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# A FEASIBILITY STUDY OF SELF-TUNING REGULATORS

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## ABSTRACT

The report discusses the implementation of self-tuning regulators and the results of some industrial experiments. The feasibility study has been sponsored by STU and has been a joint project between Billerud AB and the Division of Automatic Control in Lund. The experiments clearly show that the self-tuning regulators can be feasible to use for the tuning of many different control loops. The computations in the algorithm are small and it is easy to learn how to use the self-tuning regulator.

TABLE OF CONTENTS

# 1. INTRODUCTION

Many adaptive regulators have been proposed in literature /12/. So far very few real applications have been reported. The purpose of this project has been to investigate experimentally one class of adaptive control algorithms developed at the Division of Automatic Control, Lund Institute of Technology. These regulators are called self-tuning regulators /3/, /13/ and /14/.

The project has been sponsored by STU, The Swedish Board for Technical Development, and has been a joint project between Billerud AB and the Division of Automatic Control in Lund. The practical experiments have been done at the Gruvön Mill, Grums, where Billerud AB kindly has supported the project with programmers, computer facilities and industrial processes. The aim of the project has been to:

- Make theoretical studies of the self-tuning regulators concerning the choice of the parameters in the regulators.
- Investigate how the self-tuning regulators may be implemented on process computers.
- Make experiments on industrial processes.

The report is organized as follows: In Section 2 the main features of the self-tuning regulators are briefly reviewed. Section 3 contains a discussion of implementation of self-tuning regulators. The experiments are summarized in Section 4. Section 5 contains the conclusions and references are given in Section 6.

## 2. SELF-TUNING REGULATORS

In this section a brief review of the properties of the self-tuning regulators is given. For a more thorough discussion see /3/, /13/ and /14/. The self-tuning regulators are derived to control constant but unknown systems. The algorithms are based on the natural assumption of separation between the identification of the process parameter and the determination of the control signal. The processes are assumed to be single-input and single-output and described by the equation

$$y(t) + a_1 y(t-1)+\ldots+a_n y(t-n) = b_1 u(t-k-1) +$$

$$+ b_2 u(t-k-2)+\ldots+b_n u(t-k-n) + e(t) + c_1 e(t-1) +\ldots$$

$$+ c_n e(t-n)$$

or

$$A(q)y(t) = B(q)u(t-k) + C(q)\ e(t) \qquad (2.1)$$

where

- $y(t)$ - output signal
- $u(t)$ - control signal
- $e(t)$ - independent $N(0,\sigma)$ random variables
- $q$ - forward, shift operator
- $A(q) = q^n+a_1q^{n-1}+\ldots+a_n$
- $B(q) = b_1q^{n-1}+b_2q^{n-2}+\ldots+b_n$
- $C(q) = q^n+c_1q^{n-1}+\ldots c_n$

The self-tuning algorithm can be devided into two steps:

Step 1 Estimation

Estimate the parameters $\alpha_1,\ldots,\alpha_m,\ \beta_1,\ldots\beta_\ell$ in the model

$$y(t+k+1) + \alpha_1 y(t) +\ldots+ \alpha_m y(t-m+1) = \beta_0[u(t) + \beta_1 u(t-1)+\ldots+$$

$$+ \beta_\ell u(t-\ell)] + \varepsilon(t+k+1) \qquad (2.2)$$

using the method of least squares. The parameter $\beta_0$ is assumed known.

Step 2 Minimum variance control

Use the minimum variance controller

$$u(t) = \frac{\alpha_1+\alpha_2 q^{-1}+\ldots+\alpha_m q^{-m+1}}{\beta_0[1+\beta+q^{-1}+\ldots+\beta_\ell q^{-\ell}]}\, y(t) \qquad (2.3)$$

based on the estimates obtained in Step 1.

The parameter $\beta_0$ can also be estimated without changing the properties of the algorithm.

If $C \equiv 1$ then the model (2.1) can be written on the form (2.2) where $\varepsilon(t+k+1)$ is independent of $y(t)$, $y(t-1),\ldots,u(t)$, $u(t-1),\ldots$ The least squares estimator will then give unbiased estimates of the parameters in the model (2.2) and the regulator (2.3) will obviously converge to the optimal regulator if the estimation converges. Control schemes of this type has been proposed many times, see for instance Kalman /8/ and Åström and Wittenmark /2/.

If $C \neq 1$ then the least squares estimation will in general give biased estimates. When using a self-tuning regulator it can, however, be shown that the bias will be such that the controller (2.3) still will be the minimum variance regulator if the estimation converges and if the regulator contains parameters enough. In literature this was first indicated through simulations presented by Peterka /10/. The first analysis and the proofs were given by Åström and Wittenmark /3/.

The main property of the algorithm is that if the estimation converges then certain covariances of the output and cross-covariances of the output and the input are equal to zero. This will then imply that the controller will converge to the minimum variance controller if the regulator contains parameters enough. These properties are heavily depending on the assumption that the estimation converges. By counter examples it can be shown that the algorithm does not always converge /13/. The convergence properties are further discussed in /9/. The counter examples have been possible to construct only after thorough analysis of the algorithm. In practical cases there has never been any trouble with the convergence.

It is possible to extend the basic algorithm in many different ways. Slowly timevarying parameters can be handled by introducing an exponential forgetting of old data. It is also possible to include in the control law that the parameter estimates are uncertain, see /2/, /11/ and /13/. Reference values as well as feedforward compensation can easily be included /13/.

Some parameters must be specified when using the self-tuning regulators. These are the scale factor $\beta_0$ ($\beta_0$ might also be estimated), the number of time-delays in the system, the number of parameters in the regulator, the initial values of the estimates and their covariances. The choice of these parameters has been investigated and are reported in /13/. Experience has shown that it is fairly easy to make the proper choice in practice. These parameters are also much easier to choose than to determine the coefficients of a complex control law directly.

## 3. IMPLEMENTATION ON PROCESS COMPUTERS

A self-tuning regulator can be used in several ways depending on the characteristics of the controlled process:

- o A self-tuning regulator can be used at the installation or retuning of a regulator loop. It can be removed when a proper parameter set has been obtained.

- o The self-tuning regulator can be installed among the system programs in the computer and periodically serve different control loops.

- o If the process has time varying parameters it may be desirable to have the self-tuning regulator connected to the regulator loop all the time.

When implementing the algorithm on a process computer it is sometimes advantageous to divide the algorithm into two parts, one for the tuning of the parameters and one for the control. If the algorithm is implemented on a process computer having a DDC-package then the control part in many cases can be implemented using the standard set of regulators defined in the DDC-package. The tuning part then delivers the regulator parameters to the data base used by the DDC-package. If a regulator structure is used that is not available among the standard routines it is necessary to write a special routine for the control part.

The tuning part must be specially written and included in the system programs. This routine can be used for many different loops if special care is taken concerning the storage of data.

The computations to be carried out in each time interval are very moderate. Table 1 shows the number of operations, additions or multiplications, and the computation time on a PDP-15 for different numbers of regulator parameters. The number of operations is increasing with the square of the number of regulator parameters.

| Number of regulator parameters | Number of operations | Computation time in ms |
|---|---|---|
| 2 | 34 | 5 |
| 5 | 136 | 15 |
| 8 | 301 | 31 |

TABLE 1 - Number of additions and multiplications and the computation time for the basic self-tuning algorithm. The computations are done on a PDP-15 with hardware floating point arithmetic.

It is interesting to compare the complexity of a PI-regulator and a self-tuning regulator with two parameters. The number of operations in a digital PI-regulator is about 4. The self-tuning regulator requires 34 operations. Experiments and simulations indicate that up to six parameters are a reasonable number of parameters in a self-tuning regulator. A better performance of the system can, however, compensate for the more complex computations.

The data needed for the self-tuning algorithm can be divided into three types: state variables, dummy variables and constants. The state variables are inputs, outputs, parameter estimates and their covariances. The dummy variables are temporary variables used at only one interval of time. The constants define the regulator structure.

Let the number of regulator parameters be r and assume that there are k steps of time delay in the process. The data storage of the tuning and the control parts together will be:

| | |
|---|---|
| State variables | $0.5r^2 + 2.5r + 3k + 6$ |
| Dummy variables | $r$ |
| Constants | 6 |

The control routine needs 4 constants and 2r state variables. If the tuning part serves only one loop at a time it can use the same data area for all loops.

## 4. INDUSTRIAL EXPERIMENTS

The discussed self-tuning regulator has been used on a couple of industrial processes. At the Gruvön Mill the algorithm has mainly been used for the moisture content control on paper machines. Most of the experiments have been done on PM6, which is a paper machine producing fluting. The kraft paper machine, PM4, has also been used for moisture content control.

The drying process has long time delays which make it necessary to use dead time compensation, i.e. old input signals are used to determine the current input signal. Further some of the disturbances acting on the process can be measured. Feedforward compensation can thus be used in order to improve the control. The steam pressure in the last drying section of the paper machine was used as control signal. A feedforward loop from the couch vacuum was included in the regulator. Experiments with different structures of the regulator and start-up procedures were done. Some experiments and experiences are given in /6/. That report has also been accepted for presentation at the IFAC Symposium on Digital Computer Applications to Process Control in Zürich, March 1974. A similar application of self-tuning control on paper machines is reported in /7/. A detailed survey of the different experiments done at the Gruvön Mill is given in /4/. In this report just one example will be given.

<u>Example</u>

This in an example with eight parameters in the regulator. The control law had the structure

$$\nabla u(t) = -\frac{\alpha_1+\alpha_2 q^{-1}+\alpha_3 q^{-2}}{\beta_0(1+\beta_1 q^{-1}+\beta_2 q^{-2}+\beta_3 q^{-3}+\beta_4 q^{-4})}\, y(t) +$$

$$+ \frac{\gamma_1}{\beta_0(1+\beta_1 q^{-1}+\beta_2 q^{-2}+\beta_3 q^{-3}+\beta_4 q^{-4})}\, \nabla v(t)$$

where

$\nabla u(t)$ - incremental control signal

$y(t)$ - error in the moisture signal

$\nabla v(t)$ - incremental couch vaccum signal

$\beta_0$ - fix factor with the value 10 in the experiment

The moisture signal, the control signal $\nabla u(t)$, the couch vacuum signal $v(t)$ and the parameter estimates are shown in Figure 1. The self-tuning regulator had controlled the process for about four hours before the registration started and the parameter estimates had reached their final values. There are rather large disturbances in the couch vacuum but the controller managed to make a good control.

At 07.20 the machine speed was changed from 308 m/min to 320 m/min by the operator. The machine speed change introduced a sudden disturbance in the moisture content. After a short period of time the moisture level was satisfactory again. The parameter estimates were also influenced by the speed change but new values were quickly obtained.

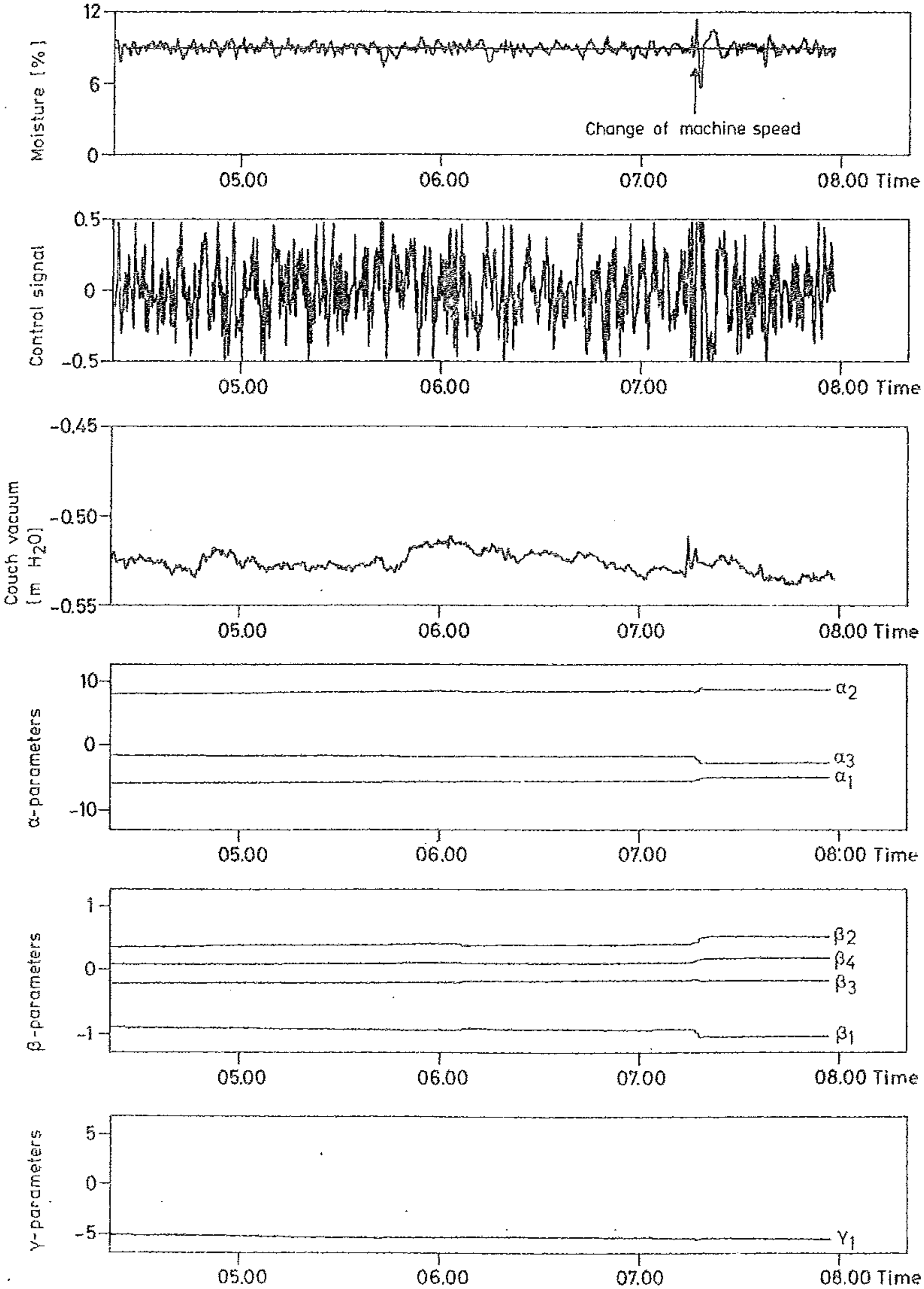


Figure 1 - Process variables and parameter estimates at an experiment with moisture content control.

Besides this STU project the self-tuning regulator has also been used for the control of an ore crusher. This was done together with LKAB in Kiruna. The controlled crusher was situated at Kiruna Finkrossverk. The control aims at keeping the production on a certain level, as high as possible, without overloading the crusher. The process has some characteristic features due to considerable transport times and special dynamics. Sometimes the ore may be accumulated on a transport band in a closed loop and then the crusher power becomes more difficult to control.

The PDP computer at the Division of Automatic Control in Lund was connected to the crushing plant in Kiruna via a public telephone line and low speed modems. The data signals were transmitted about 1 800 km, which makes the control loop the longest DDC-loop known. A special process interface was built and it was connected to the crusher in Kiruna. All practical arrangements are described in /1/.

The result of the experiments was that a self-tuning regulator with good control properties could be designed for the crusher. The regulator made it possible to operate at high power levels. The experiences from the use of tele-processing for remote control were good. Further details are given in /5/.

## 5. CONCLUSIONS

The experiences of the experiments will now be summarized and generalized in order to make it possible to determine the feasibility of the self-tuning regulators. Relevant questions are:

- the performance of the regulator
- the programming effort to make the regulator work on a process
- the practical use and the choice of regulator parameters
- the advantages obtained by using the regulator.

### Performance

The self-tuning regulator has been used in experiments of different lengths and the structure of the regulator has been varied. The experiences are very good both concerning the start-up behaviour and the steady state control.

The experiments and the digital simulations show that the regulator after very few steps (mostly less than 15) makes a very good control, even if the parameters have not reached their final values. In most of the experiments the algorithm was started up with an identification phase, i.e. the regulator only estimates the parameters and a regulator with fixed parameters is used for the control. The identification phase can be short. It is, however, also possible to start the algorithm directly without introducing any larger disturbances in the process. In the experiments on the paper machine and the crusher plant it turned out that the choice of the parameters in the regulator was not crucial. The structure of the regulator could be chosen in different ways without influencing the steady state performance drastically.

Programming

At the Gruvön Mill a DDC-package, PPCP, is used for IBM 1800 process computers on a large number of loops. The used DDC-package did not have the possibility to include directly more special control agortihms with the desired sampling interval. For the investigation some programming had to be done for each control loop that was investigated. The routine for the self-tuning regulator was all the time the same, only an administration program had to be rewritten. That program contained the logging of the experiments and the security tests that always have to be included when a regulator is used during long time and during different proccess conditions.

When several loops shall be controlled by self-tuning regulators or when the self-tuning regulators shall be used as routine tools there is a need for a special system for self-tuning control partly or totally included in a DDC-package. Such a system shall be developed at the Gruvön Mill for the PPCP. This will make the work easier, more convenient and more efficient. The way self-tuning algorithms can be included will naturally depend on the DDC-package in use, but in many packages there is a possibility to include specially written control algorithms. The main part of a DDC-package consists of data handling, checking, operator communication etc. The control algorithms are only a small part. When designing a new DDC-package it should be very easy to include a self-tuning regulator since the control algorithm is short. The computation times are also short.

## Choice of regulator parameters

The choice of the parameters in the regulator has been investigated and it has been found that the choice is not crucial. The only parameter that should be chosen with some care is the number of time-delays in the system. It has been easy to find a proper structure of the regulator for the investigated process. It is also easy to learn how to use the self-tuning regulator and there are simple rules for how to choose the parameters. So far no serious problems, such as instability or turn-off, have been noticed. Also there have never been any convergency problems.

## What can be gained?

The great advantage with the self-tuning regulator is that it is possible to obtain a good tuning of many regulator parameters. Manually it is perhaps only possible to make a good tuning if the regulator contains 2 - 3 parameters. The self-tuning regulator can tune up to 6 - 8 parameters without any difficulties. There might be a need for many regulator parameters for instance if the process contains large transport times or if feedforward control is used together with feedback control.

Manual tuning is best done on the basis of transient responses in the control loop. It is, however, in many cases desirable to have a good stationary control in order to minimize the influence of stochastic disturbances. The self-tuning regulator is designed to tune the parameters in such a way that a good stationary control is obtained. Further if a forgetting factor is used it is possible to follow changes in the process characteristics and all the time have a properly tuned regulator.

The self-tuning regulator used in the experiments is well suited for stationary control of processes where the aim of the control is to minimize the variance around some desired reference value. This makes the self-tuning regulator feasible for many control loops in process industry.

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