ELEMENTS OF AUTOMATION AND CONTROL

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Summary

Automation and control is pervasive in modern society. Virtually every complex engineering system—an aircraft or spacecraft, a home or building, an oil refinery or paper plant, an automobile or robot—depends crucially on sensing, feedback, and actuation for its predictable, safe, and efficient operation. This article reviews the "controller" versus "plant" distinction, noting its multifaceted nature.

The control loop is reviewed with specific attention to sensors, feedback, and actuation. Particular attention is paid to elements of control systems that relate to information technology; processors, input and output interfaces, communication networks, and wireless are discussed.

Three trends are identified as indicative of future developments in automation and control: enterprise optimization, autonomous and semi-autonomous systems, and embedded controllers.

1. Introduction

We're so immersed in today's human-engineered world that it's easy to forget it wasn't always this way. Life in modern societies bears little resemblance to how people lived even a few generations ago. The environments we inhabit, the materials we use for many of our assets, the foods we eat, the means by which we transport ourselves, were all nonexistent and in many cases unimaginable in the recent past.

A variety of machines, devices, and artifacts has enabled these and many other developments. A list of these is a litany of engineering achievements spanning a century of technological progress: aircraft, automobiles, oil refineries, power plants, office buildings, paper mills, chemical manufacturing facilities, textile factories, ships, industrial robots, communication networks, traffic management systems, airports, electric power grids, and numerous other inventions of the modern age.

These systems vary, in terms of their physical scales, from continent-size power grids and the planetwide Internet to biomedical and other small-scale devices. The systems also operate at different time scales—compare the speed-of-light operation of a communication network with the crawl of a congested highway. The physical principles underlying the operation of an engineering system also vary widely, as is evident from the number of separate engineering disciplines that have evolved over the course of technological development: electrical, chemical, mechanical, civil, petroleum, aerospace, and others.

Yet, despite the diversity, the engineering artifacts mentioned above, and others we'll note later on, share an important and distinctive attribute. Specifically, the systems represent an integration of a physical structure and a component that is conceptually and logically distinct from it. This component is an automation and control subsystem.

We press a button, turn a wheel, or push a pedal, and a complex system with hundreds of thousands of parts miraculously does the right thing (not always, of course, but the wonder is that the system works at all). It is the automation and control subsystem that is responsible for this apparent miracle. And note that the system's functioning must be ensured under a variety of unpredictable environmental and external conditions, ranging from turbulence in flight to occupancy levels in a conference room.

In virtually every case, the automation is hidden from view, so the fact that its presence is by and large unrecognized should elicit little surprise. The parts that comprise it are often embedded within the physical structure and are often not apparent as separate from it. Sensors, switches, wires, processors—these are not what we think of, or see, when we see a factory, even though no factory today could operate without them.

A subtler problem is that automation and control has to do with information, not tangible, physical "stuff." When we marvel at a jet aircraft streaking across the sky, it's the gleaming fuselage that catches our eye and imagination, not the behind-the-scenes millisecond-by-millisecond information processing and decision making that is ultimately responsible for the aircraft's flight—and that typically occurs without any pilot input. The story is similar across the technological spectrum.

2. Elements of the Control Loop

2.1. "Plant" and "Controller"

The distinction between the physical system and the automation and control element is captured in Figure 1, which introduces the shorthand terms *plant* and *controller*. The automation component or controller obtains information about the state of the physical system through sensors that measure various properties of interest, such as temperatures, pressures, positions, velocities, and chemical composition. And it influences the behavior of the physical system using actuators such as motors, pumps, valves, and switches. Usually human operators interact with the controller to ensure that the behavior of the physical system is satisfactory. The human operator obtains information about the physical system through displays associated with the controller, which also provides the means for the operator to directly effect any changes to the system's operation.

Much of the complexity that we intuitively associate with machines such as aircraft or chemical plants has to do with the coupling of the physical, chemical, or other phenomena that govern the operation of the machine (these, being prescribed by nature, we have no liberty to modify) and the dynamic actions that are taken by the automation system to influence the plant's behavior. The details of the plant vary widely across the range of complex engineering systems, but the principles and concepts involved in the automation and control of different plants are remarkably similar.

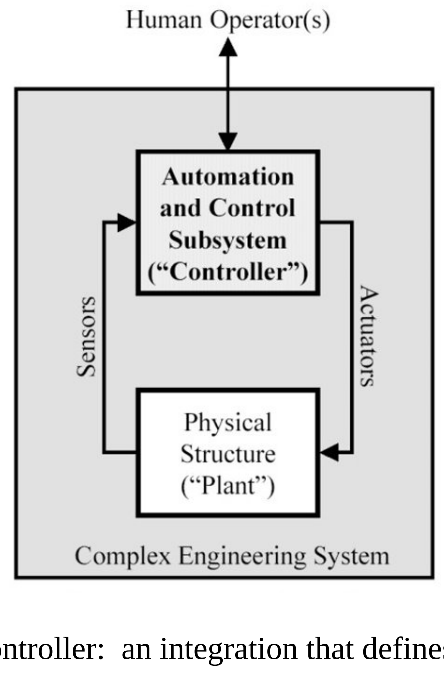

Figure 1: Plant and controller: an integration that defines complex engineering systems.

The schematic of Fig. 1 considerably simplifies reality. Two particular simplifications are worth noting here. First, the clean partition between the plant and the controller in the figure, although literally quite accurate, is complicated by the fact that both these components have complex, hierarchical structures. Thus although at a high level we can generally identify an information processing and algorithmic component that is separate from the physical structure, the latter itself is often composed of physical subsystems with associated subcontrollers. This "loops within loops" hierarchy can be many levels deep. Analogously, the concepts of "sensor" and "actuator" get abstracted as we move up the hierarchy.

For example, physical sensors such as temperature transducers provide information directly to low-level controllers that may be responsible for maintaining the room temperature in a hotel by adjusting damper settings. At the next level in the hierarchy, calculations based on temperate and humidity may provide a comfort measure that can be regulated through "setpoint" commands to low-level controllers. Higher-level controllers may measure aggregate properties such as the cost of energy being consumed by the building. Their actions, in a deregulated utility marketplace, may involve the rescheduling of "shiftable" loads such as laundry and maintenance operations or switching from purchased electricity to on-site microturbine generators.

A second important simplification is the omission of the "environment" within which the system operates. Variations in the environment affect the plant as *disturbances* (a term with a rather precise meaning in control engineering). In many cases, automation would be trivial in the absence of disturbances; *disturbance rejection* is one of the principal functions of most control systems and often the reason for much of their sophistication.

A typical example of a disturbance is a wind gust for an aircraft. Similarly, a chemical plant is affected by ambient temperature variations since chemical and material properties are often temperature-sensitive. Process plants such as oil refineries, chemical factories, or fossil-fuel power generators are exposed to the elements, and thunderstorms and lightning strikes can affect their operation. Disturbances are caused not only by natural phenomena. Variations in occupancy levels in a commercial building or in the manufactured raw materials for a factory must be accommodated for safe, reliable, and efficient operation.

The extent of automation provided by any control system is "incomplete" in the sense that operators and other personnel are required to monitor and sometimes to take over control. Process plant operators, cockpit crew in aircraft, air traffic controllers, facility management personnel, can all be thought of as "operators" in this general sense (as depicted in Fig. 1). Information about the current state of the engineering system is conveyed to a human operator through displays that are part of the control system. Manually commanded changes are also effected through the control system. The automation can enable the operator to directly modify the engineered system—to close a valve, for example, or to change the deflection angle of an aircraft wing flap. In addition, the operator action may refer not to the plant but to the controller. Commands to the controller can include set-point changes to adjust something like the desired flow rate for an intermediate product serving as input to a refinery distillation column, or mode switches to change from climb to cruise in a commercial airliner. The automation system can also suggest actions for the operator to take, such as fault management recommendations for replacing or fixing components identified as likely to fail.

The role of the human operator is evolving as increasingly many functions related to the operation of engineering systems that used to be performed by her have become the control system's responsibility and as new developments in the engineering systems themselves make their automation a more challenging task. *Human-machine interaction* is an integral facet of automation and control and will remain so for the foreseeable, and perhaps even conceivable, future.

2.2. The Role of Automation

Getting an aircraft to fly reliably from point A to point B, or producing gasoline of a required octane specification from raw crude, or maintaining temperature and humidity within comfortable ranges in a large hotel, would all have seemed incredible feats a century or so ago. Today we give them hardly a second thought. Familiarity masks the magnitude of the achievement.

Whereas the engineering systems that are the beneficiaries of automation and control are all visible to us, the automation component weaves its wonders unobserved. Yet the cost, the performance, or even the very existence of the end product we take for granted would be problematical were it not for a controller. One gets reminders of the existence of the controller, and hints of its complexity (automation systems themselves are complex engineering systems in a sense), on occasion. From a window seat on a commercial airliner encountering turbulence, for example, the subtle but effective movements of the wing flaps suggest that there's more to comfortable and reliable flight than meets the passenger's eye.

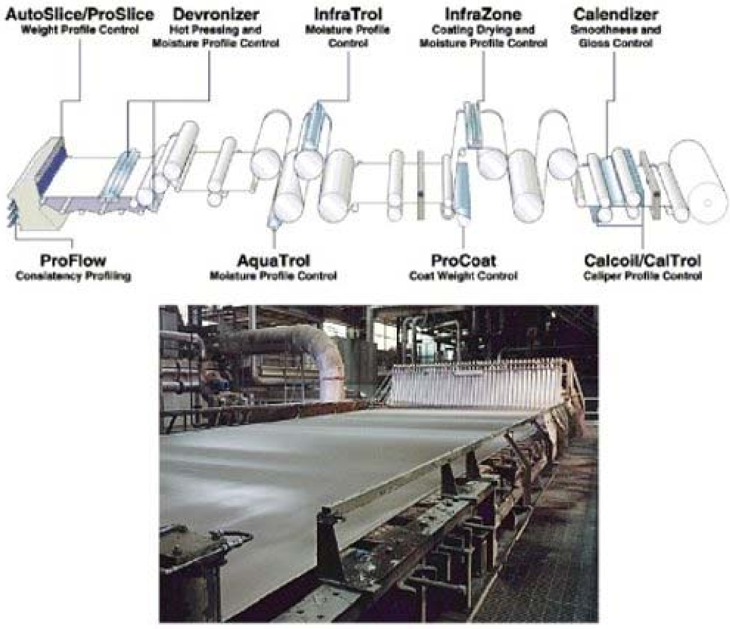

Figure 2: A schematic of a paper machine (top) showing some of the control equipment used to manufacture paper. The photograph shows a view looking toward the first stage of a machine. The machine shown is 200 meters long and the paper travels over 400 meters. (Figure courtesy of Greg Stewart, Honeywell Process Solutions.)

Fig. 2 illustrates a papermaking machine, a sophisticated, high-performance control system that is one of the unsung heroes of engineering. A high-end machine is a $100 million ticket item that extends well over the length of a football field and can produce over 100,000 tons of paper per year—that's one ton every five minutes. The paper is produced in a single, continuous sheet over ten meters wide that travels at over 100 km/h (over 60 mph) and is ultimately wound on a roller for subsequent cutting and packaging. This throughput is accomplished despite the fact that the input to the paper machine is water and wood pulp slurry that is over 99% water whereas the output is a sheet of paper the thickness of which is uniform to within microns (thousandths of a millimeter). The manufactured paper's areal weight (weight per unit area usually in grams per square meter (gsm)), moisture content, and other parameters are also tightly regulated. In order to achieve quality specifications and the rate of production, thousands of sensor readings and control actions are continuously being taken by the controller. The automation and control system provides the mechanisms and the "intelligence" to ensure that the actions are the right ones in particular situations, automatically taking into account variations in the input, the wear and tear of the machinery equipment, ambient temperatures and pressures, the current state of the paper sheet, and other intrinsic and extrinsic factors.

Given their performance, it should not occasion any surprise that automation and control systems are invariably specialized for the engineering systems they operate (typically with human supervision). Yet there is much in common among the different applications.

2.3. Sensing, Feedback, and Actuation

It is a truism that "We can only control what we can measure." Without quantitative measurements of temperatures, pressures, positions, velocities, flows, chemical concentrations, reflected light, and innumerably many other parameters, automation would not only be difficult; it would be impossible. Large industrial plants have thousands of *sensors* to ensure that the right measurements are available for monitoring and control.

Traditionally, sensors have been used for basic physical properties such as temperatures, pressures, flows, levels, positions, forces, and accelerations, but with advances in microelectromechanical systems (MEMS) and nanotechnology new vistas for sensing are opening up. For example, gas chromatographs (GCs) have been miniaturized to the point where they can be used online for detecting chemicals—potentially replacing the offline sample collection and lab analysis process required by today's GC systems.

The rapidly increasing quantity and variety of sensors are leading to the prospect of a "pervasive sensors" umbrella over oil refineries, commercial buildings, and the like. The parallel development of wireless communications is a key enabler in this trend—the largest cost of installing a sensor in a plant is usually the wiring.

Even with advances in physical sensors, it will continue to be the case that we may want to monitor and control parameters that we cannot directly measure, because sensors for the parameter do not exist or they are infeasible to use because of cost or installation difficulties. In such cases we often employ estimation algorithms to infer the property from the data that can be directly measured. *Inferential sensors* are even used for abstract properties such as occupant comfort in building control systems. Indeed, the International Standards Organization has adopted a thermal comfort index standard (ISO 7730) that specifies how comfort can be estimated from parameters such as room temperature and humidity.

The reason sensors and measurements are critical to control is that they provide *feedback* regarding the state of the plant to the controller. Actions taken at any time can thereby be informed by and customized for how the plant is operating relative to our objectives for it. A common feedback strategy is to compute the difference between what we want the plant's output to be and what it is measured to be, and use an algorithm to calculate what change should be made to the plant in order to reduce the discrepancy.

Calculating the optimal control action requires knowledge about how the plant will respond to different hypothetical actions. How does the rate of a chemical reaction that takes two feed inputs and produces a third desirable chemical vary as the reaction vessel is heated or cooled? How does a rudder movement affect an aircraft and how does this effect vary as a function of altitude and airspeed? How long does it take an infrared actuator on a paper machine to have a noticeable drying effect on the paper sheet? Not only do the answers to such questions need to be known, but the knowledge needs to be quantitatively precise. It isn't sufficient to assert that a rudder movement to the left will cause the aircraft to turn left; we need to know the probable motion over time of the aircraft. The answers inevitably depend on the specifics of the application—which chemical and at what concentration? What aircraft type and under what loading conditions? Which paper machine, with what slurry concentration and what kind of wood pulp?

This knowledge is expressed as *mathematical models* of plants. Models come in various types and can be obtained in different ways. They are also used in different ways. Sometimes, a model is used in the design of the controller but is not explicitly present in it—the calculations the controller performs have been designed (through automated or manual means) using the model but there may not be any separate module in the control system that contains the model. In other cases, the model is an explicit element of the controller and the controller's calculations rely on the model for predicting the plant's behavior to possible control actions. Model-based controllers are in general capable of better performance—faster response, better disturbance rejection, less energy expenditure—than non-model-based ones, and the exponential growth in solid-state electronics has resulted in these more memory- and computation-expensive designs becoming popular for a wide variety of problems.

Although feedback is often considered a prerequisite for control, not all control is feedback control. Most advanced control strategies also have a *feedforward* component. This allows actuation commands to be computed in advance based on assumptions of how the plant will behave. Feedback is necessary to ensure that correct responses are made to disturbances that arise unpredictably, but feedforward control, through its anticipatory mechanism, can improve the speed of operation of the plant.

Tolerating the uncertainties of the operating environment and the normal wear and tear of equipment is challenging enough, but in many cases we demand performance even under component failures and other faults.

A small oil refinery may have over 5,000 valves. The likelihood that they will all be functioning correctly at any moment in time is small, and yet the automation system must be able to manage the operation of the refinery at all times. Analogously, all modern twin-engine commercial aircraft are capable of flying safely if one engine fails—but obviously the control strategy used is very different than for the nominal plant. *Fault management* used to be largely a manual task, but it has steadily been automated and remains a high priority area for future automation developments.

Control is ultimately about action—affecting changes to the plant that attempt to modify its behavior in accordance with the objectives of its operators and owners. These changes are now computed by information processing algorithms, but they must be realized through physical devices, *actuators*.

Like sensors, actuators are becoming more sophisticated, with built-in calibration and diagnostic capabilities. Miniaturization trends are making an impact here too, especially in cases where the systems under control are small scale: computerized fuel injection in automobiles, LCD (liquid crystal display) projectors in conference rooms, biomedical implants in human patients, etc. In more conventional domains for control, where large volumes or forces must be handled, miniaturization is less relevant—the size of a valve controlling flow to a tank in a chemical plant or of the rudder in an aircraft must continue to be commensurate with the scale of the system.

3. Information Technology Elements of Automation

The sensing-control-actuation loop has always been at the conceptual heart of all control systems. When it comes to implementation, however, the information technology revolution has had a dramatic impact. Below we discuss the role, and evolution thereof, of several IT-related elements in automation and control.

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Biographical Sketch

Tariq Samad is a Corporate Fellow with Honeywell Automation and Control Solutions. He has been with various R&D organizations in Honeywell for 17 years, during which time he has been involved in a number of projects that have explored applications of intelligent systems and intelligent control technologies to domains such as autonomous aircraft, building and facility management, power system security, and process monitoring and control. He was editor-in-chief of *IEEE Control Systems Magazine*. His recent publications include the edited volumes *Automation, Control, and Complexity: An Integrated View* (Wiley), *Perspectives in Control: Technologies, Applications, New Directions* (IEEE Press), and *Software-Enabled Control: Information Technology for Dynamical Systems* (Wiley). He also holds 11 patents. Dr. Samad is the recipient of a Third Millennium Medal from IEEE, an Excellence Award for Technical Publications from the Society of Technical Communications, and a Distinguished Member Award from IEEE Control Systems Society, among other honors. He has given plenary and keynote presentations at several international conferences and he was the Program Chair for the 2004 IEEE International Symposium on Intelligent Control, Taiwan. Dr. Samad received a B.S. degree in Engineering and Applied Science from Yale University and M.S. and Ph.D. degrees in Electrical and Computer Engineering from Carnegie Mellon University.