two parts: interactions are handled with linear equations, and nonlinearity is taken into account by membership definitions. The general LE model can be presented by

$$\sum_{j=1}^{m} A_{ij} X_j + B_i = 0, \qquad (1)$$

where X_j is a linguistic level for the variable j, $j = 1...m$. The direction of the interaction is represented by interaction coefficients A_{ij}. The bias term B_i was introduced for fault diagnosis systems.

Linguistic levels of the input variables are determined by membership definitions, which scale the real values of variables to the linguistic levels with the range of [-2, +2] which combines normal operation [-1, +1] with handling of warnings and alarms. (Juuso, 2004*b*)

3.1 LE controllers

The basic controller is a PI-type LE controller represented in the following form (Juuso, 1999*a*)

$$\Delta u = e + \Delta e, \qquad (2)$$

which is a special case of the matrix equation $AX = 0$ with the interaction matrix $A = [\,1\ 1\ -1\,]$, and variables $X = [\,e\ \Delta e\ \Delta u\,]^T$.

The first LE controller was implemented in a solar plant (Juuso *et al.*, 1997) and later it has been introduced to control a lime kiln (Järvensivu *et al.*, 2001) and a flotation unit (Joensuu *et al.*, 2004).

3.2 Monitoring with soft sensors

Benefits of model-based software sensors have been clearly demonstrated in water treatment applications (Ainali *et al.*, 2002). The software sensor of the fuel quality is also the corner stone of the rotary kiln controller presented in (Järvensivu *et al.*, 2001). Both these applications use model-based performance analysis of the control actions, i.e. chemical dosage and fuel feed, respectively. In solar application, effective solar irradiation, temperature difference between inlet and outlet temperatures and ambient temperature were used to define the working point by an additional linguistic equation (Juuso and Valenzuela, 2003).

3.3 Adaptation

The adaptation models are based equations similar to Eq. 1, and various special control strategies also use similar equations. All these are additional features which activated if the matrix calculation gives for them a non-zero value. The implementation is very compact since no special switching programs or rules are needed.

The scaling of nonlinearity was introduced to the first linguistic equation controllers developed to maintain the outlet oil temperature of a 1MWt solar power plant (Juuso *et al.*, 1997). Operation of the controller is modified by variables describing operating conditions (Eq. 3). The same adaptation method was applied in the lime kiln control (Järvensivu *et al.*, 2001): the working point depends on loading state of the process, power of the control variable, and the cumulative rate of the control actions. In the water treatment case, the water quality indicator (Ainali *et al.*, 2002) is essential in avoiding on the other hand oscillations and on the other hand too slow operation (Joensuu *et al.*, 2004).

The adaptation is very fast as the predefined actions remove the need for on-line identification, or for classical mechanism based on performance analysis. In many cases controllers could be called as a linguistic equation based gain scheduling (LEGS) but the adaptation also includes possibility to change membership definitions, e.g. braking and asymmetrical actions.

3.4 Modelling and simulation

Simulation is a fast method to achieve control parameters, but it requires a reliable dynamic model. Dynamic LE models have been used for control design in three processes: solar power plant (Juuso, 2003), lime kiln (Juuso, 1999*b*) and water treatment (Ainali *et al.*, 2002). According to testing results, the models predict the output very well: the collector field model the outlet temperature, the lime kiln model the hot end temperature, and the flotation model the outlet turbidity, respectively.

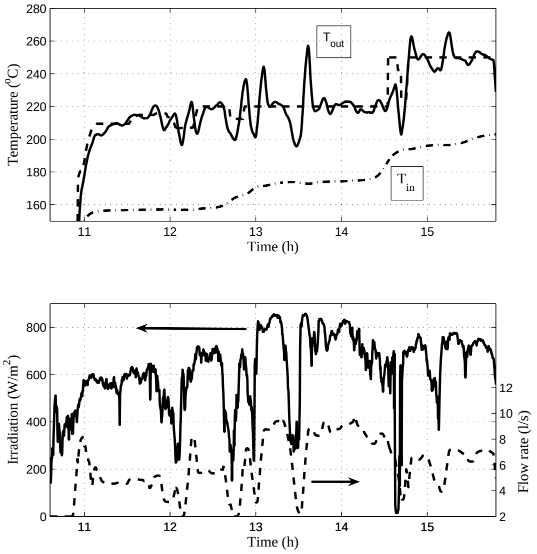

Fig. 3. Testing results of the multilevel LE controller on a solar collector field: temperatures, oil flow and irradiation.

A realistic dynamic behaviour, including oscillations, is necessary, and this was achieved in all these models. In the water treatment application, the model is a part of the water quality indicator. Benefits of predefined operation increase with complexity of the control system.

3.5 Predictive control

Normal model-based predictive control has difficulties in coping with quickly changing operating conditions. Therefore, a braking action based on analysing the speed of the change was developed in the solar application (Juuso *et al.*, 1997). Following a good trajectory is built in and the membership definitions are adapted to the changing operating conditions. The braking action is a correction factor for the importance of the change of error. This implementation is very compact if compared to the model predictive controllers. (Juuso, 1999*a*; Järvensivu *et al.*, 2001).

Additional predictive actions were later introduced for avoiding oscillatory conditions in the solar application (Juuso and Valenzuela, 2003). These additional smart control features prevent too high temperatures usually resulting in following cases: (1) fast increase of the inlet temperature, (2) too fast temperature increase, and (3) too high temperature difference between the inlet and the outlet compared to acceptable level corresponding to the recent corrected irradiation level. Additional change of control is introduced if at least one of these cases is active.

3.6 Hybrid control systems

In the solar application, adaptive set point procedure and feedforward (FF) features are essential for avoiding overheating and oscillations, limitations of the actuators are taken into account. The set point is automatically lowered if the heating effect is too low for the required temperatures.

The multilevel LE controller has already very many actions extending the basic PI type LE controller, which is designed for the normal operation. Operation condition controller changes the control surface of the basic LE controller. Predictive LE controller adapts the operation with the braking and asymmetrical actions. All these are used in the solar application. The lime kiln control does not include the asymmetrical action. The water treatment is based on the first two levels. Modularity is beneficial for the tuning of the controller to various operating conditions, and most important is that the same controller can operate on the whole working area.

4. APPLICATIONS

The adaptive linguistic equation control approach has been tested in three applications, which need fast adaptation in a wide operating area. Almost all the modules presented in Figure 1 have been used online in these cases. On-line modelling approach has not been used because all these processes are characterised by strong and fast disturbances.

The aim of *solar thermal power plants* is to provide thermal energy for use in an industrial process such as seawater desalination or electricity generation. The controller combines smoothly various control strategies into a compact single controller (Juuso and Valenzuela, 2003). The operation is very robust in difficult conditions: start-up and set point tracking are fast and accurate in variable irradiation conditions; the controller can handle efficiently even multiple disturbances and avoids overheating. The new adaptive technique has reduced considerably temperature differences between collector loops. Efficient energy collection was achieved even in variable operating conditions (Fig. 3).

In the *lime kiln* process, the LE based control system (Järvensivu *et al.*, 2001) integrates almost all the approaches described above. The system uses several FF controllers: rotational speed, feed of different fuels and draught fan speed. The fuel feeds need also a feedback controller. In addition to the easily quantifiable energy savings and increase in production rate, improvements in lime quality have also been obtained by the significant reduction in the variability of the hot-end temperature (the quartile range and the standard deviation of the hot-end temperature have declined nearly 50 % and more than 30 %, respectively). The main ecological benefits were a decrease of over 10 % in total reduced sulphur emissions and a reduction of about 50 % in the proportion of high emission periods (Järvensivu *et al.*, 2001). With efficiently operating controller, it is finally possible to optimise the kiln operation (Fig. 4).

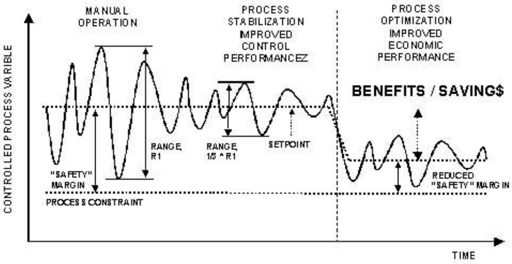

Fig. 4. Optimisation of the lime kiln temperatures (Juuso, 2004a).

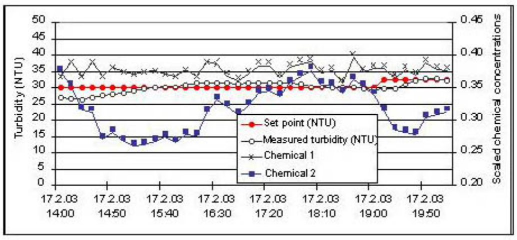

Fig. 5. Dosing control in water treatment (Juuso, 2004a).

In the *water treatment* processes, the appropriate chemical dose depends on the quality of the raw water and the purification target. Operational principle of the adaptive feedback LE-controller is different compared to the self-tuning PID-controller. Modification of the control parameters is based on the information obtained from the properties of water in a predefined way. One chemical is controlled by a model-based FF controller. Pre-tuning facilitates fast operation in changing process conditions (Joensuu *et al.*, 2004): the controllers do not need any identification time for finding correct parameters (Fig. 5).

5. CONCLUSIONS

Adaptive, decentralized control systems can be built for integrating variety of control strategies. Pretuning facilitates fast operation in changing process conditions. The adaptive linguistic equation control system is a good example of a smart adaptive application consisting of practical and interactive small scale intelligent systems. The performance of these systems has been demonstrated in three applications.

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