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A SURVEY OF ADAPTIVE CONTROL APPLICATIONS[†]

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Abstract

This paper gives examples of industrial adaptive controllers and of true industrial applications of adaptive control. Adaptive control algorithms are found in single-loop controllers as well as in distributed control systems. The applications are from a wide range of industries, from process control to engine control in cars.

1. Introduction

The substantial progress in adaptive control over the past ten years has been widely published. There have also been a large number of applications. Some are mentioned in Seborg *et al.* (1986), Åström (1987), and Åström and Wittenmark (1995) but many applications have not been reported. Industrial experiments with self-tuning regulators were performed in 1972. Full-scale experiments with adaptive autopilots for ship steering were done in 1973. Special purpose adaptive systems have been in continuous use since 1974. Commercial autopilots for ship steering have been in continuous operation since 1980.

The first adaptive controllers were implemented using minicomputers in the early 1970s. The industrial impact of adaptive control did not occur until the 1980s when microprocessor enabled cost-effective implementations. The number of adaptive systems used industrially then increased drastically. Use of adaptive techniques in single-loop PID controllers also became feasible. It is now a feature of practically all new single-loop controllers for process control. It is increasingly becoming an element in distributed systems for process control. There are also many adaptive systems for special applications such as ship steering, motor drives, industrial robots etc.

The purpose of this session is to indicate the present state of the art of applications of adaptive control. This paper gives an overview. The following papers describe a number of different systems reflecting the richness of the applications.

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2. How to use adaptive techniques?

A number of studies have been performed to explore the usefulness of adaptive control. They cover a wide range of control problems, such as autopilots for missiles, ships, and aircraft; engine control; motion control; machine tools; industrial robots; power systems; distillation columns; chemical reactors; pH control; furnaces; heating; and ventilation. The studies have shown that there are cases in which adaptive control is very useful and others in which the benefits are marginal. This section summarizes some findings.

Automatic tuning

Automatic tuning of simple PID controllers is the most widely spread use of adaptive techniques. This may at first seem surprising because adaptive control was originally developed to control systems that operate under widely changing conditions. The reason is that there are so many simple controllers in industrial use. All adaptive techniques can be used for automatic tuning. The adaptive controller is run until the performance is satisfactory; then the adaptation loop is disconnected, and the system is left running with fixed controller parameters. Perturbation signals may be added to improve the parameter estimation. Special techniques have also been developed for automatic tuning of PID controllers, see Åström *et al.* (1993a), Hang *et al.* (1993) and Åström and Hägglund (1995). A well-designed auto-tuner is very easy to use, even for unskilled personnel. Experience has shown that auto-tuners are useful both for commissioning of new systems and for routine operation.

Automatic construction of gain schedules

Gain scheduling is a very useful technique. It has, however, the drawback that it may require a considerable effort to obtain a schedule by performing control design for many different operating conditions. Autotuning can, however, conveniently be used to generate gain schedules semi-automatically by repeating automatic tuning at several operating conditions that cover the full operating range. Industrial experience has shown that substantial improvements for simple control loops can be obtained with schedules that only have a few entries. This use of automatic tuning is now found in several commercial products, see Hägglund and Åström (1991).

Continuous adaptation

There are of course applications that require continuous adjustment of the controller parameters. In such cases it is important to have a good operator interface and a good safety network. An adaptive controller also has parameters that must be chosen. The choices can be restricted for special applications. Techniques for automatic tuning can be used to find parameters automatically, see Lundh and Åström (1994). It is of course necessary to tell the controller what it is expected to do. This can be done by introducing dials that give the desired properties of the closed-loop system. Such dials are characterized as ***performance-related***. For example, it is possible to have a controller with one dial, labeled with the desired response speed.

Parameter estimation is a crucial element of an adaptive controller. The estimation is relatively simple for processes with disturbances that excite the process all the time. If there is not enough excitation of the process it is necessary to introduce a code in the algorithm that ensures that controller parameters are not changed when there is no excitation of the process.

Adaptation can also be combined with gain scheduling to make it possible to follow variations faster. A gain schedule can be used to get the parameters quickly into the correct region, and adaptation can then be used for fine-tuning.

Adaptive feedforward

Feedforward control is very useful when some of the disturbances acting on the process can be measured. The effect of the disturbances can then be reduced substantially. However, feedforward control, being an open-loop compensation, requires good models of process dynamics. Adaptive control is therefore a prerequisites for effective use of feedforward compensation. Adaptive feedforward was used in the early applications of self-tuning regulators, it is also found in several single-loop controllers.

3. Industrial controllers

There is a wide variety of industrial products where adaptation is used. For the purpose of presentation we will group them into categories and give some examples of each group.

Tuning devices

There are many tuning devices for standard controllers. It is typically a system that is connected to a controller of PID type, see Åström *et al.* (1993a) and Åström and Hägglund (1995) for a more detailed presentation. The devices are connected to the process for the tuning. Some kind of system identification experiment is initiated, a model is obtained, and suitable controller parameters are computed. The tuner is then disconnected, the ordinary controller is connected and the controller parameters are entered manually. The devices may be viewed as packaging of techniques for system identification and control design with a good man-machine interface. By restricting the application to special tasks such as tuning of PID controllers it is possible to construct devices that are very easy to use. Since the external tuner can be used for different types of standard controllers, it must have detailed knowledge about the parameterization and implementation of algorithms from different manufacturers.

The systems are either based on parametric or nonparametric models. In the parametric approach the model is typically a low-order pulse transfer function. The identification experiments are typically performed in open loop. Examples of input signals are steps, pulses or pseudo-random binary sequence (PRBS) signals. The parameters of a PI or PID controller are then determined by using empirical tuning rules or a pole placement technique.

The nonparametric approaches are either based on transient or frequency responses, which are characterized by a few features. In the nonparametric model approach, a point on the Nyquist curve is generally estimated by using relay feedback. Based on this information a modified set of Ziegler-Nichols tuning rules are used to determine the controller parameters.

A good example of tuning devices is the Protuner from Techmation which is implemented on a PC with special boards for process communication.

Standard process controllers

Most industrial control problems are solved by standard controllers of the PID type. These controllers can be implemented as separate units, they also appear as function blocks in PLCs and distributed control systems. Adaptive techniques are build into many of these systems. Automatic tuning is probably the most common feature, but it is often combined with continuous adaptation of feedback and feedforward control and gain scheduling.

A wide variety of models are used, parametric as well as nonparametric. The model-based controllers are typically based on first- or second-order models with time delay. The parameters are estimated by a recursive least-squares algorithm. Control design can be made by pole placement or some frequency domain technique. Empirical tuning rules that are modifications of the Ziegler-Nichols rules are also commonly used. The modifications are necessary because the original Ziegler-Nichols rules give closed loop systems that are very poorly damped. Many special techniques have also been applied. One example is to use pattern recognition to adjust controller parameters directly.

If the adaptive techniques are closely integrated with the controller it is possible to make systems that are very easy to use. Several systems are designed in such a way that tuning is simply accomplished by pushing a button, so-called "one-button-tuning". The first system of this type was a PID controller developed by Leeds and Northrup in 1981. This was followed by a large number of systems. SattControl in Sweden introduced auto-tuning and gain scheduling for PID controllers in a small DDC system in 1984 and a single-loop controller in 1986. Practically all PID controllers that come on the market today have some kind of built-in automatic tuning or adaptation.

Several of the adaptive standard controllers have adaptive feedforward and the possibility to build up gain scheduling tables automatically. These features are very useful and can improve the performance considerably.

The controllers Yokogawa SLPC-181/281 and Toshiba Tosdic 215 are typical systems that are based on parametric models.

The controller ECA 400 from AlfaLaval Automation (formerly SattControl), see Hägglund and Åström (1990) is an example of a controller that is based on a nonparametric model. This single loop controller has automatic tuning, continuous adaptation of feedback and feedforward gains and gain scheduling. A special feature of this system is that identification is done in closed loop by relay feedback. This gives a robust way of determining the point of the Nyquist curve where it intersects the negative real axis. In continuous adaptation this point is tracked continuously.

Pattern recognition has also been used for adaptive tuning of standard controllers. The idea is to mimic the skills of an experienced instrument engineer in terms of rules. Features that characterize the system response are extracted and used to directly adjust controller parameters. The first system of this type is the Foxboro EXACT, which was introduced in 1984, Bristol and Kraus (1984), Kraus and Myron (1984).

Controllers with more sophisticated control algorithms are now appearing on the market. Typical control algorithms are predictive control that also can handle multivariable systems. Several systems of this type are under development.

Toolboxes

It is sometimes desirable to have controllers that are more sophisticated than PID controllers. It is then necessary to estimate higher-order models and to have the possibility to use different design algorithms. To cover these situations, general toolboxes for adaptive control have been developed. The adaptive algorithms are usually modules or blocks in more general packages for direct digital control (DDC). Asea Brown Boveri presented a general-purpose adaptive controller as early as 1982, Bengtsson and Egardt (1984), Modén (1995). First Control Systems in Sweden introduced an adaptive controller in 1986, Bengtsson (1995). These systems have the potential to give better performance than PID controllers, but they require more sophisticated users than the simple controllers. It is also possible to implement adaptive control in distributed control systems as well as in PLC systems. This requires users who are able to program the details of control and estimation algorithms. Examples of this are found in Alam (1984) and Alam and Carlson (1995).

The approaches in simple controller and toolboxes are emerging because the techniques developed for single loop controllers are migrating to distributed control systems. Their functionality is also increased because of more computing power and better man-machine interfaces. The simpler auto-tuners are also being used to initialize more sophisticated algorithms. An example of this is described in Lundh and Åström (1994).

Special-purpose systems

For many processes, extensive process knowledge is available. To make good control, it is advantageous to use as much *a priori* knowledge as possible. Structures of the model and knowledge of integrators or time constants can be used to design the controller and to facilitate the tuning. For instance, special-purpose adaptive controllers have been developed for ships, pulp digesters, motor drives, ultrafiltration, and cement raw material mixing. Control systems for motion control is a typical example. Such systems have very similar structure. An interesting PC based system of this type has been developed by Servotronix.

4. Industrial applications

There are many applications of adaptive control in the field of industrial process control. Some typical examples are given in this section. The applications give insight into how adaptive control can be used in practice. In the literature we can find applications, for instance, in the areas

- Distillation column, Åström and Hägglund (1990)

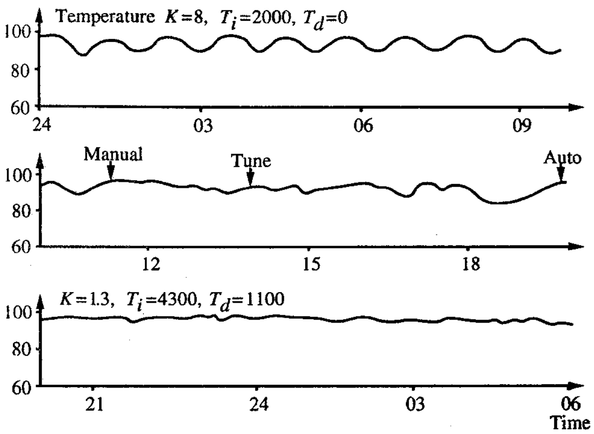

Figure 1. **Temperature control of a distillation column using the auto-tuner SattControl ECA40. (From Åström and Wittenmark (1995).)**

- Chemical reactor control, Bengtsson and Egardt (1984)
- Pulp digester, Allison *et al.* (1990), Brattberg (1994)
- Rolling mill, Bengtsson and Egardt (1984)
- Engine control, Moraal (1995)
- Ship autopilot, Källström *et al.* (1979)
- Ship roll damping, Källström *et al.* (1988)
- Disk drives, Horowitz and Li (1995)
- Ultrafiltration, Sternby (1995)
- Solar plant, Camacho and Bordons (1995)
- Thermal power plant, Matsumura *et al.* (1994)
- Blood pressure, Qu and Mao (1994)
- Heat exchanger, Åström and Hägglund (1990)
- Heating and ventilation Åström *et al.* (1993b)

Several of these applications are further described in the papers Alam and Carlson (1995), Bengtsson (1995), Horowitz and Li (1995), Modén (1995), and Moraal (1995).

In this paper we will give three applications that illustrate different approaches to adaptive control. The first example is an application of an auto-tuner to a distillation column, the second example is a general purpose adaptive controller applied to a pulp digester. The third example is a special purpose adaptive controller for ship steering

Distillation column

In this application the temperature on one tray of a distillation column is controlled using the boil-up

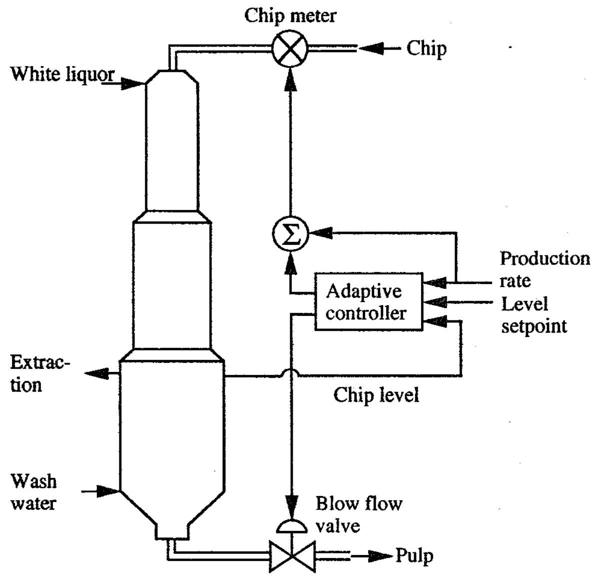

Figure 2. **Chip level controller for a continuous Kamyr digester. (Adopted from Allison *et al.* (1990).)**

as input signal. This is a crucial loop in the overall control of the distillation column. The controller is a PID controller. Due to the slow time-scale of the process it is very difficult to manually tune the controller. The behavior of the loop often becomes oscillatory. Figure 1 shows a tuning experiment with the SattControl auto-tuner ECA40. The reason for tuning the loop was that the temperature was oscillating strongly with the existing controller setting. The oscillations stop when the controller is set to manual but the temperature starts to drift. By pressing the tune button on the controller the tuner then automatically determine the properties of the process by relay feedback. New controller parameters are determined, in this case the tuner automatically chooses a PID controller and the loop is switched into auto after the experiment. The performance with the new controller parameters is drastically improved as shown in the figure. Notice that the tuning experiment did not introduce larger disturbances than those obtained with the the initial PI controller.

The use of auto-tuning and adaptive stand-alone controllers is a very large and growing area for adaptive control. These adaptive controllers are, in general, easy to install and can be used without too much knowledge about adaptive techniques.

Pulp digester

The following application of adaptive control of pulp digesters is found in Allison *et al.* (1990). In this example a general-purpose adaptive controller, developed by Paprican, Canada, is used to control a continuous Kamyr pulp digester. The adaptive controller

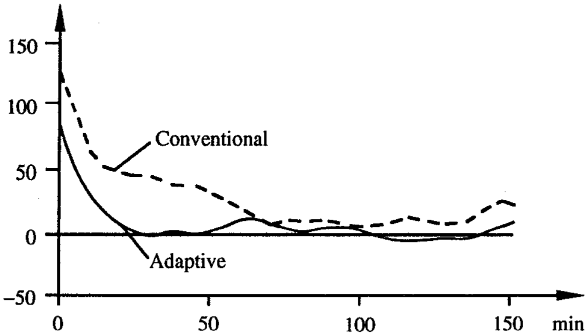

Figure 3. Autocovariance of the chip level control under conventional and adaptive control. (Adopted from Allison *et al.* (1990).)

can be used for multivariable control and the adaptive algorithm is based on generalized predictive control. A schematic block diagram of the process is shown in Figure 2. The blow flow is the primary control signal and the chip level is the controlled variable. The chip feed is an additional control signal. The purpose of the control is to minimize the variation of the chip level. This will increase the quality of the produced pulp. Identification experiments indicated that the process could be represented by a model with one pole, two zeros and a time delay. The zeroes was introduced to accommodate variations in the delay of the process.

Figure 3 shows the autocovariance under conventional and adaptive control. With the adaptive controller the variance and the low frequency content of the chip level is lower than for the conventional controller.

Secondary effects of the adaptive control are a reduced need for operator intervention, elimination of manual retuning, and help to predict hang-ups in the chip column.

Ship autopilot

This example illustrates how special features of the process can be built into an adaptive controller. The purpose of the autopilot is to keep the course of the ship as steady as possible. The measured outputs are heading and velocity of the ship. The design of the controller is based on LQG control and Kalman filtering. The controller parameters are gain scheduled using the velocity of the ship. Adaptation is used primarily to cope with disturbances generated by wind and waves. Figure 4 shows the rudder position and the heading from tests on a 255 000 dwt tanker, Källström *et al.* (1979). The figure gives a comparison under similar weather and loading conditions of the conventional autopilot and the adaptive autopilot. The variations in heading error are reduced substantially with adaptive controller without causing excessive rudder action. The improvement shown in the figure translates to fuel savings of a few percent.

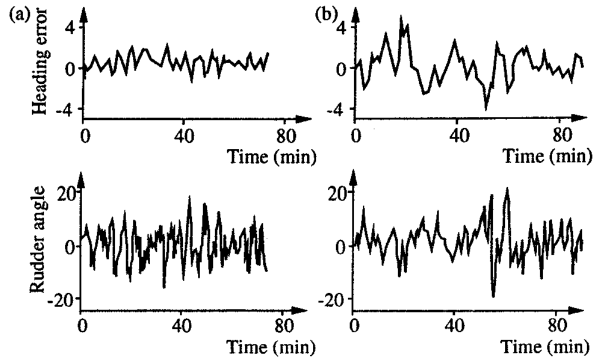

Figure 4. Variation in heading and rudder movements in ship control. (a) Adaptive autopilot. (b) Conventional autopilot of PID-type. (From Åström and Wittenmark (1995).)

The example illustrates the possibility to build process knowledge into the adaptive controller. This will decrease the need for the operator to specify parameters in the control algorithm. Instead there may be performance related knobs. In the autopilot case the operator may choose between tight control or economic control.

5. Conclusions

Although there are many applications of adaptive control, it is clear that adaptive control is not a mature technology. Automatic tuning has a very widespread use, particularly for PID controllers where the techniques can be packaged in such a way that the systems are very easy to use. Many industrial processes are also such that the dynamics do not change too frequently. Generation of gain schedules by automatic tuning has also proven useful and easy to apply.

Good indicators of performance improvements with continuous adaptation are: when the system has long time delays, when feedforward can be used, and when the character of the disturbances is changing. In all these cases it is necessary to have a model of the process or the disturbances to effectively control the system. It is then beneficial to be able to estimate a model and to adapt to changes in the process.

Systems with continuous adaptation of more complicated algorithms are more difficult to apply. Particularly in situations when the excitation is changing significantly. It is then necessary to introduce many "fixes" to ensure that the system work well under all possible operating conditions. The need for supervision logic is not specific to adaptive control, because similar precautions must be taken in all practical control systems, but since adaptive control systems are complex, the safety nets that are required can be quite elaborate.

The human-machine interface is very important because it often determines how easily the system can be used. The one-button-tuning feature of the simple controllers has contributed significantly to their acceptance.

The computing power that is available has a significant influence on the type of control algorithms that can conveniently be implemented. The basic auto-tuners use simple 8-bit microprocessors, whereas some of the more advanced systems use 32-bit architecture. The computing power that is available also has a significant impact on what human-machine interface can be implemented.

6. References

Alam, M. A. (1984): "A multivariable self-tuning controller for industrial application." In *Preprints of the 9th IFAC World Congress*, pp. III:259–262, Budapest.

Alam, M. A. and D. H. Carlson (1995): "Adaptive control, 3M experience." In *Preprints 1995 IEEE Conference on Decision and Control*, New Orleans, LA. Session WA06.

Allison, B. J., G. A. Dumont, L. H. Novak, and W. J. Cheetham (1990): "Adaptive-predictive control of Kamyr digester chip level." *AIChE Journal*, **36**, pp. 1075–1086.

Åström, K. J. (1987): "Adaptive feedback control." *Proc. IEEE*, **75**, February, pp. 185–217. Invited paper.

Åström, K. J. and T. Hägglund (1990): "Practical experiences of adaptive techniques." In *American Control Conference (ACC '90)*, San Diego, California.

Åström, K. J. and T. Hägglund (1995): *PID Controllers: Theory, Design, and Tuning*. Instrument Society of America, Research Triangle Park, NC, second edition.

Åström, K. J., T. Hägglund, C. C. Hang, and W. K. Ho (1993a): "Automatic tuning and adaptation for PID controllers—A survey." *Control Engineering Practice*, **1:4**, pp. 699–714.

Åström, K. J., T. Hägglund, and A. Wallenborg (1993b): "Automatic tuning of digital controllers with applications to HVAC plants." *Automatica*, **29**, pp. 1333–1343.

Åström, K. J. and B. Wittenmark (1995): *Adaptive Control*. Addison-Wesley, Reading, Massachusetts, second edition.

Bengtsson, G. (1995): "Industrial experiences with adaptive control." In *Preprints 1995 IEEE Conference on Decision and Control*, New Orleans, LA. Session WA06.

Bengtsson, G. and B. Egardt (1984): "Experiences with self-tuning control in the process industry." In *Preprints 9th IFAC World Congress*, pp. XI:132–140, Budapest, Hungary.

Brattberg, O. (1994): "Adaptive control of a continuous digester." In *Preprints of the Control Systems 94*, pp. 298–306, Stockholm. Swedish Pulp and Paper Research Institute.

Bristol, E. H. and T. W. Kraus (1984): "Life with pattern adaptation." In *Proceedings of the 1984 American Control Conference*, pp. 888–892, San Diego, Calif.

Camacho, E. F. and C. Bordons (1995): *Model Predictive Control in the Process Industry*. Advances in Industrial Control. Springer-Verlag, Berlin.

Hägglund, T. and K. J. Åström (1990): "A frequency domain approach to adaptive control." In *Preprints 11th IFAC World Congress*, volume 4, pp. 265–270, Tallinn, Estonia.

Hägglund, T. and K. J. Åström (1991): "Industrial adaptive controllers based on frequency response techniques." *Automatica*, **27**, pp. 599–609.

Hang, C. C., T. H. Lee, and W. K. Ho (1993): *Adaptive Control*. Instrument Society of America, Research Triangle Park, North Carolina.

Horowitz, R. and B. Li (1995): "Adaptive control of a disk drive." In *Preprints 1995 IEEE Conference on Decision and Control*, New Orleans, LA. Session WA06.

Källström, C. G., K. J. Åström, N. E. Thorell, J. Eriksson, and L. Sten (1979): "Adaptive autopilots for tankers." *Automatica*, **15**, pp. 241–254.

Källström, C. G., P. Wessel, and S. Sjölander (1988): "Roll reduction by rudder control." In *Proceedings of the Spring Meeting*, pp. 67–76, Pittsburgh, Pa. Society of Naval Architects and Marine Engineers.

Kraus, T. W. and T. J. Myron (1984): "Self-tuning PID controller uses pattern recognition approach." *Contr. Eng*, June, pp. 106–111.

Lundh, M. and K. J. Åström (1994): "Automatic initialization of a robust self-tuning controller." *Automatica*, **3:11**, pp. 1649–1662.

Matsumura, S., K. Ogata, S. Fujii, H. Shioya, and H. Nakamura (1994): "Adaptive control for the steam temperature of thermal power plants." *Control Engineering Practice*, **2**, pp. 567–575.

Modén, P.-E. (1995): "Experiences with adaptive control since 1982." In *Preprints 1995 IEEE Conference on Decision and Control*, New Orleans, LA. Session WA06.

Moraal, P. E. (1995): "Adaptive compensation of fuel dynamics in an SI engine using a switching EGO sensor." In *Preprints 1995 IEEE Conference on Decision and Control*, New Orleans, LA. Session WA06.

Qu, X. J. and Z. Mao (1994): "Self-adaptive control for blood pressure." *Control Engineering Practice*, **2**, pp. 659–664.

Seborg, D. E., T. F. Edgar, and S. L. Shah (1986): "Adaptive control strategies for process control: A survey." *AIChE Journal*, **32**, pp. 881–913.

Sternby, J. (1995): "Adaptive control of ultrafiltration." *Trans. Control Systems Technology*, **3**. Submitted.