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UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org

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India.

Final Report Submitted to UNIDO by Dr. Irving Lefkowitz in Performance of Services as Expert in Industrial Control in Delhi, India, during Period 6-15 September 1986.

A. SUMMARY OF ACTIVITIES IN PERFORMANCE OF MISSION

1. July 1986: Preparation of position paper "Integrated Control of Industrial Systems" for presentation at the International Seminar on Distributed Control (ISDC 86).

2. 8 September: Meet with UNIDO officials in New Delhi, take care of some administrative matters.

3. 9 September: Discussions concerning program with AAFF Coordinator G.S. Varadan and Mission Experts Dr. T.M. Stout (USA), Prof. T.J. Williams (USA), and Prof. D. Popovic (FRG).

4. 10-12 September: Attend ISDC 86 conference and participate in discussions with various people from Indian industry and government agencies who are attending the meeting.

5. 11 September: Present plenary talk on theme "Integrated Control of Industrial Systems" and participate in discussions following the talk.

6. 13 September: Visit control laboratories of the Electrical Engineering Department of IIT Delhi. Present a lecture on the theme "Developments in the Area of Expert Systems in Application to Control of Industrial Systems." This program was organized by Prof. Lambba of IIT.

7. 13 September: Meet with G.S. Varadan and T.J. Williams to discuss the possibility of the Systems Engineering Department of Case Western Reserve University presenting a summer educational program on the subject "Hierarchical Computer Control for the Steel Industry." This educational program is to be modeled after the program developed at Purdue University under Prof. Williams' direction. The proposed Case program is being considered to run in parallel with Purdue's repeat of the program this summer.

B. GENERAL COMMENTS AND OBSERVATIONS

1. I agree with the premise that, of the many benefits to be obtained from the implementation in industry of computerization and advanced control, the focus on improved product quality and more efficient utilization of resources (e.g., energy and raw materials) is particularly appropriate to Indian industry. These would seem to be very important factors in making Indian products competitive in world markets.

2. The decision to go first with the steel industry via the Integrated Control Systems for Steel Plants (INCOS) project makes a great deal of sense for the following reasons (already cited by Prof. T.J. Williams and others in prior reports):

a) Steel-making involves a complex interplay of many very diverse production processes (e.g., mechanical, thermal, chemical, and metallurgical). As a result, production efficiency and product quality are closely related to the effectiveness with which the variables are controlled and the degree to which the system is integrated. Further, the production operations are very energy intensive. Thus, steel-making offers opportunities for significant improvements in performance through the proposed integrated control system.

b) The technology is, for the most part, known and its benefits have been well demonstrated in a number of steel plants around the world. In particular, we cite the experiences in several modern Japanese steel plants (e.g., Kimitsu and Ohgeshima Works).

c) Prof. T.J. Williams and the Purdue Laboratory for Applied Industrial Control, consultants on the INCOS project, have extensive background in modeling and the application of hierarchical and distributed control to steel-making.

3. It is important to look ahead to the extension of the INCOS-type program (or similarly motivated programs) to other industries in order for the country to realize benefits on a broader base of products and markets. Likely candidates for consideration include oil, chemical, paper, and fertilizer industries.

4. The proposed undertakings are ambitious and challenging - but they are "doable" with today's technology. What I feel is most important to a successful outcome is the sustained commitment of resources (funds and people) and support (moral and political) on the part of the government and industry units involved in the program.

It seems to me that, in particular, the Appropriate Automation Promotion Programme (AAPP) with Mr. G.S. Varadan as Chief Coordinator has been playing a key role in promoting the introduction of advanced control technology into Indian industry and of catalyzing the efforts of various groups to bring about appropriate implementation. I believe the AAPP program has accomplished a great deal in its few years of existence; however, there is still much more to be done with respect to implementation in the Bhilai steel plant and particularly, as noted above, with respect to extensions to other industries.

Mr. G.S. Varadan, AAPP Coordinator, appears very knowledgeable in the area of computers and their applications to control, and he is surely a very enthusiastic and dedicated promoter of the program. It is important to maintain the momentum generated in the group, and I strongly recommend renewal of the AAPP program for at least another two to three years.

5. In listening to the presentations at the International Seminar on Distributed Control (ISDC 86), I was generally favorably impressed with the level of knowledge and understanding displayed by the Indian participants at the conference. Similarly, in my interactions with various people at the conference, I felt there was strong interest and commitment to the goals of the AAPP and INCOS programs. This feeling also came through in my discussions with many students and staff (e.g., during my visit to IIT Delhi).

Thus, there already exists a pool of capable and motivated Indian nationals who could now or who could potentially take on responsibilities for development, design, and maintenance of the proposed computer control systems. In particular, there appears to exist a pool of people who have the pre-requisite skills, background, and orientation and can benefit directly from the specialized training in computer-based hierarchical and distributed control such as that offered by Prof. Williams and the Purdue group to SAIL engineers.

This kind of training is an essential component to minimizing dependence on foreign sources for the expertise needed to implement and maintain the proposed modern computer control technology.

ISDC 86

Integrated Control of Industrial Systems

Presented at:
INTERNATIONAL SEMINAR ON DISTRIBUTED CONTROL
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Organised by

Government of India
Department of Electronics

Integrated Control of Industrial Systems

Irving Lefkowitz
Case Western Reserve University.
Cleveland. Ohio. USA

Abstract - There is an increasing focus on the concept of integrated system control in applications to industrial systems. e.g. chemical processing and steel. Many factors have contributed to this focus : (1) the need for more efficient utilization of resources (e.g.. energy. water. labour. materials) because of increasing cost. limited availability. or both; (2) demands for higher productivity to meet international competition; and (3) more stingent requirements concerning product quality, environmental impact, and human safety. 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, we consider control to include not only the traditional process control functions, but also real-time applications of information processing and decision making, e.g., production planning, scheduling, optimization, operations control, etc. The common characteristic underlying control, in the sense employed here, is the basing of actions, responses, decisions. etc. on information describing the current state of the system (and its environment) as interpreted through appropriate models.

Industrial systems are inherently large scale and complex, time-varying and subjec to disturbances and constraints of various kinds. Effective control of such systems has been made feasible through the tremendous advances in computer technology, proving the means for information processing, on-line control, decision-making in real time, and man-machine interaction.

The hierarchical control approach provides a conceptual framework for handling the complexity and uncertainty characteristic of industrial systems and for organizing the integration of the many diverse decision-making and control functions which affect system performance. Basically. the overall control problem is decomposed into subproblems according to topological, functional, and temporal considerations. Compensations for model approximations and interaction effects are effected through the coordinating efforts of a supremal control unit. The hierachical structure induces orderings with respect to time scale, degree of aggregation, and frequency of control action, and also provides mechanisms for effective utilization of feedbacks for control and decision making.

The approach is illustrated through examples taken from the chemical, steel, and electric power industries where integrated systems control based on hierarchical control concepts and distributed computer control architectures have seen rapid developments in recent years.

The discussion of integrated systems control is extended to embrace batch production systems - an areas of renewed interest because of the exciting possibilities offered by modern control technology in addressing some of the challenging control problems associated with batch processing.

Finally the subject of expert systems is introduced with respect to the perceived potential of such

systems with respect to further advances in control of industrial systems. In particular, some opportunities are described for applying expert systems methodology to facilitating the higher layers of the control hierachies and in operator training and technology transfer.

1. Introduction

Many factors contribute to the need for more effective control of industrial systems : (1) the need for more efficient utilization of resources (e.g.. energy, water labour. materials) because of increasing cost. limited availability, or both; (2) demands for higher productivity to meet more intense international competition: and (3) more stringent requirements concerning product quality, environmental impact. and human safety because of government regulations and greater consumer awareness.

Industrial systems are inherently complex and large scale. They are characteristically multivariable, nonlinear, time varying, and subject to disturbances and constraints of various kinds. Effective control involves consideration of dynamic couplings among the system components. multiobjective decision-making under uncertainty, man-machine interactions. etc. The hierarchical control approach provides a rational and systematic procedure for resolving these problems.

The control of industrial process has evolved very considerably over the past half century. Early objectives of automatic control were to relieve human operators of the tedium and drudgery of maintaining certain key variables of the plant at desired values through feedback actions. At the same time, control devices provided the means of achieving better accuracy and more consistent and dependable results. The introduction of electronic instrumentation enabled remote sensing and actuation which led to the development of central control rooms where the operator could keep track of a large number of control loops. This role became increasingly one of supervision to adjust controller set-points whenever called for by changes in environmental conditions, process performance, or in product specifications The operator also had the responsibility of monitoring the performance of the various control loops to make sure that the plant was operating properly, to make changes whenever product qualitiy of production efficiency fell below tolerance limits, and to respond to contingency events (e.g., a malfunction of a piece of equipment) with proper emergency actions.

It was soon recognised that some of the more elementary supervisory functions could be carried out automatically. For example. controller were introduced that could maintain fixed functional relationship among several process variables so as to improve process performance (e.g., yield, efficiency, product quality). At the same time, sophisticated monitoring and alarm systems were developed that automatically sensed the status of plant variables and alerted the operator if any of them exceeded preset limits.

The advent of the digital control computer in the 1950s initiated a revolution in the control of industrial plants. The computer made it possible to store and process large quantities of data and to implement complex algorithms in real-time so that we could advance from simple control objectives of maintaining process variables at fixed desired values to the more interesting objectives of determining how these variables should be changed with time or in relationship to other variables in order to optimize plant performance. The control computer also provided the capability of rapid switching from one computational task to another. Thus, one machine could handle a large number of control loops as well as various auxiliary tasks such as monitoring, start-up sequences. operational control. etc.

Unfortunately, the early process control computers were costly and had limited speed, memory capacity, and software capabilities. Reliability was another problem, i.e., it was extremely difficult to assure safe and dependable performance of the system over months and even years of continuous plant operation. As a result, many of the initial attempts at computer control, while boldly conceived and implemented with great fervor and effort, fell dismally short of expectations.

Developments in computer technology over the past fifteen years have resulted in tremendous reductions in hardware costs and computation speeds, and storage capacities have increased dramatically. User-oriented programming languages have greatly eased the man-machine interaction problem, e.g., in programming, debugging, the updating computer control algorithms. Also, system reliability has improved substantially as a result of more reliable components and the increased feasibility of fault-tolerant design, redundancy, and diagnostic routines - enhanced by low hardware costs and more sophisticated design techniques.

More recently, advances in real-time applications of minicomputers and microprocessors have had a profound effect on the directions of current effort in industrial systems control. Specifically, these have opened up new opportunities for system configuration based on (i) distributed data acquisition and control, and (ii) hierachical computer control where each computer performs selected tasks appropriate to its position in the hierarchy. These approaches (in contrast with the initial idea of lumping all tasks in one giant control computer) have contributed to design flexibility, improved reliability and security, better performance, etc.

2. Integrated Systems Control

A consequence of these development has been a vast broadening of the domain of what is technologically and economically feasible to achieve in the application of computers to control of industrial systems. The ability of the computer system to gather, process, and store large quantities of data, to carry out complex computational tasks at high speeds, to interact effectively with the human component of decision-making functions, and to adapt readily (via software) to changing system requirements means that now all aspects of information procesing, data gathering, process control, on-line optimization, operations control - even real-time scheduling and production planning functions - may be included in the range of tasks to be carried out by the computer control system. This has made possible the realization of integrated systems control in which all factors influencing plant performance (including the couplings, interactions, and complex feedback paths existing in the system) are taken into account in an integrated fashion to achieve an overall optimum performance.

A variety of benefits are ascribed to the integrated system control approach as experienced in modern steel works. These include :

(a) Improved efficiency of operating units and increased plant productivituy as result of better quality and the ability to control to optimum conditions.

(b) Better utilisation of resources, e.g., energy, scares materials, manpower.

(c) More effective compliance with technological and environmental constraints, e.g., ensuring that air and water effluents meet government standards.

(d) Adaptability to time-varying conditions such as those induced by changing product demands, costs, availability of raw materials equipment obsolescence, etc.

(e) Capability of responding safely

and securely to contingency events. e.g.. equipment breakdown. delayed delivery of needed supplies. etc.

(f) Capability of providing effective and immediate updates on the status of the system. e.g., orders in process. inventories, equipment maintenance, etc.

The problems of realisation of implementation of an integrated system control are generally formidable because of the complexity of the production processes. the variety of constraints to be satisfied. the nonlinear. time-varying dynamics. etc. Multilevel and multilayer hierarchical control approaches provide rational and systematic procedures for resolving these problems. In effect. the overall systems control problem is decomposed into more easily handled subproblems; the subproblem solutions are coordinated by a higher level controller so as to assure compliance with overall objectives and constraints [1, 2].

3. Functional Multilayer Control Hierarchy

The functional control hierarchy is characterized by the diagram in Fig. 1 in which four classes of control functions are identified, namely : direct, supervisory. adaptive, and self-organising control functions [3].

a) The first or direct control layer constitutes the interface between the controlled plant and the decision-making and control aspects of the system. A important characteristic of this layer is that it interacts directly with the plant and in the same time scale. We distinguish three subfunctions:

(i) Data Acquisition : responsible for providing the controller with the necessary data to carry out its control functions. including data from plant sensors and operator inputs. Data may be processed (smoothing, averaging, normalising. linearising. transforming. etc.. before being inputted to the control system for storage and subsequent utilisation.

(ii) Event Monitoring : responsible for detection of discrete event occurrences which affect the control. The event may cause the controller to initiate an action or response, or to signal the completion of a task, the introduction of new parameter values. or a change in operating mode.

(iii) Direct Control : responsible for implementing the decisions generated by the higher-layer functions of the controller. Specifically the direct control function implements the target of strategy defined by the second-layer function through direct actions on the plant.

b) The second layer or supervisory function is concerned with the problem of defining the immediate target or task to be implemented by the first layer. In the normal mode, the objective may be control of the plant for optimum performance according to the assumed mathematical model. Under emergency conditions, different objectives may take precednece through implementation of appropriate contingency plans.

In the conventional process control application, the second-layer intervention takes the form of defining the set-point values for the first-layer controllers. In the discrete formulation. the output of the supervisory function may be a specified or "next state" to be implemented by the direct controller through a predetermined sequence of actions.

c) The third-layer or adaptive function is concerned with updating the algorithms employed at the first and second layers. reflecting current operating experience.

d) The fourth-layer or self-organising

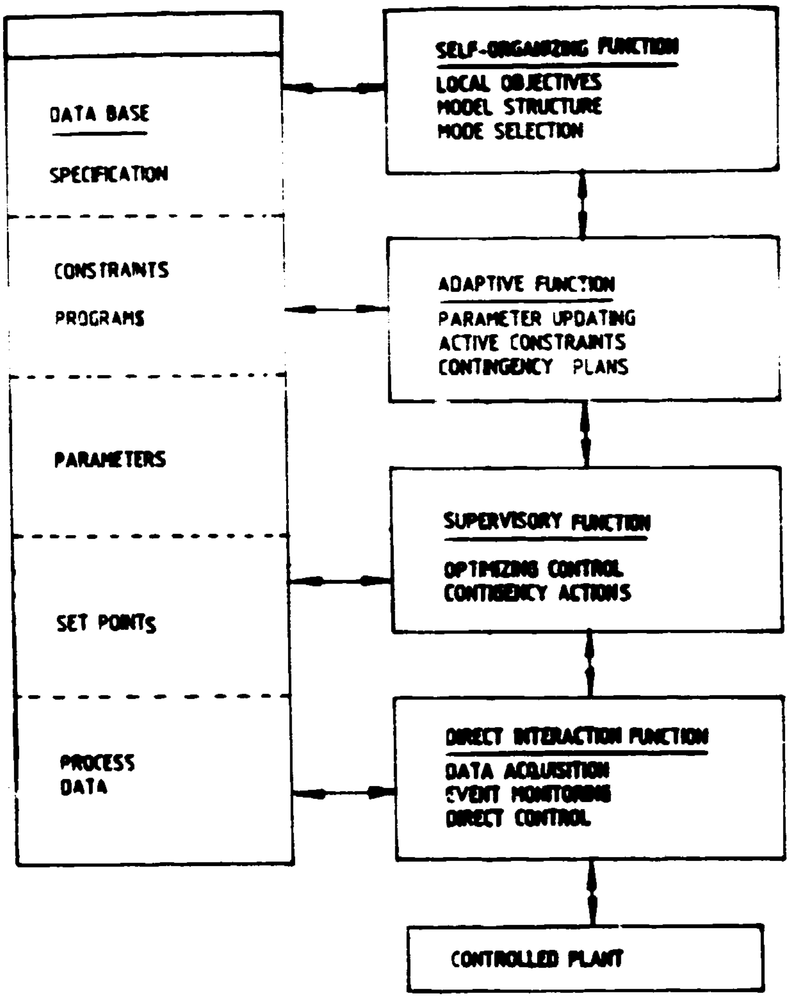

Fig. 1. Functional multilayer
control hierarchy

function is concerned with decisions relevant to the choice of structure of the algorithms associated with the lower layers of the hierarchy. These decisions are based on overall considerations of performance objectives, priorities, assumptions of the nature of the system relationships and input patterns, structuring of the control system, coordination with other systems, etc.

Attributes of the multilayer structure are:

(a) The structure provides a natural hierarchy in which each layer has a priority of action over the layer below. In general, information passes up the hierarchy via the common data base: the results of decision making and evaluation proceed down the hierarchy either via the data base or via the computer executive programme.

(b) The layers of the hierarchy represent different kinds of control functions, hence require different kinds of computation and information processing algorithms. This means that we can do a better job of tailoring the hardware and software to the specific needs of the subproblem associated with each control layer.

An application of the multilayer control approach is described in the context of a catalytic reactor process. [4]. The process inputs are controlled as continuous functions of time; however, at discrete points in time, the "normal" operating mode is disrupted to go into a "regeneration" mode for the purpose of restoring catalyst activity. Thus, a scheduling problem is superimposed on the continuous problem.

The direct control function is concerned with the task of controlling the process variables, e.g., pressures, temperatures and flow rates according to the trajectories of set-point values defined by the superpvisory control function. This function is implemented by means of conventional feedback control loops, with perhaps some feed-forward considerations. The local objectives are essentially the maintenance of the controlled variables at their respective set-point values within acceptable tolerances.

The determination of set-points at the second layer is based on a model of economic performance approprite to the mode of operation. Thus, in the normal oprating mode we may determine values for the control variables which will tend to maximise product yield consistent with system constraints and specifications on product quality. In the catalyst regeneration mode, we may want to operate the plant so as to minimise the duration of the regeneration period, i.e., the period during which product is not being produced. There are at least two distinct tasks assigned to the third layer. The first relates to the updating of selected parameters of the lower-layer control algorithms to take care of the effects of normal variations in operating conditions, catalyst activity, etc. The second task relates to the criterion function for switching from the normal operating mode to the regeneration mode. The conditions for switching may be determined through solution of a scheduling problem whose objective is to maximise an overall profit function in which is imbedded the optimisation model used at the second layer.

The fourth control layer has the responsibility of selecting the operating mode and, consequently, the programmes to be used by the lower-layer control functions. In particular, we note in this example that a transfer of mode requires extensive changes in the control structure; these are coordinated by fourth-layer intervention.

4. Multilevel Control Hierarchy

In the multilevel control approach, the overall plant system is decomposed into subsystems, each with its own local controller. In this scheme:

(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 system requirements so that actions of the local controllers are consistent with the overall objectives of the system.

In effect, the subsystem problems are solved at the first level of control. However, since the subsystems are coupled and interacting, 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. A schematic of a two-level multilevel structure is shown in Fig. 2.

The decomposition of the overall system into subsystem may be based on geographical considerations (i.e., relative proximity of different units), lines of managerial responsibility (e.g., steel-making shop and rolling mill in a steel works), or on the type of equipment (e.g., distillation tower and reactor in a chemical plant). In general, however, the plants are designed so that these divisions correspond to lines of weak interaction, i.e., through the incorporation of various "buffer" or control mechanisms, the resulting sybsystems are partially decoupled so that interaction effects tend to be small and/or slowly varying with time.

The multilevel approach leads to 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 and aggregated data, and (iii) the upper-level action takes places at lower frequency.

(c) A reduction of development costs for the system by virtue of the fact that the models, control aligorithms, and computer software can be developed in a step-by-step, semi-independent fashion.

(d) An increase in 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.

One application of the multilevel approach is in the electric power industry where the power generation and distribution system is designed as interconnection of semi-independent subsystems [5, 6]. Thus, there is a natural decomposition induced by technological considerations at the generating unit level, geographical considerations at the generating station level, ownership boundaries at the company level, etc.

A second application of multilevel coordination is suggested by the problem of scheduling a hot strip mill [7, 8]. The function of the mill is to roll steel slabs into thin strips of specified dimensions and metallurgical properties. Wear of the surface of the mill rolls imposes constraints on the allowable sequence of strip widths and thickness that may be rolled between

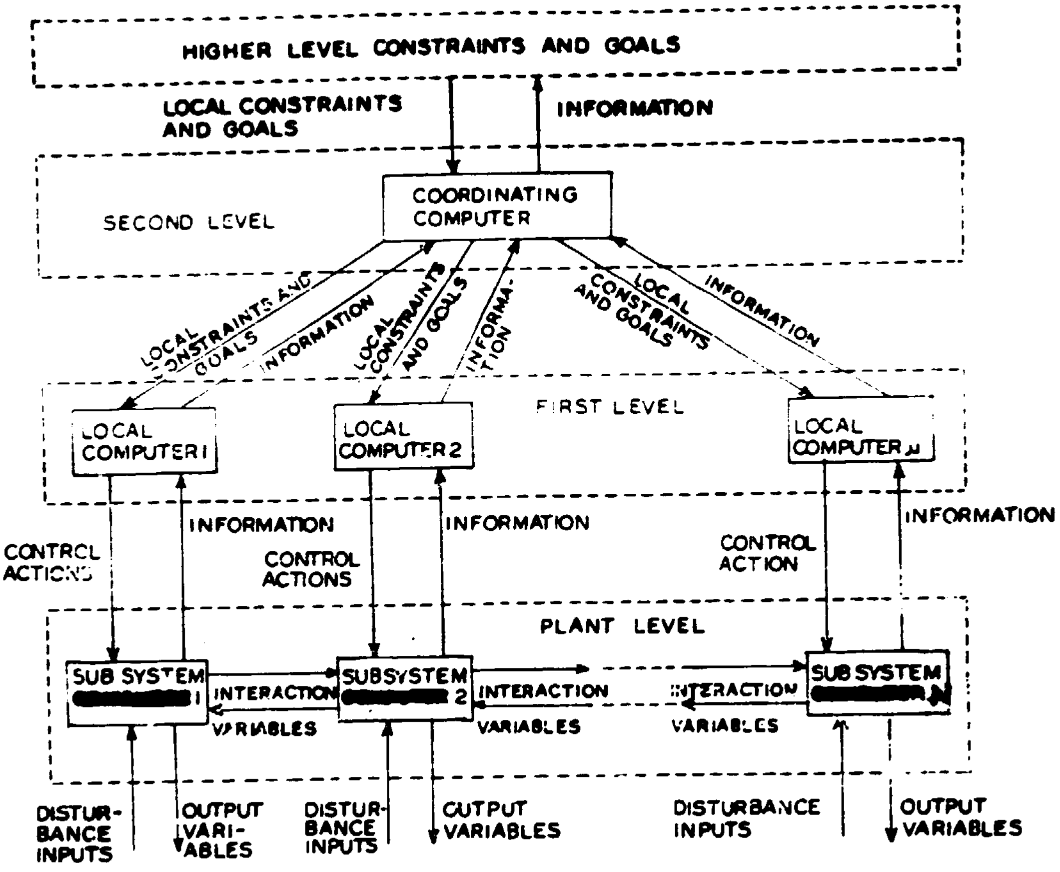

Fig.2. Typical distributed digital control system

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 minimise the number of grade changes because of the increased likelihood of off-standard product 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 minimise the frequency of slab changes. An alternative is to provide more storage of slabs in the slab yard but this may increase slab yard costs. Thus, we have a role for a higher level production scheduler that reconciles the conflicting (local) objectives of these interacting production units to satisfy overall objectives and constraints.

5. Tempral Multilayer Control Hierarchy

The multilevel control hierarchy includes an ordering with respect to time scale; spefically, 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 hierachy wherein the control or decision-making problem is partitioned into subproblems based on the different time scales relevant to the associated action functions. These time scales may reflect (i) time required to obtain the information on which the control action is based, (ii) bandwidth properties or mean time between discrete changes in disturbance inputs, (iii) time horizon associated with the control problem, and (iv) cost-benefit trade-off considerations.

Thus, in the multilayer temporal hierarchy, at kth layer controller generates a decision or control action every Tk units of time (on average), with Tk+1 >Tk, k = 1, 2, ..., based on the input information currently available, i.e. state of the plant and environmental factors; targets and/or constraints provided by a (k+1)th layer controller; feedback of prior experience provided by a (k-1)th layer controller.

The temporal hierarchy approach provides a rational mechanism for reducing the effects of uncertainty, introducing experimental feedback, aggregating variables and simplifying models, and implementing systems integration through well-defined assignments of tasks and responsibilities.

An example of the set of control functions distinguished by their temporal attributes is provided by the hot strip mill referred to earlier. Because of surface wear, the rolls have to be replaced at frequent intervals. Each roll change sets 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 receipt of a new order, involving perhaps a large number of slabs, requires new mill instructions and setups 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 at predetermined values the tension, thickness, and temperature of the steel strip at critical points in the mill. 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, common to

many industries, is provided by the articulation or production planning and scheduling functions spanning a range of time horizons, e.g., five years, monthly, weekly, daily, 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 degreee of uncertainty involved in the decision-making, the level of aggregation, the information flow requirements, etc.

6. Application of Integrated Systems Control in the Steel Industry

Some of the most advanced applications of integrated systems control based on hierarchical control concepts and distributed computer control architectues are in the steel industry [8]. Representative of some modern steel work is a computer control system organized in a hierarchy of four levels as follows:

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

B-Level : Production scheduling, data gathering, allocation of semi-products to customers, orders.

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

D-Level : Process control, operations control.

Computers carry out the various information processing, decision-making and control functions for the system. The computers access extensive data files in which are stored work instructions, order files, work-in-progress files, etc. The information flows follow the general pattern of the hierarchy described in preceding sections: 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 some horizontal channels of inforamtion flow whereby a control unit receives inforamtion on the decisions of other units at the same level that affect its decision-making. For example, the hot strip mill production scheduler receives information from the steel making 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.

7. Appliction of Integrated Systems Control to Batch Processing

Batch processes have important application in industry where (i) the product is high value and low volume (e.g. specially chemicals and pharmaceuticals), (ii) current technology doesn't lent itself to continuous processing (e.g. fermentation), and (iii) where operating conditions are critical and must be varied over time in a very precise way.

Because the basic transformations in a batch process take place over time rather than space, the system is intrinsically time-varying and non-linear; hance, these characteristics may have to be explicitly considered in the design of the control algorithms. By the same token, the incorporation of adaptive control features may be particularly important in batch process control. Another consequence of the nature of the batch process is that optimisation (to an economic objective) is a variational problem and the methodology must provide for on-line implementation and appropriate feedback mechanisms. Here again, adaptation may be an essential component of the system, particualrly where the optimisation model is only an approximation of the process relationships.

Another distinguished feature of the batch process is that discrete operations (e.g. loading the reactor, adding reagents at specific points in time, etc.) are typically superimposed upon continuous-time functions (e.g., control of reactor temperature). This induces, of course, many special requirements with respect to the development of integrated algorithms for control and decision making, as well as the hardware and software means for implementation. At a higher level, we may consider the case where production facilities are time-shared over a number of distinct products. This introduces problems of scheduling and production planning, particularly as they interact with the optimizing and direct control functions.

8 Expert Systems - Methodology and Applications to Control

There is a very rapidly evolving interest in export systems as an approach with broad implications for expanding the scope and range of effectiveness of computers applied to the control of industrial systems. There are already a number of applications of the methodology proposed - and even some scattered practical realizations - in such diverse areas as adaptive control, process diagnostics, production scheduling, and batch process control. A few motivating factors behind this direction of interest are: (i) improving the range of effectiveness of the control system,(ii) extending the domain of automatic control, i.e. automating some of the activities/operations currently carried out by humans, (iii) facilitating the process of system design, startup, updating to new knowledge and new conditions, (iv) increasing overall system reliability and robustness.

An expert system may be defined as a computer programme that performs an intellectually demanding task at least as well as most (human) experts [10]. The important distinction made here is that the task be "intellecltually" demanding as opposed to merely "mechanically" demanding. Examples of the former are game playing programs (e.g. chess) and diagnosis programs (e.g. medical diagnosis); examples of the latter include a matrix inversion routine or a statistics package. The system consists of a knowledge base which contains the knowledge and rules needed to make decisions, data base which contains the data (e.g. sensor readings, alarm signals, etc.) that the system uses in its decision process, and an inference engine which manipulates the knowledge to arrive at and explain decisions.

Some commonly identified attributes of the expert system are:

1. It can capture the judgemental, experimental, and intuition aspects of a good operator (or "good" designer or "good" decision-maker).

2. It can imbed objectives and constraints as logic statements.

3. Heuristics, reasoning, and rules of inference may be easily incorporated.

4. There is a clear separation of the domain dependent (knowledge base) and the domain independent (inferential engine) aspects of the problem.

5. The chain of reasoning can be made transparent to the user, i.e. providing the "why" of the systems output.

We describe briefly below a number of control applications of expert systems - both current and potential.

a) Process disgnostics

This area is perhaps the most prominent application discussed in the literature, particularly in the medical domain, e.g. in the diagnosis of disease [10, 11]. The analogy to the problem of detecting and identifying faults in process control systems is immediate and direct. An increasing number of applications are being reported; references include: fualt diagnosis for electric power systems [12], for nuclear reactors [13], for a relay network [14], and for a chemical process [15]. The contributions of the expert system here may be the effective encapsulating of judgemental and experimental factors in interpreting observations. For example, an abnormal rise in a temperature reading may be related by a set of rules and inference statements to some action or conclusion based, not only on quantifiable functional relationships (e.g. mass and energy balances, known reaction kinetics, etc.), but also on such factors as the source/quality of raw materials, prior history (e.g. has the temperature rise been slow or abrupt, monotonic or fluctuating), on environmental conditions, etc. More specifically, we may consider the inference of faults from patterns of behaviour of key process variables; we may incorporate heuristics to distinguish between actual fault conditions and the confounding effects of noise and dynamic interactions.

b) Adaptive control

There would seem to be many opportunities for improving the robustness and range of effectiveness of adaptive controllers by superposition of expert systems methodology [16, 17]. In particular, the expert system can utilize qualitative measures of the closed-loop system's response charactersistics, e.g. reflecting an operator's assessment of what constitute a good controller response. In this, it is important to be able to distinguish between feedback-induced and disturbance-induced response characteristics, as well as to distinguish interaction effects in multiloop feedback situations. We see opportunities for handling anomolous behaviour due to essential nonlinearities in the process, asymmetric dynamic response characteristics, "reverse" action response, multimode operations, etc. Finally, there is the opportunhity of coupling the process diagnostics subsystem with the adaptive control to identify abnormal behaviour of the system due to fault occurrences and thereby avoid compounding potential problems resulting from misguided action by the adaptive unit. One commercial manifestation of the expert systems concept is the Foxboro EXACT controller.

c) Smart sensor/automated inspection

Two successful examples of the application of expert systems to the problem of inferring physical attributes from available sensor outputs and perhaps qualitative and/or subjective observations of physical attributes important to a subsequent control or decision-making action, are [11]: (i) a programme that identifies molecular structures from mass spectral and nuclear magnetic response data, and (ii) a programme that determines guides for mineral exploration from soil and geological deposit data. These applications would seem to be similar to the generic problem of on-line measurement of product quality and its extension to automated inspection. Finally, closing the loop in an automated quality control system must invariably invoke considerations of cause and effect, i.e. what is the likely cause of an observed quality deviation and how many it best be corrected? Again, these considerations are often governed by judgmental and experilential factors.

d) Production scheduling/planning

A dominant factor affecting overall plant performance is the effective integration and coordination of production units. Thus, a plant-wide computer control system must incorporate means for implementing production scheduling and planning, particularly in a time-varying and partially uncertain environment. Unfortunately, however, this class of problems tends to be combinatorial in nature which usually implies prohibitive computational requirements. The human scheduler is able to come up with at least adequate solutions through the ability to abstract the dominant features of the problem and to apply heuristics (which serve to reduce the search domain).

An expert system that can emulate the human scheduler or planner would enable this aspect of plant-wide control to be automated. In an early study along these lines [18], a multiproduct batch chemical plant was scheduled every time a disturbance even (e.g. a change in the order book made obsolete the previously computed schedule. Heuristics coupled with a fast-time simulation of the process rendered the approach feasible. More recent applications cited in the literature include electric power generation scheduling [19, 20], reshuffling of reactor fuel rods, and steel mill scheduling [8].

e) Computer-aided control system design

Increasing attention is being given to automating control system design using computer-aided-design (CAD) methodology. The opportunities may be greatly enhanced by superimposing expert system methodology, particularly as it facilitates the coupling of the process engineer's expertise with that of the control engineer. The process engineer communicates his know-how of the process needs and constraints; the control engineer provides the knowledge needed for configuring the measurement and control sytem [21].

f) Hierarchical control structure

The hierarchical control approach induces an ordering with respect of time scale, problem complexity, degree of uncertainty and other attributes. In general, as we go up the hierarchy, time scale, complexity and uncertainty all tend to incease. This suggests a design philosophy wherein algorithmic methods are applied at the lower layers of the hierarchy and expert system/artificial intelligence methologies are applied at the higher layers. This point of view is consistent with that expressed in [11]: "Knowledge of a domain takes many forms. When that knowledge is firm, fixed, and formalized, algorithmic computer programmes that solve problems in the domain are more appropriate than heuristic ones. However, when the knowledge is subjective, ill-codified and partly judgemental, expert system embodying a heuristic approach are more appropriate." In a sense, the time scale ordering is fortuitous. At the lower layers we tend to have better defined and more precise models and algorithmic methods are fast and easily implemented. The AI type programmes suggested for the higher layers tend to be relatively slow and require larger and more sophisticated machines. However, at the higher layers the time period between actions is very much larger, hence speed of computation (in the search process) need not be a constraint. Further, there is the increasing opportunity of time-sharing the facility, hence prorating costs.

The self-organizing layer is particularly appropriate to this discussion. This layer is concerned generally with decisions relevant to how the overall system is structured, the characterization of the knowledge base, assumptions regarding the nature of the system relationships and input patterns, the assessment of performance objectives, priorities and constraints, and other aspects of the problem formulation. This layer of activity is characterized by complexity, uncertainty (fussiness), multiple and not easily quantified objectives, and, in general, a lack of effective analytical or computational tools for problem resolution. As a result, with very few exceptions, the implementation of this layer has been exclusively the domain of the human expert who, through experience, intuition, heuristics, reasoning, etc. is able to come up with reasonable (perhaps suboptimal) decisions.

It would seem from the foregoing that there are interesting prospects for automating at least some segments of the self-organizing layer function via expert systems methodology. Of particular interest from a "control" perspective, is the automation of fourth-layer responses to discrete disturbance events that affect system relationships and structure. Examples include occurrence of a fault in the process of control system, major changes in product mix, raw materials, or cast factors, etc. Fourth-layer action may also be in response to new knowledge accumulated through operating experience with the production process. Thus, knowledge acquisition may be an important component of any proposed study of an expert system implementation. This has two aspects: (i) communication of the experiences of humans interfacing with the system in a form that can be properly interpreted by the expert system, and (ii) self-learning capabilities of the expert system, i.e., automating the knowledge acquisition task (meta-level knowledge base).

The above arguments apply equally well to the upper levels of a multilevel control hierarchy (horizontal decomposition). Here, the overall process is decomposed into subprocesses, each with its own computer control system responsible for satisfying local constraints and local objectives. The role of the higher level controllers is to coordinate the actions of the local controllers so that overall goals/constraints are met. This involves, typically, the implementation of scheduling functions, integration of often disperate processing units, multiple objectives, etc. which call for "expertise" in the solution of the problems. Thus, the rationale for an expert systems approach has meaning here too.

g) Technology transfer applications

An area of application of expert systems which should be of particular interest to countries in the process of developing or modernizing their industrial base is that of operator training or, more generally, of technology transfer. Here, we consider two important features of the expert system: (i) the learning capability, and (ii) the explaining capability.

In the learning process, the expertise of the "expert" or trained operator is encapsulated within the computer program. This is usually facilitated through the efforts of a knowledge engiener who is able to (i) identify, by means of appropriately posed questions, the essential facts, behavioral characteristics, rules and heuristics which are needed to achieve the desired level of performance out of the production sytem, and (ii) translate this "knowledge" into appropriate code that can be utilized by the expert system programme for transmission to the operator in a training or operator guidance mode.

In the explanation process, the expert system diagnoses the current state of the process and makes recommendations to the operator for actions to take. On request, the computer can then explain the reasons underlying the recommendations; i.e., how it interpreted the available information, what assumptions were employed, and perhaps even what weightings or priorities were assigned to conflicting observations or inferences. In this way, the operator is able to learn from the experiences and understanding incorporated into the expert system. Equally important, the operator can question the bases under which conclusions were drawn, inputting his own judgement or experiential factors to arrive at a more acceptable computer output.

This area of application is still very much in its infancy; it seems clear that there is considerable potential for significant contributions to technology transfer as the associated artificial itelligence methodologies become more cost effective and efficient.

9. Summary

Goals of improved productivity, efficiency, and product quality have motivated, over the years, a continuing development of control theory and practice in industrial applications. 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 the central role in making feasible integrated control of the industrial system where it serves the functions of information processing, on-line control, and decision-making in real time. The hierarchical control approach provides a conceptual framework for organizing the integration of the many diverse decision-making and control functions which affect system performance.

Integrated systems control and the hierarchical control approach are discussed also in the context of the control of batch production processes. Finally, some potential applications of expert systems methodology are presented with respect to advancing the goal of integrated control of industrial systems.

The various approaches described are illustrated through examples taken from the chemical, steel, and electric power industries where substantial advances have been made in applications of hierarchical and distributed control.

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