THE APPLICATION OF ADAPTIVE CONTROL IN A
STEAM-JACKETED KETTLE

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CHAPTER ONE

INTRODUCTION

The objective of this thesis is to apply adaptive identification and controls to the temperature of a steam-jacketed kettle.

The main idea of adaptive control is to perform an on-line analysis and simultaneous tuning of the control parameters (Fig. 1) [1]. The procedure for this on-line identification is the main part of this control technique. Large amounts of data have to be processed. This is usually the most time-consuming stage in the whole control procedure. Therefore, a computer is used when applying an adaptive control technique.

In addition to the computer, other hardware connecting the computer to the process (sensor, D/A converter, A/D converter, amplifier and electropneumatic transducer) is required. The software for adaptive control is a sequence of computer commands which simulates the specific control algorithm.

The performance of computer control is deeply affected by the qualities of both hardware and software. A large amount of hardware is available commercially. Therefore combining these elements to achieve the most flexibility is the primary task left to the control
engineer. The primary concern of this thesis is the software.

A principle difference between computer control and analog control is that the digital computer can only handle information on a discrete-time basis while the analog controller handles continuous input. The computer acts only at discrete-time intervals; it cannot recognize any change or send a control action during the interval. So, the use of Z-transforms and difference equations, which is the theory of sampled data system, is required to analyze the characteristics of the digital control system. The sampling period and time-delay constant are crucial to the derivation of discrete-time process models [2].

Emphasis in this thesis will be on the influences of the sampling period, the order of model and the control strategy on the temperature control performance in a steam-jacketed kettle. In addition, the performance of adaptive control will be compared to those of PID control.
CHAPTER TWO

BACKGROUND

The idea of adaptive control was first reported in early 1950 [3]. Investigators have been interested in using this control technique to handle nonlinear and time-varying processes since that time. Moreover, this technique also provides a tool to handle stochastic processes. In addition, use of this technique can help in the study and analysis of process dynamics and the relationship between manipulated variables and output properties under control conditions [1].

Compared to the adaptive control system, efficient use of a traditional controller depends on having a good knowledge of the controlled process in advance. Quite often processes are poorly understood or their physical or chemical parameters are not available. It is hard to maintain effective control in such cases. Additionally, studying the process dynamics can be very time-consuming if the time constant of the process is very long. Even though a good model of the controlled process can be derived initially, it might not be sufficient for long term operation. This insufficiency is caused by the following factors:
(1) Many chemical processes are nonlinear. The characteristics of the corresponding linearized models change with the operating point, i.e., the point of linearization [4].

(2) Chemical processes are nonstationary; that is, several important physical or chemical parameters (e.g., overall heat transfer coefficients) can change with time.

There are two problems involved in the adaptive technique:
(1) How to quickly regress the data coming from the process in order to provide the model of the controlled system in a timely fashion.
(2) How to adjust the parameters of the control law given the model.

These two objectives can be achieved using a digital computer because of its ability to process a large amount of information in a very short period of time. Based on the capability of fast arithmetical operation, the computer makes adaptive control able to achieve precise and reliable performance.

In the early days, the definition of adaptive control was ambiguous [2],[5]. There were several surveys attempting to classify adaptive control systems according to the view-point used to design the controller. This has little relevance to specific
applications and no relevance to relative performances. Currently, about one hundred papers are published every year on the subject of adaptive control [3], almost all of them dealing with the research of methods for data regression, the stability analysis of control systems in stochastic process and the application of adaptive control in delay systems.

So far, adaptive control is not popular in industrial applications. Although adaptive control is very convenient and theoretically reliable, in practice engineers still need to pay too much attention to too many problems to make adaptive control attractive. One question is, can a lower-order model appropriately represent higher order process dynamics in order to achieve successful control. Another question concerns how to carry out the identification of process dynamics if the time delay of the process is not a constant. The sampling period is also an important factor for this kind of digital control. These questions open the scope for further research.
CHAPTER THREE

SCOPE

A laboratory steam-jacketed kettle was used to perform the experiments. The controlled system is shown in Fig. 2. The water in the kettle, which is well-agitated, is heated by condensing steam in the jacket at a uniform temperature. The temperature of the water inside the kettle is measured and converted into digital signals by a sensor and an A/D converter (ADC). These signals are transmitted to a computer. Through the control algorithm, the computer takes action and sends analog control signals outwards. After going through an amplifier, which adjusts the voltage or current to a value accepted by the electropneumatic (E/P) transducer, the control signal is sent to the control valve. The control signal adjusts the flowrate of low-pressure steam flowing into the jacket.

The computer programs used in this work are designed so that the user can select the control strategy, the order of model and the sampling period. It is interesting to know what will happen if the order of the model is not the same as the process dynamics and also to know what the influences of the sampling period are on the control efficiency.
A principal restriction in this experimental apparatus is that the operational range among the DAC, the E/P and the control valve is not 100 percent. The actual range of the control valve is from 4.7 psig to 14.1 psig, not the normal range of 3 to 15 psig. This phenomenon affects the control performance because it causes slower response. But the crucial problem is that the steam pressure and flowrate of the inlet water are not constant. Disturbances affect the precision of the model estimated from input and output data. When such disturbances are not random and their mean is not zero, they cause offset. They can also bias the estimated model and deteriorate the control action.

The control valve in the experimental apparatus adjusts the steam flowrate instead of the steam pressure. This makes the dynamics of the heating system more complicated because the steam pressure is not always constant. This situation makes the system more nonlinear and time-varying. The effects of these nonlinearities on the control performance of the adaptive controller will be tested.

The performance of an adaptive controller will also be compared to that of a PID controller.
An adaptive controller performs two simultaneous functions: it learns about the controlled process and, at the same time, it controls its behavior. Basically, it is a feedback control system. The adaptive control system should be composed of three main elements to achieve the control action [1]. One is a standard feedback law in the form of a difference equation which acts on a set of values including the measured output, input and current set point, etc. Another is a recursive parameter estimator, a so called process identifier, which monitors the output and input of the process and computes an estimate of the process dynamics in terms of a set of parameters in a prescribed model. The final one is a control design algorithm which accepts the model estimated from the process identifier and provides a set of parameters for the control device. The general structure of the adaptive control system is shown in Fig. 3.

The process can be represented as a set of differential equations. Although these differential equations are usually nonlinear, regulation can be generally achieved using models which are derived
through local linearization around the current operating point [1]. The feedback control system can be distinguished into two types of control problems: the servo problem and the regulator problem.

4.1 Servo Problem

In this type of application, the controlled system used in this experiment can be considered as a single-input-single-output (SISO) system. The temperature of the water in the kettle is the only state variable (or output) and the pressure to the control valve is the only manipulated variable (or input). The linearized process model for SISO system can be represented in the Laplace-domain as:

\[ \bar{Y}(s) = e^{sd} \frac{B(s)}{A(s)} \bar{U}(s) \]  

where \( s \) is the Laplace-domain variable; \( A(s) \) and \( B(s) \) are the polynomials concerning the process characteristics and manipulated characteristics respectively in the \( s \)-domain; \( \bar{Y}(s) \) and \( \bar{U}(s) \) are Laplace transform of \( Y(t) \), the state variable, and \( U(t) \), the manipulated variable, respectively, and \( d \) is the lag in the process.

For a digital computer control system, it is more convenient to represent eq. 4.1 in the \( Z \)-domain [7].
where \( H \) is the pure time lag of the process, \( Y^*(z) \) and \( U^*(z) \) are the \( Z \)-transforms of the functions \( Y(t) \) and \( U(t) \) respectively, and \( A(z^{-1}) \) and \( B(z^{-1}) \) are polynomials in the time shift operator.

The relationship between \( H \) and \( d \) is:

\[ d = H \times T + L \]

where \( H \times T \) is the pure delay, and \( L \) is the fractional delay related to the control sampling period \([l]\).

There are several properties of eq. 4.2:

1. The leading coefficient of \( A(z^{-1}) \), i.e., \( a_0 \), is 1 [6].
2. If the system order (degree of \( A(s) \)) is \( n \), the order of \( A(z^{-1}) \) is also \( n \) [6].

So, eq. 4.2 can be rearranged as follows:

\[
Y^*(z) = \frac{B(z^{-1}) z^H}{A(z^{-1})} \quad U^*(z)
\]

In such a discrete-time expression, the definition of \( Y^*(z) \) is:

\[
Y^*(z) = \sum_{n=0}^{N} Y(nT) z^{-n}
\]
It has the further property [7] that
\[ Y_{n-1} = z^{-1} \{ z^{-1} Y^*(z) \} \]  
\[ 4.5 \]
Eq. 4.4 can be expressed in the form of a finite difference equation:
\[ Y_n + a_1 \cdot Y_{n-1} + a_2 \cdot Y_{n-2} + \cdots + a_k \cdot Y_{n-k} \]
\[ = b_1 \cdot u_{n-H-1} + \cdots + b_k \cdot u_{n-H-k} \]  
\[ 4.6 \]
This is the general form of k-th order model with the lag equal to H times the sampling period for discrete-time system [8].

For the sake of convenience, eq. 4.6 can be rewritten as:
\[ Y_n = a_1 \cdot Y_{n-1} + a_2 \cdot Y_{n-2} + \cdots + a_k \cdot Y_{n-k} \]
\[ + b_1 \cdot u_{n-H-1} + \cdots + b_k \cdot u_{n-H-k} \]  
\[ 4.7 \]
The only difference between eq. 4.6 and eq. 4.7 is that the signs of \( a_1, a_2, \ldots, a_k \) in eq. 4.7 are opposite to those in eq. 4.6.

Based on this general expression, after values of \( k, a_1, a_2, \ldots, b_1, b_2, \ldots \) are estimated, the process dynamics can be studied. There are several mathematical tools to estimate these values after a reasonable number of sets of \( Y_n \) and \( u_n \) are available.

In real processes, some noise occurs. This noise affects the model which is estimated based on the input and output data. No matter where this noise comes from,
the process dynamics can be represented by:

\[ Y_n = \varphi_n \cdot \hat{\theta} + v(n) \quad 4.8 \]

where \( v(n) \) is the term relating the influence of the noise,

\[ \hat{\theta} = [ \hat{a}_1, \hat{a}_2, \ldots, \hat{a}_k, \hat{b}_1, \hat{b}_2, \ldots, \hat{b}_k ]^T \]

\[ \varphi_n = [ Y_{n-1}, Y_{n-2}, \ldots, Y_{n-k}, u_{n-H-1}, \ldots, u_{n-H-k} ] \]

In eq. 4.8, \((\varphi_n \cdot \hat{\theta})\) is the deterministic term and \(v(n)\) is the stochastic term of the process analysis [6], [8], [9].

Omitting the stochastic term, the process model found from any estimation can be represented as:

\[ Y_n = \varphi_n \cdot \hat{\theta} \quad 4.9 \]

where

\[ \hat{\theta} = [ a_1, a_2, \ldots, b_1, b_2, \ldots ]^T \]

Theoretically, if \( \hat{\theta} = \hat{\theta} \), the control error only comes from the omitted noise. But the noise does have an influence on the estimation of parameters of the process model. As a whole, there are two sources of errors involved in the adaptive control system: one is from the model estimation and the other from the noise. Fortunately, if the ratio of the influence of noise to the process gain is less than 0.1, it is safe to ignore the noise [2].
4.2 Regulator Problem

In this type of application, the controlled system is no more an SISO system. Load changes have to be taken into consideration in eq. 4.7. The modification of eq. 4.7 is as follows:

\[
Y_n = a_1 \cdot Y_{n-1} + a_2 \cdot Y_{n-2} + \ldots + a_k \cdot Y_{n-k} \\
+ b_1 \cdot u_{n-H-1} + \ldots + b_k \cdot u_{n-H-k} \\
+ c_1 \cdot w_{n-G-1} + \ldots + c_k \cdot w_{n-G-k}
\]

where \( w \) is the load change variable. Similarly, eq. 4.10 can be expressed in the same form as eq. 4.9 except that:

\[
\Omega_n = \\
[Y_{n-1}, \ldots, Y_{n-k}, u_{n-H-1}, \ldots, u_{n-H-k}, w_{n-G-1}, \ldots, w_{n-G-k}]
\]

\[
\delta = [a_1, \ldots, a_k, b_1, \ldots, b_k, c_1, \ldots, c_k]^{T}
\]

When there is no load change in the process, i.e., \( w_i = 0 \), eq. 4.10 is the same as eq. 4.7.

It should be kept in mind that the parameters of eq. 4.7 and eq. 4.10 are dependent on the operating conditions. They will converge to one set of values as the state and operating variables become constant.

In this thesis, the Recursive-Least-Square (RLS) method has been used to estimate parameters of the
process model. Furthermore, two control laws, one-step-ahead and two-step-ahead controls, are introduced.
CHAPTER FIVE

CONTROL ALGORITHM

The adaptive control algorithm is composed of two parts: recursive process model identification and adjustment of parameters in the control law.

5.1 Recursive Process Model Identification

In regression analysis, the process dynamics can be represented as follows:

\[ y_n = a_1 \cdot y_{n-1} + a_2 \cdot y_{n-2} + \ldots + a_k \cdot y_{n-k} \]
\[ + b_1 \cdot u_{n-H-1} + \ldots + b_k \cdot u_{n-H-k} \]
\[ + c_1 \cdot w_{n-G} + \ldots + c_k \cdot w_{n-G-k} \]
\[ + v_n \]

where \( y \) is the output or the state variable, \( u \) is the input or the manipulated variable, \( w \) is the load variable, and \( v_n \) is the noise.

After \( N \) observations are made, where \( N > k \), the collection of data from sampling times through \( N \) can be expressed as:

\[ y_N = x_N \cdot \hat{\delta} + v_N \]
where $Y_N = [Y_N, Y_{N-1}, \ldots Y_1]^T$

$\hat{\delta} = [a_1, \ldots, a_k, b_1, \ldots, b_k, c_1, \ldots, c_k]^T$

$X_N = [\phi_N \phi_{N-1} \phi_{N-2} \ldots \phi_1]^T \quad (N \times 2k)$

The observation (output) is hypothesized to be a linear combination of some known data, such as previous information of state variables, manipulated variables (input) and load variables.

The procedure of identification is to find out one set of parameters which minimizes the loss-function (LF) [1]. That is,

$$\hat{\delta} = \arg \lim_{\delta} LF(Y_N - \hat{Y}_N) \quad 5.3$$

where $Y_N$ is the true process response.

In this thesis, the least-square method has been used. The loss-function is defined as:

$$LF(Y_N - \hat{Y}_N) = \hat{\delta}^T N (Y_1 - \hat{Y}_1)^2 \quad 5.4$$

The relationship between the most current estimated parameters and the input and output information is [1], [10], [11], [12].

$$Y_N = X_N \cdot \hat{\delta} \quad 5.5$$

where $N > n$. 

The vector $\hat{\theta}$ in eq. 5.5 can be further derived as:

$$\hat{\theta} = (X_N' \cdot X_N)^{-1} \cdot X_N' \cdot Y_N \quad 5.6$$

$$= \hat{\theta} + (X_N' \cdot X_N)^{-1} \cdot X_N' \cdot V_N \quad 5.7$$

Assuming that the noise is random, i.e., $V_N$ is an uncorrelated sequence, and the mean of $V_N$ is zero, the estimates are unbiased [1]. It has been shown that the least-square estimate has a minimal variance compared with all other linear unbiased estimates [21]. The accuracy of the least-square estimate can be derived from eq. 5.7.

$$E(\hat{\theta} - \hat{\theta}) \cdot (\hat{\theta} - \hat{\theta})' = (X_N' X_N)^{-1} \cdot m^2 \quad 5.8$$

where $m^2$ is the variance of the zero-mean noise.

The shortcoming of eq. 5.6 and eq. 5.7 is that they are only suitable for batch processing. Such equations might serve for off-line analysis but not for on-line identification. The reason they are not suitable is that the amount of data storage and computation increases with the passage of time. This is obviously undesirable and unnecessary. Identification by recursive means does not have these shortcomings.

The form of the equation for recursive means is [1],[6],[13],[14],[15]:

$$\text{New \ estimate} = \text{Old \ estimate} + \text{(Gain) \times \ (old \ model)}$$

$$5.9$$

Eq. 5.9 shows that the recursive identification can be characterized by two parts: one is the adaptive gain
which acts as the integral portion; the other is the error of the old model which acts as the fractional portion in the algorithm of reformulation [5].

For sampling period $N + 1$ eq. 5.5 can be expressed as:

$$
\begin{bmatrix}
Y_{N+1} \\
Y_N
\end{bmatrix} = \begin{bmatrix}
\varphi_{N+1} \\
X_N
\end{bmatrix} \delta + \begin{bmatrix}
\nu_{N+1} \\
\nu_N
\end{bmatrix} \tag{5.10}
$$

where $Y_{N+1}$ and $\nu_{N+1}$ are the values of output and noise at time $N+1$, and

$$\varphi_{N+1} = [Y_N, \cdots Y_{N-k+1}, u_{N-H}, \cdots u_{N-H-k+1}, w_{N-G}, \cdots w_{N-G-k+1}]$$

In addition, from the definition of $X_N$, $(X'_{N+1} X_{N+1})$ can be recursively derived as:

$$X'_{N+1} \cdot X_{N+1} = X'_{N} \cdot X_{N} + \varphi'_{N+1} \cdot \varphi_{N+1} \tag{5.11}$$

The current $\delta$ can be estimated by the following recursive procedure.

$$\delta(N+1) = (X'_{N+1} X_{N+1})^{-1} \begin{bmatrix}
X'_{N+1} \\
X_{N+1}
\end{bmatrix}^{-1} \begin{bmatrix}
X'_{N+1} \\
X_{N+1}
\end{bmatrix} (X'_{N} X_{N} + \varphi'_{N+1} \cdot \varphi_{N+1} Y_{N+1} + Y_{N+1} \cdot \varphi'_{N+1} \cdot \varphi_{N+1} \cdot \delta(N)) \tag{5.12}$$
Eq. 5.12 is still not immediately useful because the inverse matrix, \((X'NX_N)^{-1}\), is involved in this recursive equation. A modification of eq. 5.12 can be obtained by defining \((X'NX_N)^{-1}\) as:

\[
P(N) = (X'NX_N)^{-1}
\]

The relation for \(\delta(N+1)\) can be expressed as follows:

\[
\delta(N+1) = \delta(N) + K(N+1)e(N+1)
\]

where \(e(N+1)\) is the estimation error of the previous model, i.e.,

\[
e(N+1) = Y_{N+1} - \varphi_{N+1}\delta(N)
\]

\(K(N+1)\) is the adaptive gain, and \(K(N+1)\) and \(P(N+1)\) are given as [1],[10],[12],[16],[17]:

\[
P(N) \varphi'_{N+1} \]

\[
K(N+1) = \frac{P(N) \varphi'_{N+1}}{1 + \varphi_{N+1} P(N) \varphi'_{N+1}}
\]

\[
P(N+1) = (I - K(N+1) \varphi_{N+1}) P(N)
\]

It must be pointed out that \((X'NX_N)^{-1}\) exists only after \(k\) times the sampling period. It is convenient to initialize this procedure by an appropriate choice of \(P(0)\). Typically, \(P(0)\) is taken to be a diagonal matrix \(\bar{a}I\) where \(\bar{a}\) is a scale factor. A large \(\bar{a}\) implies little confidence in \(\delta(0)\) and causes rapid initial changes in \(\delta\); on the contrary, a small \(\bar{a}\) implies that \(\delta(0)\) is reasonable and \(\delta\) changes slowly [1].

According to eq. 5.16 and eq. 5.17, if the set
point change is sufficient, the values of norm $\| K \|$ and norm $\| P \|$ tend to zero and $\delta$ approaches a constant vector. The above situation is acceptable only when the values of the "true" dynamics parameters are constant. In practice the adaptation tries to track the slow-varying parameters. The most popular modification for the purpose of handling time-varying processes is the use of a "forgetting factor", $\beta$ [1], where $0 < \beta \leq 1$. This factor is introduced into the loss-function as:

$$\text{LF} = \sum_{i=1}^{N} \beta^{N-i} e^2(i)$$  \hspace{1cm} 5.18

And, the definition of $P(N)$ becomes:

$$P(N) = (X'_N [\beta]_N X_N)^{-1}$$  \hspace{1cm} 5.19

where $[\beta]_N$ is the weighted matrix.

$$[\beta]_N = \begin{bmatrix}
1 & 0 & 0 & 0 & \cdots \\
0 & \beta & 0 & 0 & \cdots \\
0 & 0 & \beta^2 & 0 & \cdots \\
\vdots & \vdots & \vdots & \vdots & \ddots \\
0 & 0 & 0 & 0 & \beta^{N-1}
\end{bmatrix} \quad (N \times N)$$

When eq. 5.4 is replaced by eq. 5.18, eqs. 5.16 and 5.17 become:

$$K(N+1) = \frac{P(N) \phi'_N}{\beta + \phi_{N+1} P(N) \phi'_N}$$  \hspace{1cm} 5.20

$$P(N+1) = (I - K(N+1) \phi_{N+1}) P(N)/\beta$$  \hspace{1cm} 5.21

In this case, $\| P \|$ and $\| K \|$ do not tend to zero, so $\delta$ can vary when $N$ is large. Although $\delta$ is
affected by all previous data, the value of $\beta$ indicates the amount of data which is dominant in the current identification. This amount is referred to as the "asymptotic sampled length" \[l]. The relationship between the asymptotic sampled length (ASL) and $\beta$ is:

$$\text{ASL} \approx \frac{1}{1 - \beta}$$  \hspace{1cm} 5.22

Typically, the value of $\beta$ is within the range of 0.95 (fast time-varying) to 0.999 (slow); the corresponding value of the ASL are 20 to 1000 times the sampling period \[l].

The recursive procedure for the new estimate is as follows:

1. Obtain the current $\phi$ vector.
2. Determine the $K(N+1)$ vector using the previous $P(N)$, eq.5.16 or eq.5.20.
3. Determine the error, $e(N+1)$, from eq.5.15.
4. Make a new estimate of $\hat{\phi}$, using eq.5.14.
5. Determine the $P(N+1)$ matrix, using eq.5.17 or eq.5.21.
6. Prepare to obtain the $\phi$ vector at the next sampling time.

5.2 Control Laws

Two control laws, one-step-ahead control and two-step-ahead control, were used. The following
derivations are all based on the assumption that there is no time delay in the system.

5.2.1 One-step-ahead control [6]:

This is an intuitive strategy. It attempts to maintain the state variable at the set point at each sampling period.

\[ u_n = \arg(Y_{n+1} = Y_{sp}) \]

After the parameters of the process model are available, eq. 4.7 or eq. 4.10 is specified. This control law becomes:

\[ u_n = \frac{1}{b_1} \left( Y_{sp} - (a_1 Y_n + a_2 Y_{n-1} + \ldots + a_k Y_{n-k} + b_2 u_{n-1} + \ldots + b_k u_{n-k} + c_1 w_n + \ldots + c_k w_{n-k}) \right) \]

It has the characteristics of a deadbeat (or minimal prototype) control. Theoretically, the error is zero at every sampling instant.

5.2.2 Two-step-ahead control:

This is a modification of the above strategy.
The control action is designed to force the state variable to the set point in two sampling periods. That is,

\[ u_n = \arg( Y_{n+2} = Y_{sp} : u_{n+1} = u_n ) \]  

Similarly, the control law is derived as:

\[
\begin{align*}
  u_n &= \left( \frac{1}{(a_1 b_1 + b_1 + b_2)} \right) (Y_{sp} - \\
  &\quad \left[ a_1 Y_n + a_2 Y_{n-1} + \cdots + a_k Y_{n-k+1} \\
  &\quad + b_2 u_{n-1} + \cdots + b_k u_{n-k+1} + c_1 w_n + \cdots \\
  &\quad + c_k w_{n-k+1}) \right] + a_2 Y_n + \cdots + a_k Y_{n-k+2} \\
  &\quad + b_3 u_{n-2} + \cdots + b_k u_{n-k+2} + c_1 w_{n+1} + \cdots \\
  &\quad + c_k w_{n-k+2})
\end{align*}
\]
This chapter describes the sequence of computer commands used in the control algorithm. The algorithm is written in BASIC.

The functions required for an adaptive control system should include capabilities for timing, error calculation, process identification, controller parameter tuning, and input variable calculation. For this experiment, the program for the adaptive controller (shown in Appendix B) is composed of the following parts:

1. Main program
2. Subroutine for determining the initial model
3. Subroutine for timing
4. Subroutine for retrieving data from A/D converter
5. Subroutine for identification
6. Subroutine for input variable correction
7. Subroutine for releasing data to D/A converter

These routines will be described individually.
6.1 Main Program

The main program starts with the input of indicators specifying the type of controller. Next, the normal operating conditions (initial steady state) are established. Then the process model order, the sampling period, the set point and the load change are specified. The normal pressure to the control valve has to be within the range of 4.7 - 14.1 psig. After reaching the steady state of the normal operating conditions, the control action starts. A simple flow chart is shown in Fig. 8.

Lines 200 to 430 in Appendix B are the main program.

6.2 Subroutine for Determining the Initial Model

Data relating the open-loop response are analyzed to estimate the parameters of the initial model. This assumed model is only used for the first two sampling periods. Different model orders and different sampling periods chosen by the user will create different models.

Subroutine 1500 is designed to determine the initial model (App. B).
6.3 Subroutine for Timing

The binary program for the dual thermistor, THERM, supplies data to measure the elapsed time as well as temperature. The data are stored in a memory at address TM + T10, where TM and T10 are defined in the dual thermistor operator's manual [18]. The error of this timer is less than 7 seconds in every 64 seconds.

Subroutines 2100 and 2200 are designed to be the timers in the program (App. B).

6.4 Subroutine for Retrieving Data from the A/D Converter

This subroutine contains many variables which are defined by the dual thermistor manual [18]. The binary program, THERM, is used to measure the temperature. The instruction POKE TM + T7 is used to interrupt the action of this binary program, and POKE TM + T8 is used to return control.

Subroutine 2000 is designed to measure the temperature (App. B).

6.5 Subroutine for Identification

This subroutine uses the RLS method. It contains
two parts: the first is used to calculate the estimation error of the previous model; the second is used to estimate the current model following the recursive procedure.

Due to insufficient data, identification cannot proceed on the first two sampling times. The model from the open-loop analysis is introduced initially.

Subroutine 3500 is designed to complete the identification (App. B).

6.6 Subroutine for Input Variable Correction

Through subroutine D, the temperature is measured at every sampling instance. Based on the model estimated by identification, the parameters of the control law are calculated for a specific control strategy, as are the input variables (pressure into the control valve).

There are two control strategies in this subroutine: one-step-ahead control and two-step-ahead control. The control law for each case is described as follows:

(1) One-step-ahead control:
First order model:

\[ u_n = (y_{sp} - a_1 y_n - c_1 w_n)/b_1 \] 6.1
Second order model:
\[ u_n = (y_{sp} - a_1y_n - a_2y_{n-1} - b_2u_{n-1} - c_1w_n - c_2w_{n-1})/b_1 \]  

(2) Two-step-ahead control:
First order model:
\[ u_n = [y_{sp} - a_1^2y_n - (a_1c_1 + c_1)w_n] / (a_1b_1 + b_1) \]  

Second order model:
\[ u_n = [y_{sp} - (a_1^2 + a_2)y_n + a_1a_2y_{n-1} + a_1b_2u_{n-1} + (c_1^2 + a_1c_1)w_n + a_1c_2w_{n-1}] \times [1 / (a_1b_1 + b_1 + b_2)] \]

Subroutine 9000 is designed to calculate the control input variable (App. B).

6.7 Subroutine for Releasing Data to the D/A Converter

After the required input variable is calculated, it has to be converted to a digital number within the range of 0 to 255 in an 8-bit computer in order to be accepted by the D/A converter. This range is equivalent to 00000000 to 11111111 in the binary system. Using a D/A converter and an electropneumatic transducer, this digital value is first converted to a voltage between 0.7 to 25.3 mv and then to a pressure between 4.7 to 14.1 psig. The instruction "POKE-16176, a" is used to
send the digital signal to the D/A converter in order to create an equivalent analog signal, where the variable \( a \) is any integer within the range of 0 to 255.

It must be noticed that while the input variable may theoretically be very large or very small, the opening of the control valve is constrained. In this system, when the pressure is greater than 14.1 psig, it will be regarded as 14.1 psig. And, when it is less than 4.7 psig, it will be regarded as 4.7 psig.

Subroutine 450 is designed to transmit the required input variable through an equivalent digital number (App. B).
CHAPTER SEVEN

EXPERIMENTAL

The control system used for this thesis includes a steam-jacketed kettle, an Apple IIe personal computer with accessories (A/D and D/A converters), an electropneumatic transducer and a control valve for steam.

7.1 The Jacketed Kettle

The kettle is made of stainless steel. The inside vessel is surrounded by a stainless steel jacket covered with insulation material to avoid heat loss. The relationship between the volume and the height of the kettle is shown in Fig. 4. The inlet water flows into the kettle at the top side and flows out at the bottom center. This kettle is assumed to be a continuous-flow stirred-tank reactor (CSTR). The low-pressure steam flows into the jacket from the utility steam system, and the condensate leaves from the bottom of the jacket (Appendix C).
7.2 The Computer and Accessories [19]

7.2.1 The Computer

An Apple IIe personal computer system is used as the controller and identifier in this experiment. This computer has 48k of RAM (random access read-write memory). It is equipped with an interface bus which controls several peripherals including one disk drive, one monitor, one printer, one thermistor and one digital-to-analog converter.

7.2.2 Interface bus

There are eight peripheral connectors located at the rear of the main circuit board (mother board). Via these eight connectors, the Apple computer can communicate with external accessories. These eight connectors are referred to as slots 0 to 7.

Each slot is an individual I/O connector with 50 pins. A typical pinout of the I/O slot is shown in Fig. 5. An 8-bit digital circuit provides communication between each slot and the mother board. By inserting a specific vector card as an interface at any slot, the Apple computer can retrieve data from and send data to processes. Using software, the action of some of
the devices connected to the computer system can be controlled.

It is important to point out that every slot has 16 addresses, which makes it possible to input or output data. The BASIC instructions, PEEK and POKE, are used to input and output data through a specific slot.

Four slots are assigned for specific usage:

Slot 1 is for the printer.
Slot 7 is for the disk drive.
Slot 2 is for the thermistor.
Slot 5 is for the D/A converter.

7.2.3 Thermistor and A/D converter

A dual thermistor, manufactured by Omega, was used to measure temperature. This interface is composed of two individual parts; an ADC and a timer. Together they convert the resistance of the precision thermistors to time. The resistance to time conversion technique is the main principle for the temperature measurement [18].

The dual thermistor can be plugged into any slot of the Apple computer. In these experiments, it was in slot 2. The accuracy of the thermistor, from -20°C to 60°C, is within 0.4°C.

The dual thermistor software consists of two Apple BASIC programs and one binary program called
THERM. THERM is in the form of a machine language at a lower level than the control program written in Apple BASIC. There are two instructions, CALL TM+T8 and CALL TM+T7, to communicate between THERM and the control program.

7.2.4 D/A Converter (DAC) [20]

A simple D/A converter, shown in Fig. 6, was used for this thesis. The DAC is the AD558KD manufactured by Analog Devices. It has 8-bit voltage switching and a D-to-A converter. Detailed information on this device is given in [20]. This device makes it possible to convert a number to a voltage.

The AD558KD generates an output voltage between 0.6 mv to 25.3 mv. This range of voltage was chosen to match the specification of the downstream electro-pneumatic transducer. The relationship between the digital number and the pressure to the control valve is linear. When the digital number is equal to 0, then the output voltage is 0.7 mv and the pressure is 4.7 psig; when the digital number is equal to 255, then the output voltage is 25.3 mv and the pressure is 14.1 psig. The linear relation between the pressure and the output voltage is:

\[ PR = 0.0375 \times NUM + 4.625 \]
where PR is the pressure to the control valve, and NUM is a digital number between 0 and 255.

7.3 Electropneumatic Transducer

A Moore E/P 7714C transducer was used in this experiment. The available input voltage is from 0 mv through 25 mv. The signal is changed to 4 to 20 milliamps within the inside amplifier and then to a 3 to 15 psig output pressure. The electrical supply voltage is 117 volts, 50/60 Hz. The actual output pressure is from 4.7 to 14.1 psig in this experiment.

7.4 The Control Valve

The final control element is a control valve (POWERS W 3591 - 6280). The input pressure to the control valve is from 3 psig to 15 psig.

The relationship of the stem position and the valve position is linear (Fig. 7). For example, with 3 psig of pressure, the valve is closed; with 9 psig, the valve is half open; with 15 psig, the valve is fully open.

7.5 Materials

Water, steam and air are used in this experiment.
Steam is the heat source. Air is used for the pneumatic control valve.

7.6 Implementation

Because high-pressure steam is not available for this experiment, low-pressure steam from the utility system is used as the heat source. The pressure is less than 2 psig and variable. This makes the characteristics of the steam flowrate quite nonlinear. Additionally, the water flowrate and the temperature are not constant. These phenomena make the system time-varying. And, under these circumstances, the performance of adaptive control is much clearer when compared to that of a traditional controller with fixed parameters.

7.6.1 Experiment for the servo problem

At the beginning of this control experiment, the open-loop responses for a set point change and a water level change were observed (Fig. 9, 10 and 11). In this case, the influence of a disturbance in the water level on the control of the water temperature was not significant. After the open-loop response was studied, the values of $\hat{a}$ and $\hat{b}$ were chosen as 1000 and 0.95.
After modifying the parameters estimated from Cohen-Coon tuning method [23], the proportional gain, the integral time constant and the derivative time constant of the PID controller were specified as 2, 1.8 and 0.45 respectively.

Because of the restrictions of the computer used in this experiment, the minimum sampling period is one minute and the maximum process order is two. Since the sampling time is considerably larger than the time lag of this process, the time delay model is not discussed in this thesis.

Control responses for different set point changes and operating conditions were studied. For each case, the influences of the sampling period, process order and control strategy were observed.

A detailed description of the experiments follows:

I. Set point change from 28°C to 41°C at 0.7 GPM water flowrate
   A. Open-loop response Fig. 12
   B. Fixed model response Fig. 13
      This model is constructed from the open-loop response.
   C. PID control Fig. 14
   D. Adaptive control
      1. Control strategy: one-step-ahead
         Sampling period: 1 min Fig. 15
         Process model order: 2
2. Control strategy: two-step-ahead
Sampling period: 1 min
Process model order: 1
Fig. 16

3. Control strategy: two-step-ahead
Sampling period: 1 min
Process model order: 2
Fig. 17

4. Control strategy: two-step-ahead
Sampling period: 2 min
Process model order: 2
Fig. 18

II. Set point change from 41°C to 35°C at 0.7 GPM water flowrate
A. PID control
Fig. 19
B. Adaptive control

1. Control strategy: two-step-ahead
Sampling period: 1 min
Process model order: 2
Fig. 20

2. Control strategy: two-step-ahead
Sampling period: 1 min
Process model order: 1
Fig. 21

3. Control strategy: one-step-ahead
Sampling period: 1 min
Process model order: 2
Fig. 22

III. Set point change from 22°C to 28°C at 1.5 GPM water flowrate
A. Open-loop response
Fig. 23
B. PID control
Fig. 24
C. Adaptive control

1. Control strategy: one-step-ahead
Sampling period: 1 min
Process model order: 2
Fig. 25

2. Control strategy: two-step-ahead
Sampling period: 1 min
Process model order: 2
Fig. 26
IV. Set point change from 28°C to 35°C and then from 35°C to 41°C at 0.7 GPM flowrate

A. PID control

B. Adaptive control

1. Control strategy: two-step-ahead
   Sampling period: 1 min
   Process model order: 2

The convergence diagrams of runs I.D.4. and I.D.3. are shown in Figs. 28 and 29. The responses of the manipulated variable in runs I.D.3., I.D.1. and I.D.2. are shown in Figs. 30, 31 and 32 respectively.

7.6.2 Experiment for the regulator problem

The inlet water flowrate was selected to be changed for an example of this type of control problem. Using the procedure in 7.6.1, the open-loop response was observed first. Also, the performance of adaptive control was compared to that of PID control.

The load change in the inlet water flowrate was from 0.7 GPM to 1.5 GPM. The set point remains the same and is the initial temperature of each run.

A list of figures for this experiment follows:

V. Load change of water flowrate from 0.7 GPM to 1.5 GPM
A. Open-loop response

B. PID control

C. Adaptive Control

1. Control strategy: two-step-ahead
   Sampling period: 1 min
   Process model order: 2

2. Control strategy: one-step-ahead
   Sampling period: 1 min
   Process model order: 2

Fig. 33

Fig. 34

Fig. 35

Fig. 36
8.1 Results:

The response time and variance are used to evaluate the control performances of the adaptive controller and PID controller. The response time is the time needed for a controller to maintain the controlled variable within a range around the set point where this range is defined as 5 percent of the difference between the initial value and the final value [23]. On the other hand, for the experiments of the regulator problem, this range is defined as 5 percent of the difference between the final value and the maximum deviation. The mean is the arithmetic average of the state variables after the response time, i.e.,

\[
\text{Mean} = \frac{1}{N - \text{Tr}/T + 1} \sum_{i=\text{Tr}/T}^{N} y(i)
\]

And the variance is defined as:

\[
\text{Variance} = \frac{1}{N - \text{Tr}/T + 1} \sum_{i=\text{Tr}/T}^{N} (y(i) - \text{Ysp})^2
\]

where \(\text{Ysp}\) is the set point.
The response time, the mean and the variance of each run are in the following table.

<table>
<thead>
<tr>
<th>Run Strategy</th>
<th>Model</th>
<th>Sampling Period</th>
<th>Set Point °C</th>
<th>Response Time Min.</th>
<th>Mean °C</th>
<th>Variance °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.B. Fixed*</td>
<td>2</td>
<td>1</td>
<td>41.</td>
<td>7.</td>
<td>39.85</td>
<td>1.36</td>
</tr>
<tr>
<td>I.C. PID†</td>
<td>n/a</td>
<td>1</td>
<td>41.</td>
<td>20.</td>
<td>40.97</td>
<td>.117</td>
</tr>
<tr>
<td>I.D.1.</td>
<td>1x</td>
<td>2</td>
<td>41.</td>
<td>8.</td>
<td>40.85</td>
<td>.312</td>
</tr>
<tr>
<td>I.D.2.</td>
<td>2@</td>
<td>1</td>
<td>41.</td>
<td>15.</td>
<td>40.68</td>
<td>.156</td>
</tr>
<tr>
<td>I.D.3.</td>
<td>2</td>
<td>2</td>
<td>41.</td>
<td>9.</td>
<td>40.98</td>
<td>.011</td>
</tr>
<tr>
<td>I.D.4.</td>
<td>2</td>
<td>2</td>
<td>41.</td>
<td>12.</td>
<td>41.09</td>
<td>.143</td>
</tr>
<tr>
<td>II.A. PID</td>
<td>n/a</td>
<td>1</td>
<td>35.</td>
<td>8.</td>
<td>34.98</td>
<td>.1145</td>
</tr>
<tr>
<td>II.B.1.</td>
<td>2</td>
<td>2</td>
<td>35.</td>
<td>7.</td>
<td>34.91</td>
<td>.017</td>
</tr>
<tr>
<td>II.B.2.</td>
<td>2</td>
<td>1</td>
<td>35.</td>
<td>9.</td>
<td>35.15</td>
<td>.099</td>
</tr>
<tr>
<td>II.B.3.</td>
<td>1</td>
<td>2</td>
<td>35.</td>
<td>7.</td>
<td>35.11</td>
<td>.102</td>
</tr>
<tr>
<td>III.B. PID</td>
<td>n/a</td>
<td>1</td>
<td>28.</td>
<td>8.</td>
<td>28.01</td>
<td>.029</td>
</tr>
<tr>
<td>III.C.1.</td>
<td>1</td>
<td>2</td>
<td>28.</td>
<td>6.</td>
<td>27.99</td>
<td>.038</td>
</tr>
<tr>
<td>III.C.2.</td>
<td>2</td>
<td>2</td>
<td>28.</td>
<td>10.</td>
<td>28.14</td>
<td>.027</td>
</tr>
</tbody>
</table>

* : fixed model control  + : PID control
x : one-step-ahead control  @ : two-step-ahead control
Table 8.2 Results of Experiment for Regulator Problem

<table>
<thead>
<tr>
<th>Control Strategy</th>
<th>Model Order</th>
<th>Sampling Period</th>
<th>Set Point Min. °C</th>
<th>Response Time Min. °C</th>
<th>Mean Variance °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>V.B. PID</td>
<td>n/a</td>
<td>1</td>
<td>29.13</td>
<td>27.06</td>
<td>0.013</td>
</tr>
<tr>
<td>V.C.1.</td>
<td>2</td>
<td>2</td>
<td>29.29</td>
<td>10.32</td>
<td>0.005</td>
</tr>
<tr>
<td>V.C.2.</td>
<td>1</td>
<td>2</td>
<td>29.61</td>
<td>8.23</td>
<td>0.021</td>
</tr>
</tbody>
</table>

8.2 Discussion:

1. From the open-loop responses of set point changes in Fig. 10, it is obvious that the control system has a small time delay. The lag is not constant and varies according to the operating conditions.

2. In Fig. 12, two open-loop responses are shown which have the same operating conditions. The responses were not exactly the same. This difference indicates that this system is time-varying. It is also seen that there was some disturbance from the inlet water flowrate and temperature and from the steam pressure.

3. From the result of experiment I.B. (Fig. 13), it seems that the estimated second order model, which was established from an open-loop analysis, cannot be used
to represent the process dynamics at the operating condition of the open-loop response.

4. The response time and variance is smaller for the second order model than for the first order model (Table 8.1). The lower variance indicates that the response is much smoother. This can be seen by comparing Figs. 16 and 17 and also Figs. 21 and 22.

5. A comparison of Figs. 30 and 32 shows that the response of the manipulated variable in the adaptive control with a second order model converges faster than that with a first order. This comparison also indicates that the control performance of the adaptive controller with a first order model was less stable than that with a second order.

6. The dynamics of the control system could not be exactly derived because this system was time-varying and nonstationary. Based on Points 4 and 5, it can be seen that a second order model yields a more accurate simulation of the control system model than a first order model.
7. Referring to Table 8.1, the response time and variance of run I.D.3 are lower than those of run I.D.4. This indicates that the performance of the digital controller was more stable when the sampling period was one minute than when it was two minutes (Figs. 17 and 18). This comparison coincides with the discrete-time theory [2].

8. Because of the fractional delay in this system, one of the poles of $B(z^{-1})$ is outside the unit circle on the $Z$-plane, i.e., $b_1 < b_2$ for the second order model (Fig. 29). This signifies that the manipulated system is not stable [22]. In this case, the response of the manipulated variable using one-step-ahead control strategy will not converge (Fig. 31). In contrast, the response of the manipulated variable converged when the two-step-ahead control was used (Fig. 30).

9. The response time and variance of the control response were lower when the two-step-ahead control strategy was used than they were when the one-step-ahead was used (Table 8.1). This suggests that the performance of an adaptive controller with a two-step-ahead control strategy is more stable than with a one-step-ahead control strategy (Figs. 15 and 17 and also Figs. 20 and 22).
10. The estimated model may be quite inaccurate in the first few sampling instances. This inaccuracy may be caused by the order of the assumed model being different from that of real process dynamics and/or by noise being involved in the system. There is too little data collected at the beginning of the control response to identify the nature of the process dynamics (Figs. 10 and 26). However, the estimated parameters converged very fast immediately after the rise time (Figs. 28 and 29). This made the overshoot of the adaptive controller relatively small compared to that of the PID controller.

11. From Figs. 28 and 29, the parameters of polynomial A, i.e., $a_i$, are roughly the same as those constructed from the open-loop response. But this was not the case for polynomial B. This indicates that the process characteristics did not change significantly, while the manipulated characteristics greatly varied under different operating conditions.

12. In the experiments for control with a load change, no major difference was found between the control performance of the two control strategies introduced in this thesis (Figs. 35 and 36). The response time was shorter when the one-step-ahead control strategy was used (table 8.2). However, the two-step-ahead control
strategy is still preferred in this system because of its lower variance.

13. The response time of PID control is significantly longer than that of adaptive control in the load change experiment (Table 8.2). This may be due to major improper parameter selection; in fact, this is the shortcoming of the PID controller. The reason for this phenomenon is that if the load change (or disturbance) can be predicted (or measured), the manipulated variable can be adjusted forward in the adaptive control, but not in the PID control. This is the major advantage of the adaptive control system.
CHAPTER NINE

CONCLUSIONS

1. Adaptive control was tested for the temperature control of a steam-jacketed kettle and was found to give more precise control than PID control.

2. A second order model was adequate to represent the process dynamics under local operating conditions.

3. One-step-ahead control, an example of adaptive deadbeat control algorithm, was not suitable for this system. Two-step-ahead control, a modified control version of one-step-ahead control, gave better results.

4. A one-minute sampling period was short enough to produce a satisfactory representation of the process dynamics.

5. The combination of the two-step-ahead control strategy, the second order model and a one-minute sampling period was determined to give the most precise and flexible control for this steam-jacketed kettle.
The mark "^" on the top of variable means that this variable concerns the true process dynamics. The subscript "'" means the transpose of matrix.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A(s)</td>
<td>A polynomial in the s-domain</td>
</tr>
<tr>
<td>B(s)</td>
<td>A polynomial in the s-domain</td>
</tr>
<tr>
<td>A(z^-1)</td>
<td>A polynomial in the Z-domain</td>
</tr>
<tr>
<td>B(z^-1)</td>
<td>A polynomial in the Z-domain</td>
</tr>
<tr>
<td>a_i</td>
<td>Parameters of the estimated model</td>
</tr>
<tr>
<td>b_i</td>
<td>Parameters of the estimated model</td>
</tr>
<tr>
<td>c_i</td>
<td>Parameters of the load process dynamics</td>
</tr>
<tr>
<td>d</td>
<td>Time delay</td>
</tr>
<tr>
<td>E</td>
<td>Determinant</td>
</tr>
<tr>
<td>e(N)</td>
<td>[e_N, e_{N-1}, \ldots, e_1]^T</td>
</tr>
<tr>
<td>G</td>
<td>The delay of the load process dynamics</td>
</tr>
<tr>
<td>H</td>
<td>The pure delay of the process dynamics</td>
</tr>
<tr>
<td>k</td>
<td>The order of the estimated model</td>
</tr>
<tr>
<td>K(N)</td>
<td>A (2xk)-vector</td>
</tr>
<tr>
<td>L</td>
<td>The fractional delay</td>
</tr>
<tr>
<td>LF</td>
<td>The loss-function</td>
</tr>
<tr>
<td>N</td>
<td>The current sampling instant</td>
</tr>
<tr>
<td>NUM</td>
<td>A digital number</td>
</tr>
<tr>
<td>PR</td>
<td>The pressure (psig) to the control valve</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>( P(N) )</td>
<td>A ((2 \times 2)) matrix</td>
</tr>
<tr>
<td>( s )</td>
<td>The Laplace domain variable</td>
</tr>
<tr>
<td>( T )</td>
<td>The sampling period</td>
</tr>
<tr>
<td>( t )</td>
<td>( i \times T )</td>
</tr>
<tr>
<td>( \bar{U}(s) )</td>
<td>The Laplace transform of ( U(t) )</td>
</tr>
<tr>
<td>( U(t) )</td>
<td>The manipulated, or input, polynomial in the time-domain</td>
</tr>
<tr>
<td>( U^*(n) )</td>
<td>The ( Z )-transform of ( U(t) )</td>
</tr>
<tr>
<td>( u_n )</td>
<td>The value of ( u ) at sampling time ( n )</td>
</tr>
<tr>
<td>( V_N )</td>
<td>A term relating noise, ( N )-vector, ([v_{N,1}, \ldots, v_1]^T)</td>
</tr>
<tr>
<td>( v_n )</td>
<td>The value of ( v ) at sampling time ( n )</td>
</tr>
<tr>
<td>( w_n )</td>
<td>The value of ( w ) at sampling time ( n )</td>
</tr>
<tr>
<td>( X_N )</td>
<td>An ( N \times (2 \times 2) ) matrix, ([\varphi_N, \varphi_{N-1}, \ldots, \varphi_1]^T)</td>
</tr>
<tr>
<td>( Y_N )</td>
<td>An ( N )-vector, ([Y_N, Y_{N-1}, \ldots, Y_1]^T)</td>
</tr>
<tr>
<td>( \bar{Y}(s) )</td>
<td>The Laplace transform of ( Y(t) )</td>
</tr>
<tr>
<td>( Y(t) )</td>
<td>The state, or output, polynomial in time-domain</td>
</tr>
<tr>
<td>( Y^*(n) )</td>
<td>The ( Z )-transform of ( Y(t) )</td>
</tr>
<tr>
<td>( y_n )</td>
<td>The value of ( y ) at sampling time ( n )</td>
</tr>
<tr>
<td>( z^{-1} )</td>
<td>The inverse ( Z )-transform</td>
</tr>
<tr>
<td>( z )</td>
<td>The time shift operator</td>
</tr>
<tr>
<td>( \hat{a} )</td>
<td>The initial gain for the Recursive-Least-Square method</td>
</tr>
<tr>
<td>( \beta )</td>
<td>The forgetting factor</td>
</tr>
<tr>
<td>([\beta] )</td>
<td>The weighted matrix</td>
</tr>
</tbody>
</table>
\[ \delta \]

The vector of estimated parameters, a $(2k)$-vector

\[ \varphi_N \]

\[ [Y_{N-1}, \ldots, Y_{N-k}, u_{N-Nd-1}, \ldots, u_{N-Nd-k}] \]

\[ m^2 \]

The variance of the noise
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APPENDIX A

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APPENDIX B

PROGRAM FOR THE ADAPTIVE CONTROLLER
1  HOME
2  DS = CHR$(4): PRINT DS: "Pr#1"
3  REM
4  REM
5  REM  *************************************************************
6  REM  ***** ADAPTIVE CONTROL  *****
7  REM  *************************************************************
8  REM
9  REM
10  PRINT  "***** PROGRAM FOR ADAPTIVE CONTROLLER  *****"
11  PRINT DS: "Pr#2"
12  OMERB GOTO 9200
13  DIM Y(50), U(50), VX(10), VK(10), Z(10), NA(10), W(50)
14  DIM MP(10, 10), MX(10, 10), MQ(10, 10)
15  T3%(0) = 2
16  TO = 2.99: T7 = 383: T3 = 65536: T8 = 395: TR = 10000
17  TA = 9.37283692E - 4: TB = 2.20813136E - 4: IC = 1.28007163E - 7
18  T1% = 1022
19  T2% = 1: T3% = 3: T5% = 16: T8X% = 238
20  TPX% = 336
21  TM = PEEK (116) / 256 + PEEK (115)
22  TM = 256 * INT (TM / 256) - 1280: HIMEM: TM
23  PRINT DS: "$LOAD THERM.A": TM
24  T = INT (TM / 256): POKE TH% + 1, T: POKE TH%, (TM / 256 - T) * 256
25  CALL TM + T8
26  POKE TM + 1, T3%(0)
27  T = INT ((TM + 502) / 256): POKE I1% + 1, T: POKE I1%, ((TM + 502) / 256 - T) * 256
28  T = PEEK (TM + 10)
29  POKE TM + 9, T
30  CALL TM + TPX%
31  FOR I = 1 TO 1000: NEXT I
32  ALFA = 1000: BETA = .95
33  REM
34  REM  *************************************************************
35  REM  ***** MAIN PROGRAM  *****
36  REM  *************************************************************
37  REM
38  REM
39  CALL TM + T7
40  PRINT "1-STEP-AHEAD (1) OR 2-STEP-AHEAD (2) CONTROL STRATEGY"
41  INPUT CS
42  PRINT "INPUT ORDER OF THE MODEL. 1 OR 2"
43  INPUT KSET
44  PRINT "INPUT THE SAMPLED PERIOD. 1 OR 2 MIN"
45  INPUT SM
46  GO SUB 1500
47  CALL TM + T8
48  GO SUB 1000
49  CALL TM + T7: PRINT DS: "Pr#1"
50  PRINT "INPUT SET TEMPERATURE"
276 INPUT TSP
280 PRINT "INPUT CHANGE IN WATER FLOWRATE"
281 INPUT CW
285 FOR I = 0 TO 50
286 W(I) = CW
287 NEXT I
315 GOSUB 3500
317 CALL TM + T8
318 NT = 0
320 GOSUB 2100
322 TI = 0: GOSUB 2000: G = T: Y(0) = 0
324 PRINT "NT = " : NT, "TEMP = ", T
325 GOSUB 9000
330 GOSUB 450: PRINT "INPUT BEGIN...", RP
340 U(NT) = PR - UI
345 PRINT "Y(" : NT : ") = " : Y(NT), "U(" : NT : ") = " : U(NT)
355 GOSUB 3500: GOSUB 5000
360 NT = NT + 1
370 GOSUB 2100: GOSUB 2000
380 PRINT "NT = ", NT, "TEMP = ", T
390 Y(NT) = T - G
400 GOTO 325
410 PRINT DI="PR#2"
420 CALL TM + T7
430 END : REM *** THE END OF THE CONTROL PROGRAM ***
435 REM
440 REM ********************************************
450 REM ***** RELEASING DATA TO D/A CONVERTER *****
455 REM ********************************************
465 REM
455 IF RP > 14.1 THEN : PP = 14.1: GOTO 475
460 IF RP < 4.7 THEN : PP = 4.7: GOTO 475
470 PP = RP
475 YY = 26.67 : PP = 123.33
480 NUM = INT (YY + 0.5)
490 POKE _16176,NUM
495 PR = 0.0375 * NUM + 4.625
500 RETURN
1000 REM ***** ESTIMATION OF THE INITIAL STEADY STATE *****
1003 CALL TM + T7
1005 PRINT "INPUT INITIAL PRESSURE":
1010 INPUT INITP
1015 CALL TM + T8
1020 IF INITP > 14.1 THEN : INITP = 14.1: GOTO 1040
1030 IF INITP < 5 THEN : INITP = 5: GOTO 1040
1040 YY = 26.67 * INITP - 123.33
1050 NUM = INT (YY + 0.5)
1060 GOSUB 2200
1070 POKE -16176, NUM
1080 UJ = 0.0375 * NUM + 4.625
1160 BFT = 0
1170 TI = 0
1180 GOSUB 2200
1203 IF ABS (T - BFT) < .05 THEN 1210
1205 MT = MT + 1:BFT = T
1207 GOTO 1170
1210 PRINT D$: "PR#1"
1220 PRINT "INITIAL MANIPULATED VARIABLE": UJ: " PSI" 
1224 PRINT D$: "PR#2"
1230 RETURN
1250 REM
1490 REM *****************************************
1500 REM ***** THE FIRST ASSUMED MODEL *****
1505 REM *****************************************
1510 REM
1520 IF KSET = 2 THEN 1550
1525 ZZ(1) = .89542465522(2) = .2416799922(3) = -1.32352448
1527 PRINT D$: "PR#1"
1530 FOR I = 1 TO KSET: PRINT "A(1:" =",ZZ(I),"B(" =",I,"="=.22(KSET + I): ":C(1:" =",.22(2 + KSET + I): NEXT I
1533 PRINT D$: "PR#2"
1535 RETURN
1540 ZZ(1) = .79755952622(2) = .46604724322(3) = -2.49666739: GOTO 1527
1550 REM
1560 IF SM = 2 THEN 1570
1565 ZZ(1) = .969:22(2) = -.094:22(3) = .248:22(4) = .304:22(5) = -.5:22(6) = -1.142: GOTO 1527
1570 ZZ(1) = .820922129:22(2) = -.0573505934:22(3) = .31789475:22(4) = 
1.21415621:22(5) = -1.838:22(6) = -2.558: GOTO 1527
1980 REM
1990 REM *****************************************
2000 REM ***** RETRIEVING DATA FROM A/D CONVERTER *****
2005 REM *****************************************
2006 REM
2100 IF CA = PEEK (TM + 10) THEN 2120
2120 FOR AA = 1 TO 10: NEXT AA
2130 RETURN
2135 CB = PEEK(TM + 10)
2140 IF INT(CA / (64 * SM)) < > INT(CB / (64 * SM)) THEN 2190
2150 CA = CB: GOTO 2120
2160 RETURN
2195 REM
2196 REM ********************************
2200 REM **** TIMER FOR SUB 1000 ****
2205 REM ********************************
2206 REM
2210 CA = PEEK(TM + 10): CB = CA
2220 FOR AA = 1 TO 10: NEXT AA
2225 CB = PEEK(TM + 10)
2230 IF INT(CA / (16)) < > INT(CB / (16)) THEN 2290
2235 CA = CB: GOTO 2220
2290 RETURN
3480 RM
3490 RM
3500 REM **** SUBROUTINE FOR IDENTIFICATION ****
3510 REM ********************************
3511 REM
3520 ER = Y(NT)
3530 FOR I = 1 TO KSET
3535 IF NT - I < 0 THEN: YI = 0: UI = 0: WI = 0: GOTO 3537
3536 YI = Y(NT - I): UI = U(NT - I): WI = W(NT - I)
3537 VX(I) = YI: VX(KSET + I) = UI: VX(KSET + 2 + I) = WI
3540 ER = ER - ZZ(I) * VX(I) - ZZ(KSET + I) * VX(KSET + 1) - ZZ(KSET + 2) * I) * VX(KSET + 2 + I)
3550 NEXT I
3555 PRINT "THE ESTIMATION ERROR OF OLD MODEL IS", ER
3560 GOSUB 4000
3560 FOR J = 1 TO KSET + 3
3570 Z(J) = ZZ(J) + VK(J) * ER
3580 NEXT J
3590 FOR L = 1 TO 3 * KSET
3600 ZZ(L) = Z(L)
3610 PRINT "ZZ(", L, ") = ", ZZ(L)
3620 NEXT L
3630 RETURN
3690 REM
4000 REM **** ESTIMATING THE VECTOR K ****
4001 REM
4005 FOR I = 1 TO 3 * KSET
4010 MA(I) = 0
4015 NEXT I
4020 FOR I = 1 TO 3 * KSET
4030 FOR N1 = 1 TO 3 * KSET
4040 MA(I) = MA(I) + NP(I,N1) * VX(N1)
4050 NEXT N1
4060 NEXT I
4070 SUM = BETA
4080 FOR I = 1 TO 3 * KSET
4090 SUM = SUM + VX(I) * MA(I)
4100 NEXT I
4110 FOR I = 1 TO 3 # KSET
4120 VK(I) = MA(I) / SUM
4130 NEXT I
4200 RETURN
4300 REM
5000 REM ***** ESTIMATING THE MATRIX P *****
5001 REM
5005 IF NT = 0 THEN 5900
5010 FOR I = 1 TO 3 # KSET
5020 FOR J = 1 TO 3 # KSET
5030 IF I > J THEN 5060
5040 MQ(I,J) = 1 - VK(I) * VX(J)
5050 GOTO 5065
5065 MX(I,J) = 0
5070 NEXT J
5080 NEXT I
5100 FOR I = 1 TO 3 # KSET
5110 FOR J = 1 TO 3 # KSET
5120 FOR N1 = 1 TO 3 # KSET
5140 MX(I,J) = MX(I,J) + MQ(I,N1) * MP(N1,J)
5150 NEXT N1
5170 FOR I = 1 TO 3 # KSET
5180 FOR J = 1 TO 3 # KSET
5190 MP(I,J) = MX(I,J) / BETA
5195 NEXT J
5200 NEXT I
5200 RETURN
5900 FOR I = -1 TO 3 # KSET
5910 HP(I,I) = 1
5920 NEXT I
5930 RETURN
5940 REM
8990 REM ********************************************
9000 REM ***** INPUT VARIABLE CORRECTION *****
9001 REM ********************************************
9002 REM
9003 IF CS = 2 THEN 9100
9005 IF KSET = 2 THEN 9055
9010 PN = ((TSP - G) - ZZ(1) * 2 * Y(NT) - (ZZ(1) * ZZ(3) + ZZ(3)) * W(NT))
9020 PN = PN / (ZZ(2) * (1 + ZZ(1)))
9040 RP = PN + UJ
9050 RETURN
9055 IF NT = 1 < 0 THEN : YI = 0: UI = 0: WI = 0: GOTO 9060
9057 YI = Y(NT - 1): UI = U(NT - 1): WI = W(NT - 1)
9060 PN = (TSP - G) - (ZZ(1) * 2 + ZZ(2)) * Y(NT) - YI * ZZ(1) + ZZ(2) - ZZ(1) * ZZ(4) * UI - (ZZ(5) + ZZ(6) + ZZ(1) * ZZ(5)) * W(NT) - ZZ(1) * ZZ(6) + WI
9070 PN = PN / (ZZ(3) + ZZ(4) + ZZ(1) + ZZ(3))
9080 GOTO 9040
9100 IF KSET = 2 THEN 9155
9130 PN = ((TSP - G) - (ZZ(1) + Y(NT) + ZZ(3) + W(NT))) / ZZ(2)
9140 GOTO 9040
9155 IF NT - 1 < 0 THEN :YI = 0: UI = 0: WI = 0: GOTO 9160
9157 YI = Y(NT - 1): UI = U(NT - 1): WI = W(NT - 1)
9160 PN = (TSP - G - (ZZ(1) + Y(NT) + ZZ(2) + ZZ(3) + UI + ZZ(5) + WI) + T) + ZZ(8) + WI) / ZZ(3)
9170 GOTO 9040
9180 REM
9190 REM
9200 REM ***** ALARM *****
9210 PRINT "FAIL TO CONTROL THE SYSTEM"
9220 GOTO 430: REM *** GO BACK TO THE END OF THE PROGRAM ***
PROGRAM FOR THE PID CONTROLLER
HOME
PRINT : PRINT : PRINT
PRINT "PID CONTROL"
REM *** DIRECT DIGIT PROPORTIONAL INTEGRAL CONTROLLER ***
PRINT : PRINT : PRINT
REM *** THE THERMISTER RANGE IS FROM -55C TO 150C ***
T3%(0) = 2
T0 = 2.99:T7 = 383:T3 = 5536:T8 = 395:TR = 10000
TA = 9.37283692E - 4:T6 = 2.20813136E - 4:TC = 1.280071e3E - 7
T1% = 1022
T1% = 1.223 = 1:5% = 10:TH% = 238
TP% = 326
DS = "$" (4)
REM *** LOAD AND START THERM.A BINARY PROGRAM COMING WITH THE THERMISTER INTERFACE THAT TAKES THE TEMPERATURE DATA ***
TM = PEEK (116) * 256 + PEEK (115): REM *** TM=HIMEM ***
TM = 256 * INT (TM / 256) - 1280: HIMEM: TM: REM *** MOVE HIMEM **
TM
110 PRINT D$, "LOAD THERM.A":TM
114 REM *** STORE HILOC AT TM% ***
115 T = INT (TM / 256): POKE THX% + 1,T: POKE THX.,(TM / 256 - T) $ 256
120 CALL TM + T8
130 POKE TM + 1,T3%(0)
140 T = INT ((TM + 502) / 256): POKE 11% + 1,T: POKE 11%,((TM + 502) / 256 - T) $ 256
150 T = PEEK (TM + 10)
160 POKE TM + 9,T
170 CALL TM + TP%
175 FOR I = 1 TO 1000: NEXT I
177 REM *** ESTABLISHMENT OF THE NORMAL OPERATION CONDITIONS ***
180 GOSUB 1000
195 PRINT "INITIAL TEMPERATURE =",T,"C"
300 REM *** CONTROL SECTION ***
302 CALL TM + T7
303 PRINT D$: "PR$1"
304 PRINT "INPUT SET TEMPERATURE"
306 INPUT SPT
310 KC = 2
312 ITC = 1.8
314 ID = .45
316 PRINT "INPUT SAMPLING TIME :"
318 INPUT TST
320 DS = "$" (4)
321 PRINT DS: "PR$1"
322 PRINT "PID CONTROL ": PRINT
330 CALL TM + T8
324 NT = 0
325 PO = INITP
326 TI = 0: GOSUB 2000
338 ERR = SPT - T: IF NT = 0 THEN 340
339 E1 = ERR; E2 = ERR
340 P = PO + KC x ((ERR = E1) + TST / ITC x ERR + ID / TST x (ERR - 2 x E1 + E2))
346 GOSUB 370
347 PRINT "NT = "'NT,"TEHP = "'TEHP
348 E2 = E1; E1 = ERR
350 PO = P
363 GOSUB 2100
364 IF NT > 60 THEN 368
365 NT = NT + 1
366 GOTO 336
368 CALL TM * TT
369 END
370 REM
380 IF P > 14.1 THEN : RP = 14.1: GOTO 400
390 IF P < 4.7 THEN : RP = 4.7: GOTO 400
395 RP = P
400 Y = 26.67 x RP - 123.33
410 NUM = INT (Y + 0.5)
420 POKE -16176, NUM
424 RP = 4.625 + .0375 x NUM
425 PRINT "INPUT BEGINS..."; RP
430 RETURN
1000 CALL TM + TT
1001 PRINT "ESTABLISHMENT OF THE NORMAL OPERATION CONDITIONS"
1002 PRINT : PRINT
1004 PRINT "SELECT THE PRESSURE TO THE CONTROL VALVE IN THE RANGE 4.7 - 14.1"
1006 INPUT INITP
1007 TST = 1
1008 Y = 26.67 x INITP - 123.33
1010 NUM = INT (Y + 0.5)
1040 POKE -16176, NUM
1045 CALL TM + TB
1050 TI = 0
1055 GOSUB 2000
1060 PRINT "TEMP="'T," C"
1065 BFT = T
1070 GOSUB 2100
1075 TI = 0
1080 GOSUB 2000
1085 PRINT "TEMP="'T," C"
1090 IF ABS (T - BFT) < 0.05 THEN GOTO 1150
1100 GOTO 1065
1150 PRINT "TEMP=", T, " C"
1155 PRINT D$ "PR#1"
1160 PRINT "NORMAL OPERATION POINT"
1165 CALL TM + TB
1170 RETURN
1177 REM **** A/D CHANNEL 3 ****
1198 REM **** ANALOG TO DIGITAL CONVERSION ****
1199 REM **** GET TEMPERATURE DATA ****
2000 TJ = T5X + TI * T5% / TO + TM
2010 CALL TM + T7: T = PEEK (TJ) + PEEK (TJ + 1) * 256 + PEEK (TJ + 2 ) * 65536: CALL TM + TB
2020 TZ = T + TR / T3
2030 T = T1% / (TA + TB + LOG (TZ) + TC * ( LOG (TZ)) * T3%) + TK
2040 T = INT (T * 100) / 100 - 273
2050 RETURN
2100 REM TIMER
2110 CA = PEEK (TM + 10)
2120 FOR AA = 1 TO 10: NEXT AA
2130 IF CA = PEEK (TM + 10) THEN 2120
2135 CB = PEEK (TM + 10)
2140 IF INT (CA / (64 * TST)) < > INT (CB / (64 * TST)) THEN 2190
2150 CA = CB: GOTO 2120
2190 RETURN
1. The sketch of the steam-jacketed kettle used for the experiment of the servo problem.

2. The sketch of the steam-jacketed kettle used for the experiment of the regulator problem.