

AN INTEGRATED HIERARCHICAL CONTROL SYSTEM FOR FULLY-AUTOMATED DYEINGS

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ABSTRACT

Complete automation of production cycles and factories is one of the main goals of researchers and engineers in the field of automated control. This paper discusses the basic structure and characteristics of efficient, effective control systems based upon computers and computer networks. An application of the design guidelines is also presented for a fully-automated dyeing.

1. INTRODUCTION

The future developments of world economics will require a massive introduction of automated production and control systems in an increasing number of factories [1]. Nowadays, distributed control systems based on computer networks, their flexibility, their programmability and their computing power make more and more attractive and feasible the perspective of fully-automated factories.

In this paper we present and discuss some criteria for designing advanced distributed computing system which are dedicated to automated management of plants. In particular, we consider a practical study case: automating dyeings of yarns and fabrics.

The main characteristics of factory automation is the large spectrum of different problems that must be contemporaneously afforded and solved [1] [3] [5] [6]: from mechanics to electrotechnics, from fluidodynamics to electronics, from robotics to vision, from economics to personnel management. The control system must be able to cope with all these aspects. Modularisation of the control system is thus required to customise each subsystem to a given goal. Distribution of computation and control is the immediate consequence of specialisation.

The great amount of data and signals that must be treated enhances the requirement of control distribution to satisfy the time constants of plants and production processes, to guarantee the proper response time to events and personnel's interrogations and interactions. For each subsystem the proper hardware support based upon digital/analog controllers and computers must be designed.

Management and control of plants or production processes require the interaction of different personnel at different abstraction levels of the view of the plants or production processes. Their jobs need different information and supports. The control system must be thus hierarchical to collect information from the lower level, which is directly connected to the plant and the production process, to interact with the controlled system and to report condensed information at the higher levels of the management.

Control distribution and hierarchy can be effectively implemented only if the whole control system provides the proper support for integration and coordination of activities and information. System integration is an other guideline in designing advanced control systems for complete automation. Such goal may be achieved by introducing communication networks at different levels.

Finally, the practical realisability and the actual possibility of introducing fully-automated production systems is strictly related to the costs of such systems. High automation costs are usually acceptable for the first experimental implementations of fully-automated control systems or for plants which controlled parts are intrinsically highly expensive. A different approach must be adopted in small plants, or when investments for restructuring and automation cannot be large, or when the production costs must be strongly minimised to sell the products with reasonable profits. In such cases the costs of the automated system must be as cheap as possible: an accurate choice of components, subsystems and functionalities is thus required.

Sections 2 and 3 discuss hierarchy, modularity, distribution and integration in advanced control systems for full-automated factories. In section 4 the study case and the overall structure of the control system are presented: details of the production process and control problems are given. From section 5 to section 8 the structure, the functionalities and the architectural solutions for the different control levels are discussed, with particular reference to the case study.

2. HIERARCHICAL CONTROL

The basic criterion of the design of a control system for factory automation is the hierarchical design of the system at different abstraction levels. A typical hierarchy is composed by:

- the control level 0 for engine control,
- the control level 1 for plant and process control,
- the control level 2 for factory control,
- the control level 3 for factory management.

At each level of the hierarchy, the most adequate views of the control and controlled systems are presented to the user. In particular, the information and functionalities are customised and tailored on the job of the user and on his responsibilities in the factory personnel. For example, the data treated by the lowest level and presented to the worker, are strictly related to the functioning of the engine; while the data available to the general manager of the company consists of summaries about the marketing trends, the production and the personnel management.

At the lower level (engine control) there is, for example, the control of engines and object movement. Such operations should be executed as fast as possible to guarantee the safety of the working environment, to prevent possible damages to the plant itself, to improve the productivity of the factory by reducing the dead-time between subsequent production phases and by optimising the production scheduling, to increase the quality of the products, to decrease the overall costs for production.

Such level is at direct contact with the production system and must reports to an upper level (the plant control) some information about the state of each part of the plant and production statistics. This level must coordinate the work of each component of the plant itself to optimise the whole production activity and must receive commands about the working plan of the current day to adapt and reconfigure the subsystem. The main task of this level is the execution of the production schedules defined by the upper level to match the requirements defined by general management. This level interacts directly with the manufacturing cells and material flow.

All plant control systems must then send state reports to the third level (the factory control), which must provide a complete scheduling of works and manage factory resources. Such level should deliver information to the company control to assure correct supplies, a optimised store management, a personnel management. In parallel to the factory control there are the administrative and personnel subsystems which must treat the economical problems. Besides, other subsystems must deal with the marketing activities, the order planning and the customer services.

The managers of the factory can obtain data on the activities and costs of the factory from the company control system to create a strategic planning of the whole production and identify a dynamic approach to the market. The strategic management uses a central data base which contains information about the company, including summaries of data on production, quality control, machine tools, material handling, assembly facilities, personnel management, and material costs. Access to all lower data bases is performed through the hierarchy of subsystems and control computers. The short- and the long- term production schedules may be defined and monitored at this level. In case of production problems, rescheduling may be dynamically activated. When scheduling and resource allocation has been properly optimised, the company will use efficiently and cost-effectively the available resources, minimize the production costs and speed-up the fabrication of the products. Optimisation can be supported by mathematical optimisation techniques.

Hierarchical control systems allow to optimise the operation performed in each control unit since the view of the factory is accurately defined and specialised. This reduces the development and maintenance costs of each component since the goals of each of them are bounded. Design and testing of each unit is in fact simplified, while modularising the project allows to fully exploit the possibility of parallel and independent detailed design, implementation and testing by assigning each component to different teams.

Great attention must be given to design and implementation of each level of the hierarchical control system. In particular, the functionalities,

the structure and the architecture of each control subsystem at each level must be accurately designed to fully support the job of the user. To simplify the daily activities the subsystems must be designed and implemented by enhancing the capabilities of being user friendly. For example, schematics and graphic interfaces are greatly appreciated to present information at higher levels, with a simple, powerful, customisable interaction based upon structured pull-down menus, windowing and pointing devices. At lower levels, a compact, standard presentation of data and a structured interaction are often appreciated by the personnel without specific knowledge about informatic systems.

3. DISTRIBUTED CONTROL

Hierarchy is effective only if a distributed system is adopted as hardware support to guarantee high response performances [6]. This architecture presents high possibility of specialisation of the single components: this implies that better performances can be achieved at each level by introducing special-purpose devices and subsystems. Characteristics of such devices are strictly related to the goals of the considered subsystem: e.g. fast sensor and actuator interfaces may be used in engine controllers, while high-throughput and high-capacity mass storage devices should be connected to the factory and company levels.

The use of special-purpose devices should not induce (as much as possible) the complete fragmentation of the system into completely different subsystems. Modularity is in fact a key point to reduce the design and development time and to assure high availability to the whole system.

As design and development are concerned, it is possible to exploit previous experiences on the same hardware components and reduce the cost of automation by reusing hardware and software components designed and tested for similar applications. Software reusability become nowadays more important in the field of software engineering since the total costs of a computer-based system is essentially due to the software component, namely to the costs of their development and testing.

In particular, for example, the use of homogeneous controllers, based on microprocessors for the engine control, allows to assure a high flexibility of the system to hardware developments both of control systems and controlled engines. Besides, this approach allows to reduce the costs of automating because of the number of similar controllers that must be used.

As availability is concerned, the use of highly modular systems has been proved effective since a little stock of spare parts can be maintained at reasonable costs to cover the most of the possible faults in the control system. As soon as a fault is detected and localised, the faulty unit can be often substituted easily and rapidly, by repairing and restarting the control system in a short time.

The choice of the most suited hardware support for each component of the distributed, hierarchical control system is strictly related to the functionalities of the system itself, the production process, the plant structure, the economic state of the company and the future trends.

At the engine level, the control may be performed by using special-purpose boards based upon microprocessors, A/D and D/A converters and communication interfaces. They are often directly produced and distributed by the customer of the engines. At the plant level, coordination and control are provided by programmable logic controllers (PLC). They contain processing units, I/O interfaces for different kind of electric signal and communication interfaces. To improve the capabilities of the human interface, sometimes industrial personal computers are added to the PLC-based control system.

As factory control is concerned, the higher requirements of computational power and information storage impose the use of minicomputer or powerful personal computers. These computers must be in fact concentrate and store the information produced by the lower levels to give a comprehensive view of the whole factory and production process.

For the management of the factory and the other corporate services, it is necessary to adopt a wide spectrum of solutions which matches the variety of activities. Personal computers, minicomputers, superminicomputers and mainframes are used to support the general management of design, production and distribution: from the production planning to the production control, from the personal management to the administrative activities, from the management of materials and products to the managements of clients, from design to research and development.

Distributed computing and control require communications among computing units by means of computer networks [6]: the use of a suited network for the factory is a key point for automating to assure high performances and acceptable response time. Different interconnection schemes can be

adopted according to the specific characteristics and hierarchical level of the functionalities and of the hardware that must be supported. In particular, specific solutions must be adopted to connect control subsystems which are at the same hierarchical level or between different levels.

At engine level, the interconnections and the data exchange between each controller and the controlled engine are numerous and strictly related to the kind of signals that must be treated. Direct electrical interconnection between the controller, the sensors and the actuators is the most suited solution. Between controllers at engine level is not usually required any direct connection since each component is dedicated to a specific engine or part of the plant, without or with a strongly limited view of the other engines.

At the level of plant control, the control systems need to communicate with the environmental sensors, the actuators and the engine controllers to supervise and coordinate the activities of the whole plant. In this case interconnections of each controller with low-level components may be achieved by using point-to-point links or common-bus structures, according to the characteristics of the hardware components, the performances required and the characteristics of the environment. Possible solutions are based upon standards RS232, RS422 or RS485. Also connections between controllers, which coordinate the activities in a single plant, can be implemented by using similar supports.

Interconnections of computers of the factory level with computers of the lower level or between themselves may be accomplished by adopting different topologies and hardware supports. In particular, it is possible to adopt a star or a common-bus structure or a mixed solution according to the topology of the factory, and the performance and the functionalities of the control system. As hardware support, the Ethernet cables or the fiber optics may be used to cover large areas, when the other connections are not capable of guarantee an acceptable signal level at long distances or a sufficient protection against electric noise.

The upper level of factory management has connectivity characteristics which are different from the other levels: data exchange between computers at the same level is very intensive. To support the activities of management, production planning and control, personnel management, material and production flow, administration and marketing, the specialised computers must be connected by a network whose topology may be highly complex and structured in subnetworks. Typical topologies are star, common-bus, rings and hierarchical interconnection of them. As hardware support of such structures the standards of the other levels may be used: the most effective solutions with respect to the amount of data transfer are based upon Ethernet cables and optical fibers. Possibly, subsystems may be connected by using modems, optical fibers and satellites to implement wide area networks and geographic networks which cover areas larger than the local area networks in a building or in a group of adjacent buildings.

As software supports [6] of communication networks at different levels are concerned, the researchers have developed some standards which can be effectively used to guarantee compatibility of interconnections between different computers. For example, MAP/TOP standards are available at the first levels of the control system. For the higher levels, communications should conform to the seven-layers standard of ISO Open System Interconnection: examples of some layers are given by Digital Equipment's Decnet, IBM's SNA, Unix's TCP/IP.

The choice of the topology and the interconnection support is a complex task which involves a detailed knowledge of the environment, the plants, the production processes, the functionalities and the area distribution of facilities and services. Such task requires not only technical choices, but also an economic, personnel, strategic, politic planning of the structure of the company and an evaluation of the future trends of markets and production technologies.

When complete automation is concerned, the fault-tolerance capabilities of the hierarchical distributed system become important as the other nominal features, since the factory should continue its activities as long as possible, even if with degraded performances in bounded time intervals, and must guarantee complete safety of the working environment. Some components or subsystems may be in fact so critical that the availability of the whole system or, at least, the possibility of operation without supervised control of higher levels is an important feature of the adopted architecture.

To such purpose different techniques are available in literature [2] [4] at hardware or software level for error detection, error correction, fault masking, fault localisation, hardware reconfiguration in computing systems. The use of one of these approaches must be accurately considered and evaluated with regards to the implementation costs, the critical operations of

the computing unit and the influences on the other components and the whole production system. In particular, design and implementation both of hardware and software must accurately consider self-testing and diagnosis supports to simplify fault detection and localisation, i.e., ultimately, to reduce the repair time and to increase the overall availability of the complete functionalities of the control system.

4. THE CASE STUDY: THE DYEING FACTORY

All previous features and goals are discussed and evaluated in the following sections by presenting a practical implementation of a fully-automated dyeing factory. In particular our attention will be focused on the different aspects of this futuristic factory: from the hardware architecture of the distributed control system to the structured modular software components, from the communications to the interactive software interfaces, from the system features to the overall performances.

In a dyeing factory there are different typical activities, which correspond to specialised computing subsystems: a schematic view is given in fig. 1.

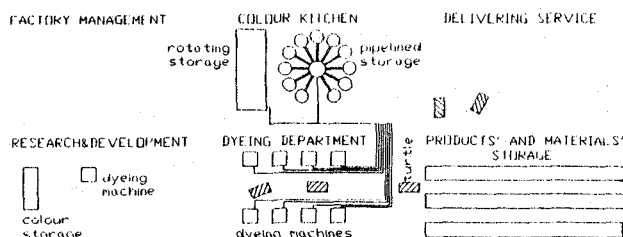


Fig. 1 - Structure of a dyeing factory

Dyeing of yarns and fabrics is executed in the dyeing department. The boilers and the pressure cookers are filled of water, colours and other chemical additives: yarns and fabrics are put into such containers and treated by imposing suited thermic cycles. Controllers must provide the corresponding control signals for example to engines for water mixing up, to valves for cooling and warming supplies, to valves for water loading and unloading. Besides, they must guarantee an accurate execution of the thermic cycle to achieve a correct dyeing of the material. After dyeing, the yarns or the fabrics are dried in air or in special ovens. Finally, they are prepared for forwarding by creating skeins, spools and rolls. Possibly, carding and trimming may be performed on fabrics before rolling.

The second basic department is the colour kitchen, i.e. the place where the colours and additives are prepared by mixing basic chemical substances. The recipes for new colours are created by specialised personnel by experimenting new mixtures of basic components. When a recipe has been successfully tested, it is stored for subsequent use during dyeing. In the colour kitchen the recipes are reproduced for each production. To such purpose, it is necessary to take from storage and weight accurately each fluid or powder to respect the amounts of the selected recipe. Two kinds of storage systems are actually supported: the rotating storage and the pipelined storage. In the first case, the containers are fixed in rows onto supports, which can be rotated to present at each step a new row in front of the worker. In the second case, the containers do not move: colours are delivered to the weighting and mixing system through pipes. Then, the mixtures must be obtained and maintained until they are required by the dyeing department. Automatic introduction of these substances is achieved by using a pipelined distribution controlled by computer: it provides correct routing by opening and closing valves and suited pipes maintenance through periodic washing.

The previous basic subsystems allow to introduce the first step of automation in the factory by simplifying the most dangerous and critical operations. To achieve a full automation, other subsystem should be added. The most important subsystem is the automatic movement of yarns and fabrics from the initial storage to the dyeing department, back to final storage and possibly onto distribution vans. For this subsystem robots are necessary: arms must load the materials from storage to automatic carriage, put them into the dyeing machines from the carriage, remove and store the dyed materials.

Global coordination among the dyeing, colour preparation and movement requires the introduction of a centralised control system of the whole factory. On such computer the personnel choose and activate the daily working plan by defining the works of each machine, the recipes and the dyeing programs that must be used. Statistics are collected from all control units of lower hierarchical level to create an updated image of the system and to evaluate some performance parameters. Optimisation of the production

will take advantage of the low level information collected periodically: by running classical algorithms for resource and working planning, it is possible to improve the productivity, the profitability and the product quality.

To complete the factory automation, computer supports should be provided also for the administrative and personnel departments. Integration of production control and administrative activities is useful to increase the synergies for optimisation of store management, contacts with clients and tradesmen, salary generation. In other words, a correct planning obtained from real on-line production data allows to decrease the production costs and the capital immobilisation and to improve the image of the factory towards the external world, in particular towards the clients. Finally, the research & development department should be included in the computer revolution: in dyeing factory, the aid of computer is important in creating and preview the recipe for a new colour or a new matching of colours, starting from the chromatic characteristics of each chemical component, yarns and fabrics.

Each of the previous subsystems is structured in hierarchical levels to guarantee the maximum flexibility of the whole system and the proper distribution of information. Besides, the previous subsystems themselves are interconnected in a hierarchical way. A schematic view of the structure of the whole control and information system for the fully-automated dyeing factory is given in fig. 2.

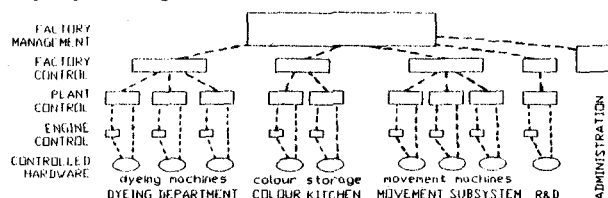


Fig. 2 - Structure of the control and information system

Each worker or clerk has the visibility and the control of the part of the whole system that is strictly related to his job. These structured specialised views allow to simplify the interaction between the computer system and the employees by presenting the information and the user interface of the control system in the way which is the most suited for the considered employee, for his skills and for his job. For each subsystem and each level, characteristics and the features of the computing system must be accurately chosen and defined to fully support the activities of the factory and to minimise the interactions with the employees, at least for the jobs in the worst environments. Next sections will discuss the design and implementation choices for the dyeing factory and the application of the theoretical guidelines presented in section 2 and 3.

5. CONTROL LEVEL 0: ENGINE CONTROL

The lowest level in each subsystem is dedicated to control the basic activities of the engines. In particular, it acquires signals from sensors and provides input data for actuators.

In the dyeing department, the engine control has been introduced to automatise the definition and the execution of thermic cycles in the dyeing boilers. The upper level sets the basic cycle parameters (e.g. the final temperature, the gradient and the maintenance time). The engine control, based upon a microprocessor board, guarantees the realisation of such cycle by generating the sequence of electric signals which open and close the valves of steam and cooling water. The input of this controller is the actual temperature received by the thermal sensor. The water in the boiler is in fact warmed by the steam through thermal transfer, while cold water reduces the temperature by cooling the external surface of the boiler. The control signals are produced by using a PID (proportional integrative derivative) control algorithm.

The same low-level controller is used also to measure the amount of water introduced in the preparation pool, which may be attached to the boiler for special preliminary phases of dyeing. In this case the PID algorithm receives information about the level of the water in the pool and generates the signals for the input valves. The same controller is used also to fill up some large preparation pools in the colour kitchen: controlled, optimised filling is in fact very useful to minimise the time required to prepare some colouring solutions. This is a practical example of the effective use of modularisation and reuse of standard parts: the use of the same controller reduced both the development and the maintenance costs.

In the colour kitchen, the engine control is used to coordinate and move the rotating storage. In this case, custom boards, based upon mi-

croprocessors, were designed to activate the electric engine of the rotating storage when a row of containers has been selected. Movements are verified and controlled by acquiring data from proximity switches, stroke ends and encoders. A second board controls the valve of the selected container to extract the proper weight of colouring material. A third board guides the movements of the mechanic arm which sustains the container to mix colours.

The most important application of engine control is in the subsystem for automatic movement of yarns and fabrics from the initial storage to the dyeing department, back to final storage and possibly onto distribution vans. In this subsystem, intermediate and final products must be moved in the factory to provide the input material to production cycles and to extract and store the output products. These operations are implemented by a robotised system based upon mechanic carriages (turtles) and arms, guided by a complex navigation control system. Turtles run in the factory, along predefined paths, by carrying the materials for and from production cycles. Mechanic arms must load the materials from storage to automatic turtles, put them into the dyeing machines from the turtles, remove and store the dyed materials. The low-level control of turtles and arms is very similar since it consists of activating the electric engines as long as it is required to reach the final position. Such state may be defined by the absolute position of the tree in the space or by the relative rotation. Control is guaranteed by a custom microprocessor-based board which generates the electric signals for the engines starting from the movement imposed by the upper control level and from the information acquired from encoders and stroke ends. Each board is able to control three electrical engines, possibly with different movement laws. To simplify the definition of movements, a command language has been introduced: it allows to describe simple bi- and tri-dimensional trajectories by using one single statement or multiple statements executed in parallel. Therefore, the same board may be used both for turtles and arms: this is a second example of the importance of flexibility and reusability due to modularisation.

Last application of simple engine controllers is in the machines for preparation for final delivering (e.g. rolling of fabrics) and for special treatments of fabrics (e.g. carding and trimming may be performed on fabrics before rolling). In all these cases, embedded controllers, supplied by the producer of the machines themselves, were used. Such devices receive the activation commands from the upper level of the factory control and provide automatic generation of signal for mechanic movements.

6. CONTROL LEVEL 1: PLANT CONTROL

The engine control simplify the management of specific engine: coordination of operations between different engines and actuators in the same production line requires a higher level of control. It must in fact have a comprehensive view of the whole part of the factory to verify the state of production and to impose the proper commands of executors (engines and actuators). To such purpose the factory is divided in production units in which activities are directed towards a single goal (e.g. the preparation of colour mixtures in the colour kitchen, and the dyeing cycle in the dyeing department). In each unit the control and management is guaranteed by a programmable logic controller (PLC) with suited I/O channels and communication lines with other computers.

In the dyeing factory the following production units were identified:

- the dyeing machine, composed by the boiler, the pipes and the valves for water, steam, colours and sewer, the temperature controller, and the level sensors;
- the colour machine, composed by the storages of colouring powders and fluids, the pipes and the valves for colours, additives and water, the mixing tanks, and the level sensors;
- the moving platform, composed by the turtle, the arms, and the orientation system.

For this control level, different solutions may be adopted: in particular, the choice of the PLC may consider a large number of possible alternatives and manufacturers. Standard PLCs (e.g. by Siemens, General Electric, Allen-Bradley, Foster-Wheeler, Omron, Festo) are a traditional approach. Technological advances and increasing requirements of the application move towards high performance systems and simple user interfaces. To satisfy these requirements, an increasing computation power was introduced in PLCs: to add flexibility and programmability, a recent research trend developed the use of industrial personal computers (PCs) instead of PLCs.

In the study case presented here, a new, compact, low-cost industrial PC has been designed and experimented. The main goal of this research was the implementation of a competitive control system as cheapest as possible,

but with the highest, the most flexible programming capabilities and the simplest, the most interactive human interface.

The basic structure of this PC is shown in fig. 3. It is composed by standard Eurocard boards contained in a 19" rack. The available boards are:

- the CPU, which is actually based upon Intel iAPX 80186, but which will be substituted by a the Intel iAPX 80286,
- the RAM memory, up to 512 Kbytes,
- the display controller, for an alphanumeric display with a screen of 18 rows x 40 columns or a screen of 18 rows x 80 columns,
- the serial communication lines, with RS422 protocol,
- the PID controller used for engine control,
- the power supply.

The monochrome display and, possibly, a 40-columns thermic printer are inserted in the same rack.

Data acquisition from the field and generation of control signal are performed by I/O boards. These boards have a their own power supply and are connected to the PC by means of serial RS422 communication lines. These characteristics give a great advantage: the boards may be placed directly in the field near the engines, while PCs may be installed in a place which is more comfortable or accessible for workers without requiring complex cabling for sensors' and actuators' signals.

The communication lines may be used also to connect the PC to the local printer, to other industrial PCs and to the computers of the higher level. Communication with other PCs is used to coordinate activities controlled by computer of the same level. For example, a modular dyeing system may be implemented by using large production units obtained by connecting up to four identical basic production units through suited piping and PCs communication. These structure allows to dye properly large quantities of materials in a single cycle, but it may be reconfigured in smaller production units when small quantities are required. When the basic production units work together, one industrial PC is the master of the whole system, while the others repeat locally the same sequences of operation delivered by the master.

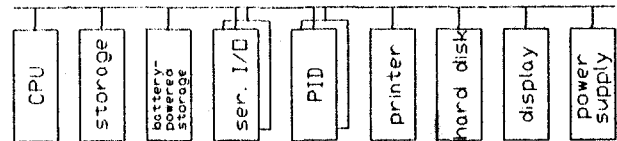


Fig. 3 - The structure of the PC controller

Hardware and software of this PC was designed to be as much as possible compatible with standard PCs, even if it has some enhanced features which guarantee efficiency in system control. For example, the serial communication lines, the higher frequency of the clock interrupt, and the availability of timers automatically updated. The operating system we adopted is the MS-DOS, with custom device drivers, to guarantee a flexible, powerful development environment. High-level languages (e.g. Pascal or C) may thus be used to implement advanced control programs with user-friendly interfaces, even if, at the moment, no graphic capability is supported.

The use of such PC controller and the control programs are different in the various applications in the dyeing factory. Nevertheless, the modularity of the system both in hardware and in application software allowed to reduce the development and implementation costs for the different applications. In particular, the reuse of software was greatly exploited to design a highly-programmable controller whose basic structure is common to all controllers, but which can be easily programmed. Three application of software reusing were identified: the screen library, the controller programming languages and the run-time support for control execution.

To support the management and the design of friendly interfaces and interactive menus, even on a small industrial PC, we introduced a simple, efficient screen library. It provides a standard frame to define the layout of the screen, with the position of data fields, their visualisation characteristics and their accessibility constraints. Functions are also available for input/output of data through screen fields and data checking. Facilities are also available to support definition of messages in different human languages.

A low-level programming language for industrial control (Industrial Control Language) was designed and implemented to allow definition of complex operations by testing input signals, internal counters, timers and flags. Such language is similar to the assembler of a microprocessor: it allows, for example, to read or set a signal on an I/O line, a counter, a flag, a timer or the temperature, and to control the execution flow of the

control program. Additional features are provided to start and control the execution of parallel tasks on the same PC controllers. This language allows to define a maintenance sequence and a group of functions. The maintenance sequence is a basic sequence of operations that must be continuously repeated when the dyeing machine is running in automatic mode to control the state of the machine itself and dangerous events. The functions are sequences of basic operations, which are provided to the user to simplify dyeing programming by avoiding a detailed knowledge of the characteristics of each dyeing machine. From the point of view of the user, in fact, the control activities are constituted of a sequence of functions (e.g. the boiler loading, the colour sampling, the thermic cycle, the downloading).

The user of the PC controller do never program the controller by means of the low-level language ICL, but only the predefined functions: ICL is used only by the producer of the automated subsystems of the dyeing factory to generate the complex control functions by starting from well-tested basic operations. A compiler was implemented to translate the textual form of these complex functions into fixed-format instructions, which can be fastly interpreted and executed by the run-time support of the PC controller.

The third application of software reusability is the run-time support of the ICL language. When the PC controller is set in automatic mode, the PC executes the user program to control the activities of its production units. In particular, the PC starts and controls the execution of the maintenance sequence, the control program and, possibly, the parallel control tasks. This run-time support consists of an efficient ICL interpreter, which fetches and executes the instructions defined by the producer of the dyeing subsystems for each function, for the maintenance sequence and the parallel tasks.

Since the MS-DOS operating system is monotasking, the control program of PCs was designed, structured and implemented by simulating the execution of parallel tasks. To such purpose, a coroutine-based scheme was adopted by introducing a scheduler and suited functions for control transfer. The maintenance sequence, the user functions and the parallel tasks are thus concurrently executed on the PC controller.

To simplify design and implementation of the whole control program for PCs, also the other functionalities and activities were based upon the use of concurrent tasks. For example, concurrent task were introduced also to manage data acquisition from I/O devices, output signal for I/O boards and PIDs, communication among computers, printing facilities, screen updating, interaction with the user, statistic generation. The partitioning of the typical control program into concurrent tasks is shown in fig. 4.

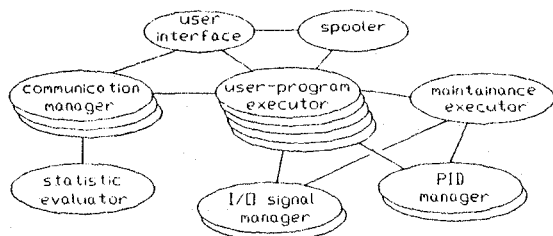


Fig. 4 - Parallel tasks in the controller program

In the dyeing department, this controller is customised to manage the dyeing activities. On the basic structure, the following functionalities were added:

- the editor for the user programs, i.e. to define the sequence of predefined functions which constitute a user program for dyeing;
- the listing facilities to visualise or print the list of predefined functions and their parameters, the list of user programs stored in the controller, a specific user program;
- the loading/downloading facilities to load new user programs from the higher control level of the factory, or to store a program of the PC controller into the higher level;
- the loading/downloading facilities to store or retrieve a new program into or from the battery-powered storage on the PC controller;
- the execution facilities to start, stop or abort a user program on the PC controller;
- the reset function to completely reset and, possibly, reconfigure the controller;
- the configuration functions, which allow to chose some configuration parameters of the controller (e.g. the date, the time, the connection with other controllers for master/slave configurations, the parameters for each PID controller, the use of the local printer);
- the automatic loading of orders, which loads and activates the proper user program as defined in the list of production orders

When a user program has been loaded and started, the PC control acquires input data from the field and generates the suited control signals for the actuators. In parallel, the controller stores low-level statistics about the production (e.g. the alarms, the functioning time, the operation performed); these data are periodically transferred to the factory control for storage and further elaborations. The controller guarantee also the management of the interactions with the user, which can modify the execution of the program or the program itself.

In the colour kitchen, the PC controller is used to control and co-ordinate preparation and delivering of colour mixtures and additives. In this department, the controller was customised by introducing the following functions:

- the editor for the recipes, which allows to define the list of chemical components and the delivering time for the recipe of a specific dyeing cycle;
- the listing facilities to visualise or print the list of user recipes stored in the controller or a specific user recipe;
- the loading/downloading facilities to load new user recipes from the higher control level of the factory, or to store a recipe of the PC controller into the higher level;
- the loading/downloading facilities to store or retrieve a new recipe into or from the battery-powered storage on the PC controller;
- the execution facilities to start, stop or abort a user recipe and the visualisation of single dosing on the PC controller;
- the reset function to completely reset and, possibly, reconfigure the controller;
- the configuration functions, which allow to chose some configuration parameters of the controller (e.g. the date, the time, the connection with other controllers for master/slave configurations, the parameters for each PID controller, the use of the local printer);
- the automatic loading of orders, which loads and activates the proper user recipe as defined in the list of production orders in the higher control level.

Even if some functions of this kind of controllers appear similar to those of the dyeing department, their meaning and their implementation are different. In colour kitchen, in fact, the PC controller must identify the position of the desired colouring materials or additives in the storage, receive the proper quantity of materials, send these materials to the mixing containers, preparing the mixtures and send the mixtures to the corresponding dyeing machine in which the production order will be executed.

The last application of the PC controller is the coordination and control of material and product moving in the dyeing factory. Motion of turtles and mechanic arms needs in fact a higher control, which is able to acquire information about the position of turtles and arms and to impose the proper motion parameters to obtain the correct trajectories.

The on-board controllers for turtles and the controllers for fixed arms were customised by introducing the following functions:

- the editor for the trajectories, which allows to define the parameters of a motion and its execution time;
- the listing facilities to visualise or print the list of motions stored in the controller or the parameters of a specific user motion;
- the loading/downloading facilities to load new motions from the higher control level of the factory, or to store a motion of the PC controller into the higher level;
- the loading/downloading facilities to store or retrieve a new motion into or from the battery-powered storage on the PC controller;
- the execution facilities to start, stop or abort a motion;
- the reset function to completely reset and, possibly, reconfigure the controller;
- the configuration functions, which allow to chose some configuration parameters of the controller;
- the automatic loading of orders, which loads and activates the proper user motions as defined in the list of production orders.

The controllers of fixed arms use information from encoders and lower level controllers to define the position of the arms in the space and, thus, to compute the parameters of the motion that must be applied to reach the final positions in the space, possibly with a given motion law.

Turtle control is more complex since the position of the turtle in the factory must be accurately evaluated to avoid collisions with other turtles, machines or personnel. To simplify installation and control of automated transfer of materials and products, the use of sonar and radio-beacons. Sonar identify the presence of unexpected obstacles on the path of the turtle and impose the immediate stop of the motion. Radio-beacons allow the

PC controller of the turtle to compute the absolute position of the turtle itself in the factory by using triangularisation techniques. Control of the motion of arms on a turtle must consider also the possibilities of interferences or collisions during the motion itself. When the user or the factory control defined the final position that must be reached by the turtle, the PC controller on the turtle itself is able to automatically determine the path towards the final position and to control navigation by interacting with the factory control.

7. CONTROL LEVEL 2: FACTORY CONTROL

Global coordination among the dyeing, colour preparation and movement requires the introduction of a centralised control system of the whole factory. On such computers the personnel choose and activate the daily working plan by defining the works of each machine, the recipes and the dyeing programs that must be used. Statistics are collected from all control units of lower hierarchical level to create an updated image of the system and to evaluate some performance parameters.

In the dyeing factory of this study case, the factory control may be implemented by using minicomputer or a distributed system, in which each computer supervises a part of the whole factory. The high modularity and the realisation of an open, expandable system suggested the second solution: to such purpose we designed an efficient, low-cost architecture based upon high-performance personal computers. In particular, we adopted a standard PC AT based upon Intel iAPX 80286 or iAPX 80386 according with the requirements and the workload of the specific factory. These PCs are equipped with:

- a standard 80 x 25 alphanumeric display,
- at least 640 Mbytes RAM,
- a considerable amount of storage (at least 700 Mbytes for each) to guarantee the capability of recording large quantity of statistics for a reasonable time,
- a communication board,
- a printer.

Interconnection between computers of plant and factory controls consists of a low-cost structure based upon a fast RS422 communication system to minimise the implementation costs, while acceptable performances are guaranteed.

The operating system of PCs is MS-DOS with the extensions embedded in the control program to simulate parallel execution of concurrent tasks, as in the plant control programs.

Onto such platform, the specialised control programs for dyeing department, colour kitchen and material movements were designed and implemented. As at the lower level, all these programs have common features and parts. Some examples are the communications between computers, the spooling facilities, and the screen library, multitasking simulation. These facilities are similar to those of the plant control, even if they may take advantage of the higher capabilities of the computer of factory control. In particular, the user interface is more appealing and accurate than in plant controllers. Besides, the use of a graphic display (EGA or VGA standards) and printer may be exploited to present some statistics in a graphic form, instead of using more traditional tables and reports.

An interesting feature of our implementation is the possibility of remote control of a plant controller through the communication network. In this case the personnel may connect to the remote controller in the factory from the central supervisor system at factory level. The distributed architecture simulates the interaction of the user through the supervisor computer as if he was in front of the remote controller. In particular, the user can give the same commands as he used the keyboard of the remote controller and he can see a copy of the display of such controller continuously updated onto the screen of the supervisor.

Also the structure of the application software of the factory control for each department is similar to that of the lower level. The control program is structured in a set of parallel tasks executed concurrently. Specialised tasks are dedicated to manage the user interface, the computer communications between hierarchical levels and between computer of the same factory level, data acquisition, statistic storage, and production ordering and planning.

Details of the implementation of each feature, in particular the user interface and the available commands, change from a supervisor to another, according to the part of the factory which is controlled by the supervisor itself.

The supervisor of the dyeing department coordinates and supervises the dyeing activities. It provides the following functionalities:

- the local editor, which allows the user to write programs to control the dyeing machines directly onto the supervisor, without interacting with

the plant controller;

- the listing facilities to visualise or print the list of user programs, the list of functions, and specific programs;
- the loading/downloading commands to move user programs through the network from/to the plant controllers;
- the automatic acquisition of statistics about the activities of the plant controller of dyeing machines;
- the generation of detailed reports of statistic information for groups of machines or production orders;
- the editor of the daily orders for production activities;
- the automatic downloading of programs through the computer network to the plant controllers to perform the list of daily orders;
- the panoramic overseeing of all plant controllers through a schematic view of the most important information about the state of each controller;
- the acquisition and generation of statistics about the functioning, the usage and the state of the different parts of the plants;
- the automatic remote tracing of temperature cycles to verify the activities of the dyeing machines and the quality of products.

Through this factory controller, the user can supervise all plant controllers of dyeing machines, define the order planning and acquire statistics. In large factories, more than one supervisor could be introduced to improve the efficiency of the whole system by applying the modularity growth of the basic control system. In this case an additional interaction between controllers at the same level is required.

The supervisor of the colour kitchen guarantees coordination between plant controllers of the kitchen itself. It provides the following specific features:

- the local editor, to write recipes directly onto the supervisor without interacting with the plant controller;
- the listing facilities to visualise or print the list of user recipes and specific recipes;
- the loading/downloading features to transfer the user recipes through the network from/to the plant controllers;
- the automatic acquisition of statistics about the activities of the plant controller of colour kitchen;
- the generation of detailed reports of statistic information for groups of controllers or production orders;
- the editor of the daily orders for production activities in the colour kitchen;
- the automatic downloading of programs through the computer network to the plant controllers of the colour kitchen to perform the list of daily orders;
- the panoramic overseeing of all plant controllers through a schematic view of the most important information about the state of each controller;
- the acquisition and generation of statistics about the functioning, the usage and the state of the different parts of the plants in the colour kitchen;
- the automatic remote tracing of colouring materials and additives for storage management.

The user can interact through this supervisor with the complete colour kitchen to define the daily activities and to receive statistics about the state of this subsystem.

The supervisor of the transport subsystem manages and coordinates the movements of materials and products in the factory, to minimise the personnel presence in dangerous or critical activities. It provides the following functionalities:

- the local editor for the definition of the movements directly onto the supervisor, without interacting with the plant controllers;
- the listing facilities to visualise or print the list the movements and the parameters of a specific movement;
- the loading/downloading of movements through the network from/to the plant controllers;
- the automatic acquisition of statistics about the activities of turtles and arms;
- the generation of detailed reports of statistic information for groups of machines or production orders;
- the editor of the daily orders for production activities;
- the automatic downloading of programs through the computer network to the movement controllers to perform the daily orders;
- the panoramic overseeing of all controllers through a schematic view of

the most important information about the state of each controller;
 - the acquisition and generation of statistics about the functioning, the usage and the state of the different parts of the movement subsystem.
 To simplify the interaction with the factory control, the system can be configured so that the definition of the list of orders contains all information required to manage the complete production cycle. Data for each subsystem (dyeing, colour kitchen and movement) will be split and extracted from the global information about orders and, then, delivered to the supervisor of the corresponding subsystem. The complete definition of the orders may be performed on any computer of the factory control. A better solution dedicates a small PC to such activity, to guarantee a simpler coordination between the personnel.

The research&development department may be included in the computer system by connecting its PC to the factory control system. In this department, the aid of computer is important in creating and preview the recipe for a new colour or a new matching of colours, starting from the chromatic characteristics of each chemical component, yarns and fabrics. When completed a recipe may be delivered to the factory for production directly through the computer network.

8. CONTROL LEVEL 3: FACTORY MANAGEMENT

The highest level of the control and management system is basically dedicated to collect information about the state of production, the activities of the personnel and the orders of clients. Such data are essential to a correct strategic planning of the activities of the factory. Besides, together with data on new trends of markets, customers and technological research, this level should provide guidelines to identify possible future developments and diversifications of the production to increase the global profits of the company. Thus, the users of such information system should be the managers of the company, which have the responsibility of choosing the strategies and the tactics on the markets and in research.

The basic functionalities of factory management are connected with the capability of acquiring, storing and retrieving large amount of information in a data base. These characteristics require the implementation of a high-performance data-base system. The dimensions of the data that must be stored suggest the use of an hardware architecture based on an efficient minicomputer or, better, a superminicomputer with a multi-user operating system.

The choice of the proper hardware solution is strictly related to the structure, the dimensions and the activities of the company. Usually, a centralised information system is enough to satisfy all requirements of management: to such purpose, it is possible to adopt a Digital Equipment's MicroVAX, an Hewlett Packard's HP830 or a Sun's WSL Sun 4, with the proprietary version of the Unix operating system (or VMS on MicroVAX). User interrogations are executed through traditional terminals. In present implementation a Microvax 3200 with Ultrix operating system has been used.

When the company is very large, the user are many or the elaborations on data are massive, the computing power of the central server may be not satisfactory to provide an acceptable response time for transactions. In this case, it is possible to connect some workstations at the central server to implement a distributed computing system. The data base is maintained in the server, while user interface and computations are performed locally in the workstation. An alternative solution may be designed by adopting a completely distributed data-base system. Data are not stored in the unique server, but are distributed on a group of servers connected in a cluster by an high-performance network. Each of these servers is specialised on different aspects of the factory activities and, thus, on different subsets of data. Interrogations are implemented by exploring all servers in which are stored information related to the interrogation patterns.

As software platform, we have chosen the DBMS Oracle of the Oracle's Corporation, a well-known relational data base. This solution, as similar ones based upon other standard DBMS, avoids the implementation of a custom data-base system and guarantees the portability of data on different hardware platforms, without any external modification. Also application programs for data introduction or retrieval do not need maintenance except possibly for the graphic interface and the calls to the operating system. An accurate programming style and the use of a standard graphic library avoid also these drawbacks. To such purpose we have adopted the X-Windows graphic presentation interface to implement a flexible, powerful, portable interaction with the user.

On the previous architectures, the control and management system of the whole factory has been implemented and developed. Data about the

production are received from the factory control level to store a continuous trace of the final information of factory activities. Such control level provides also data about the overall state of the engines, their productivity and their efficiency. In parallel, the quality control deliver summary information about the characteristics of the input materials, the intermediate and the final products to guarantee a continuous check on the quality of products and on the efficiency of workers. Data of orders and clients are introduced to allow planning of production at high level. Also summaries of data about administration and personnel are received by the higher control level from the computers of the administrative and personnel departments to complete the view of the company. Activities of these department are executed on other computers with suited programs. Integration of all these subsystems guarantees on-line data for detailed, optimised planning of short-, medium- and long- term strategies, which minimise all production and financial costs and maximise efficiency and profits.

Interrogation of the company's data base for managers has been implemented by direct questioning through the standard command language of the DBMS. To simplify interaction, a set of predefined, structured interrogations has been implemented which present the main information in tables or different graphic forms. The basic interaction requires the knowledge of some implementation details. The second approach is completely separated by implementation since search and reports are generated starting from a guided data selection through interactive menus. To support planning the system has been structured to include optimisation algorithms and direct interaction.

9. CONCLUDING REMARKS

The full automation of factories has been discussed. At the moment, it is one of the main goals of the research activities in system control since in many applications, in particular in critical or dangerous systems, the presence of personnel may be not convenient and safe, both for the controlled plant or process and for the personnel itself. The quality of the work environment, the quality of the job, the satisfaction for the personnel in its own job, the safeness of the personnel must be in fact greatly enhanced to assure the increase of the quality of the human life.

The use of automatic control and computers is an effective aid towards this goal. In this paper we discussed some guidelines that allow to introduce a high degree of automation and to design integrated control systems. In particular we consider the concepts of hierarchy, modularisation and distributed control as the key features to achieve an efficient system.

The research presented here has been suggested and experimented in a real case: a fully-automated dyeing factory. Such case study has been completely designed. Implementation of its subsystems is at different development stages. The control system of dyeing machines was completed, tested and it has been already distributed. The control system of the colour kitchen was implemented and tested. The implementation of the robotised system for movement of materials and products is at the final stage. The integration of these subsystems through the centralised control system is under implementation: the subsystem for automated planning of production, the interfaces to the administrative and management departments, the production and management controls are at the first implementation stages, while the research&development subsystem is planned for the future. Further research will be developed to improve integration and information exchange: moreover, the integration of fabric printing will be studied and implemented to complete the spectrum of the automation proposals in the production of yarns and fabrics.

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