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INTERFACE REQUIREMENTS, TRANSDUCERS, AND COMPUTERS FOR ON-LINE SYSTEMS

Survey on Digital Computers in Control
Fourth Congress-International Federation of Automatic Control
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INTRODUCTION

On-line process control, through the medium of the digital computer, has been the most popular discussion topic of industrial manufacturing circles over the recent past. Although only seventeen years old since first practical proposal[16,36] it's influence on the industrial scene is already revolutionary and promises to be even more so within the next few years. Only now, however, almost ten years after the first industrial application and nearly fifteen years after the first military application of this technique,[11] can we begin to see clearly the path our future progress should take for us to derive maximum benefit from this magnificent servant - the digital computer.

Any new technique which has its origins in the civilian economy in many different companies in many different industries at nearly the same instant in time will inevitably result in much duplication of effort, many false starts, and many repetitions of the same mistakes. This is due to the natural desire of industrial concerns to keep their newly acquired proprietary information secret, to the difficulty of communicating between different engineering disciplines, and to the general lack of knowledge of the requirements and potentials of a new field on the part of all concerned.

With the passage of time all of these difficulties and obstacles have eased. We are now discussing our problems and our failures as well as our successes with each other. We are learning the requirements for successful applications: hardware, software, and process analysis. Perhaps even more importantly we are learning that much of the resulting knowledge can be translated directly from one user industry to another.

It is not our prupose here to review the many and rapid developments which have occurred in this field during its short but rapidly changing life. This has been done admirably by this author's several predecessors in this survey,[19,24,25] in the several IFAC/IFIP Symposia,[20,21,35] along with several important reviews in other journals[1,12,23]. Instead we wish to take this opportunity which appears at a turning point of the field to outline the needs of the field and to postulate how these needs may be met in the relatively near future.

We will consider each of the major hardware subdivisions of a process control system in our discussion: sensors and transducers, wiring systems, computer mainframes, output and backup devices, actuators, as well as overall systems requirements. In addition the importance of software in the overall process control system is emphasized and its probable development path outlined.

SENSORS - PAST, PRESENT AND FUTURE NEEDS AND PRACTICES

In most process control systems active in industry today, the best that one can expect in the overall accuracy of the representation of a sensed variable in its final form, as a recorded value or as a translation to controller action is a minimum error of one to two percent of full scale or worse[17]. This is due to many causes such as: a linearization of the sensor output by transducers, offset and dead space in these elements, and to a lack of calibration of the transducers and/or the recording and controlling gear associated with the variable. This latter may be due to changes in sensor response, to a mechanical change or an electrical drift of the control elements, or to an error in the original calibration itself.

One can always make effective use of newer and better ways of translating the changes in a system's physical variables into signals intelligable to the process control system and indeed one can make a long list of desirable potential developments of this type[26,27]. However, these developments come under the heading of inventions and they are thus very hard to schedule within the design period of a new process control project.

It would therefore seem that our most desirable avenue of progress in the next few years should be to accept any developments in the above areas which appear but to count in our planning on using those types of sensors which are common today.

Several of the developments which will be mentioned in other sections of this report will be extremely helpful in compensating for our present day problems in detecting changes in plant variables and a lack of the invention or discovery of new sensors. They will do this by eliminating the need for many of the elements which are now in the computational loop and thus eliminate their contributions to the overall sensed variable's error.

The use of remote digitization can take the place of a transducer and its inherent errors. A nonlinear digital computer based conversion of this digital presentation of the sensor's output to a representative set of units can eliminate the errors due to linearization as well as much of the drift of analog conversion and recording units. The use of additional complementary inputs along with built in computational cross checks can allow the computer system to regularly recalibrate its overall conversion of the real variables of the process to a suitable representation of them to the operator or to the plant control system.

Additionally, one can expect the digital control system of the future to do much more dynamic system simulation to allow them to compute variables which would not otherwise be measureable. Also we can expect much use of the computer to carry out even quite complex computations to develop system performance functions such as efficiency, yield, costs, etc., for presentation to the operator in place of the measured temperatures, pressures, levels, etc., which he usually sees at the present day[5,6,7].

SYSTEMS WIRING PRACTICES - PRESENT STATUS AND A HOPE FOR THE FUTURE

One of the major difficulties with early digital computer systems for process data collection, analysis, and control was the extreme problems encountered in suppressing systems noise. However, the systems vendors quickly learned by experience, by proper communications engineering, and by a translation of their findings from complimentary installations in the aerospace industries. They can now make the proper use of twisted leads,of shielding, of balanced input leads, of correct grounding practices, of analog and digital filters, and of the socalled flying capacitor sampling systems so that systems noise pickup should no longer be a problem in any type of industrial environment[22,28].

Unfortunately, the properly combined use of each of these techniques results in a very expensive wiring system, both from the standpoint of the physical cost of the components involved and also from the installation and check-out labor charges. A promising remedy for this would appear to be available to us soon. This is the possibility of the use of a set of remote multiplexing and analog to digital conversion units with a resulting serial digital transmission of the signal to the central computer. Should the remote multiplexers each handle 25 inputs, this would result in a better than 25/1 reduction in system wiring costs between multiplexer point and computer with an even greater reduction in noise potential since high level digital signals should be less noise sensitive.

Still another potential technique offers even further reductions in systems wiring costs if and when it can be proven practical. Should overall data frequency requirements permit, the possibility arises of running one set of cables about the plant capable of selecting and carrying the digital representation of each point in its turn. Remote digital to analog converters would allow the same method of handling output signals as well. This latter technique was suggested several years ago by J. M. Keating of British Petroleum[13]. So far it has not been tried in a full-scale installation because of the frequency requirements mentioned above.

Recent developments in the aerospace field in the signal system wiring for large transport planes[10] has emphasized the practicality and desirability of one or both of the above techniques. In addition, integrated circuitry already has the capability of producing the remote multiplexers and A/D and D/A Converters at attractive cost levels when compared to conventional practices. Keating's suggestion involves a heavy computational load on the digital computer controller in selecting and controlling the remote multiplexers. The recent appearance of small and inexpensive communications switching computers promises a remedy to this in that one of these machines could be imposed between the control computer and the plant data system to handle the selection task. Should this make Keating's suggestion practical, the resulting savings in system wiring and check out costs could pay for the small computers many times over.

Until we become heavily involved in remote multiplexers and other more sophisticated data collection systems, the present centralized multiplexer, A/D converters systems are becoming an ever larger part of the hardware costs of a computer based control or data system as the computer itself decreases in cost and systems become larger. It is hoped that the application of integrated circuits in this area plus some badly needed standardization will aid in a much needed cost reduction here.

REQUIREMENTS FOR COMPUTER MAINFRAMES FOR PRESENT AND FUTURE SYSTEMS

The process computer control field is now old enough and advanced enough that we have established well recognized classes of applications of these machines. In addition, we can now quite accurately detail the requirements or specifications for present generation computing equipment to carry out the control and data handling functions usually ascribed to that class of installation. Table I outlines the presently accepted classes today and this authors recommendations for hardware for each task[34].

By far the most important factor today in the acceptability of process control computers in the eyes of user company managements and the major stumbling block in the further progress as is discussed in this paper is the question of overall systems availability. That is, what percent of the total time can the computer control system be counted upon to carry out its assigned task. This is, of course, a combination of a very long MTBF (mean time between failures) and a very short average repair time. A figure of 99.95% has been generally accepted by the industry as a desirable goal for overall systems availability[5,6,7].

Figure 1 shows the recent trends in computer mainframes MTBF. Note that industrial control computers seem to lag the military systems by about three years (one generation of computer designs). The recent U.S. Air Force requests for bids on guidance computers with a MTBF of 20,000 hours[3] (nearly three years) is most heartening for the future well being of the process control computer field.

TABLE I

THE CLASSES OF APPLICATIONS OF CONTROL COMPUTERS - SOME NOTES AND REQUIREMENTS FOR EACH

1. The Supervisory Machine

Initially used for data logging, monitoring, etc. Now used as means for optimizing the steady-state operation of a plant or as the middle member of a hierarchy system. Still comprises the majority of process control applications. Requirements for these machines are as follows:

a. Need all the speed available from the manufacturer in order to make use of present and potential design and programming aids as a supplement to their process control tasks.
b. 32K or larger core memories again needed to take full advantage of possible executives, compilers, optimization routines, etc.
c. Bulk memories of at least 500K and preferably more for storing the above programs. Speeds of drums or "drisks" would be helpful if above memory can be attained at low enough cost.
d. At least 16 bit word length plus memory protect, and parity necessary. More bits helpful if they serve to significantly improve the instruction repetoire and addressing capability of the machine.
e. Card handling equipment, and line printers required.

2. Direct Digital Control (DDC)

First applied to full-scale plant control in 1962. The third generation has been much influenced by requirements for these applications which can be divided into two classes.

a. Dedicated Special Control Functions - Should use 16K of core memory of 4μ sec cycle time or less. No drum or line printer needed. Paper tape equipment for input sufficient. 14-16 bits adequate.

TABLE I CONT.

b. General Purpose Control Applications - Very similar to Supervisory System above except that 16K core may be sufficient. Line printer needed only for system check-out purposes, not full-time.

One would use the dedicated system when he could specify the control requirements completely ahead of time. Use the general purpose system to get maximum possibility of on-line compilation of control algorithms and flexibility of updating of complete control package.

3. Mixed Mode Systems

A system combining the functions of the first two classes above. Generally necessary where pure DDC will not give an economic payout or overall needs are too small to justify two separate computers. Second most common application to Class One above. Requirements same as Class One.

4. The Hierarchy Member

The trend in industry is toward complete plant hierarchies of the type of Figure 3. Requirements for the upper members of these are as follows:

a. Machines of considerably higher capacity and capability than that possible with even the largest versions of those considered above, i.e., need longer word length for wider addressing capability and larger repetoire of instructions.
b. Magnetic tape, line printer, card handling and bulk storage equipment are all necessary for present requirements. Multiprocessing capability is also very important.
c. Again all possible speed can be utilized.

5. Special Purpose, Dedicated, Non-Modified Systems

Machines used for very special-purpose tasks such as component testing, system checkout, analytical instrument monitoring etc. Justified for one special task only and

TABLE I CONT.

no program modification contemplated. Such machines can be much slower than any of the above and can be machine-programmed in the interests of conserving memory. Usually 4-8K core are sufficient and no bulk storage is required. Only simple input-output or man-machine interface is required again decreasing memory requirements.

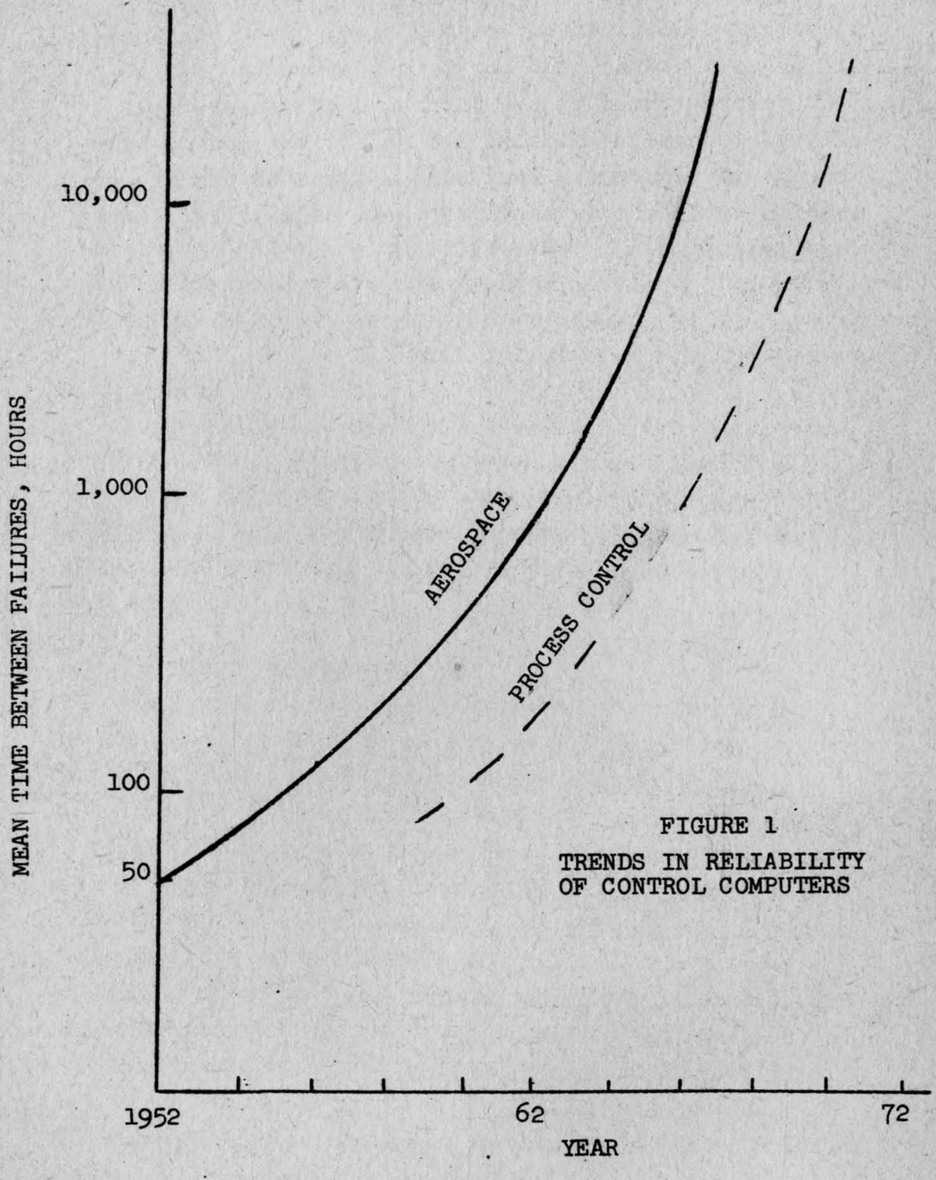


FIGURE 1
TRENDS IN RELIABILITY OF CONTROL COMPUTERS

The second problem in this area, that of rapid and accurate maintenance, can probably only be solved by the use of sophisticated diagnostic techniques by the computer itself and the "swapping" of major units of the system which are indicated by the diagnostics to be marginal or to have failed. It is interesting that Ferranti Limited has already instituted such a procedure for maintenance of their ARGUS 500 systems[8].

There are several other developments which have already started and which are expected to accelerate in their application to process control computers. These are as follows:

1. The small or mini-computers will take over all specialized tasks for which their size and speed is applicable such as the operation of large cathode ray tube display systems, monitoring and control of analytical instruments, handling of data collection and data transmission tasks, etc.[14,15].
2. The use of read-only memories for established and standardized programs in place of the present hardware or software memory protect system which is not infallible.
3. A trend toward a card oriented rather than paper tape oriented program system. Even though card handling equipment is more expensive, the ease of handling, greater durability, and easy capability of modification of programs is all in favor of the card based system.

THE PRESENT SITUATION REGARDING COMPUTER OUTPUT AND SYSTEM BACKUP DEVICES AND EXPECTED DEVELOPMENTS

The early unfamiliarity of plant process control personnel with the characteristics and capabilities of digital systems, the lack of knowledge on the part of both user and vendor personnel of the requirements in terms of memory size and mainframe computing speed for effective digital systems, along with the overall unreliability of the early combined hardware and software systems installed created a natural desire in the users mind to require an elaborate backup control system to the digital one and to depend upon established analog techniques for this function[5,6,7,9].

The result has been the creation of a "monster" from the standpoint of the economic payout of digital control systems and their future development both as to design techniques and to applications possibilities. At the present time the requirements for analog set point change devices, analog standby controllers, and DDC output stations imposed a cost of about $250.00 U.S. per loop beyond the cost of the analog control loop the digital system was originally designed to replace. Thus instead of a potential of about $1,000.00 U.S. saving per loop as an economic incentive for their use we are instead faced with an economic penalty involved with their application.

Since one digital computer is a perfectly good backup for another and since two machines, each with a 99.95% availability will have a fantastically long overall system MTBF of the order of decades we have the possibility of reversing the above trends once these availabilities are attained and accepted by user company management. In addition the digital data handling techniques involved with the remote multiplexers mentioned earlier will also preclude the analog backup systems and thus promote cost savings in these systems.

A second area of large cost committment in past digital plant control systems has been in the area of man-machine interactions, i.e., alarm devices, logging printers and typewriters, operator's panels and displays, manual valve operation devices, etc. Again these systems have become much more elaborate than a proper use of the latest available techniques would require. Cathode ray tubes with disk memories and "mini-computer" directors[2,4,29,30] can eliminate most of the need for the previously mentioned devices by "management by exception" techniques and scope presentation of any and all data necessary for the plant operator or supervisor.

The coming major use of digital components in industrial control systems which we are discussing in this paper will, however, miss one very important component of the control loop. The present almost universally used pneumatic diaphragm valve operator has successfully resisted all efforts to displace it by other types of actuators. Its reliability, power per unit size, and low cost will keep it a feature of flow process control systems for a long time to come.

STANDARDIZED SOFTWARE - A HOPED-FOR SOLUTION TO A MAJOR PERSONNEL PROBLEM

As stated earlier, most of the major hardware problems which were prevalent with the early process control computer systems have now either been solved or the path to their solution is clear. These problems have been replaced, however, by a set of equally difficult ones concerned with the system programming or software.

In our early applications, we consistently underestimated the size and complexity of the programs required to effect a successful control system. Also these early computers lacked the programming aids which are now available with most manufacturer's equipments. As a result large programs had to be squeezed into a too small memory by a programming staff which was itself too small. As a consequence the final installations of the early machines were invariably late and required a very long and frustrating check-out period.

While programming aids such as compilers and special process control languages have recently eased the programming task greatly, this has been almost compensated for by the much increased size and complexity of recent overall software packages required for the newer and more sophisticated installations.

The result has been a major shortage of personnel qualified by training, experience, and innovative ability to carry out the programming of one of today's systems. There is thus a major incentive to reduce this total programming load by developing new and more universal programming aids, by standardizing them for easier personnel training and use, by instituting a ready transfer of successful programs to new computer systems, and by the exchange of mathematical models and their pertinent programs between different companies and industries.

The goal for the standardization effort can be stated as follows:

"As a long term goal it should be unnecessary for user company systems and instrumentation engineers and programmers to have a knowledge of the basic machine language of the computer involved or even of an assembly language for this machine. However, they must be thoroughly grounded in computer and control concepts. They should be able to communicate with the system, construct new programs, and initiate or modify the sampling sequences and data manipulation techniques through the use of a standardized high level language, through the use of a specialized process control program which can handle simple tabular formats, and/or through an operators console in some equally simple manner.

Programming systems adopted should also have as long range goals machine and configuration independence. They should, in addition, contain provisions for automatic or semiautomatic documentation of all changes to systems program and/or system configuration."

Table II outlines a set of requirements for such a standardized set of process control programs. Achievement of these goals and requirements will go a long way toward completing the digital revolution in industrial control now well under way.

TABLE II

DESIRABLE REQUIREMENTS FOR SOFTWARE STANDARDIZATION

1. There should be available a high level programming language. For example, a language which includes USASI Standard FORTRAN (X3.9-1966) as a subset should admirably satisfy such a need.

2. The high level process control programming language should contain the necessary capabilities to permit the following industrial control functions to be programmed completely in this language:
   a) Bit Manipulation
   b) Bit Testing
   c) Process Interrupt Handling
   d) Interrupt Inhibit and Permit
   e) Parallel Task Execution
   f) File Handling

3. Goal of software design should be to minimize the amount of specific information which a process engineer needs to know about a control computer and its associated software to implement computer control for a known plant.

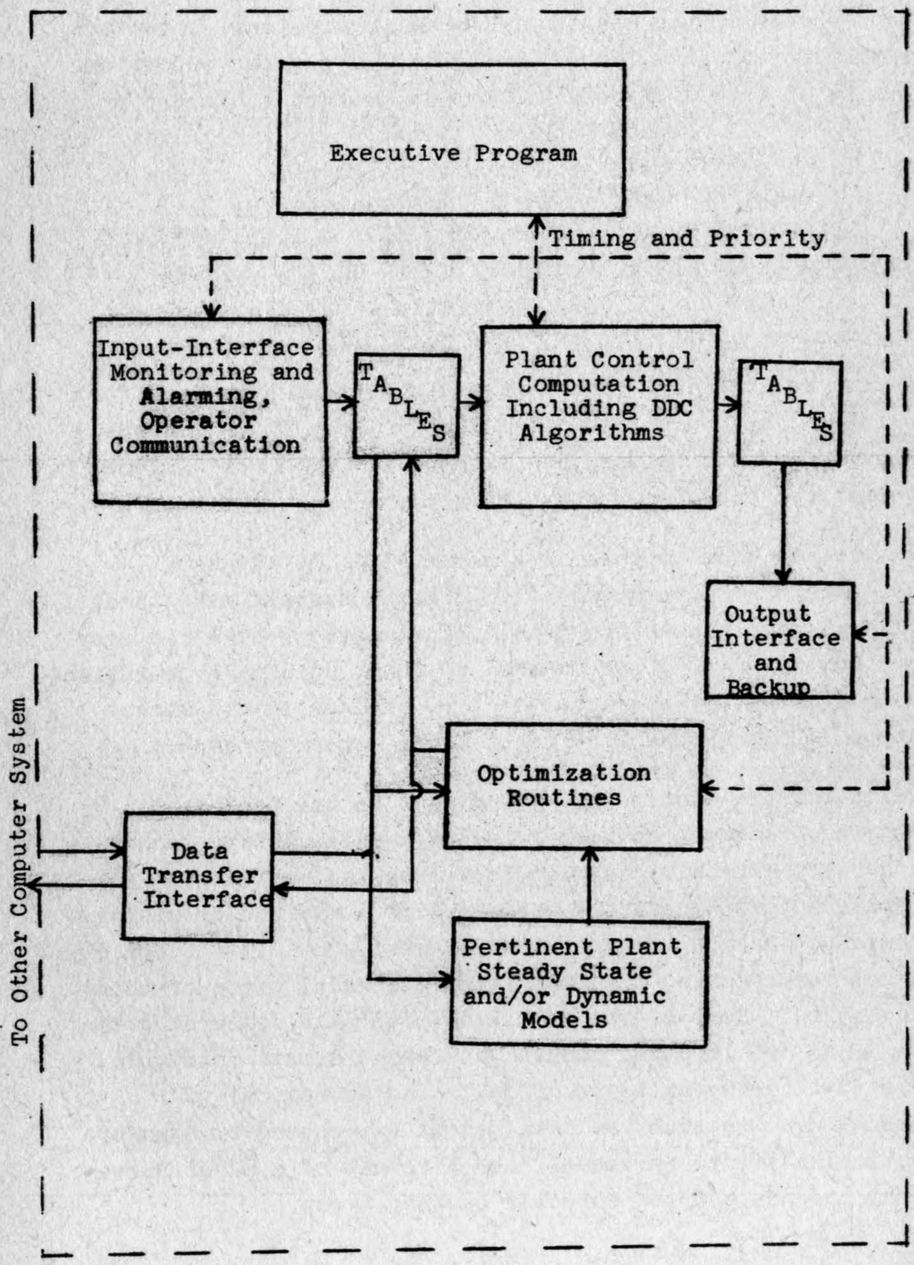
4. Specialized process control programming systems should be developed which carry out the following:
   a) Make the organization and development of a process control computer system as simple as possible.
   b) Contain an organizational method by which the user can carry out any functions possible with conventional control systems with only a very minimum knowledge of programming such as by using a "fill in the blanks" technique.
   c) Preserve at least as much compatibility between the control practices of different industries as is possible with conventional analog control hardware.
   d) Permit on-line addition or deletion of inputs, control computations, and outputs, and changes of coefficients, without recompilation or reassembly.

TABLE II, CONT.

5. Variable names, etc., should conform to ISA Standard ISA-S5.1, 1968.

6. Software systems should be developed in a modular fashion to the maximum extent possible with the functions of the modules rigidly defined. These modules should communicate through tables to the extent possible. Table format should be such that they will permit substitution of complete blocks as newer, more efficient forms are developed and reassembly of the program without the necessity of reworking the other blocks. Figure 2 presents one form which such a system might take. This will permit standardized software to be used in a multicomputer system.

BLOCK DIAGRAM OF PROPOSED INDUSTRIAL CONTROL PROGRAM SYSTEM



OVERALL COMPUTER CONTROL SYSTEMS - HARDWARE AND SOFTWARE

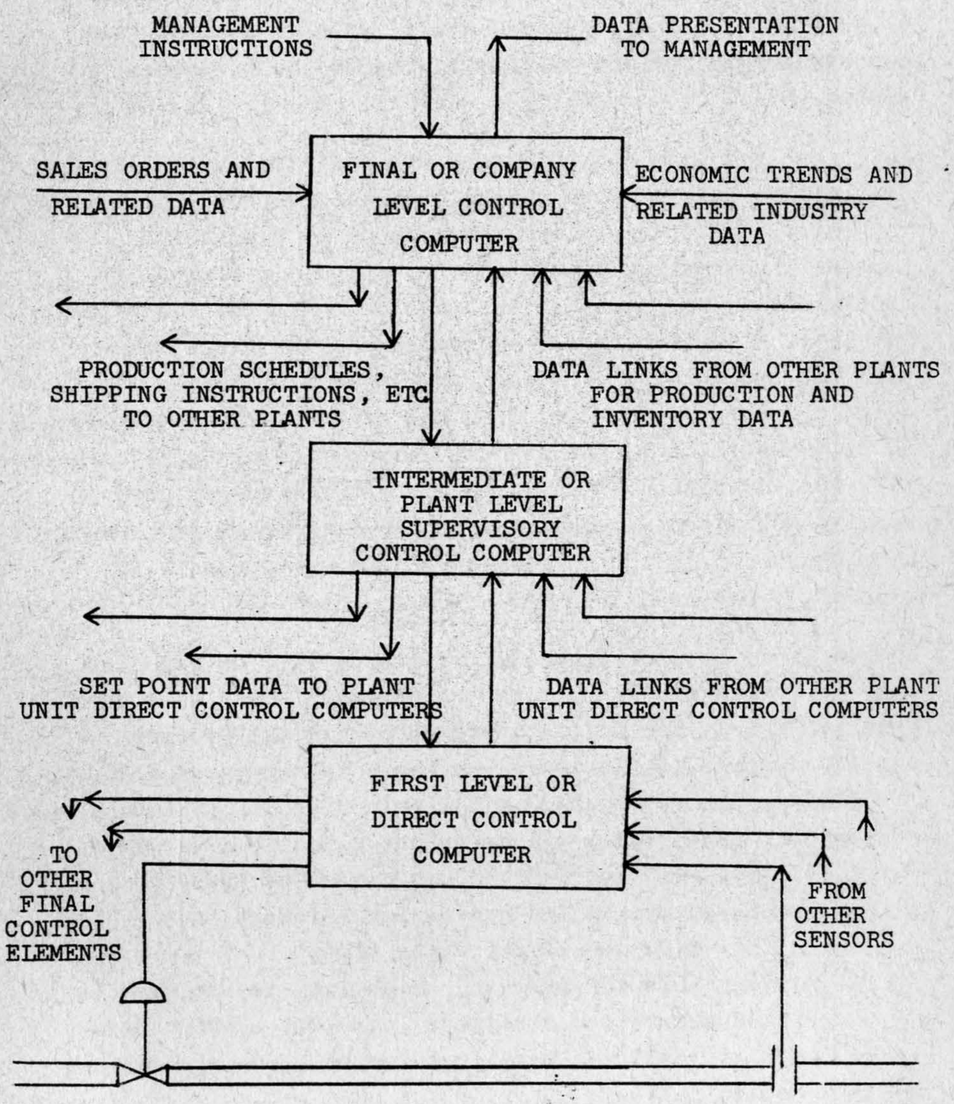
Recent trends in the manufacturing industries have shown the desirability of and, indeed, has revealed a great effort on the part of both users and vendors to perfect a hierarchy type of overall computer control system which integrates first level or direct digital control with plant supervisory control and finally with the company level or management information system computers. This would operate somewhat as outlined in Figure 3. Full implementation of such a large scale concept must await the full development of the all-digital systems mentioned earlier for their economic realization. They must also wait on a major effort in software standardization for them to be practical systems in terms of the personnel committment involved for systems mathematical modeling and programming.

Work already done in this area along with the forseen developments and improvements in digital systems makes their full scale use almost inevitable as management seeks an ever wider and more immediate control of their company's operations and an ever better means to react to changes in the market place and in the capabilities of their competitions.

Predictions are continually being made in the technical press in an attempt to forsee the path which future technical developments will take and how they will affect the degree of implementation, and the economics of a new and promising technique. Because of the wide interest shown in it, computer control has received even more than its usual share of this speculation. Some of the resulting proposals concerning the form of future computer control systems are most intriguing while still being quite technically and economically creditable. One such has been recently proposed by Stanford Research Institute personnel[18] as a result of a major survey of the process control industry by that group.

FIGURE 3

HIERARCHY CONTROL AS APPLIED IN THE PROCESS INDUSTRIES



Making use of the full digital techniques mentioned earlier they developed the following concept and related costs for a 1250 loop digital control system for a large industrial plant such as a complete petroleum refinery. This is sketched in Figure 4. Table III outlines the characteristics of the machines involved while Table IV presents the expected costs for the system as compared to a similar system today.

Note that the 1250 control loops are distributed equally for convenience between five separate direct control computers. The remote multiplexers each have about 25 inputs and transmit information to the control computers digitally. These in turn can transmit information on to the supervisory machine. Note also that the crossbar in the large machine plus the appropriate provision at the small machines will allow all information coming to one of the small computers to be transmitted to the standby computer should the former fail for any reason. The large disk of the supervisory machine would contain an image of the program on each small machine for instant transmission to the backup as it is needed.

Should these predictions come to pass by 1975 as expected they will very nearly meet the requirments which have been made previously for full acceptance of digital process control systems in the United States. These are as follows:

Digital control systems will replace analog control systems for essentially all new plant situations provided,

1. A five fold increase in basic mahcine speed is achieved over third generation hardware (now 1.75 - 2.0μ sec memory cycle time)
2. A four fold increase in reliability is achieved over third generation equipment (now 2000 - 4000 hours MTBF for all electronic equipment - not electromechanical)

FIGURE 4

PREDICTION OF DIGITAL PROCESS CONTROL SYSTEM OF THE NEXT DECADE

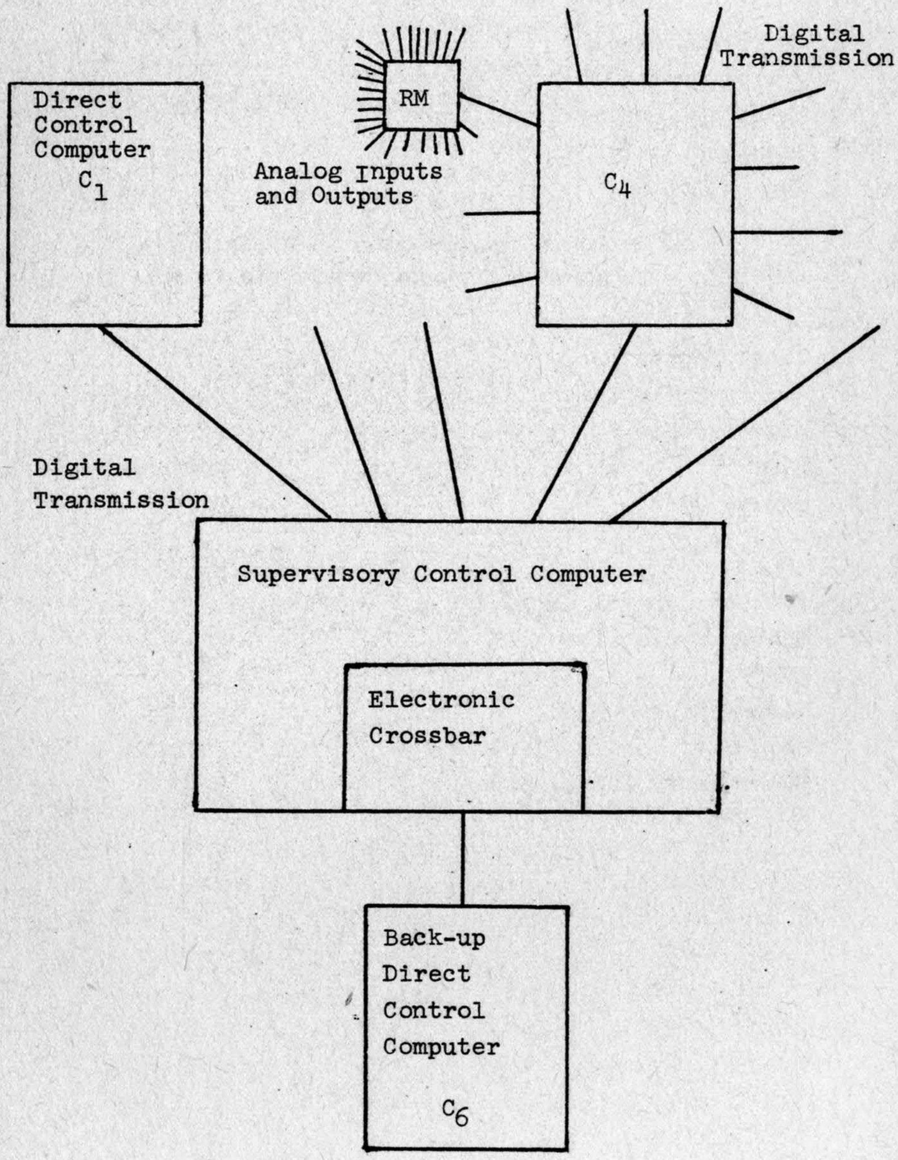


TABLE III

CHARACTERISTICS OF COMPUTER SYSTEMS INVOLVED IN PROPOSED FUTURE DIGITAL PROCESS CONTROL SYSTEMS

1. Remote Multiplexers	
Approximate Number of Inputs	25
Length of Analog Input Leads	$<$ 100 feet
Sampling Rate	Very fast because of burst mode operation
2. Direct Control Computers	
Total Inputs Each	~ 250
Memory Cycle Time	0.5μ sec
Organization	Parallel
MTBF	10-20,000 hours
Memory Size	32 K
Work Length	18 bits
3. Supervisory Control Computer	
Memory Cycle Time	0.4μ sec
MTBF	5-10,000 hours
Memory Size	160 K
Word Size	36 bits
Bulk Memory (Disk) Size	5 $\overline{M}$

TABLE IV

PREDICTED COSTS OF PROPOSED FUTURE DIGITAL PROCESS CONTROL SYSTEM

1.	Direct Digital Control Computers	$25,000.	Each
		$150,000.	Total
2.	Supervisory Control Computer (including peripherals)	$150,000.	
3.	Instrumentation Wiring and Distributed A/D and D/A	$250,000.	
	Total	$550,000.00	

Compares with a total cost of $2,500,000. to $3,000,000. for an equivalent third generation system at todays prices.

3. A five-fold decrease in computer system costs over third generation equipment (now $250,000.-400,000. for typical application equipment of single machine for 50 - 250 loops)

In implementing these larger and more advanced systems it is expected that the user companies will be doing all the specialized programming required for the system themselves. However, this will be much less than is necessary today and will consist mainly of that contained within the mathematical model block of Figure 2. Hopefully, the remainder of those areas of Figure 2 will have been standardized and will be available in that form from the vendor. In addition, it is expected that much more use will be made of the modern control theory now being produced by our university and research organizations[31,32] but at present getting little use in industry. The further research now going on plus the increased capabilities of the machine used should solve the problems now hindering its wider application.

CONCLUSIONS

As a conclusion to this survey, this author would like to list the following as his opinion of some aspects of the probable path of development of our field over the next ten years. The reader will find that most of the items listed here are in addition to those related developments already mentioned in the text of this paper.

1. We can expect one full new generation of process control machines and probably another. This will mean at least a five fold increase in raw computing speeds.
2. A greatly increased reliability in terms of a much longer MTBF (mean time before failure) of the computing hardware will be achieved. While equivalent sized systems to those used today will also be more easily maintained, this easier maintainability will be more than compensated for by the larger size and more

complex nature of the foreseen systems in order to accomplish the much more complex control and data tasks envisioned.

3. An ever increasing use of "natural language" programming for process control tasks will take place. Present trends would indicate that this natural language will probably be an extended FORTRAN with many built in process control functions.

4. The passage of time will make much more information available in the literature on mathematical models of various processes and on applicable control and optimization techniques as well as accurate information on the relative importance of computer control for these processes. Notice we did not say "justification." The next ten years should have long since reduced the question of "if" and "when" to one of "how."

5. Acceptance of digital control as the basic control method and an ever increasing use of "vendor standard" if not industry standard routines along with a burgeoning need for company information systems will cause user company application engineers to be ever more concerned with the overall systems aspects of their installation rather than the many intimate details of application as at present.

6. We cannot expect any greater compatibility of machine languages through similar instruction sets and codes. Compatibility of programs between different machines if achieved at all must be at the compiler or natural language level. Thus all of our present symbolic and machine language programs will probably be worthless as soon as the machines for which they are written are obsoleted.

7. The "housekeeping chores" involved in managing the interconnections, data links, etc., in the major hierarchy systems which will be in existence will require memory allocations and commitments of machine duty cycle which

would horrify us if we knew them today.

8. The capabilities of the envisioned system and the requirements of competition within the industry will demand a sophistication of application far beyond that common today. While ten years may not be enough time to achieve it, we must eventually "optimize" all of our plant operations. As we are well aware, even today, this increase in application requirements occurs much more rapidly than the normal assimilation of the necessary engineering knowledge and techniques into industry. Thus either a major educational effort beyond anything presently dreamed of or a whole new method of application will be required before this is accomplished.

9. Large executive programs for management information system hierarchies and subroutine procedures for plant optimization required will be vendor supplied. Needs for very wide applicability will tend to make these overly large and inefficient.

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