PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Integrated Control of Industrial Systems

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Integrated control of industrial systems

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There is an increasing focus on the concept of integrated systems control in applications to industrial systems, e.g. chemical processing and steel. Motivating factors include (i) rising costs (and limited availability) of energy and various raw materials, (ii) competitive pressures to improve production efficiency, labour productivity, flexibility, etc., and (iii) more stringent government regulations concerning environmental impact and product quality. At the same time, the tools for effecting systems control (analytical techniques, systems methodology, computer hardware and software) have become increasingly powerful, reliable, and available. Here, control is considered in a very general context to include all aspects of decision-making applied to the operating system, ranging from process control to production scheduling and planning.

The digital computer plays a very central rôle in making feasible the modern industrial control system where it serves the functions of information processing, on-line control, and decision-making in real time through man-machine interaction. The hierarchical control approach provides a conceptual framework for organizing and implementing integrated control of large industrial systems. Various aspects of the control hierarchy are considered; these will be described in the context of integrated systems control applied to the steel industry.

Introduction

The traditional concept of control, applied to industrial systems, concerns the problem of how to manipulate inputs to the system so that (*a*) designated output variables follow predetermined time trajectories (which may be constants over finite intervals) or (*b*) the state vector of the system is transferred (optimally) from some initial value to a specified final value. However, there has been an increasing tendency to consider control from a broader and more general perspective. Strong contributing factors in this trend are (*a*) the increasing application of computers in process control, providing the hardware and software means for implementing more sophisticated control concepts, and (*b*) the growing awareness and acceptance of a 'systems approach' in the design and control of industrial process systems looking at the system as an integrated whole. A manifestation of this trend is given by figure 1 which indicates an exponential growth in the number of computer control installations by Japanese industry over the ten-year period from 1960 to 1970.

We adopt, for convenience, the term *control* to mean all aspects of control and decision-making that are applied to the industrial system operating in real-time, e.g. planning, scheduling, operations control, process control. The common characteristic of the control function, in the sense employed here, is the basing of actions, responses, decisions, etc. on information describing the state of the system (and its environment) interpreted through the medium of appropriate models relevant to system performance. By the same token, we will use *controller* to denote the means or agent by which the control/decision-making functions are carried out.

Performance of the system depends on a variety of factors including: (i) technological design of the system and its components; (ii) the nature of resources available and environmental constraints; (iii) the choice of operating conditions, allocation of resources, scheduling of operating sequences, etc.

The purpose of the control system, basically, is to make the best decisions with respect to (iii) within the limitations and constraints imposed by (i) and (ii).

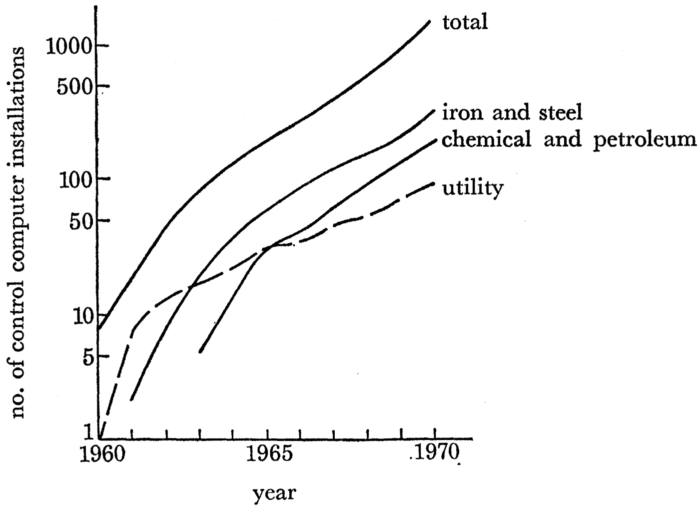

FIGURE 1. Computer control installations by Japanese industry over the period 1960 to 1970.

The steel industry represents perhaps the most advanced area of technology at the present time with respect to the application of an integrated systems control approach and in the use of computers for real-time information processing and decision-making. In addition, it is a very complex industry with a wide variety of different types of processing and manufacturing facilities and, hence, rich in the broad spectrum of systems and control problems found in industry. Thus, we have used the steel industry as the source of examples to illustrate the various concepts and approaches presented in this paper.

Figure 2 illustrates very schematically some of the production processes and operations involved in the steel making. Very briefly, iron ore and coke are heated to a high temperature in the blast furnace producing a very impure molten iron. In the steel making furnace, the iron is purified by burning off dissolved carbon and separating out other impurities. The molten steel may then be cast into ingots and subsequently rolled into various shapes called slabs, blooms and billets. These, in turn, are rolled into bars, plates, strip, etc. with the dimensions and metallurgical properties called for by the customer's order. An alternative route of the molten steel is to the continuous casting machines which produce slabs for subsequent rolling. In addition to the units referred to above, there are numerous storage yards for in-process inventory, furnaces to heat the steel to appropriate rolling temperatures, facilities for heat treating the steel, for cutting it into specified sizes and shapes, etc.

In fact, there is an exceedingly large number of operations, processes and procedures involved in the steel making and these are all strongly interactive and interdependent in their effects on the overall performance of the steel works. Thus, there is strong motivation for the integrated and computerized control system to be described here.

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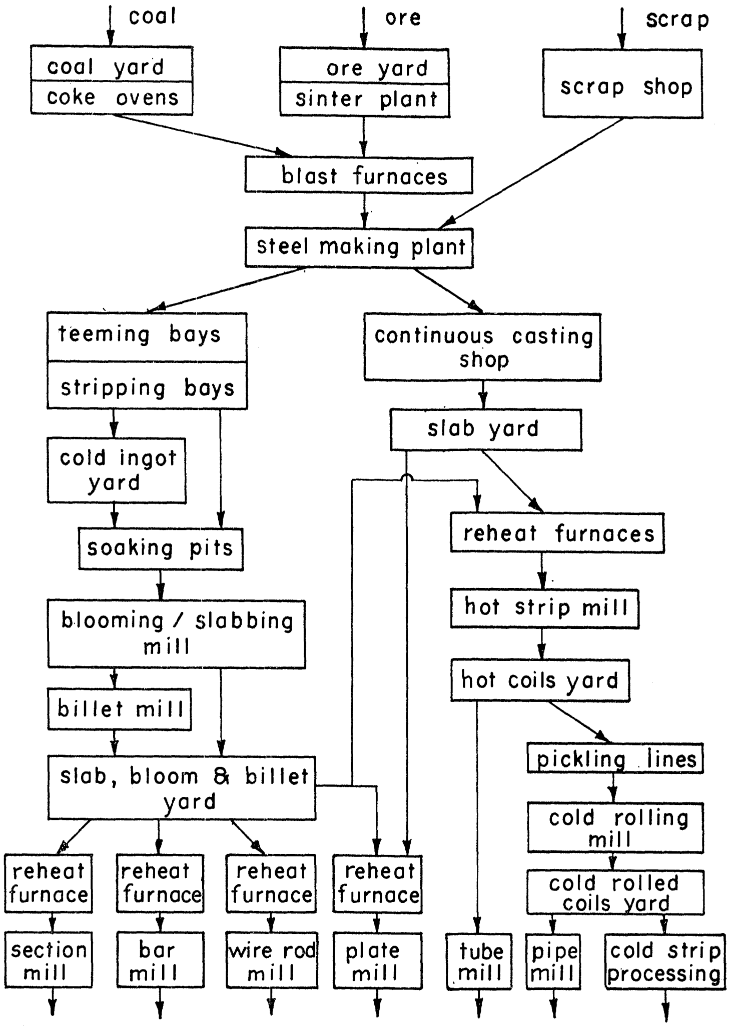

FIGURE 2. Production processes involved in steel making.

BASIC SYSTEM ELEMENTS

With respect to decision-making and control, we distinguish five basic elements of the system, identified as: plant, environment, performance evaluation, controller, information processor.

Plant

The term plant is used here to denote the controlled system or means of production. It may refer variously to a processing unit, a mill, a works or even the company, depending on the level of control being considered. We assume that the plant is governed by causal relations, i.e. its behaviour, relevant to our control objectives, may be described (in principle) by a set of input–output relations. We assume further, that some of the plant inputs are free to be selected by a decision-maker or controller so as to influence the plant's behaviour in a desired direction. Thus, we may classify the variables associated with the plant as follows:

(i) *Disturbance inputs*. These are inputs which represent the effects of interactions of the plant with its environment. In general, a disturbance input causes the plant output to deviate from desired or predicted behaviour and hence motivates control action. Some examples of disturbances are:

(*a*) The receipt of a new order may constitute a disturbance with respect to the scheduling operation if the order is of sufficient urgency and priority to require a modification of the previously determined schedule.

(*b*) A change in the size of slabs entering the reheat furnace will affect the heating pattern and may call for changes in the temperature settings of the various zones in the furnace in order to ensure that the slabs exit the furnace at the proper time and with the required temperature distribution.

(*c*) A delay in the availability of a soaking pit for charging of new ingots may affect the heating time and firing of the pit; it may also affect subsequent pit scheduling and mill throughput.

We also recognize a special class of disturbance which we call contingency occurrences. These refer to events, occurring at discrete points in time, which signal that the system is no longer operating according to assumptions implied by the current control or decision-making models. As a result, it is necessary to change the control objective, go into a new control mode, modify the structure of the system, or develop some other non-normal response. For example:

(*a*) The breakdown of a piece of equipment may cause the shutdown of the production unit it serves. This event may impact other units in the chain as well, necessitating routing and scheduling changes which may be more or less extensive. The local control objectives may change from say maximizing throughput to minimizing the time required to get back on stream.

(*b*) A failure of the finished product to meet order specifications will induce effects throughout the system as a result of efforts to redo the order and to reassign (or recycle) the 'off-spec' production.

We comment that while the compensation for disturbance inputs may be carried out either manually or automatically, the handling of contingency events is almost always under human supervision, even in the most advanced current systems. Indeed, as the system becomes more automated, the rôle of the operator focuses more and more on his responsibility for detecting and responding to contingency occurrences.

(ii) *Controlled inputs* (or decision variables). These are the results of the decision-making or control process carried out by the controller with respect to the plant. There are a variety of ways that these results may be communicated to the plant; in general, they modify the relations among the plant variables through physical actions on the plant performed either directly or indirectly. As examples, we may cite:

(*a*) Varying the fuel flow to a furnace changes the energy balance in the furnace, thereby causing the temperature to change in a desired direction.

(*b*) Changing the roll displacement on the rolling mill changes the compressive forces acting on the steel strip and consequently the strip thickness.

(*c*) Changing the sequence of slabs being rolled may affect the delivery date of a particular order as well as the performance of the rolling mill and subsequent operations.

(iii) *Outputs*. These are variables of the plant which are:

(*a*) functionally dependent on the designated input variables,

(*b*) used by the controller in determining its decisions or control actions, (*c*) relevant with respect to the evaluation of plant performance or the assessment of the effectiveness of a particular policy or action, and

(*d*) available as explicit values or functions of time either through direct measurement or through inference (via a model) from the measurement of other variables.

As illustration, we may consider furnace temperature as an output variable in the problem of temperature control of the slab heating furnace. The temperature is dependent upon the firing rate (controlled input) as well as various load disturbances (changes in slab dimensions and thermal characteristics.) In particular, the furnace temperature can be measured by means of a thermocouple or radiation pyrometer and used by the controller to determine how to vary the firing rate in order that the furnace be maintained at a proper temperature level. It is assumed that any departure from this prescribed level will adversely affect the performance of the system in that the slabs will not reach the temperature required for the subsequent rolling operation, or that the steel quality will be impaired through overheating of the surface, or furnace efficiency will be degraded because of excessive heat losses or wear of the refractory lining. Note that if the heat content or the average temperature of the slab is the output variable under consideration, it may have to be determined by inference through a heat transfer model for the slab, using measured values of the external temperature as input.

We comment that the classification of a particular variable may depend on the nature and level of the decision-making process under consideration. For example, while furnace temperature is an output with respect to the temperature control system referred to above, it serves as an input with respect to slab discharge temperature, and it is only implicitly incorporated in the parameters of the capacity model used in scheduling the furnace.

(iv) *State variables*. In essence, these are variables associated with the memory characteristics of the plant. In the case of deterministic, dynamic systems, the state vector compacts the relevant past history of the plant, such that, knowing the inputs to the plant over a given time interval, the outputs are determined uniquely over that same period. More generally, the state vector may identify the status of energy or material storages in the system, as for example, the number of slabs of each type stored in the slab yard, the current stage in its operating cycle of a production unit, and other factors which are necessary to the identification of the appropriate input–output model currently applicable.

Thus, we imply a plant model of the general form

$$y = g_s(m, z) \tag{1}$$

where y, m, z denote vectors of output variables, controlled inputs, and disturbance inputs, respectively. Here $g_s(\cdot)$ denotes a vector of functional relations indexed on the state s; these may be expressed in the form of algebraic functions, integral equations, graphs, tabulated data, or other form appropriate to the application. The variables may be continuous or discrete functions of time; they may be real-valued, integer-valued (e.g. quantized data) or Boolean-valued. The model may be developed theoretically or empirically. In the former case, we invoke known principles and relations of physics, electrical engineering, etc. to derive analytical expressions of the form of equation (1). In the latter case, we employ methods of experimental design, correlation analysis, regression, etc. to develop the desired input–output characterizations. Often we arrive at the desired result through a combination of the two approaches: theoretical analysis yields the form of the relation and identifies the dominant factors, while regression or correlation techniques are used to evaluate the parameters of the model. The models used in the integrated control systems are often simple linear algebraic equations of the form

$$y_i = \sum_{j=1}^{M} a_{ij}\, m_j + \sum_{j=1}^{Z} b_{ij}\, z_j \quad (i = 1, 2, \ldots, Y)$$

where the a_{ij} and b_{ij} are the (constant) parameters of the model, $m_1, m_2, \ldots, m_M$ denote the controlled inputs, $z_1, z_2, \ldots, z_Z$ are the disturbance inputs, and $y_1, y_2, \ldots, y_Y$ are the outputs under consideration. If the plant operates in multiple modes or states, there will be a parameter set corresponding to each state; these parameter values can be stored in the computer data base and recalled as needed.

The linear model may indeed reflect a linear relation of the plant, as for example, in a material balance model where y represents the composition of a mixture or blend and $m_1, m_2, \ldots$ represent the amounts or flowrates of the various raw materials, with the coefficients (a_{ij}) corresponding to the relative concentrations of the components of the input materials. More generally, the linear equation is an approximation to a nonlinear relation where the variables represent changes from a norm or reference condition. In this case, the coefficients of the equations are sensitivity factors; for example, a_{ij} represents the effect on the output y_i of a unit change in the input m_j. Such linear approximations are valid only when the operating conditions remain reasonably close to the established norms or to the conditions under which the coefficients were evaluated.

The algebraic model implies static or steady-state characteristics of the plant. Occasionally a dynamic model is required as when the plant is a batch or time-cycled process and we are interested in its time-varying behaviour. The steel making furnace is a case in point and a dynamic model based on differential equations (or difference equations in the discrete formulation) are used in some end-point control algorithms. Incidentally, the set of initial conditions required for the solution of the differential (difference) equations plays the rôle of the state vector in such models.

In operations control applications, the models may take the form of logic or Boolean relationships. For example, in the transfer of ingots to soaking pits, the model must describe the availability of cranes and pits, the allowable transfer paths and the sequence of operations (and constraints) necessary to implement the transfer.

Finally, many of the models employed are simply tabulations of prodution standards and operating instructions which have been determined on the basis of prior experience and which are stored in the computer data base. When an order is received, the first step in the processing of the order is to determine whether the necessary operating instructions are already on file; if so, they may be recalled from the data base to provide the detailed specifications concerning the chemical composition, metallurgical procedures, mill operations, etc. which are to be implemented – these provide the set points for the process controllers and the targets for the operations control functions.

Environment

The plant is a subsystem of a larger system which we term the environment, i.e. all aspects of the external world that interact with the plant and affect its performance with respect to the control objectives.

The interactions are of two basic types:

(*a*) inputs to the plant which change its state or affect its behaviour; we have already referred to these as disturbance inputs;

(*b*) inputs that affect the objectives or the constraints to be applied by the controller acting on the plant, e.g. order specifications.

The characterization of the environment depends on the nature of the control function as well as on what is being considered as the plant. Thus, with respect to control of the steel making furnace, we are concerned with those externalities that affect the grade of steel and the cycle times (e.g. scrap composition). At the production scheduling level, the hot strip mill and blast furnace subsystems are major components of the environment of the steel making subsystem. At the planning level, the environment is dominated by the market as it reflects the demand for different types of products, the costs and availability of raw materials, etc.

In general, the objectives that should be achieved by the plant during future operations are estimated through an analysis of the environment and a forecasting of its future interaction (e.g. demand). There are a variety of techniques routinely applied in current planning systems for forecasting product demand, economic factors, etc.; these include trend analysis, regression, exponential smoothing algorithms, correlation methods, spectral analysis, etc.

Performance evaluation

In the design of the decision-making/control system, it is necessary to have defined the criteria for measuring and evaluating plant performance in order that appropriate references or targets for control may be established. At the technological level, we may consider objectives of:

(*a*) maximizing production efficiency,

(*b*) minimizing operating costs,

(*c*) maximizing probability of maintaining the plant in a feasible or acceptable operating régime,

(*d*) minimizing the likelihood of failure of the system to perform to standards, e.g. failure to satisfy product specifications or environmental constraints.

In practice, the performance criteria used in formulating the decision-making and control algorithms for real-time application are generally simplifications of the above, reflecting the dominant factors entering into the performance measure. Thus, the control associated with a particular unit may act to maximize product yield, throughput rate, or thermal efficiency, or to minimize the consumption of a costly resource, the frequency of quality rejects, or deviations from standards.

At the economic level, objectives for decision-making may include maximizing profit, return on investment and related indices. Again, the practical criteria will be based generally on approximations and simplifications which are motivated by computational requirements, the form and accuracy of the models used, the nature of the information required and the reliability of the data available.

We assume that the performance may be expressed as a function of the system input and output variables, i.e.

$$P = f(m, y, z, w), \tag{2}$$

where m, y, z are defined as in equation (1); w denotes the vector of external inputs affecting performance, e.g. economic factors, product/order specifications, government constraints, etc. Since the system may exhibit significant dynamics (memory effects), the performance measure should represent an integration of plant behaviour over a time period which is large with respect to the effective time lag of the system response. Thus, there will be random components of the

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

variables represented in equation (2) and we imply by the notation $\bar{f}(\cdot)$ that a suitable averaging is carried out over the relevant time horizon.

Controller

In a general sense, the purpose of the controller is to generate the control inputs m applied to the plant which result in a maximum of the performance P while satisfying the variety of constraints imposed on the system. The constraints define the region of feasible or acceptable plant operation. They may characterize actual technological limits of the equipment or of the production process, e.g. the capacity limit of a machine, or the melting temperature of slabs (with respect to the reheat furnace). Constraints are also imposed to ensure the safety of operating personnel or the security of the production means, e.g. temperature limits imposed on a furnace in order to avoid too rapid deterioration of the refractory lining. Finally, we impose constraints to ensure that various quality requirements are met, e.g. product specifications, effluent pollution restrictions, etc.

Two modes of controller action may be identified:

(*a*) Programmed mode where the controlled inputs are established in advance based on given demands on the system or requirements of plant performance.

(*b*) Compensation mode where the controlled inputs are determined so as to compensate for the effects of disturbances. Their determination may be based on (i) measurement of the disturbance input and prediction of its ultimate effect on the plant (feed forward action) or (ii) measurement of the effect of the disturbance on the plant outputs directly (feedback action), or more generally, (iii) a combination of both.

As an example of the programmed mode, the specifications on a given order are translated into sets of operating instructions and constraints which are transmitted to the steel making, rolling, annealing and other production processes involved in manufacturing the order; these provide the set points, targets and operation sequences to be implemented by the local controllers.

We note that the programmed mode is essentially open loop; however, there are various feedbacks superimposed in practical applications as, for example,

(*a*) The roll settings for the hot strip mill are preprogrammed according to information on slab size, steel grade and strip gauge; adjustment of the settings may be based on the feedback of actual reductions achieved.

(*b*) The operating instructions and standards are updated periodically (or as required) based on production experiences and evaluations of system performance.

Examples of the compensation mode of control include (*a*) variation of the fuel flow to the furnace to maintain the temperature constant by compensating for changes in the thermal load, (*b*) adjusting operating conditions on the steel furnace cycle based on composition measurements of previous heats, (*c*) updating of a production plan according to the results achieved over the preceding planning period.

Note that the realization of the control function may take a variety of forms. Indeed, from the standpoint of plant performance, it is immaterial how the transformations from input information to output decisions/control actions are carried out (i.e. whether by algebraic solution of a set of equations, by hill climbing on a fast-time simulation, or simply by table look-up) except as the method might affect the accuracy, the cost or the speed with which the controller outputs its results. By the same token, the control functions may be performed by man, by machine (computer) or more generally, by an intersection of both.

The advanced applications of integrated systems control represent an integration of humans (operators, schedulers, planners) with computers serving control and information processing functions. The functions performed by man include those requiring judgements that cannot be standardized, or decision processes that have not been adequately established, or coordinations that involve the integration of a great many factors whose subtleties or non-quantifiable attributes defy computer implementation. The functions performed by computers are essentially those where the tasks are routine and well-defined and where the operating standards are quantified and established. Thus, the main planning and coordination functions are carried out by humans, with computers providing the basic information on which the operator's judgement and decisions are based. The computer is involved in the gathering, processing and dissemination of data, the distribution of operating instructions and the implementation of controls and operations at the technological level. In addition, as noted earlier, the responsibility for responding to contingency occurrences and special requirements rests generally with the human component of the system.

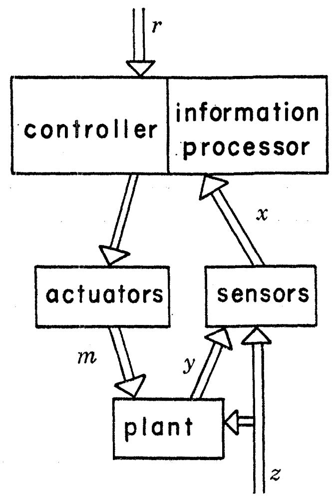

FIGURE 3. Basic elements of control system.

Information processor

As noted above, the underlying assumption in the achievement of integrated control is that the controller acts on the basis of (real-time) information concerning the state of the plant, external inputs, etc. We may distinguish several major functions of the information system:

(*a*) The gathering of data and its distribution to points of usage (including sensors, data input devices, transmission links, data banks, etc.).

(*b*) The reduction (interpretation) of raw data into the form required by the decision-making/control function, e.g. (i) data smoothing, (ii) noise filtering, (iii) prediction and extrapolation, (iv) inference of the value of a variable from indirect measurements, etc.

(*c*) The monitoring of system status for contingency events to determine whether diagnostic and/or corrective responses are to be initiated.

(*d*) Presentation of information for the people interfacing the system, e.g. monitoring and control actions by operating personnel, decision-making by management, diagnostics for maintenance and corrective actions, record keeping, accounting purposes, etc.

(*e*) The storage and retrieval of operating instructions, standards, parameter values, and other information required for the functioning of the operating system.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

A block diagram representation of the relation of the controller to the plant is given in figure 3. Current values of the output variables (feedback action) and some of the disturbance variables z (for feed forward actions) are transmitted to the controller by means of sensors or measuring devices. The raw information set x may be further processed (filtered, smoothed, transformed, etc.) by the information processor. The controller generates its outputs according to the current information concerning y and z, in relation to the input r which defines the desired behaviour of the plant, e.g. provides the set-point values at which certain output variables are to be maintained. Finally, the controller must communicate its decisions/actions to the plant – and this is the rôle of the actuator. The elements represented in figure 3 are basic to all control functions and are embedded within each of the hierarchical control structures to be described below.

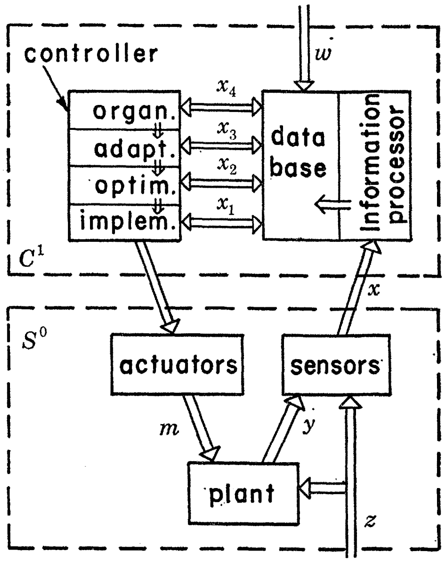

FIGURE 4. Multilayer functional hierarchy.

MULTILAYER FUNCTIONAL HIERARCHY

The problems of realization and implementation of an integrated control are generally formidable because of the complexity of the system, the variety of constraints to be satisfied, time-varying behaviour, etc. The multilayer functional hierarchy of figure 4 provides a rational and systematic procedure for resolving these problems. In effect, the overall problem is replaced by a set of subproblems which are more amenable to resolution than the original problem. These subproblems are identified by the four layers of the functional hierarchy, namely: implementation, optimization, adaptation, and organization layers. We describe the structure as follows:

(1) The control objective is expressed:

$$\max_{u \in U_s} P_s(u, x_2), \tag{3}$$

where $$U_s = \{u | G_s(u, x_2, \alpha_2) = 0, H_s(u, x_2, \alpha_2) \geqslant 0\},$$

$$x_2 = \phi_2(y^*, z^*, w, \beta). \tag{4}$$

(2) The vector x_2 characterizes the information from the plant used by the second-layer controller in generating its output u. Equation (4) represents a data processing function (e.g. prediction, averaging, aggregating) based on the measured components of y and z, denoted by y^* and z^*, respectively. The function ϕ_2 may have a (adjustable) parameter vector β (e.g. based on estimated statistical properties of z) which may be adapted to reflect changing conditions.

(3) The plant is described by the approximate model

$$G_s(u, x_2, \alpha_2) = 0. \tag{5}$$

The functions G_s are simplified approximations to the actual plant relations (equation (1)) with the parameter vector, α_2 properly chosen to give a good representation. Note that equation (5) characterizes the input–output model of the combined system consisting of the plant, actuators and measuring elements as seen by the second layer function. The subscript s indexes the state or mode of operation of the plant as identified by the organizational layer.

(4) The first-layer (direct control) function plays the rôle of implementing the decision of the second-layer function, expressed as the vector u. This implies the first-layer relation,

$$m = m(x_1, u, \alpha_1), \tag{6}$$

where x_1 denotes the information used in implementing the direct control function, α_1 is the set of parameters associated with the first-layer algorithms.

There are two useful consequences of equation (6):

(*a*) Various disturbance inputs may be suppressed with respect to the second-layer problem, thereby simplifying the optimizing control model.

(*b*) The dynamic aspects of the control problem may be effectively 'absorbed' at the first layer so that static models can be used at the higher layers to good approximation.

(5) The vector function H_s often includes, besides those constraints necessary to ensure safe and feasible operation of the physical system, various artificial constraints whose primary function is to maintain the system within the limited region of operating space for which the approximate model is valid (and hence useful). It is assumed, of course, that the imposition of such constraints will not result in any significant diminishing of the attainable performance. An example of this is the placing of bounds on the maximum rate of change of temperature in the final zone of a reheat furnace so that the assumption of slab homogeneity (on which subsequent slab rolling models are based) is reasonable.

(6) The decision algorithm may be based on (i) an explicit (mathematical) model, e.g. a set of input–output relations for the subsystem from which the algorithm is derived via an optimization procedure, or (ii) an implicit model, e.g. a decision (look-up) table based on empirical rules. In either case, the algorithm is based on some simplified, approximate image of the physical system which is valid only in the neighbourhood of a given 'state' or set of circumstances. As these change with time, it is necessary to update the algorithm, either directly by adjusting some of its parameters, or indirectly via the parameters of the underlying model. The updating is carried out by the third-layer adaptive function in response to current experience with the operating system as conveyed through the information set x_3. This means that we can eliminate from the problem formulation of equation (3) those factors or disturbance inputs which tend to change infrequently relative to the period of control action (e.g. fouling of a heat transfer surface, seasonal variations in cooling water temperature, changes in mill characteristics), since they may be compensated through the adaptive functions.

(7) The external (economic) factors contained in w are controller inputted via the data base. Changes in w may influence the weighting of terms in P_s or some of the bounds imbedded in H_s. More generally, the evaluation of performance (through the information set x_4) may lead to modifications in the structure of the control system, e.g. in the constraint set U_s. Finally, we note that contingency events may also lead to changes in the system relations or the objective function (manifest as changes in U and/or P), e.g. the shift from normal operation of a mill to an emergency mode following a cobble or breakdown.

(8) There is a large variety of ancillary tasks normally carried out in conjunction with the control functions identified in the multilayer hierarchy. These might be looked upon as 'enabling' functions that are deemed necessary or useful to the pursuit of the overall system goals. Indeed, the provision for such tasks is often a very significant factor in determining hardware and software requirements in computer control applications. Among such ancillary functions we include:

(i) data gathering (filtering, smoothing, data reduction),

(iii) record keeping (for plant operator, production control, management information, accounting, etc.),

(iii) inventory maintenance (e.g. keeping track of goods in process),

(iv) sequencing of operations (e.g. startup/shutdown operations, slab transfer operations).

The essential feature of these functions is that they are routine, repetitive and open-loop, hence, they can be handled by stored programs and fixed hardware. Considerations of decision-making and control may come into the picture at the higher layers, however, with respect to modifying the procedures, operating sequences, etc., based on evaluation of performance or in response to contingency occurrences.

Multilevel control hierarchy

We consider again the optimization problem (3) reformulated for convenience as follows:

$$\max_{u \in U(z)} f(u, y, z), \tag{7}$$

where $U(z) = \{u | y = g(u, z), h(u, y, z) \geq 0\}$, f is the measure of overall performance (objective function), u is the vector of decision variables (controller outputs), y is the vector of plant outputs, z is the vector of disturbance inputs, $U(z)$ denotes the feasibility set (conditional on z), and g and h denote vectors of equality and inequality constraints, respectively.

We assume that the problem (7) has a solution, $u^0(z)$; however, despite the simplifications introduced into the model via the multilayer approach, the solution is still too difficult or too costly to obtain directly in a form suitable for on-line implementation (limiting factors may include excessive computation time, inadequate storage capacity of the available computer, complexity of the program with respect to maintenance and reliability, etc.). The multilevel approach, where applicable, provides a means of circumventing the difficulty by decomposing the overall problem into a number of simpler and more easily solved subproblems. Thus, in application to the problem (7), we assume that the functions are separable in the sense that they can be decomposed into N subproblems as follows:

ith subproblem:

$$\max_{u_i \in U_i} f_i(u_i, y_i, q_i, z_i) \quad (i = 1, 2, \ldots, N),$$

where
$$U_i = \{u_i | y_i = g_i(u_i, q_i, z_i), h_i(u_i, q_i, z_i) \geqslant 0\}, \tag{8}$$
subject to the interaction constraints,
$$q_i = \sum_{j=1}^{N} T_{ij}\, y_j \quad (i = 1, 2, \ldots, N). \tag{9}$$
The variables are identified with reference to figure 5. Except for the q_i, the notation follows that of equation (7) with the modification that the subscript i particularizes the vectors and functions to the ith subsystem. The vector q_i denotes the inputs to subsystem i which are the result of its interactions with other subsystems. These interaction inputs may be expressed in the form of equation (9) where the T_{ij} are matrices of zeros and ones which couple the components of q_i with the appropriate components of y_j, $j \neq i$. It is assumed further that,
$$f(u, y, z) = \sum_{i=1}^{N} f_i(u_i, y_i, q_i, z_i) \tag{10}$$
when q_i is given by equation (9), and that a solution satisfying the constraint sets U_i, $i = 1, 2, \ldots, N$, simultaneous with the interaction constraints (9) will also satisfy the overall constraint set U. The subsystem problems are solved at the first level of control. However, the subsystems are coupled and interacting, hence these solutions have no meaning unless the interaction constraints are simultaneously satisfied. This is the coordination problem that is solved at the second level of the hierarchy.

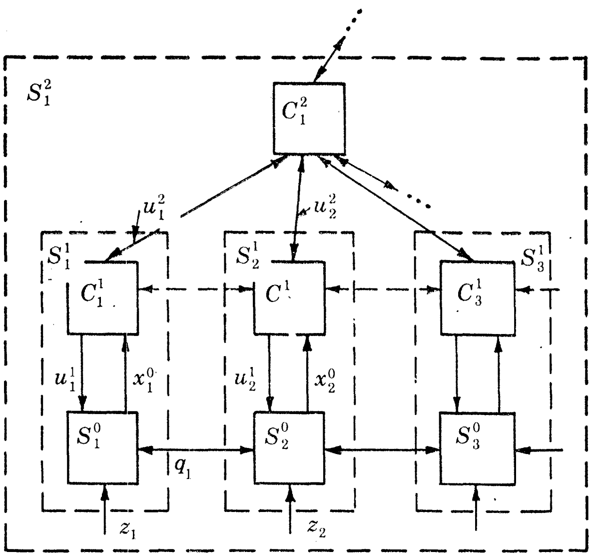

FIGURE 5. Multilevel control hierarchy.

A variety of coordination schemes have been described in the literature (Mesarovic 1970; Wismer 1971; Himmelblau 1973). The methods are similar in the sense that they serve to motivate an iterative procedure for solution of an optimization problem wherein a set of local subproblems are solved at the first level in terms of a set of parameters specified by the second level. They may differ, however, in their applicability to a specific problem, in the computation requirements, convergence speed, sensitivity to model error, incorporation on-line, and other considerations.

On-line control application

As far as the plant is concerned, it is only the final result of the iterative process that is important, i.e. the functional relation $u^0(z)$ that is established. Thus, the entire multilevel structure is internal to the computational block generating the optimum control. However, in the on-line application, the computation depends on the current value of z and this changes with time.

If the system is decomposed along lines of weak interaction and if the coordination scheme is selected so that intermediate results are always plant feasible, then the multilevel structure provides the basis for a decentralized control wherein (see Lasdon & Schoeffler 1966):

(*a*) The first-level controllers compensate for local effects of the disturbances, e.g. maintain local performance close to the optimum while ensuring that local constraints are not violated.

(*b*) The second-level controller modifies the criteria and/or the constraints for the first-level controllers in response to changing requirements on the system so that actions of the local controllers are consistent with the overall objectives of the system.

(*c*) The second-level controller compensates for the mean effects of variations in the interaction variables.

The decentralized scheme provides the following advantages:

(*a*) A reduction in the total computational effort because of less frequent second-level action.

(*b*) A reduction in data transmission requirements because (i) most of the control tasks are handled locally, (ii) much of the information required at the second level consists of averaged, aggregated data, and (iii) the upper level action takes place at lower frequency.

(*c*) A reduction of development costs for the system by virtue of the fact that the models, control algorithms, and computer software can be developed in a step-by-step, semi-independent fashion. By the same token, the problems of system maintenance, modifying and debugging programs, etc. are considerably simplified.

(*d*) There is increased system reliability because (i) a computer malfunction at the first level need only affect the local subsystem, and (ii) the system can operate in a suboptimal but feasible mode for some time in the event of a failure of the second-level computer.

Weak interaction linkages are readily motivated in industrial process systems because the plants are composed typically of interconnections of semi-independent processing units. The interaction may be further weakened by design; for example:

(*a*) The introduction of storage units between subsystems serves to buffer one from the other. This is common practice in the steel industry as evidenced by the presence of slab yards, coil yards, etc.

(*b*) Key interaction variables may be independently controlled to reduce their variations. Examples here include ore blending to minimize the variability of ore feed to the blast furnace, the grouping of slabs scheduled for the reheat furnace to minimize size variations from slab to slab (which affects the time required for heating a slab to its desired temperature).

(*c*) The local controllers may be designed to reduce the sensitivities of select output variables to local disturbances, thereby maintaining interaction effects relatively invariant. For example, temperature control of the slab furnace reduces the variation of slab temperatures from target values and hence decouples various furnace disturbances from the downstream rolling operation.

We remark that the measures taken to decouple the subsystems are not without cost (both capital and operating). For example, increased storage tends to reduce the coupling between successive production units at the expense, however, of increased costs associated with in-process inventory, material tracking and handling, and product deterioration.

Applications

There is a variety of applications of the multilevel concept in steel making; indeed, industrial systems have tended to evolve along well-defined hierarchical structures based on the characteristics of the technological processes involved and on the management organization. This is illustrated in figure 6 which shows the sequence of major processing units in going from iron to steel strip product. Each unit is controlled by a local scheduler/controller with overall coordination performed by the production scheduler.

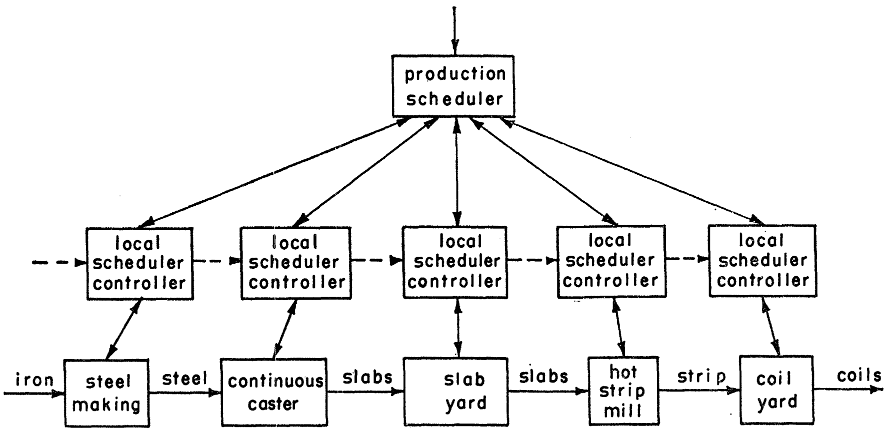

FIGURE 6. Application of multilevel control structure in steel making.

Two examples of multilevel coordination are cited:

(1) The wear of the working and backup rolls of the hot strip mill impose constraints on the allowable sequence of strip widths and thicknesses that may be rolled between successive roll changes. Deviations from this sequence result in either degraded strip surface quality or reduced mill production, both undesirable with respect to mill performance. In order to follow the prescribed sequence (and still meet delivery commitments, etc.) slabs of different sizes and grades are often required. However, the steel shop scheduler wants to minimize the number of grade changes because of the increased likelihood of off-standard heats during the transition from one grade to another. Similarly, there is a significant set-up cost associated with changing slab dimensions on the continuous casting machine, hence, the slabbing department wants to minimize the frequency of slab changes. An alternative is to provide more storage of slabs in the slab yard but, as we have already stated, this may increase slab yard costs. Thus, we have a rôle for a higher level production scheduler that reconciles the conflicting (local) objectives of these interacting production units to satisfy overall objectives and constraints.

(2) When the demand for steel exceeds the total capacities of the blast furnaces, or of the steel making facilities it is necessary to allocate the steel among the various product types and mills (strip, plate, sections, etc.) The supremal unit determines an allocation which attempts to maximize overall performance (say company profit); the infimal units operate to minimize costs subject to constraints of order due dates, specifications, etc. Feedback of infimal

performances, constraint violations, etc. provide the supremal unit with inputs on the basis of which the allocation rule may be improved.

We make two final remarks:

(1) The multilevel structure extends in an obvious fashion to a hierarchy of three or more levels with each supremal unit coordinating the actions of a group of infimal units according to the same principles as described above. Figure 5 illustrates a multilevel structure with C^i_j denoting the jth controller at the ith level, and S^i_j representing the jth subsystem with respect to the ith level. Note that the structure of infimal units may be collapsed to an equivalent single level structure, e.g. controller C^2_1 'sees' its infimal units as subsystems S^1_1, S^1_2, etc.

(2) The multilevel control hierarchy is particularly compatible with the trend to distributed computer control structures based on minicomputers and microprocessors performing dedicated tasks which are coordinated through the systems integration.

Temporal control hierarchy

As we remarked in the discussion on the multilevel control hierarchy, the structure induces an ordering with respect to time scale; specifically, the mean period of control action tends to increase as we proceed from a lower to a higher level of the hierarchy. In addition, any controller within the multilevel structure may itself represent a series of control tasks that tend to be carried out with different frequencies or time priorities. This motivates the concept of a temporal control hierarchy wherein a control or decision-making problem is partitioned into subproblems based on the different time scales relevant to the associated action functions. These time scales reflect such factors as:

(1) The minimum time period required for obtaining the necessary information, e.g. the determination of statistical parameters require sufficiently long data records to be meaningful; the composition of a heat is available only after completion of the steel-making cycle.

(2) The minimum time period for the system to respond to prior actions, e.g. the dominant time constant for a continuous process, the construction time for a new plant or equipment installations.

(3) Time-varying characteristics of the disturbance inputs as displayed by bandwidth properties, mean time between discrete changes in input conditions, etc. (e.g. seasonal and diurnal changes in cooling water temperature, mean time between receipt of an order requiring special processing).

(4) Minimum time horizon for which the solution to the control problem has meaning.

(5) Trade-off considerations relating the benefit of control action to its cost.

An example of a set of control functions distinguished by their temporal attributes is provided by the hot strip mill. The mill rolls are replaced periodically because of wear – the back-up rolls are changed on a cycle of eight to ten days and the working rolls on a six-to eight-hour cycle. With each roll change, there is set in motion a sequence of events by which the mill goes from its normal operating mode to a roll change mode and back again, with the attendant shutdown and start-up procedures. The roll change also affects the sequencing of slabs over the subsequent operating periods. The advent of each new order, involving perhaps a great many slabs, requires new mill instructions and set-ups determined by the order specifications and other factors. As each individual slab enters the mill it initiates a series of actions relating to roll settings, speeds, etc. Finally, various feedback mechanisms apply in almost continuous action to maintain the tension, thickness and temperature of the steel strip at critical points in the mill at predetermined values. Thus, there is a broad spectrum of control and decision-making activities ranging in time scale from seconds to weeks and these activities interact in a special way because of the temporal relations.

A second example, of particular relevance to our discussion of the temporal control hierarchy, is provided by the planning and scheduling operations. Thus, common to much of the industry is an articulation of planning functions with progressively shorter time horizons, e.g. ten years, five years, annual, monthly, weekly, daily, shift, hourly. Besides the obvious ordering with respect to time scale, there are related characteristics that have to do with the form of the model, the degree of uncertainty involved in the decision-making, the level of aggregation, the information flow requirements, etc. These are discussed further below.

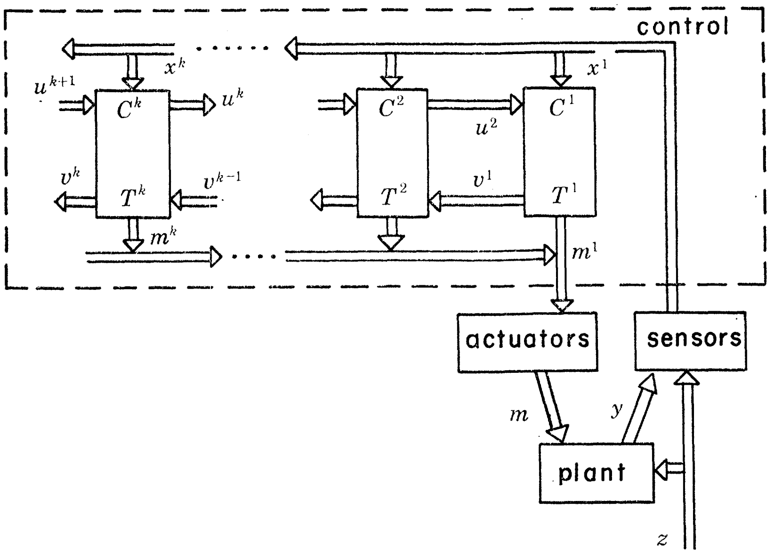

FIGURE 7. Temporal control hierarchy.

Figure 7 shows the basic structure of the temporal control hierarchy. It is assumed that the control problem is partitioned to form an L layer hierarchy where C^k, the kth layer control function, generates a decision or control action every T^k units of time (on average)†, with

$$T^{k+1} > T^k \quad (k = 1, 2, \dots, L-1).$$

Associated with the kth layer control function are the following inputs and outputs:

x^k: information set describing the state of the plant and environmental factors relevant to the kth layer decision process.

u^{k+1}: decisions of the $(k+1)$th layer controller that exert priority over the kth layer control process; in particular, u^{k+1} provides targets and/or constraints for the kth layer problem such that the actions of C^k are consistent with goals set for the overall problem.

v^{k-1}: information from the infimal unit C^{k-1} relevant to the kth layer function, e.g. feedback of the results of prior actions of C^k.

m^k: actions of the kth layer controller applied directly to the plant; tasks to be carried out in conjunction with the control output u^k.

† In the case of a periodic control policy, T^k is predetermined and constant. For an on-demand policy, T^k denotes the mean period of kth layer action. For convenience, we assume T^k is constant in the analysis that follows.

Let t^k denote the most recent time, prior to some specified time t, at which a kth layer control action has occurred. We assume that a kth layer action automatically triggers actions at all lower layers in order to ensure consistency with the notion that C^k exerts priority over C^{k-1}. Accordingly, we have the ordering,

$$t^{k+1} \leqslant t^k \leqslant t < t^k + T^k \leqslant t^{k+1} + T^{k+1}, \ (k = 1, 2, \ldots, L-1).$$

At time t^k, the kth layer controller generates the output $u^k(t^k)$ based on input information currently available, Thus,

$$u^k(t^k) = f^k[u^{k+1}(t^{k+1}), \ x^k(t^k), v^{k-1}(t^k)].$$

The control u^k is assumed to remain fixed over the time interval $(t^k, t^k + T^k)$ at the value† determined at time t^k, i.e.

$$u^k(t) = u^k(t^k), \quad t^k \leqslant t < t^k + T^k.$$

In a similar manner, the temporal structure implies the relations,

$$v^k(t^k) = g^k[x^k(t^k), \quad v^{k-1}(t^k)],$$

$$m^k(t) = h^k[u^k(t^k)], \quad t \in [t^k, t^k + T^k].$$

We assume further that the information set $x^k(t^k)$ is obtained by measurement of various plant inputs and outputs that are important to the kth layer action (and are available); in particular,

$$x^k(t^k) = \theta^k[\bar{y}^k(t^k), \quad \bar{z}^k(t^k)],$$

where $\bar{y}^k(t^k)$ and $\bar{z}^k(t^k)$ denote, respectively, the subsets of plant outputs and external inputs, averaged over the interval $[t^k - T^k, t^k]$, that are observed and are relevant to C^k. Since y^k is functionally related to the inputs m^k and z^k via the plant model, we have also

$$x^k(t^k) = \phi^k[\overline{m}^k(t^k), \quad \bar{z}^k(t^k)],$$

where z^k denotes the subset of environmental inputs to the plant that are significant in their effect on the kth layer decision process. The over bar again denotes an averaging or aggregating process over the interval $[t^k—T^k, t^k]$. Thus, the external inputs to the system (disturbances, order inputs, etc.), represented by z, are partitioned into subsets where the ith subset z^i is associated with the control period T^i, $i = 1, 2, \ldots, L$. In effect then, the kth layer controller generates a control action at time t^k based on the following information sets:

- v^{k-1}: characterizing the residual effects of z^i over the interval $(t^k - T^i, t^k)$, $i = 1, 2, \ldots, k-1$.
- x^k: characterizing the effect of z^k over the interval $(t^k - T^k, t^k)$.
- u^{k-1}: characterizing the residual effects of z^i over the interval $(t^k - T^i, t^k)$, $i = k+1, k+2, \ldots, L$.

We note that the effects of z^i on C^k for $i < k$ are filtered through the corrective actions of controllers $C^1, C^2, \ldots, C^{k-1}$. Similarly, for $i > k$, the effects of z^i on C^k are modified through the actions of $C^{k+1}, \ldots, C^L$.

The kth layer control action is determined with reference to a decision horizon τ^k where, in general, $T^k \leqslant \tau^k$. When $T^k = \tau^k$, we have the standard formulation of the stationary horizon

† More generally, the control may be time varying over the interval. In this case, the trajectory $u^k(t^k, t^k + T^k)$ is determined at time t^k based on the currently available information, $u^{k+1}(t^{k+1})$, $x^k(t^k)$, $v^{k-1}(t^k)$.

problem. When $\tau^k > T^k$ and, more particularly, when $\tau^k = rT^k$, where r is an integer greater than one, then the problem is of the moving horizon type. Viewed as a control problem, τ^k is irrelevant (except as it affects the optimizing procedure), and T^k is the significant parameter. Thus, every T^k units of time, the controls are updated based on the current information set.

We comment that the kth layer controller may require many detailed and complex iterations in generating u^k; further, the information set x^k, on the basis of which u^k is determined, may come from a variety of sources where data may be collected over periods of time. We assume, however, that the results of control action or decision-making is inputted to the system at specific points in time with period T^k. Thus, the iterations are internal to the decision-making block and have no effect on the output except for the introduction of a delay between the information input and the control output. This delay may also be influenced by the data collection process.

The temporal control hierarchy provides a basis for simplication and aggregation of the models used in generating the control functions. The classification of the disturbance inputs into subsets z^i, $i = 1, 2, \ldots, L$ may be based on correlation methods, sensitivity analysis, spectral analysis, etc. For example, if w_0 is the lowest frequency at which a particular input exhibits significant energy content (in terms of its power density spectrum) and then $T_0 = 2\pi/w_0$,

$T^k > T_0$: we may consider the effects of variations of the input to average out over T^k and hence C^k needs to use only the mean or expected value of the input.

$T^k \approx T_0$: the disturbance appears as a non-stationary input with respect to C^k and hence should attempt to apply compensating action.

$T^k \ll T_0$: the disturbance is essentially constant over the period T^k and it can be absorbed within the model as a parameter (which may be updated by an adaptive function at a higher layer).

Thus, with respect to the kth layer control function, (i) the model excludes input variations whose effects tend to average out over T^k, (ii) variables whose effects are relatively constant over the decision horizon are parameterized at their mean values, and (iii) remaining variables are aggregated. The period T^k is selected (out of a set of feasible control periods) so that the mean deviation of the results described by the model from those actually achieved by the plant is acceptably small.

We may use again the slab heating furnace as an example. Here we distinguish four layers of control action according to relative time scale:

Layer 1: process control functions vary the fuel flowrates into the furnace in order to maintain the furnace temperature along a specified trajectory.

Layer 2: the optimizing control model determines the desired temperature trajectory based on load and mean operating conditions; minor disturbances and transients are neglected.

Layer 3: the scheduling model calculates the cycle time as a function of the charge, assuming a mean value for the furnace temperature.

Layer 4: the planning model makes use of the mean cycle time as a standard in determining furnace production capacity.

Note that each of the models may be updated with changes in the underlying assumptions.

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

The planning and scheduling process represents a special application of the temporal hierarchy. The essence of the problem is that the overall decision horizon is long, the system is complex with many diverse inputs, and we have only very limited information concerning the inputs. The temporal control hierarchy formalizes a rational basis for mitigating these difficulties through aggregated models and through feedbacks which tend to reduce the effects of uncertainties and model approximations.

We consider, in this application, the following special characteristics:

(1) The decision horizon is an integral multiple of the control period, $\tau^k = rT^k$, $r > 1$.

(2) The kth layer control period equals the decision horizon for the $(k-1)$th layer, $T^k = \tau^{k-1}$.

(3) The kth layer control problem is solved repetitively every T^k time units. The solution at time nT^k is associated with the interval $[nT^k, nT^k+\tau^k]$; however, $u^k(nT^k)$ need reflect only the initial segment of the solution function, i.e. the output segment for the interval $[nT^k, (n+1)\ T^k]$. This constitutes the allocation or target for the $(k-1)$th layer control problem.

(4) The control output $u^k(nT^k)$ is determined on the basis of

(*a*) The target or allocation u^{k+1} set by the supremal unit.

(*b*) The current estimate of the nature of the environmental inputs forecast over the interval $[nT^k, nT^k+\tau^k]$ as presented by the information set $x^k(nT^k)$.

(*c*) The feedback $u^{k-1}(nT^k)$ from the infimal unit identifying deviations of performance from the target values (with respect to the $(k-1)$th layer subproblem and the preceding control interval $[(n-1)\ T^k, nT^k])$.

(5) The above sequence is repeated with period T^k; as a result, u^k is continually updated based on the current information available.

(6) The above procedure extends to each layer of the hierarchy, resulting in an articulated L-layer decision-making structure.

In summary, the following benefits accrue to the above approach:

(*a*) A rational basis is provided for aggregating the variables, permitting simplification of the complex initial formulation of the problem.

(*b*) The effects of uncertainty are reduced because the subproblems (at the lower layer) are solved based on a prediction of the disturbance input over a shorter horizon.

(*c*) Local constraints and locally dominant factors are handled at the lowest control layer consistent with timing, information requirements and related considerations.

(*d*) There is a natural mechanism for the introduction of feedback of experience both in plant operation subject to the prior control and in the prediction of the disturbance inputs over the horizon period.

(*e*) Features of the multilayer functional hierarchy may be superimposed to provide for information processing, implementation (direct control), and adaptive functions, and the handling of contingency occurrences.

(*f*) Systems integration is achieved through a well-defined and clearcut assignment of tasks and responsibilities to the various layers of control and through information feedback which provide the basis for coordination of the interacting decision function.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Applications of hierarchical control in the steel industry

The concept of hierarchical control structure found early motivation in the steel industry, starting with the application of digital computers to implement various operational control and process control functions on the hot strip mill (where the Spencer Works of British Steel played a pioneering rôle). This led quickly to considerations of integrated plant control based on a four-level control hierarchy comprising planning, scheduling, production control and process control functions, along with a variety of ancillary tasks related to recordkeeping, operator communications, accounting, etc.

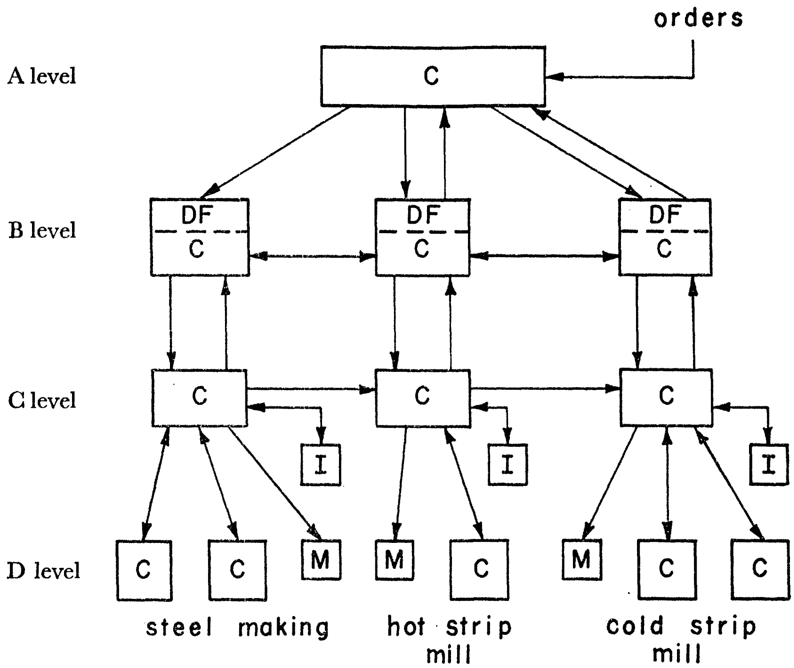

FIGURE 8. Integrated control system in modern steel works.

An integrated and highly computerized control system representative of some modern steel works is shown in figure 8. The figure shows only a part of the system – that associated with the steel making shop, the hot strip mill and the cold strip mill (with much of the detail omitted for purposes of clarity). There are almost replicate structures for some of the other production units, e.g. the plate and section mills, etc. – and these too have been omitted to simplify the diagram.

The system is organized in a hierarchy of four levels as follows:

A level: Production planning, order processing, material requisitioning, order status, shipping, reports.

B level: Production scheduling, data gathering, allocation of semiproducts to customers orders.

C level: Production control, preparation and display of work instructions, data gathering, reports.

D level: Process control, operations control.

The blocks labelled C in the diagram refer to computers which carry out the various information processing, decision making and control functions for the system. The label DF refers to

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data files in which are stored work instructions, order files, work-in-process files, etc. The M blocks identify minicomputers which are assigned to dedicated, special purpose tasks.

The information flows follow the general pattern of the hierarchy described in this paper: decisions and control actions proceed from higher to lower level control, units, with information feedback on the results of prior actions going in the reverse direction. There are also horizontal channels of information flow whereby a control unit may receive information on the decisions of other units at the same level that affect its own decision-making. For example, the hot strip mill production scheduler receives information from the steelmaking shop on the slabbing schedule; the mill, in turn, sends back information concerning its results with previous slabs as they may affect future schedules of the steel making shop.

The man-machine interfaces are a very explicit and important part of the system. These interfaces are indicated by the I blocks in the diagram, representing keyboard, printer, display panel, manual input console, and other means by which the operator/scheduler interacts with the system.

Other aspects of the hierarchical structure, e.g. considerations for the effects of disturbances and contingency events, coordinating control of interacting production units, updating of models and algorithms and an ordering of decision-making according to time scale (temporal hierarchy), are not explicitly shown on the diagram; however, most of these are integral to the functions provided.

Summary

Integrated systems control is concerned with integration of the broad spectrum of decision-making and control functions which play a rôle in the effective operation of a production system with respect to its production goals. The hierarchical control approach provides a conceptual framework for organizing this integration and provides a rational basis for its design and implementation.

The approach is predicated on replacing the initially complex control problem by a set of subproblems which are more easily solved and implemented. Compensations for model approximations and interaction effects are effected through the coordinating efforts of a supremal control unit. The hierarchies provide motivation for orderings with respect to time scale, degree of aggregation, frequency of control action and other attributes that are to be considered at the system design stage. The hierarchical structure also plays an important rôle with respect to organizing the flow of information through the system and in providing the mechanisms for effective utilization of feedbacks for control and decision making. Finally, the hierarchical approach is compatible with modern concepts of distributed computer control and with the use of minicomputers in a coordinated system of plant control.

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