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Adaptive Control

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1979

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Åström, K. J. (1979). *Adaptive Control*. (Technical Reports TFRT-7183). Department of Automatic Control, Lund Institute of Technology (LTH).

Total number of authors:
1

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CODEN: LUTFD2/(TFRT-7183)/1-012/(1979)

ADAPTIVE CONTROL

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DECEMBER 1979

ADAPTIVE CONTROL

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Document name
Internal report

Date of issue
Dec 1979

CODEN: LUTFD2/(TFRT-7183)/1-012/(1979)

Author(s)
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Sponsoring organization

Title and subtitle

Adaptive control

A4 A5

Abstract

This is an elementary account of adaptive control which was prepared for McGraw-Hill Encyclopedia of Science and Technology.

Key words

A4 A5

Classification system and/or index terms (if any)

Supplementary bibliographical information

Language
English

ISSN and key title

ISBN

Recipient's notes

Number of pages
12

Price

Security classification

Distribution by (name and address)

DOKUMENTDATABLAD enl SIS 61 41 21

ADAPTIVE CONTROL

Adaptive control is a special type of nonlinear control system which can alter its parameters to adapt to a changing environment. The changes in environment can represent variations in the process dynamics or changes in the characteristics of the disturbances.

A normal feedback control system can handle moderate variations in process dynamics. The presence of such variations is in fact one reason for introducing feedback. There are, however, many situations where the changes in process dynamics are so large that a constant linear feedback controller will not work satisfactorily. Control of a supersonic aircraft is a typical example. The dynamics of the airplane changes drastically with Mach-number and dynamic pressure. A flight control system with constant parameters will not work well for an aircraft which operates over wide ranges of speeds and altitudes.

Adaptive control is also useful for industrial process control. In a given operating condition most processes can be controlled well with regulators with fixed parameters. Since delay and holdup times depend on production, it would, however, be desirable to retune the regulators when production changes. Adaptive control can also be used to compensate for changes due to ageing and wear. Typical examples are variations in catalyst activity in chemical reactions and slow changes in heat transfer due to sediments. Wear in valves and mechanical systems are other examples.

Gain_scheduling. It is sometimes possible to find auxiliary variables in a system which correlate well with the changes in process dynamics. It is then possible to eliminate the influences of parameter variations by changing the parameters of the regulator as functions of the auxiliary variables. See Fig. 1. This method of eliminating variations in process dynamics is called gain_scheduling. Gain scheduling could be considered as an extension of feedforward compensation It can be seen from Fig. 1 that there is no way to correct for an incorrect schedule.

There is a controversy in nomenclature whether a system with gain scheduling should be considered as an adaptive system or not. Gain scheduling is nevertheless a very useful

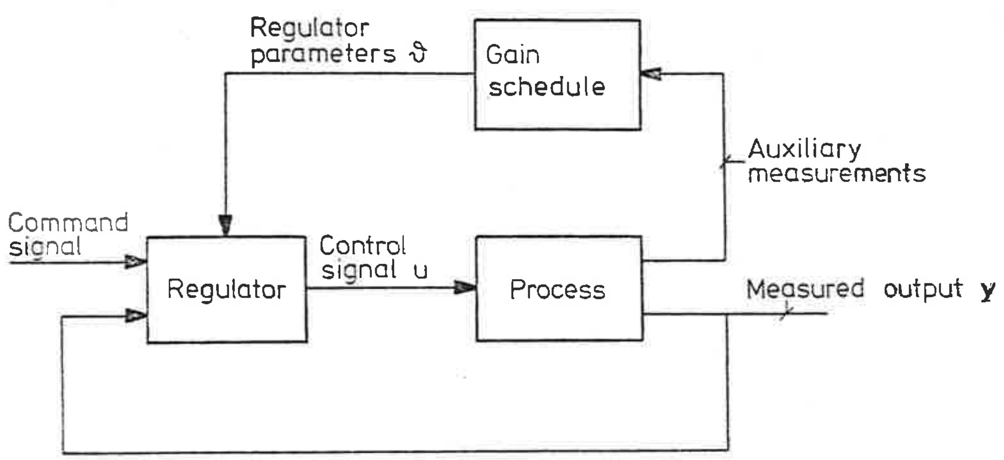

Figure__1. Block diagram of a system where parameter variations are eliminated by gain scheduling.

technique to eliminate parameter variations. It is in fact the predominant method to handle parameter variations in flight control systems. In that case the Mach-number and the dynamic pressure are measured by airdata sensors and used as scheduling variables. The parameters of the flight control system are then determined by table look up and interpolation.

One drawback with systems based on gain scheduling is that the design is time consuming. The controllers must be designed for each operating condition. The interpolation method and the safe operation of the system must also be varified by extensive simulations. It is sometimes possible to obtain the gain scheduling by using normalized dimension-free parameters. The auxiliary measurements are used together with the process measurements to obtain the normalized variables. The normalized control variable is calculated as the output of a linear constant coefficient system driven by the normalized measurements. The control variable is retransformed before it is applied to the process.

Model reference adaptive systems. MRAS. In model reference adaptive systems the dynamic specifications are given in terms of a reference model which tells how the process output ideally should respond to the command signal. Notice that the reference model is part of the control system. See Fig. 2. The regulator can be thought of as consisting of two loops. The inner loop is an ordinary control loop composed of the process and a regulator. The parameters of the regulator can be adjusted. The adjustments are made in the outer loop, which attempts to drive the regulator parameters in such a way that the error between the model output y_m and the process output y becomes small. The outer loop thus also looks like a regulator loop. The key problem is to determine the adjustment mechanism so that a stable system which brings the error to zero is obtained. This problem is nontrivial. It is easy to show that it can not be solved with a simple linear feedback from the error to the controller parameters.

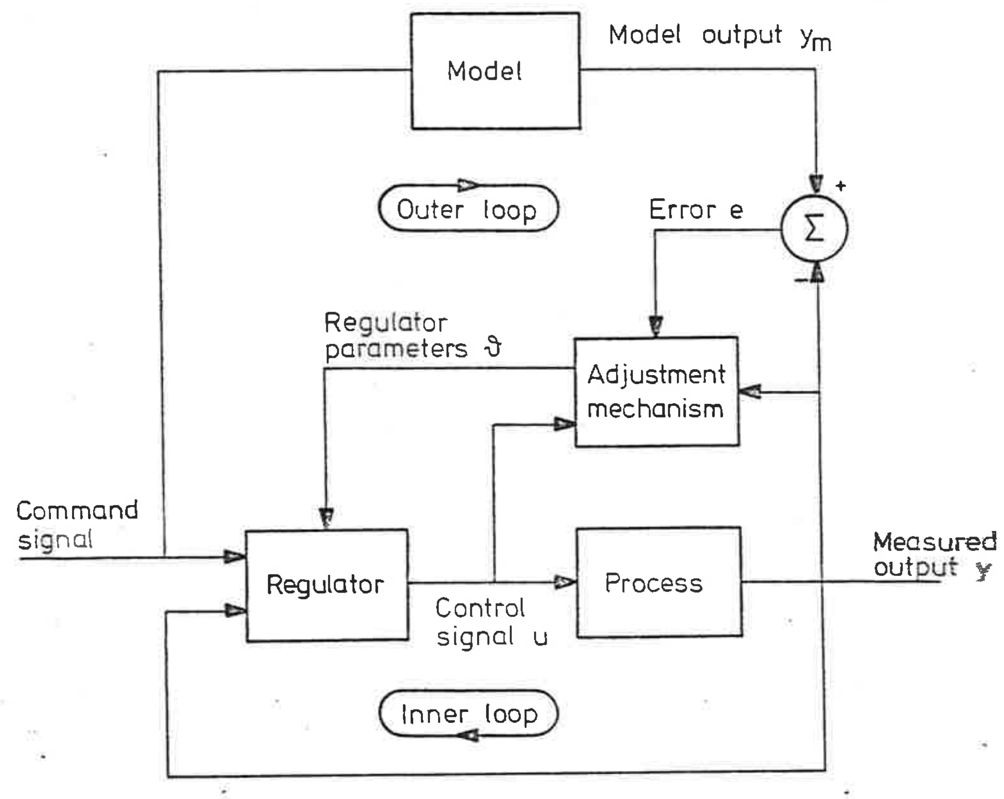

Figure_2. Block diagram of model reference adaptive system (MRAS).

The following parameter adjustment mechanism, called the 'MIT-rule', was used in the original MRAS:

$$\frac{d\vartheta_i}{dt} = -k \frac{\partial}{\partial \vartheta_i} \cdot e, \qquad i = 1, \ldots, n. \tag{1}$$

The variables $\vartheta_1, \ldots, \vartheta_n$ are the adjustable regulator parameters, $e = y_m - y$ is the error, $\partial e/\partial \vartheta_i$ are the sensitivity derivatives and k is a parameter which determines the adaptation rate. The Equation (1) represents a parameter adjustment mechanism which is composed of three parts: a linear filter for computing the sensitivity derivatives from process inputs and outputs, a multiplier, and an integrator. This configuration is typical for many adaptive systems.

The MIT-rule can unfortunately give an unstable closed loop system. The rule can be modified using Lyapunov or Popov stability theory. It is, however, only recently (1979) that real progress has been made in the theory of stability for adaptive systems.

<u>Self-tuning regulators. STR</u>. The self-tuning regulator, Fig. 3, can be thought of as composed of two loops. The inner loop consists of the process and an ordinary linear feedback regulator. The parameters of the regulator are adjusted by the outer loop, which is composed of a recursive parameter estimator and a design calculation.

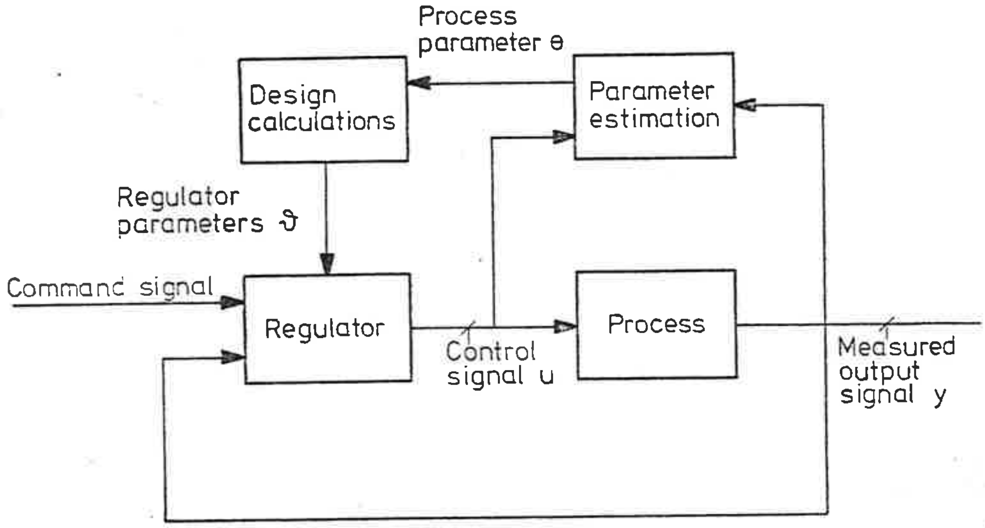

Figure 3. Block diagram of a self-tuning regulator (STR).

The regulator shown in Fig. 3 is called a regulator based on identification of an explicit process model. It is sometimes possible to reparametrize the process in such a way that it is expressed in terms of the regulator parameters. The self-tuning regulator is then considerably simplified, because the design calculations are eliminated. Such a self-tuner is called an algorithm based on estimation of an implicit process model. It is very similar to a model reference adaptive system because the parameter estimator can be interpreted as an adjustment mechanism for the regulator parameters. Compare Fig. 2 and Fig. 3. There are many variants of the self-tuners because there are many combinations of design and parameter estimation schemes.

The self-tuning regulators can be used in several different ways. Since the regulator becomes an ordinary constant gain feedback if the parameter estimates are kept constant, it can be used as a tuner whose purpose is to adjust the parameters of a control loop. In this case the self-tuner is connected to the process which is run until satisfactory performance is obtained. The self-tuner is then disconnected and the system is left with the constant regulator parameters obtained. Since the tuning is done automatically, it is possible to use control algorithms with many adjustable parameters. The self-tuner can also be used to build up a gain schedule. The system is then run with the self-tuner at different operating points. The controller parameters obtained are stored. In this way it is possible to obtain suitable regulator settings for different operating conditions. The self-tuner can of course also be used as a true adaptive controller for systems with varying parameters.

Stochastic adaptive control. Regulator structures like MRAS and STR are based on heuristic arguments. It would be appealing to obtain the regulators from a unified theoretical framework. This can, in principle, be done using nonlinear stochastic control theory. The system and its environment are then described by a stochastic model. The criterion is formulated as to minimize the expected value of a loss function which is a scalar function of states and controls.

The problem of finding a control which minimizes the expected loss function is difficult. Useful explicit conditions for existence are not known in general. Under the assumption that a solution exists a functional equation for the optimal loss function can be derived using dynamic programming. This equation, which is called the <u>Bellman equation</u>, can be solved numerically only in very simple cases. The approach is nevertheless of interest because it gives an insight into the structure of the optimal controller. See Fig. 4. The controller can be thought of as composed of two parts, an estimator and a feedback regulator. The estimator generates the conditional probability distribution of the state from the measurements. This distribution is called the <u>hyperstate</u> of the problem. The feedback regulator is a nonlinear function which maps the hyperstate into the space of control variables. To solve a nonlinear stochastic control problem it is necessary to determine the estimator, i.e. the formula for updating the hyperstate, and to solve the Bellman equation. The structural simplicity of the solution is obtained at the prize of introducing the hyperstate, which is a quantity of very high dimension. For a problem where the state space is R^4 the hyperstate is for example a distribution over R^4.

Since it is difficult to solve the Bellman equation approximative solutions are of considerable interest. A simple example will be used to illustrate some common approximations. Consider a process described by

$$y(t+1) = y(t) + bu(t) + e(t), \qquad (2)$$

where u is the control, y the output, e white noise, and b is a constant parameter. Equation (2) can be

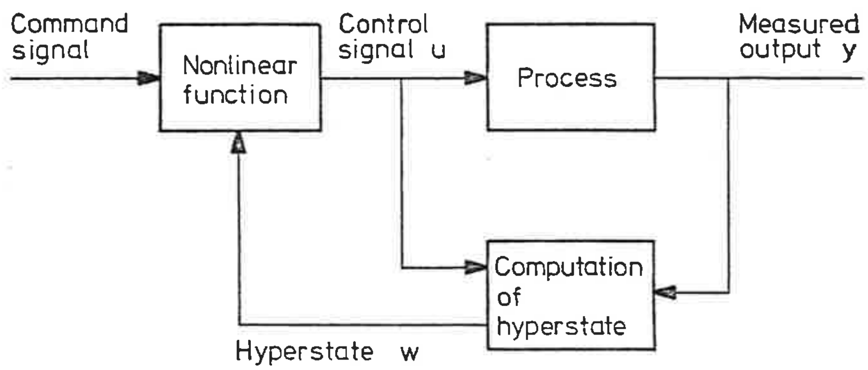

Figure 4. Block diagram of an optimal nonlinear stochastic controller. The hyperstate is generated from a dynamical system using u and y as inputs. The regulator is a static nonlinearity which gives the control variable as a function of the hyperstate and the command signal.

interpreted as a sampled data model of an integrator with unknown gain. Let the criterion be to minimize

$$\lim_{N\to\infty} E \frac{1}{N} \sum_{1}^{N} y^2(t). \tag{3}$$

If the parameter b is known the control law which minimizes (3) is given by

$$u(t) = -\frac{1}{b} y(t). \tag{4}$$

If the parameter b has a gaussian prior distribution it follows that the conditional distribution of b, given inputs and outputs up to time t, is gaussian with mean $\hat{b}(t)$ and variance P(t). The hyperstate of the problem can then be characterized by the triple $(y(t),\hat{b}(t),P(t))$. In this simple case the Bellman equation can be solved numerically. The control law obtained can not be characterized in a simple way. It has, however, a very interesting property. The control signal will not only attempt to bring the output close to zero. When the parameters are uncertain the regulator will also inject signals into the system to reduce the uncertainty of the parameter estimates. The optimal control law will give the right balance between keeping the control errors and the estimation errors small. This is called dual control.

The following control law

$$u(t) = -\frac{1}{\hat{b}(t)}\,y(t) \qquad (5)$$

is an approximative solution. This control is called the certainty-equivalence control. It is obtained simply by solving the control problem in the case of known parameters and substituting the known parameters with their estimates. The self-tuning regulator can be interpreted as a certainty-equivalence control.

The control law

$$u(t) = -\frac{\hat{b}(t)}{\hat{b}^2(t)+P(t)}\,y(t) = -\frac{1}{\hat{b}(t)}\cdot\frac{\hat{b}^2(t)}{\hat{b}^2(t)+P(t)}\,y(t). \qquad (6)$$

is another approximation, which is called cautious control because it hedges and uses lower gain when the estimates are uncertain. Notice that the cautious control law minimizes the criterion

$$E\,[y^2(t)\,|\,y(t-1),\ y(t-2),\ \ldots] \tag{7}$$

but that it is not optimal for (4).

<u>State of the art</u>. The word adaptive control is unfortunately used in many different ways and its precise meaning is subject to controversy. The field is nevertheless in a state of rapid development. The availability of microprocessors, which make it possible to implement the controllers economically, is a strong driving force.

The theory of adaptive control is still in its infancy. Major steps have recently been taken towards an understanding of the stability problem. Much research is, however, needed to develop the appropriate conceptual framework and the key theoretical problems.

There have been a reasonable number of experimental feasibility studies of adaptive control based on MRAS, STR and other adaptive techniques on pilot plants, industrial processes, and aerospace systems. A few adaptive controllers based on microprocessors have also recently been announced.

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Encyclopedia

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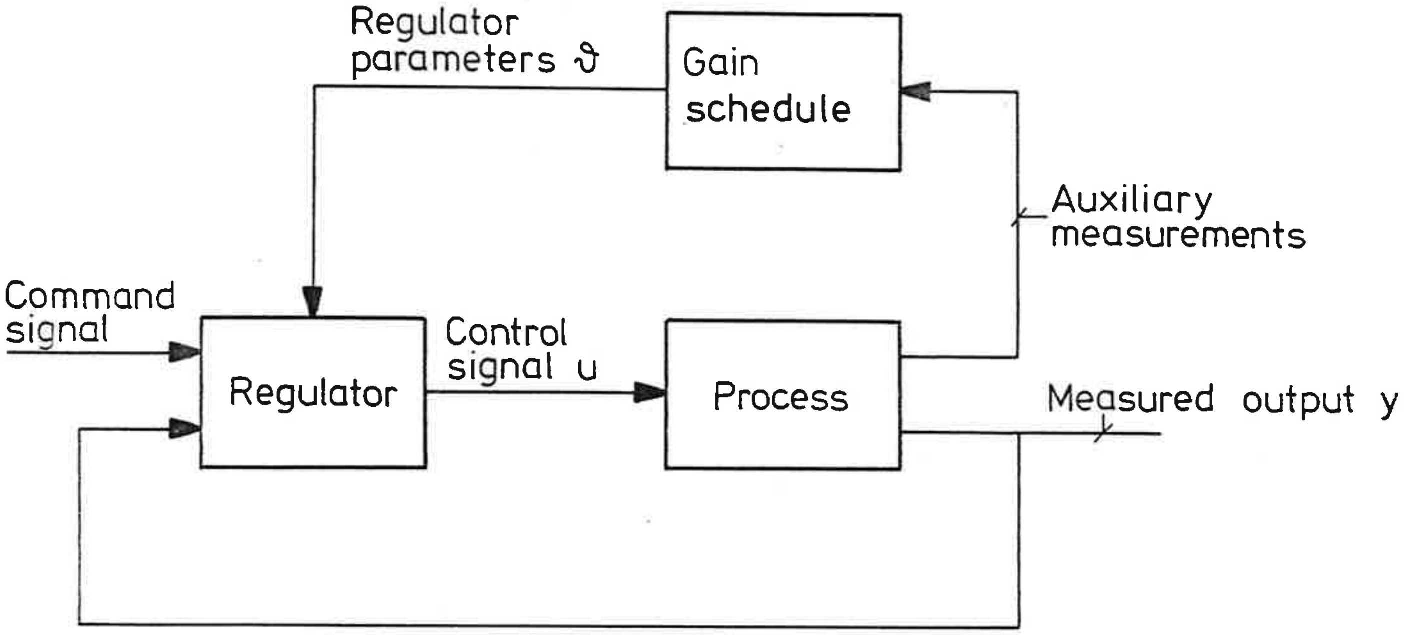
Regulator
parameters ϑ
Gain
schedule
Auxiliary
measurements
Command
signal
Regulator
Control
signal u
Process
Measured output y

Fig 1

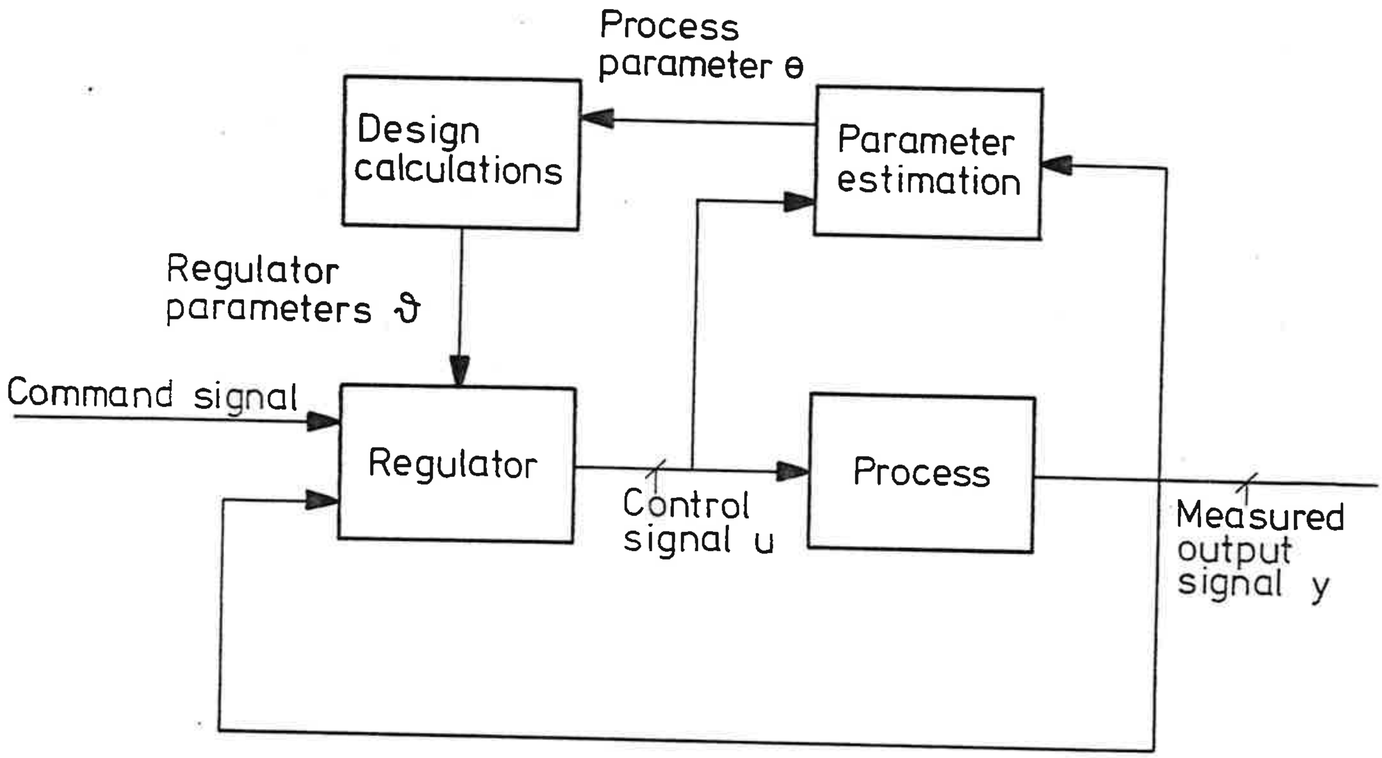
Process
parameter θ
Design
calculations
Parameter
estimation
Regulator
parameters ϑ
Command signal
Regulator
Process
Control
signal u
Measured
output
signal y

Fig 3