Process Control: From Developer Charging to Production Shop Management

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Abstract

A revolution in process control theory occurred in academia during the 1960s – 80s. A plethora of mathematical techniques were developed that promised to stabilize arbitrary processes against disturbances. The applications of these techniques have yielded economic benefits in aerospace, chemical process and automotive industries where stability and performance under tightly constrained operational conditions were required by performance, economic, safety, or regulatory constraints. The elements of the document production process from materials design to work processes on the shop floor are fit subjects for migration of function and predictable performance to silicon-based sensing, computation, and actuation.

Xerox is taking the idea of feedback control as a model for driving changes in hardware design, machine operation, work process, and services delivery.

Introduction

During the period from the 1960's to the 1980's a tremendous series of advances in the development of process control theory swept over the academic community. Prior to that time, simple PID (Proportional, Integral, Differential) type control algorithms were most widely used and their place in the application space is well established. During this period, government regulation combined with pressure for increases in performance, economy, and safety in the aerospace, automotive, and chemical process industries. These pressures demanded improved process stability in increasingly complex systems. Industry needed technological improvements that provided theoretical proofs of stability and robustness. Earlier approaches were simply inadequate to maintain competitive advantage and regulatory compliance. The academic community in electrical and mechanical engineering responded to this need by formulating a wide variety of mathematical techniques for application to the problems faced by their industrial colleagues.

In parallel with this tsunami within academia, the Silicon Revolution has enabled the fruits of the control systems research and engineering to be realized in systems as inexpensive as desktop ink jet printers and toasters. Closed loop control systems using the theoretical advances of the last few decades are now in common use in everyday devices - operating invisibly under the covers.

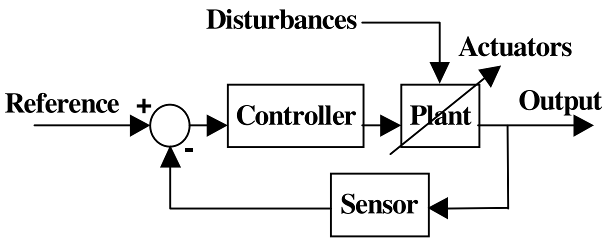

Figure 1. Basic control system block diagram

Controls are implemented to maintain the output of a system within specified limits when those limits are exceeded in the absence of control. Consider the diagram in Figure 1. The plant is the term used to refer to the set of hardware devices that produce the output. The inputs to the plant are of three types. First are those normal stimuli that cause the plant to produce output. In addition, there are adjustable internal parameters that govern the behavior of the plant. Disturbances are those external or internal forces that produce undesired variation in the output. Sensors measure the performance of the plant by observing the output and/or internal states. Actuators attach to the adjustable inputs of the plant to correct for the effects of the disturbances. The controller accepts readings from the sensors and calculates how to change the actuators to maintain the output within the desired limits.

Open loop control systems are frequently employed where the disturbances on the inputs and the plant may be measured and the behavior of the plant predicted from them. In this approach, the actuators are adjusted according to a predefined set of rules from equations or a look-up table relating the inputs and disturbances to the actuator settings. The advantage of this approach is that calculations are used in place of the more expensive sensors. The disadvantages of the approach include 1) the combinatorial factors that require many experiments to validate the equations or to fill the look-up table, and 2) the necessity of including all the important sources of variation in the system.

Closed loop control adjusts the actuators during plant operation using sensor readings of the states of the plant and an algorithm that computes the best settings to stabilize the output. Closed loop control is usually more expensive in terms of hardware cost because of the necessity of including sensors in the system. Its advantages are that the actual variations of the system are determined and even though not all the possible excursions of the input and state variables are known *a priori*, a well designed controller can compensate even for a poorly modeled plant. Unanticipated sources of variation may be compensated for gracefully.

Complex electromechanical systems are typically composed of recursive structures. Layers of function stack upon one another to aggregate their capabilities to provide the desired system behavior. The interactions between the components and layers within these hierarchical structures combine to make the system behavior difficult to describe using traditional techniques. What process control does is to stabilize systems against the negative impacts of input and process variations to their operation. Optimal performance is achieved when control is used throughout the system. In many cases, though, adequate performance may be achieved through judicious application in order to obtain an optimal cost/performance/delivery relationship for the product.

How Control Applies to the Marking Device Hierarchy

The electrophotographic process, as embodied in various marking devices, is an example of a recursively structured complex system. Components are aggregated into subsystems that perform a process. Processes in hardware and software aggregate into a system that is, in turn, placed into an environment where it performs useful work. The remainder of this paper articulates the nature of the control problems.

As we traverse up the structure, we move through increasing levels of abstraction in the nature of the controlled parameters and the output. These higher levels assume more complexity and thus require greater amounts of data to characterize them. Longer sampling times require that the plant being sampled be stable over the sampling interval. Thus, the control loops operate in increasing time domains. Lower levels cycle their sense–calculate–actuate cycles more frequently than the control structures above them in the hierarchy.

The Component Level

The individual components of the system reside at the base of the hierarchy. Typically, control at this level consists of the problem of stabilizing a single measurable parameter. As an example, consider the elements involved in controlling the photoconductor voltage at the developer housing location.

Often, development voltage stabilization is left to open loop prediction to avoid sensor costs. We have found that, for color applications, an electrostatic voltmeter (ESV) is valuable in a closed loop system. The disturbances include local environmental factors (temperature, %RH) together with the charge acceptance and dark decay properties of the photoconductor. Scorotron shield voltage in the charging device is adjusted by the controller extrapolating the shield setting and the ESV reading to predict and stabilize the voltage at the housing. Thus, a single parameter in a single subsystem is stabilized in a closed loop control structure.

The Subsystem Level

The media handling subsystem integrates the behavior of a number of controlled components in order to deliver sheets to the transfer station. The toned photoconductor image is placed in the proper location on a properly oriented sheet. When this subsystem fails, the results are either visible, as in the case of an improperly registered image, or inconvenient, as in a paper jam. The subsystem must contend with wide substrate variations expressed as size, basis weight, and surface energy. The drive components also experience wear and their friction surfaces get coated with paper fibers and talc. These disturbances lead to timing errors.

These subsystems almost always receive the attention of a real-time closed loop controller because of the magnitude of the disturbances and the visibility of subsystem failures. Presence detectors, usually light touch mechanical switches or photon flux interrupters, are used to detect media arrival times at a number of points in the media path. These timing inputs may be used in a trajectory-planning algorithm that adjusts the velocities and timing of the drive motors, clutches, rolls, and solenoids.

The Process Level

At the process level, the relevant xerographic plant consists of the subsystems that construct a single color separation. The stability of tone reproduction is a crucial step in color predictability. There are varieties of implementation possibilities. One of these sets of choices will be described. In this example, there are two steps. The first is an infrequently performed calibration step followed by a real-time sense-calculate-actuate sequence. This approach permits uninterrupted job flow while maintaining stability for this process between calibrations.

Each of the primaries is controlled to a tone reproduction curve determined from a calibration of the equivalent neutral densities (END). These ENDs are the mixing coefficients for the primaries that yield process gray for a number of values of L*. The END values for a separation are aggregated to form a curve relating the input byte to an output byte that reflects the value to be printed. The calibration step determines the END on the output medium using a spectrophotometer while previously sensing the value for that toned patch on the photoconductor. The photoconductor density curve is constructed using the same patches that are read by the spectrophotometer afterward. The patch readings then constitute the “setpoint” that the controller uses as the objective function during run-time. Interdocument zone sample patches are printed for each separation and halftone density. The sensed density is compared to the setpoint curve to determine an error. The error is used by the controller to construct a compensating TRC that brings the printer behavior to the setpoint.

There are an inadequate number of unused degrees of freedom in the marking hardware to accommodate the level of control required to maintain a stable TRC. Fortunately, there is a source of actuators in the halftoning algorithm. The halftoner uses a set of thresholds to determine which halftone dot to associate with a particular contone image input value. By adjusting these thresholds in the conversion process, arbitrary variations in the TRC may be accommodated [ThiT88].

The System Level

Color printing is often implemented by connecting a series of process elements, each of which is responsible for a single color separation, into a press. A computer takes images from a scanner or in the form of printable files and converts them in to a half-toned bit map. This bit map is the input from which the color separations are printed. It is the controlled coordination of the hardware in the printer and the software in the controller that produces the results at the output tray.

Human vision places a stringent requirement on color reproduction because of its sensitivity to subtle differences. Thus, the stability and predictability demands on color printing systems greatly exceed those for monochrome. The magnitudes of variation associated with black and white printing are no longer acceptable when color is included.

Colors are constructed from recipes that instruct the controller how to mix the available colorants to yield the desired result. Even in the presence of the control systems at lower levels of the hierarchy outlined above, the variation in color output can exceed the visual threshold. The scope of the controlled space is the color gamut, a 3-dimensional volume representing all the colors printable on the marking system. The TRCs, controlled at the process level, stabilize the portions of this space defined by the 4 linear domains beginning at the white level and extending to the color of the fully saturated primaries (usually Cyan, Magenta, Yellow, and Black). The remainder of the gamut requires system level stabilization if the goal is to be achieved.

This complex problem in representation and control is a subject of active research at Xerox. How to sample the space and represent the complex, nonlinear, multi-dimensional, time-varying relationship between the input (CMYK) and the output (L*a*b*) spaces is a key problem. Some promising results have been made in the refinement of existing printer calibrations using a minimal number of samples [BalT98] but there is still much to be done.

The Environment

Document production environments combine marking systems, finishing systems, people, and revenue producing jobs together into a meta-system that may also be a subject of control theory application to improve job flow and productivity.

Print shops can be broadly classified into three categories based on the types of activity they perform—transaction printing, on-demand publishing, or a combination of both. A transaction printing environment produces documents such as checks, invoices, etc., where each document set is different. Mail metering and delivery are part of the workflow. On-demand publishing environments focus on producing several copies of identical documents with more finishing options such as cutting, punching and binding. Examples of such products include books, sales brochures, and manuals. Other environments have both types of document production going on simultaneously with varying emphasis on each one.

Sources of uncertainties in print shops include machine failures, operator unavailability, and a dynamic job mix. A print shop designed and optimized for one set of operating conditions will not necessarily function optimally when the nominal system deviates due to the effect of disturbances and uncertainties. As shown in Figure 2, the goal of feedback control is to guarantee optimal performance even in the presence of these disturbances.

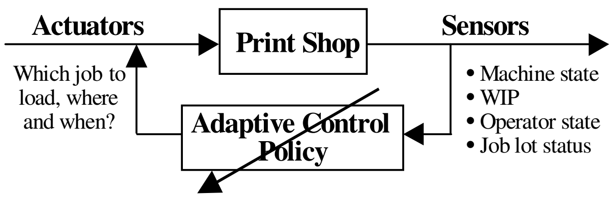

Figure 2. Schematic description of a feedback control structure applicable to print shop operations.

From our perspective, document production has not been seen as a manufacturing activity. Therefore, current practices in other industries, say, the automotive industry, have not been applied to modern print shops. As an example, most print shops are organized in departments (printing department, finishing department, etc.), and use the batch-and-queue approach for processing jobs. This causes large turnaround times and low equipment utilization.

Lean manufacturing practices [WomJ90] have enjoyed tremendous success in the automotive industry and in the aircraft industry. The overall "lean goal" is to eliminate the sources of waste in production. To achieve this one should eliminate/reduce defects, work-in-progress, unnecessary part and operator movement, resources waiting idling for an upstream activity to finish, and overproduction. The application of these practices to document production was investigated.

However, document production has some significant differences when compared with automotive or aerospace manufacturing to which lean manufacturing has been successfully applied. The primary difference is the print-job stream is very dynamic. Print shops have to produce different types and quantities of documents at different points of time. Xerox has developed a systematic methodology to adapt and enhance the lean manufacturing framework to the dynamic job stream of document production. This methodology has been validated and refined through application to a variety of print shops.

The salient features of this methodology include restructuring the layout of equipment on the floor and corresponding resources into autonomous cells, splitting jobs into small batches and routing these batches through the cells using real-time feedback control policies [RaiS99]. Application of feedback control policies enables the attenuation of uncertainties and disturbances on production processes [GerS93].

Recent tests of the restructuring of print shop workflow into cells according to lean principles reveal that, under reasonable conditions for a variety of print shops, the productivity of these print shops can be improved by factors of two or more. By the use of custom-developed simulation tools, the job flow in two of the Xerox Business Services group's Document Technology Centers (DTCs) has been analyzed, a restructuring of the work flow was proposed and implemented, and productivity increases of over a factor of two were achieved as measured on the floor. Clearly, such productivity increases result in greater customer value, either through reduced cost to produce the same output, and/or through increased revenue gained by filling the additional production capacity with new jobs.

Conclusion

Complex electromechanical systems are typically composed of recursive structures, with layers of function nested within one another to aggregate their capabilities into a system that provides the desired system behavior. Applying controls can improve the performance at each individual layer of the structure, and help to optimize the overall performance of the electromechanical system. Controls can also be applied in the context of the environment in which the system is used to provide customer value in order to increase the customer value provided. The Xerox Corporation is implementing controls at all of these levels in order to deliver optimal performance and maximum value to our customers.

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Biography

Steven B. Bolte is Vice President and Center Manager, Joseph C. Wilson Center for Research and Technology, the Document Company Xerox, for Xerox Corporation's Research and Technology Group. He holds 22 patents and is a member of the American Physical Society, the Society for Imaging Science and Technology, the College of Engineering & Applied Science Trustees' Visiting Committee at the University of Rochester, the Academic Advisory Board in the Center for Imaging Science at the Rochester Institute of Technology and the Industrial Advisory Board, Center for Electronic Imaging Systems at the University of Rochester. In 1970 Bolte received his doctorate in physics from the University of Illinois and later that year joined Xerox as a research scientist. He has held a series of R&D management positions instrumental in launching a broad spectrum of Xerox products.

Kenneth J. Mihalyov received his B.S. degree in Electrical Engineering from the Rochester Institute of Technology in 1982. He joined Xerox in 1977, and has worked in both product development and technology organizations in the areas of embedded controls and control systems. He presently manages a group in the Wilson Center for Research & Technology in Webster, N.Y. focused on dynamic systems, control systems and system modeling. He holds 3 patents.

Sudhendu Rai received his B.Tech degree from IIT (India) in 1988, MS degree from Caltech in 1989 and a Ph.D. from MIT in 1993, all in Mechanical Engineering. Since 1995 he has worked in the Wilson Center for Research & Technology at Xerox Corporation in Webster, N.Y., focused on multiobjective optimization of xerographic processes, design of distributed control systems for paper handling and printshop workflow optimization and control. He holds 3 patents and is a member of ASME and Sigma Xi.

Tracy E. Thieret received his B.S. degree from the University of Vermont in 1973 and a Ph.D. in Physical Chemistry from Duke University in 1978. Following Postdoctoral studies in low temperature NMR under R.W. Kreilick at the University of Rochester, he joined Xerox in 1981 where he is currently a Principal Scientist in the Wilson Center for Research and Technology in Webster, New York. His work has focused on xerographic control and information flows surrounding networked services delivery. He is a member of the Futurist Society.