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Project Summary

Automated Control: A Review and Applications in Industrial Environmental Protection

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The objective of this study was to examine automatic control theory and its practical applications to environmental processes. A summary is given emphasizing those aspects of the theory that are likely to find application in optimizing environmental control systems. Several case studies, chosen based on the potential applicability of automatic control processes, are used to illustrate applications of several automatic control concepts. The basic equations are introduced in the development of a closed-loop transfer function for a blast furnace scrubber water recycle system. The mathematical complexities of handling a distributed parameter system are illustrated in a study of an acid gas removal system. The possibility of utilizing feedforward control is illustrated in an examination of fluidized-bed combustion with limestone control. Evaluations of various control options are considered within the context of a limestone scrubber slurry treatment system.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

A control system has been defined as a system in which deliberate guidance or manipulation is used to achieve a prescribed value of a variable. A control system is generally designed to meet some performance specification at a minimum cost. Classical control system design techniques can be very effectively applied to the control of processes that are designed to reduce or eliminate potential environmental hazards associated with discharges from utilities or industrial plants.

Control theory deals with the dynamic response of a system to commands or disturbances. For control system problems that engineering experience and intuition cannot solve, the approach to process analysis and control system design is consistent, involving the following steps:

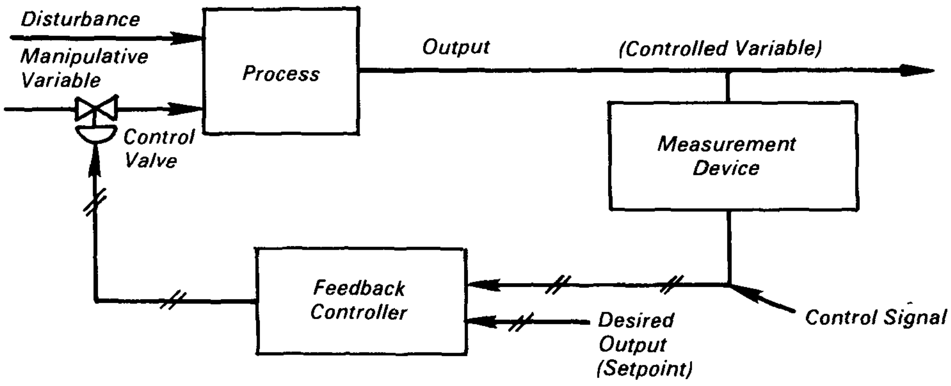
1. Define a system and its components.
2. Establish performance criteria for the controlled system.
3. Formulate the mathematical transient model (*i.e.*, examine process dynamics) of the uncontrolled system, and list the necessary assumptions
4. Write the differential equations that describe the model.
5. Solve the equations for the desired output variable.
6. Examine the solution and the assumptions, and compare them with performance criteria.
7. Propose appropriate control strategy and design the controlling system.
8. Perform a dynamic analysis of the complete system to ensure stability.
9. Test the design by nonlinear simulation to confirm response.
10. Construct and test the system.

Summary and Discussion

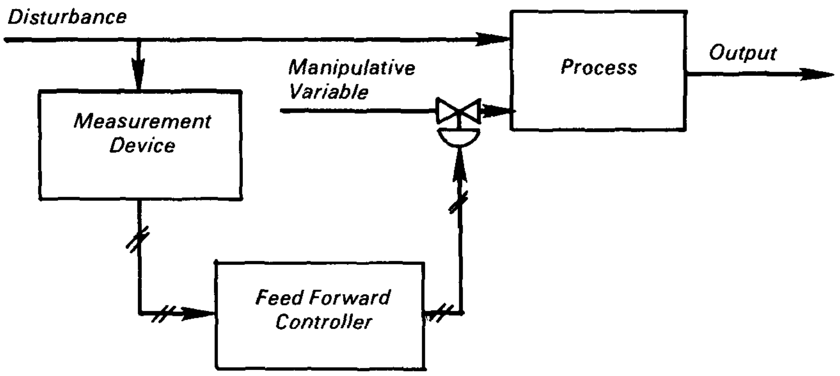
An appropriate control strategy and design is based on the output/input response determined by the dynamic analysis of the uncontrolled system and certain performance criteria. To be considered are the required levels of accuracy, speed, cost, reliability, and ease of operation and maintenance. Functional requirements for process control systems are stability, reduction or elimination of the effects of long-term disturbances, and reduction or elimination of the effects of short-term disturbances.

To automate the control of a process, it is necessary to "feed" information to a controller which will, in turn, effect some change in a process variable, called the manipulative variable. The information received by the controller is data or a signal generated by a measuring device that senses fluctuations in some system parameter. In process instrumentation, the *error* is the algebraic difference between the indication of the signal and the ideal value.

The two basic configurations for control systems are *feedback control* and *feedforward control*. In feedback control, information from the output variable is "fed back" to an input manipulative variable. In feedforward control, the disturbance is detected in the input variable before it enters a process so that adjustments can be made before the disturbance propagates through the process. The basic control configurations are shown in Figure 1.



Feedback Control



Feedforward Control

Figure 1. *Feedback and feedforward control (adapted from Luyben, 1973).*[1]

The advantages of feedback control include:

1. A decrease in the sensitivity of the system to variations in the parameters of the process.
2. Ease of control and adjustment of the transient response of the system.
3. Improvement in the rejection of the disturbance and noise signals within the system.
4. Improvement in the reduction of the steady-state error of the system.

The objective in feedforward control is to detect the disturbances as they enter a process and to immediately adjust the manipulative variables so that output variables are held constant. In theory, feed-forward control can result in perfect control; in practice, it is usually difficult to detect the disturbance ahead of the process and predict how the disturbance and the manipulative variables affect the process.

The *transfer function* is one of the most useful concepts in control theory. The transfer function of a linear equation describing system behavior is the ratio of the transform of the output variable (response function) to the transform of the input variable (forcing function). In the Laplace domain, the transfer function, frequently designated G(s), is defined by Equation 1 where s is a complex variable that is the Laplace transform argument.

$$G(s) = \frac{\text{Transform of output variable}}{\text{Transform of input variable}} = \frac{\text{Output(s)}}{\text{Input(s)}} \quad (1)$$

The transfer function is an output/input description of the behavior of a system but does not include any information concerning the internal structure or internal behavior of a system.

Either mathematical or experimental methods may be used to obtain the transfer function. In the experimental approach, a known input, typically a step function, is applied to the system, and the output is measured. The transfer function is then constructed from these data. Similarly, the transfer function may be obtained from operating data and curves.

The Laplace transformation is primarily a method of transforming linear differential equations with constant coefficients into algebraic equations. The chief advantages of the Laplace transform are:

1. It permits rapid solution for problems involving simultaneous linear differential equations with constant coefficients.
2. Initial boundary conditions are automatically incorporated in the solution for the response to any arbitrary forcing function.
3. In many cases, the nature of the response can be seen simply by inspecting the transformed equation.

The principal motivation for applying the Laplace transform arises in connection with the time derivative which occurs frequently in the equations describing process dynamics.

The three basic types of controllers that are frequently used in industrial processes are:

- Proportional Control Action--Control action in which there is a continuous linear relation between the input and output.
- Derivative (rate) Control Action--In process instrumentation, control action in which the output is proportional to the rate of change of the input.
- Integral (reset) Control Action--Control action in which the output is proportional to the time integral of the input; i.e., the rate of change of output is proportional to the input.

The three actions described above may be used individually or combined in three basic commercial controllers:

- Proportional (P): with proportional action; i.e., output signal directly proportional to the error signal.
- Proportional-integral (PI): with proportional plus integral action.
- Proportional-integral-derivative (PID): with all three actions.

The response of these various control systems to a disturbance is shown in Figure 2.

System *stability* is an important aspect of process control. A linear process is at the limit of stability if it oscillates even when undisturbed and the amplitude of the oscillation does not decay. In a stable system, the output response is bounded for all bounded inputs. Conditions of instability may arise in feedback systems due to unfortunate timing between the feedback variable and the input variable. The stability of a control system can be determined by applying a unit impulse to the system in equilibrium and examining the output as time increases. Stability may also be addressed from a mathematical standpoint using methods such as the Routh-Hurwitz test or the root locus method; relative stability may be examined using the Nyquist stability criteria.

Other parameters that are important in evaluating a control process are rise time, overshoot, decay ratio, and settling time. These are illustrated in Figure 3 which shows a typical response of a control system to a unit step input. The rise time is the time it takes the process to come up to the new set point. The percent overshoot is determined at M_P, the peak value of the time response. The decay ratio is the ratio of maximum amplitudes of successive oscillations. The settling time, T_s, is the time required for the amplitude of the oscillations to decay to some fraction (0.05) of the change in set point.

Four case studies are developed in the report to illustrate the approach to control system analysis and to demonstrate the applicability of automated control in pollutant abatement technologies.

A scrubber water recycle system for blast furnace exhaust gases is analyzed to illustrate development of the closed-loop transfer function. Mass balances for each process within the system and the necessary simplifying assumptions are presented. The differential equations are Laplace-transformed, and appropriate substitutions are made to obtain the desired transfer function of the system.

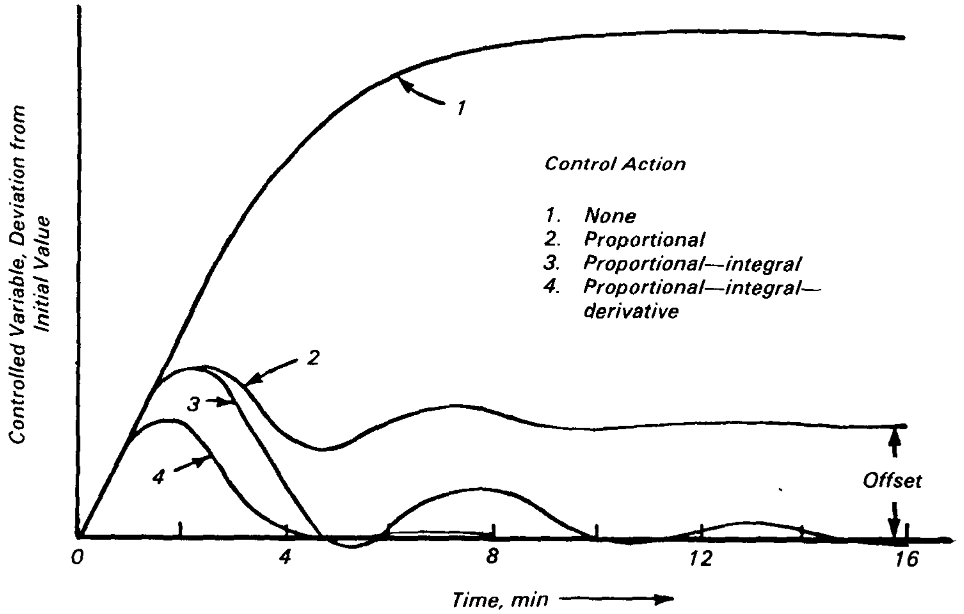


Figure 2. *Response of the various control systems (adapted from Coughanowr and Koppel, 1965).*[2]

The second case study, an acid gas removal system, is a distributed parameter system (i.e., its dynamic response is described by partial differential equations). The system model is developed along with the transfer function to relate the change in concentration of the rich acid gas to the concentration of the acid gas entering the absorber unit. A stability analysis of the system is presented together with a discussion of the implication of time lag.

Analysis of a feedforward control system for fluidized-bed combustion with limestone control is the subject of the third case study. Sulfur in the feed coal is determined via a continuous online sulfur analyzer utilizing neutron-induced gamma spectrometry with scintillation counting. The sulfur content of the coal indicated by the sensor is multiplied by the coal flow rate and then compared to the stoichiometric mix required for makeup limestone to ensure acceptable adsorption of the sulfur in the fluidized bed.

Control approaches for limestone scrubber slurry addition are presented in the final case study. The discussion is based on the results of research by Patrick Garrett of the University of Cincinnati for the U.S. Environmental Protection Agency.[4] Stoichiometric-assisted pH control was determined to be the optimum control system resulting in maximum reduction of slurry disorder. Less complex control based on slurry pH is recommended for conditions in which large changes in pH result from changes in the limestone feed rate.

Analysis of process dynamics and control systems is treated with more technical detail in the appendix to the report.

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4. Garrett, P.H. Limestone Scrubber Slurry Automatic Control Systems. University of Cincinnati, Cincinnati, OH, EPA Grant R805758, Draft Report, September 1981.

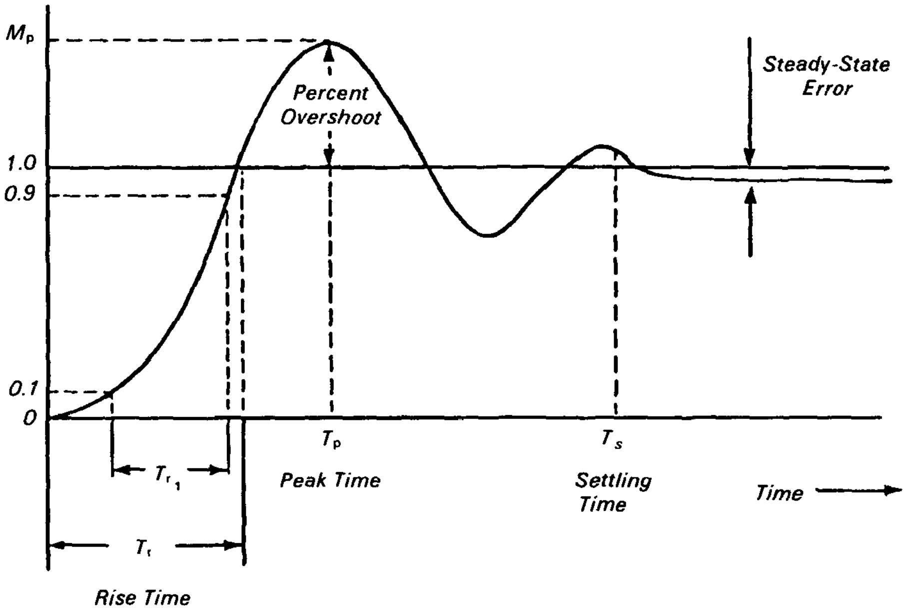

Figure 3. *Response of a control system to a unit step input (adapted from Dorf).*[3]

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The complete report, entitled "Automated Control: A Review and Applications in Industrial Environmental Protection," (Order No. PB 84-139 666; Cost: $11.50, subject to change) will be available only from:

National Technical Information Service
5285 Port Royal Road
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