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Microprocessor Applications and Building Control Systems to Achieve Energy Conservation

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ABSTRACT

A well insulated building may be considered a thermally efficient building. However, the systems and controls within the building must also be energy efficient in order to conserve energy. Thus, building controls is an important subject in energy conservation. In recent years, building control engineers have been developing energy conserving control methodologies. The availability of microprocessors and minicomputers has made it possible to apply many control strategies requiring extensive computations. Since a large segment of energy is consumed in buildings, the enhancement of control methodologies will help achieve national energy goals. This report is mainly to investigate the capabilities of microprocessors in building control applications so that requirements to expedite these applications may be developed. Microprocessor applications in both conventional control systems and in local-loop energy conservation devices are examined. In addition, special applications of microprocessors in buildings are explored. The development of microprocessor technology is also discussed.

KEY WORDS: Building automation; building energy management systems; building controls; chiller controls; distributed control systems; energy conservation; energy conservation devices; microcomputers and minicomputers; microprocessor applications; programmable controllers.

TABLE OF CONTENTS

MICROPROCESSOR APPLICATIONS AND BUILDING CONTROL SYSTEMS TO ACHIEVE ENERGY CONSERVATION

by

Yui-May L. Chang and James Y. Shih

1. INTRODUCTION

1.1 BACKGROUND

It is estimated that approximately one third of total energy consumption in this country is expended in heating, ventilation, and air conditioning (HVAC) of residential and commercial buildings. Energy consumption for HVAC is a function of building envelope design, mechanical systems design, and performance of the energy consuming equipment, such as boilers and chillers. In general, a thermally efficient building implies a well insulated and sealed building envelope and an efficient mechanical system. However, a building with efficient energy consuming equipment and a tight envelope will not necessarily perform in an energy efficient manner. The controls of the HVAC system are vitally important in determining the energy consumption of a building.

The growing complexity of HVAC systems and the energy shortage have spurred the design of more sophisticated HVAC control systems and the rapid growth of energy management control systems in buildings. In recent years, computers and microprocessors have been used in building control systems. Such systems, which are commonly known as energy monitoring and control systems (EMCS), permit close supervision of building conditions. Through the use of audible and visual alarm systems, the occurrence of problem areas in the building can also be recognized by the EMCS. The advantages of EMCS have resulted in a demand for these systems in numerous new buildings and building complexes.

EMCS are available in a wide variety of sizes and functional capabilities, with a range from less than 100-point capacity systems for small buildings up to more than 1000 points for large building complexes, where a point is defined as a finite address of a field input/output device which may be discrete or analog. Regardless of the number of points, the basic functional capability may include, but not be limited to, indication of status, change of status alarms, and energy demand monitoring. For large systems, two-way audio communication, data logging, slide projecting, and start/stop programming are generally available. Currently, most computer-based EMCS are capable of including energy conservation routines. However, most of these energy conservation routines must be written in a "custom" fashion. There are no universally adaptable routines that are applicable under all building conditions. Of course, some energy conservation techniques require custom programming. For example, chiller loading optimization requires knowledge of the configurations of chilled water and condensed water piping layouts, which could be parallel or series, in order to optimize energy consumption based on the individual chiller performance characteristics.

Energy management techniques used in computer-based EMCS may include the following strategies [1]: enthalpy optimization for mixed air systems, secondary-loop chilled and hot water optimization, chiller-loading optimization, start-time optimization, electric demand limiting, and night ventilation purge. Besides energy conservation functions, the EMCS may include a life-safety system, a building management/maintenance system, and a door security/access system.

1.2 PURPOSE

Reduction of demand growth is part of national energy goals. Since a large segment of all energy is consumed in buildings, it is important that the building industry help meet the national goals. The building industry has been working on energy conservation for a number of years. During the last 20 years, the attention of the building industry has been focused on the building shell. The heat transfer characteristics of wall materials have been studied extensively. In more recent years, much attention has been focused on the prime energy consuming machines, such as chillers, boilers, and package equipment. Control strategies for building controls also play important roles in energy conservation to optimize building energy consumption. The advent of microprocessor technology will allow more sophisticated control strategies to be used due to the capability and flexibility of the technology. Hence, in-depth study of building control strategies, as of building shells and equipment, is another requirement to achieve the goal of building energy conservation.

In order to investigate the effect of replacements and improvements of control strategies, computer simulation will have to be developed as a tool for hypothesis testing. Today, the understanding of the building shell and prime energy consuming machines has led to successful simulation of building heat transfer characteristics and the simulation of energy consuming machines. Accordingly, it is difficult to estimate the effect of control strategy on energy consumption with existing simulation programs because they simulate only load and mechanical systems without control system simulation logic. In order to extend the capability for building energy consumption calculations, it is necessary to include building control strategies in simulation programs. As for the building control system itself, both hardware design and control strategies can benefit from microprocessor-enhanced components. From the advent of the microprocessor, the development of distributed control with intelligent control devices and sophisticated programmable controllers will expand system capability to achieve significant energy conservation.

In order to better meet national energy conservation goals, a project is undertaken to anticipate what is happening in the building control field with the development of microprocessor technology and the impact of microprocessors on building controls. This report looks into microprocessor utilization in EMCS, distributed control systems, and local-loop energy conservation devices as well.

1.3 MICROPROCESSORS AND MICROCOMPUTERS

Microprocessor technology is one of the latest significant advancements in solid-state electronics. The microprocessor was introduced as a device to handle simple control and computation problems. Due to its low cost, small physical size, and expansion capabilities, the microprocessor has become a powerful device containing a complex package of logic functions that may be used in many applications. During the past 25 years, the creation and development of this microelectronic technology have contributed to successful space flights as well as a strong computer industry.

Since the introduction of integrated circuits (IC) in 1959, the number of components being placed on one chip has almost doubled every year. The implementation of very large scale integrated circuit (VLSI) technology has made it possible to incorporate an entire computer processor in one VLSI chip. Because a single chip of VLSI could contain as many as one million discrete components, much more flexibility is available for designers to implement operations of complex systems. During the last few years, numerous single chip microcomputers have been produced by manufacturers, such as the INTEL 8748, MK3870, M6800, Z8000, and others.* By definition, a microprocessor is a computer processor on one chip which includes an arithmetic unit and control circuits. The microprocessor, together with memory and input/output (I/O) units will form a microcomputer. The system including the microprocessor chip with memory chips (read-only memory, ROM, and random-access memory, RAM), I/O chips and other components gives a much greater flexibility than hardwired systems in many general applications. ROM can be programmed to define logic that has previously been possible only in hardware, and RAM allows the user to store temporary information. The trade-off of hardware for software by utilizing microprocessor-based systems will be significant, since hardware logical circuit testing and trouble shooting can be eliminated. In case of malfunction, it is much simpler to replace a ROM than to change hardwired circuits.

Because of the demand for the microprocessor/microcomputer, the cost of each unit is very low compared to hardwired devices. The low cost and small physical size have allowed the microprocessor to gain wide acceptance among electronic design professionals. The computational flexibilities of the microprocessors is now utilized for many applications.

Microprocessor-based systems for building control and monitoring already exist. It is evident that potential applications of microprocessors in future building management and control will be high since, besides EMCS and local-loop controls, other types of sensors, controllers, and controlled devices could also utilize microprocessors effectively.

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* Names of chips mentioned as examples do not indicate any NBS endorsement of these products.

A negative aspect of the microprocessor revolution is that manufacturers are not working together to develop common standards so that all users are benefited. Programming language and I/O devices for most microprocessors differ among manufacturers, and a consensus on standard hardware and software for microprocessors within the near future is unlikely. These diverse methods have caused difficulties in utilizing microprocessors in building controls.

2. AUTOMATION OF FACILITIES MONITORING AND CONTROL SYSTEMS

2.1 CENTRALIZED CONTROL SYSTEMS (NON-COMPUTER-BASED)

HVAC control systems have been playing an important role in the building industry for the past 80 years. During this time, most of the accomplishments of control devices have been in comfort control. Only in recent years has energy influenced the development of controls. The centralized control system, and the beginning of building automation systems, dates back a quarter of a century. Centralization of controls was first used to reduce manpower. Large buildings included many fan systems, each of which had gauges and thermometers in the fan room to indicate the building variables. Periodically, the building maintenance crew took readings of temperatures, steam pressures air flows, etc. A large building required a large maintenance crew to take data routinely. Maintenance and repair were carried out depending on the results of the routine data collection. Without manual data, malfunctioning of mechanical equipment was difficult to forsee. In addition, control adjustments had to be made manually. As instrumentation and control techniques advanced, the hardwired data panel was implemented. Data could then be collected at a central location in the building. It was no longer necessary for the maintenance crew to go to each equipment room to collect data. With experience, it appeared that the centralization scheme with individual hard wiring from each element of the control system was too costly and too cumbersome to be effective. The technique of multiplexing [2], which involves sending information from a number of data channels sequentially down a single conductor, was used in the second generation of centralized systems. Newer systems were capable of status indication, analog and control point alarm indication, remote analog setpoint adjustment and remote start/stop. Status and analog indication at the central console provided information on building conditions, including warning building operators of any abnormal conditions in the system before there was any effect on occupied spaces. Although these non-computer-based systems were basically hardwired, some of the systems could be expanded into a computer-based system.

During the 1970's major developments in building automation systems occurred in the building control industry. Centralized control systems are currently being adopted by building management due to economic reasons. For most buildings, maintenance man-hours saved by the use of a central control system can be utilized more effectively in other assignments, or to reduce the number of personnel. Also, the control system operator can identify system irregularities in a glance at the status summary sheet instead of checking out the building physically. In addition, the logging of equipment status provides for preventive maintenance of the equipment in the building systems. Early detection of malfunctions and routine maintenance may be performed to maintain a high level of equipment performance. However, a trained operator is still responsible for the efficient operation of the total system based on his own decision-making capability. Therefore, this type of system is dependent upon the operator for optimum system operation.

2.2 COMPUTER-BASED AUTOMATION SYSTEMS

During the 1960's, attempts were made in computer-based building automation systems. Several installations were created using custom programming for each system, and medium-sized computers were used. Since minicomputers were introduced in the early 1970's, computer based automation systems have proliferated. The minicomputer-based automation systems provide a number of features unavailable with the conventional automation systems, such as faster alarm reporting, and power-failure restart capabilities or uninterruptible power supplies. Input/output devices such as printers and alarm-reporting devices, logging printers, cathode ray tubes (CRT's), projectors, and intercoms are usually available from manufacturers. Special features which include machine run time totalization, special English language mnemonics for input/output, and passwords for operation of the systems are easily accomplished through software on the computer-based automation system. Functions of a building automation system may be performed through hardware or software logic or a combination of both.

The available energy conservation routines, which are part of the application programs for minicomputer control systems, are not direct digital control types, but are supervisory-control types. Instead of giving command signals directly to an activator device, the computer usually resets a controller set-point. Furthermore, only large buildings or a building complex have had building automation systems with sophisticated energy conservation routines.

Basic monitoring/controlling functions that a central computer control system would perform include various optimization schemes. These optimization schemes will either increase operating efficiency or conserve energy. Examples of these optimization schemes include:

- start/stop
- enthalpy optimization
- chiller optimization
- solar system optimization
- fan system optimization
- heating/cooling optimization
- lighting optimization
- electrical demand limiting.

The essential energy conservation strategies used by the computer-based automation systems are described in reference 1. Figure 1 is a functional block diagram of a typical centralized computer-based automation system. The field concentrator is wired to sensors in the same vicinity. The sensor signal is transmitted to the central console by the transmission system of multiconductor wire, coaxial cable, telephone line, or other means of transmission.

The physical configuration of building automation systems is generally similar among manufacturers. The central console is comprised of a central general purpose computer, input keyboards, alarm devices, logging devices, optional CRT's, graphic displays, intercoms, etc. Distributed within the building are sensors that communicate with the local concentrator, which may be called a data gathering panel, field cabinet, or field input device. In this report, a field concentrator will be termed a field interface device (FID). All FID's may accept a plurality of sensor inputs. There are two ways a sensor may be wired to the FID [3]. One method, which is not common today, is to wire all sensors in series to the FID. The other method is to wire sensors in parallel to the FID. Figure 2A shows direct wiring from sensor to FID and Figure 2B shows series wiring between sensors and FID. For the arrangement in Figure 2A, the identity and location of the sensor is either stored in the FID or the central console. The "intelligence" is centralized at either the FID or the central console. On the other hand, the arrangement in Figure 2B requires intelligence at each sensor because each sensor must "remember" its own identity in order to be addressed independently by the FID. The advantage of the layout in Figure 2A is lower cost at the sensors, and the advantage of Figure 2B is the lower cost for wiring between sensors and FID. As electronics technology progresses, either configuration may prove to be most economical in the future.

A variation of the communication between the central console and FID's is the hierarchy configuration. Figure 1 shows the non-hierarchy configuration of building automation systems. The hierarchy configuration includes in the wiring between the central console and the FID, a loop controller, or middle manager, as shown in Figure 3. The purpose of this configuration is to allow multiple-loop systems to operate efficiently. The central console monitors the operation of loops by communicating with each loop controller, which in turn monitors the FID's within its loop. The loop controller may be a minicomputer- or microprocessor-based and designed to allow a stand-alone configuration.

The following paragraph will describe several typical arrangements of actual systems. As an example, the A-2 system* is one of the centralized control and monitoring systems for large facilities up to 250,000 square feet (23226 m^2) of floor space. Basically, it is considered to be a computer-compatible system because it contains a custom central

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* Code letters A, B, C etc. indicate different manufacturers.

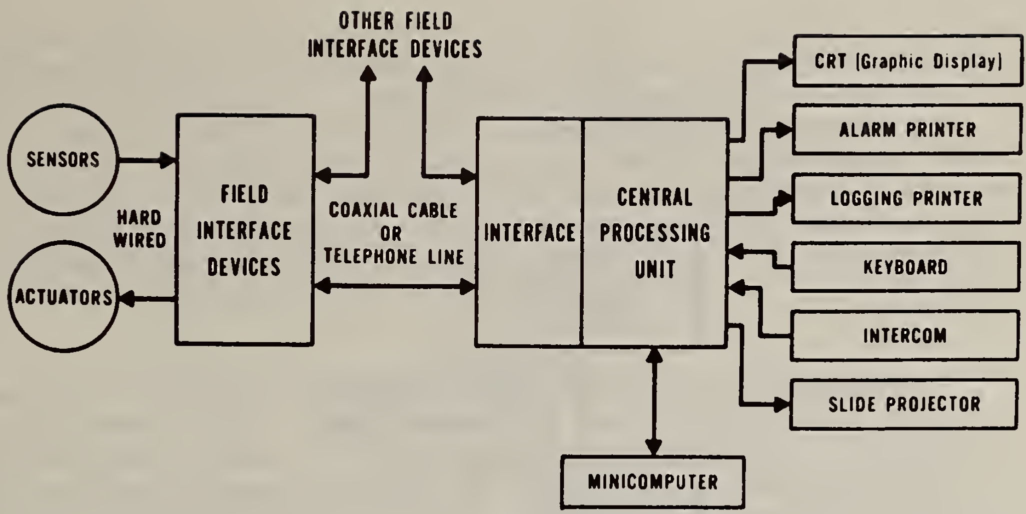
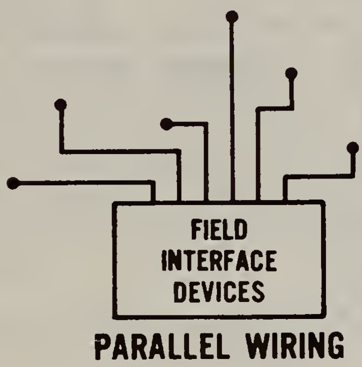


Figure 1 Functional Block Diagram of a Centralized Computer Based System

2A



2B

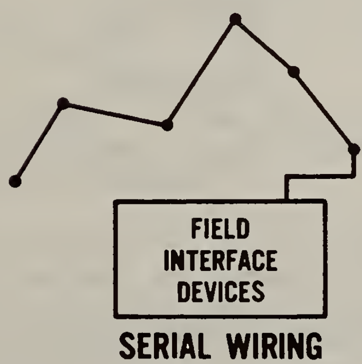


Figure 2 Connections of Sensors and Field Interface Devices

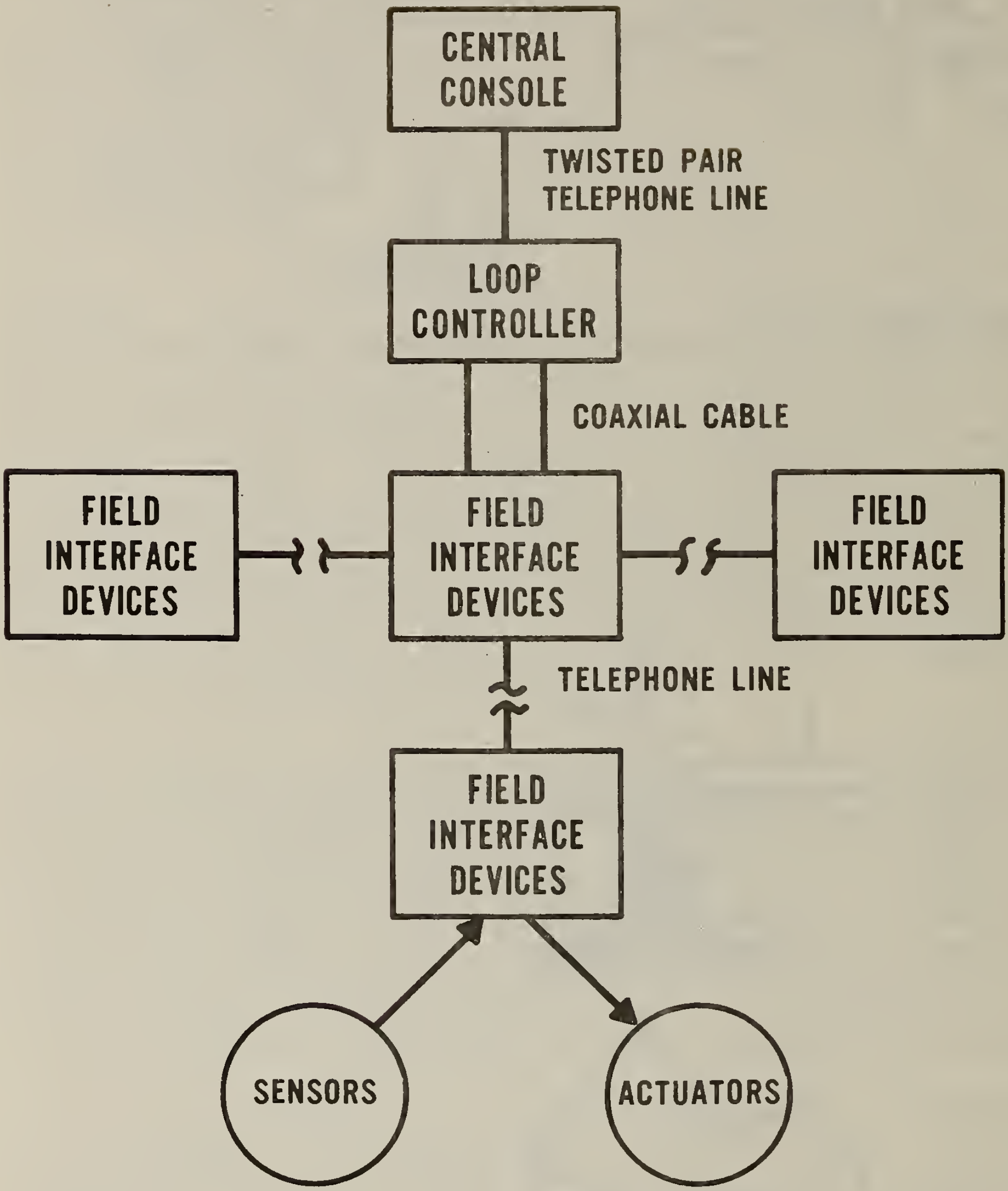


Figure 3 Hierarchy Configuration of the Centralized Control Systems

processing unit (CPU) and it can also be expanded to a computer-supervised control system by adding a real-time general purpose computer similar to the configuration of Figure 1. For smaller buildings, with fewer control points, the CPU can be replaced by a microprocessor (A-1 system). The A-1 system has the advantage of being small and of lower cost. It is mainly used for start/stop, security, and fire alarm systems. Depending on the application, systems may be wired using coaxial cables or through telephone lines, as shown in Figures 4A and 4B. In addition to the coaxial cable, additional voice transmission wiring is required for intercom.

Special features of systems from each manufacturer are distinctly different. For example, the "loop" concept of manufacturer B is unique among manufacturers. Figure 5 illustrates this concept. By transmitting data frames continuously through the loop, trouble points can be easily identified using the loop concept. When frames are not received after a certain period of time, the first FID will send an alarm frame back to the loop controller, and the building operator is advised of the condition. This provides constant digital supervision of the entire loop, and very rapid annunication and location of trouble in the loop. The data transmission rate of manufacturer B is much higher than that of the other manufacturers. However, in terms of practical use, elapsed times between an event and notification of the building operator are quite similar among manufacturers.

FID's of the automation systems are usually fixed logic used for transmitting information between central console and field sensors. Recently, a microprocessor-based type of FID has been offered by some manufacturers. These microprocessor-based FID's are programmable so that they allow a high degree of flexibility to implement more sophisticated functions, such as stand-alone capabilities when the central computer is out of service. This is an example of the concept of distributed systems -- the distribution of intelligence among lower level devices within the system.

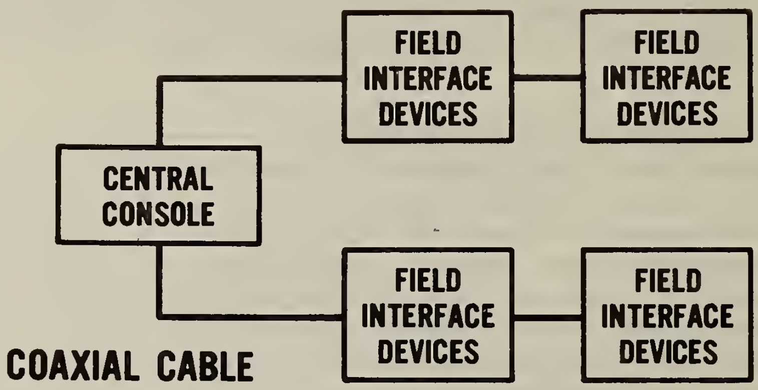
Some advantages of computer-based automation systems include:

- Reduce manpower -- central computer operator can look at the status summary from display devices instead of reading the data locally at the sensors.

- Better record keeping -- format printouts from the computer output, such as teletype, can be formatted according to the building management's needs.

- Provide continous operation of safety and mechanical systems -- with systems unattended, it is important that safety systems and essential mechanical systems be monitored at all times in order to receive alarm reporting continuously. For example, locks on fire exits can be unlocked by the automatic system in case of fire.

4A



4B

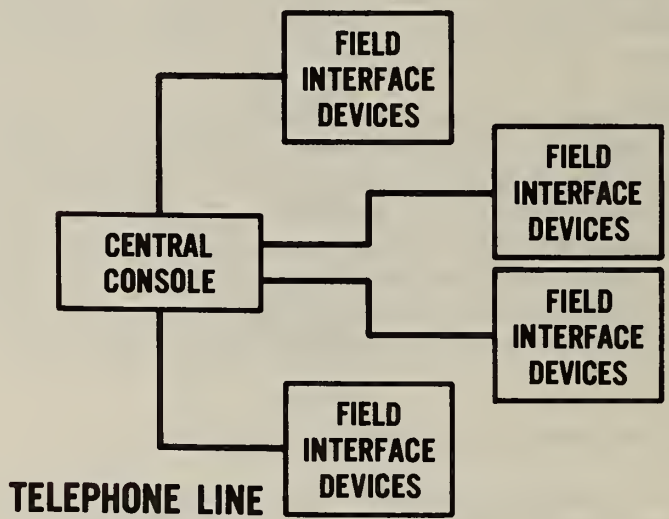


Figure 4 Typical Connections of Field Interface Devices and Central Console

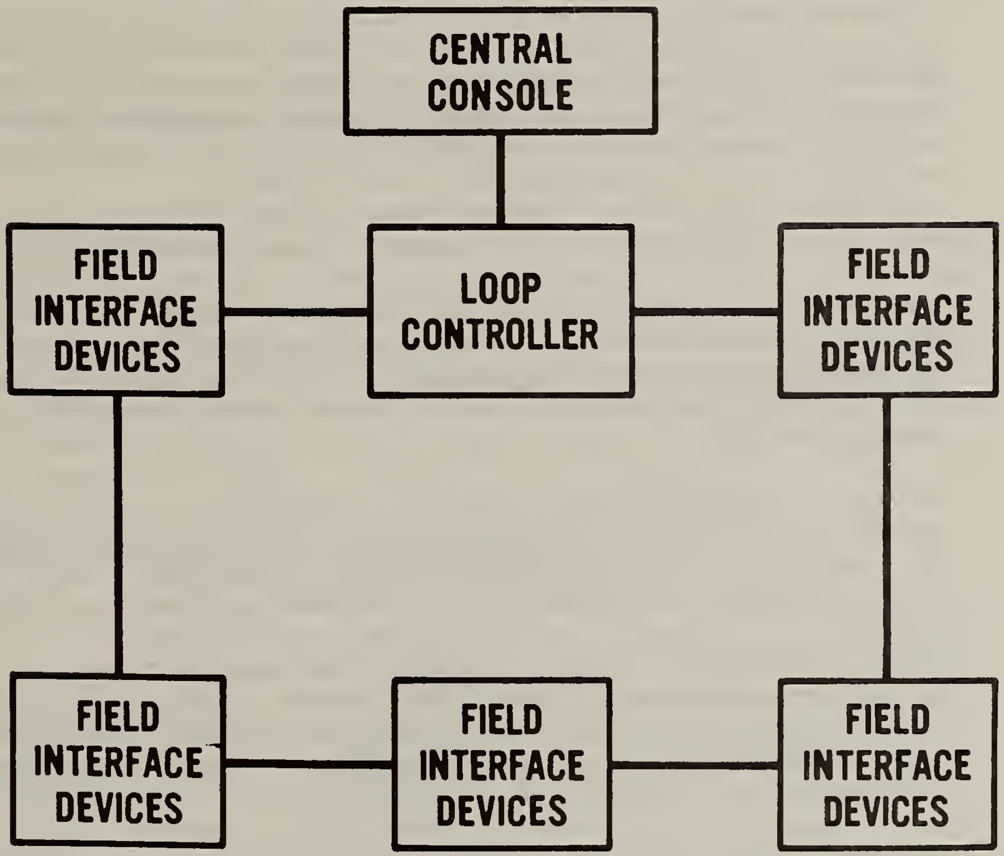


Figure 5 Interconnections of the "loop" System

- Routine maintenance -- maintenance records and scheduling can be automated, providing a daily printout of required maintenance and an improved basis for scheduling. For example, lubrication schedules for motors and fans can be based on the length of operating time.

- Computer hardware and software availability -- the system designer can fit the computer to the application through a wide choice of machine sizes and speeds, mass storage equipment, peripherals, operator interface terminals, graphic displays and I/O interfaces.

- Capabability of data storage and retrieval -- by use of memory devices, such as magnetic tapes and disks, permanent data of building operation can be stored for record keeping as future reference or for processing at a latter date.

In contrast, there are problems with computer-based automation systems:

- Dependence upon manufacturers -- presently, there are few standard specifications for computer-based control systems. Each manufacturer has designed their own system with hardware and software that are incompatible with products of other manufacturers.

- Training requirement for automation personnel -- the computer-based automation system depends largely on capable operators. The operation of such a system requires personnel with sufficient training in electronics and computer systems technology.

- System reliability -- the reliability of computer-based automation systems still needs improvement because of the technology is relatively new. A number of hardware and software problems are yet to be resolved, and specification of system performance will have to be documented.

- Software problems -- the current state-of-the-art for computer-based automation systems is to utilize the standard software package provided by manufacturers. The user's extension or modification of this software package is cumbersome because these software packages are essentially written in assembly language for the particular minicomputer manufacturer. Currently, high-level-language software packages are becoming available so that special application programs will become feasible for users to design and install.

- Cost and lead time -- frequently, a computer-based automation center may be awarded to a manufacturer based on the understanding that the installation and start-up of the system will be one year later. This is due to the nonstandard hardware and software. Most installations require certain features which involve additional costs in software development. Thus, lead time also increases. In addition to special hardware and software costs, wiring of the field equipment costs may be appreciable. The total system cost is usually quite high. However, most owners of automation systems justify the purchasing of building automation systems based on the operating cost reduction and energy savings.

- Rapid obsolescence — due to the rapid growth in electronic technology, most computer-based automation systems developed during the past 10 years are relatively obsolete. Although they are functional and continue to fulfill the design purpose, they are technically out of date. The newer automation systems based on state-of-the-art electronic technology can outperform the older systems by far.

In spite of the disadvantages, computer-based centralized automation systems are becoming more and more popular. As energy costs continue to increase, and electronic technology continues to advance, the return on investment for these systems will become increasingly attractive to building owners. Furthermore, development of feedback controls and the utilization of microprocessors for local control purposes will become a natural application in the near future. The microprocessor is capable of handling many control loops with ideal control characteristics because of its programmable nature.

2.3 DISTRIBUTED ENERGY MONITORING AND CONTROL SYSTEMS (EMCS)

As discussed previously, fixed logic in the FID of a building automation system acts as a "dumb" field cabinet for the communication between the central computer and field controllers and sensors. This concept centralizes all the building information in the central computer for monitoring and controlling purposes. The tasks involved in processing the data received are the responsibility of the central computer. The CPU overhead involved in checking for bad data, converting to engineering units, scanning, routine interrogation, checking the response to alarm conditions, making routine control decisions, etc., can require a tremendous amount of computation and become a major portion of the system load. As building automation and control technology have improved, engineers have applied larger portions of the plant monitoring and control functions to the computer. In addition to the routine building monitoring activities, many energy optimization routines, building maintenance instructions, life safety and security functions and computer graphics features, can easily cause "data" congestion. The larger and more complex the system is the greater processing time that is required to handle all these functions. The physical limitation is real. The concept of distributive computing can be adequately defined as the concept of physically and logically separating a computer control system into functional units. Each unit is dedicated to a portion of the overall control task. For example, by placing a processor in the FID it becomes a so-called "smart" FID. Thus, it possesses the capability of being a "stand-alone" local control loop of the distributed control system.

Basically, the intelligence of field hardware is the difference between the distributed computer control system and the centralized computer control system. In distributed systems, computations at the local level, including local data scanning and calculations on data, are done by the field equipment; therefore, much of the computation burden for the central console is shared by the local FID. The more responsibility the field equipment can share, the more efficient the central console can be. Distributed system FID's are usually microprocessor-based. The computation power and the speed of the microprocessor lent itself well to local data gathering and data manipulation tasks.

Some advantages of using distributed automation systems are:

- Stand-alone capability -- the programmable CPU in the remote terminal can be programmed such that the remote system may operate in a stand-alone fashion as well as communicating with the central computer. All desirable control functions for the local loop may be implemented without having to rely on the computation power of the central CPU.

- Improved systems reliability -- since remote terminals are sharing the load of the central computer, the load on the central computer is greatly reduced. It follows that the number of necessary functions dependent on the information from the central computer, is also reduced and therefore, most of the routine functions are able to continue when the central computer is out of service; this increases the reliability of the overall system.

- Better expandability -- to accommodate new data points and controlled functions, each extension stage may be added to distributed systems without replacing the central computer system data base. The "intelligent" FID may be programmed such that the local data base is dynamically created and automatically communicated to the central computer without sustaining any system downtime.

- More flexibility -- with distributed control systems, each FID may be programmed such that the special requirements of a particular area of the building will be met. For example, certain FID's may carry on security or door access functions in addition to building monitoring duties. Such special programming does not require the system to shut down for the entire building, only those points governed by the particular FID.

By adopting the concept of distributive intelligence, the building control industry has begun to promote energy management systems for small buildings by utilizing the capability and compactness of microprocessors. These systems could be operated independently, or interfaced to a host computer. Concurrently, major manufacturers of building automation systems are producing new systems with microprocessor-based FID's. Some of these systems have the capability to interface with the existing automation systems. For example, system A-5 is a microprocessor-based distributed building management systems that offer two types of FID's, P-5 and P-4. The P-5, which is microprocessor-based, has its own operating systems, data file, and application programs. The P-4 which is in fixed logic could link the P-5 and control point sensors in areas of high data density, as illustrated in Figure 6.

FID's of systems A-1 and A-2 (central systems) could be tied in directly to FID P-5 of the distributed system A-5. Thus, the centralized systems A-2 and A-1 could be converted to a distributed system without changing any field wiring. Figure 7 shows the connections. Alternatively, independent microprocessor-based central control system A-1 could be tied directly into the distributed system A-5. Figure 7 depicts the direct connection.

The distributed control system lends itself readily for long distance transmission through telephone lines using sophisticated software logic. As an example, building automation systems of two facilities, 40 miles apart, could "talk" to each other by dialing to each other automatically.*

3. TECHNOLOGY AND APPLICATIONS OF MICROPROCESSORS

3.1 ARCHITECTURE AND PERFORMANCE OF MICROPROCESSORS

A microprocessor, which is a single crystal of silicon, has the capacity to contain a circuit of up to more than 1000 transistors. It is a program-controlled component, used to execute the following three categories of instructions:

- Move data from one place to another within the system -- such as from an input line to a storage register
- Perform arithmetic or logical instruction on data -- such as to add, subtract, or perform logical operation
- Instruct where to go next in the program.

The internal architecture and instruction sets are essentially similar in most microprocessors.

According to their performance, microprocessors may be classified as memory-oriented or register-oriented. The former are mainly used for data processing applications and the latter are for dedicate applications where a large number of registers are needed.

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* See Section 5.

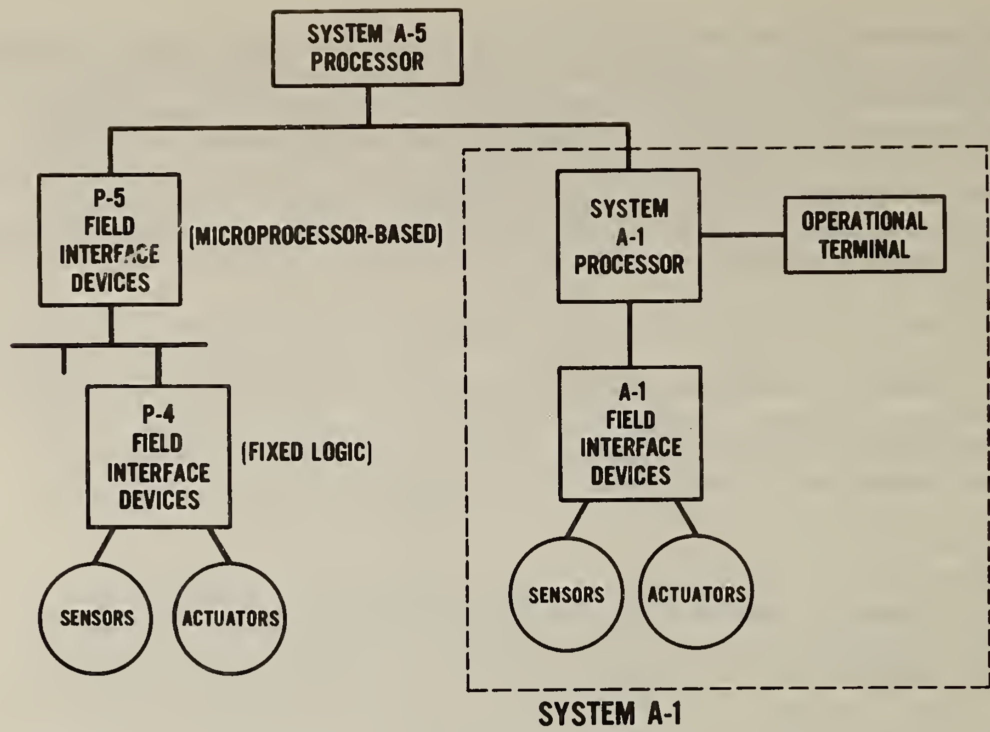

Figure 6 Configuration of Expanding Existing Central System to the Distributed System

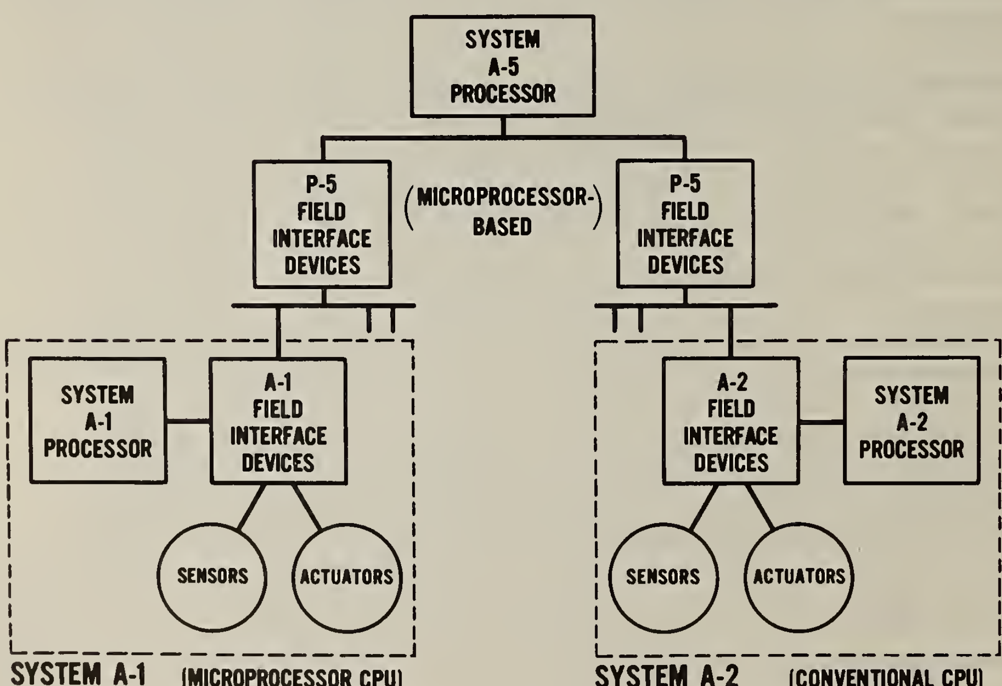

Figure 7 Configuration for Replacing Existing Central System with a Distributed System

Based on their word length, there are four major types of microprocessors.

- 4-bit: Low-End Microprocessor -- for simple applications which stand alone, such as in hand calculators, microwave ovens, TV games.

- 8-bit: Mid-Range Microprocessor -- flexible, complex, efficient, hardware-oriented, and most suitable for general-purpose use. This type, used in most controls and automation applications are currently dominating the microprocessor market.

- 12-bit: Upper-Range Microprocessor -- most suitable for double-precision calculations and straight memory referencing. This type is more accurate than the lower-bit type. For example, the IM6100 is a 12-bit microprocessor that recognizes instruction sets of the PDP-8/E minicomputer.

- 16-bit: High Level Microprocessor -- most complex, high-performance, and basically software oriented using high level language. Microprocessors of this type are able to recognize instruction sets similar to sets used in many computers, and some are ideally suited for industrial control motors, relays, solenoids, actuators, etc.

The selection of a microprocessor depends upon a combination of desired word length, speed, and memory efficiency. Manufacturers of microprocessors are continuously looking at various ways of using compact processing elements in relatively high performance applications. Today, the technology has matured to such an extent that microprocessors with impressive specifications are being offered by many manufacturers, utilizing virtually all available integrated circuit technologies. The interpretation of high performance depends upon the viewpoint and applications of the users.

Possibile applications of microprocessors in data communications, signal processing, and real time control will be likely to proliferate. The complexity of integrated circuits is becoming so high that subsystem and system level designs in the future cannot be separated from the design of the integrated circuit itself.

3.2 MICROCOMPUTERS AND SUPPORTING CHIPS

In conventional computer systems, the major components are a central processing unit (CPU), memory, and input/output (I/O) facilities. Together with memory and peripheral circuitry, microprocessor chips form complete microcomputers in which each of these components can be single chips. Regardless of the technology used, microprocessor systems are organized in basically the same way as conventional computer systems. The microcomputer utilizes a microprocessor as its central processing unit which will sequence through all instructions and execute each one. In complexity, these microcomputers fall somewhere between conventional minicomputers and small, handheld calculators. Since both the CPU and the memory are large scale integrated circuit (LSI) components, a microcomputer has the advantage of being low cost, compact, and with low power consumption as compared to other computers built without LSI components.

For the I/O circuits, transistor-transistor logic (TTL) compatible I/O ports are available from most microcomputer manufacturers. Standard peripherals, such as displays, keyboards, data modems, paper tape readers and punches, cassette tape, printers, graphic plotters, and floppy disks can utilize these I/O ports to link the microcomputer to the real world. Additionally, analog to digital (A/D) converters, digital to analog (D/A) converters, functional modules, isolated digital I/O systems and other systems also require I/O ports to enable the microcomputer to monitor and control mechanical and electrical systems.

Later enhancement of microcomputer systems offers a complete package of development software aids in ROM, which is referred to as the firmware of the microcomputer system. The firmware package can be a single chip ROM, such as the operating system for microcomputer software support, or a group of ROM's to provide the ability to generate, edit, assemble, load, execute, and debug programs for all type of applications. Including system firmware in microcomputer systems can speed up the process of software loading from some peripheral devices into RAM. Additionally, with the development aid software in ROM, all RAM is available for the user's program.

The development of memory chips by the solid-state industry has another successful advance for microcomputer technology. Large memory systems, such as multi-disk drives, derive their low cost per bit by spreading the high fixed costs of electromechanical components over a large number of bits. If the actual data capacity needed in a system is less than a few megabits, disk costs per bit go up substantially. The mini-floppy-disk drive is a partial answer to the reduced storage requirements, but actually the cost per bit will rise with lower storage capacity even as the hardware cost goes down.

The trade-off of faster and more expensive semiconductor memory and slower but lower cost magnetic disks and tapes is no longer necessary due to the introduction of CCD, (charged-couple-device) and MBM, (magnetic bubble memory) [4]. The relationship of cost per bit and access time is shown in Figure 8. The production of MBM resolves the problem of increasing the memory-access rate, as compared to the disks in the minicomputers. MBM, which is non-volatile, contains up to 1 million bits per chip and has an access rate of approximately 5 K bits per second. It is anticipated that the mass storage disk drive for microcomputers today will be replaced by the new bubble memory in the future.

The microcomputer is undergoing both hardware and software development so rapidly that the difference between a microcomputer and a minicomputer is difficult to distinguish. In essence, the level of support from minicomputer manufacturers has been higher than that from microcomputer

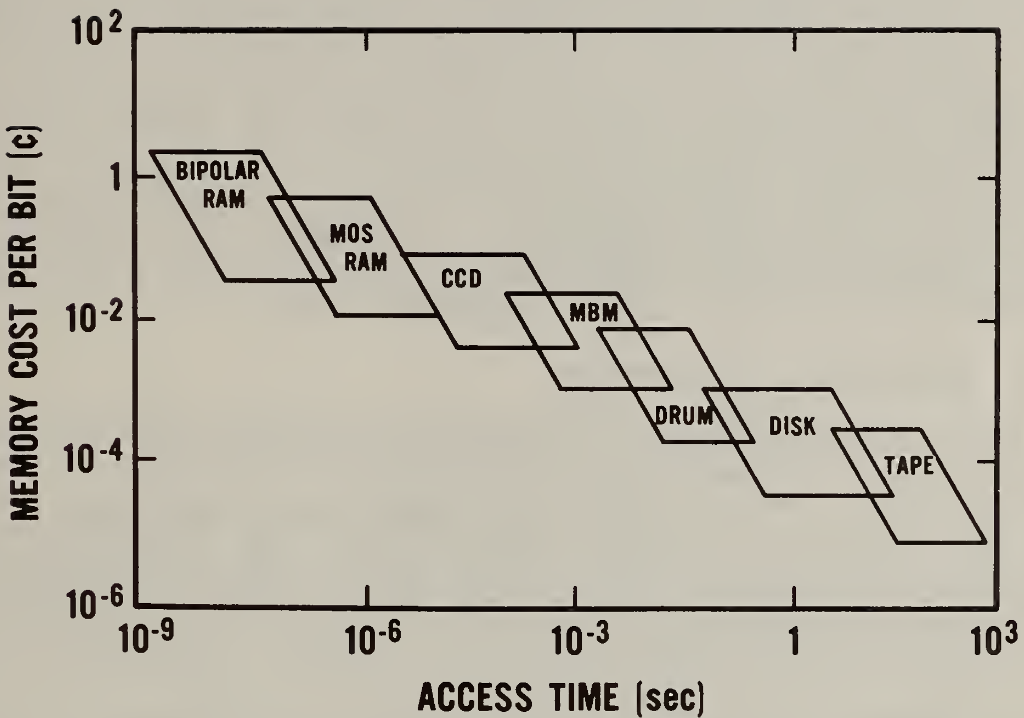

Figure 8 Comparison of Cost and Speed of Memory Systems

manufacturers, with more peripherals, more software, and more applications provided for minicomputers. However, the inexpensive microcomputer has more flexibility to control industrial applications, especially with 16-bit systems. The system reliability is reduced as the number of functions served by each computer increases. Therefore, it is practical to use distributed computer controls if the cost remains the same.

Regardless of developments in microprocessor technology, there are numerous problems, including software, interfacing, and maintenance problems, in utilizing microcomputers in building control systems today. The hardware design for many control functions has been in existence for many years. However, to duplicate the same function with microprocessors, extensive programming will be required. This is an added cost in utilizing microprocessors. Hopefully, the software cost per function will decrease in the future as small-applications-oriented languages become available. The cost of interfacing the microcomputer to external devices is the greatest hardware cost. Field sensors and actuators are expensive as well as the voltage and current conversion circuits necessary to interface these devices with the microcomputer. The problem with microprocessor maintenance is the difficulty in identifying hardware malfunctions, since the microprocessor is basically a new device, and system diagnostic is not common or well debugged. Once the hardware problem is identified, the field repair of a microcomputer itself can be done on a module replacement basis.

3.3 SINGLE CHIP MICROCOMPUTERS

A single-chip microcomputer contains the CPU, memory and I/O ports in a single unit. Only power supply and I/O devices are required for them to be operated. Some single-chip microcomputers are either not expandable, or very difficult to expand. They are mainly used for dedicated applications. In the future, the expected trend will be an increase in flexibility and computation power in these devices, such that a more complete and complex general-purpose microcomputer system may be packed on a single chip.

Early production of the single-chip microcomputer has been limited to 4-bit BCD (binary code decimal) and numerical processing type, such as those used in hand calculators. Later developments have included the 8-bit midrange microcomputer to handle more complicated processes. Again, they are still designed for dedicated controls and are difficult to expand. Some need an external resistor-capacitor (RC) network for timing control. As the technology advances rapidly, 8-bit and 16-bit single-chip microcomputers will have the I/O features similar to the multi-chip microcomputer system. They could support more ROM and RAM to expand the microcomputer system extensively. Zilog's Z8 is an example having this extension capability. General Instrument's PIC 1656 has a crystal attached directly to the chip. Motorola's MC6801 is a 16-bit microcomputer with a clock and a 16-bit programmable timer. Some manufacturers make available proprietary application programs which may be built into single-chip microcomputers at a nominal cost.

3.4 SINGLE CHIP MICROCOMPUTER WITH ON-CHIP A/D CONVERTER

A significant advancement of the single-chip microcomputer is to include an analog-to-digital converter on the microcomputer chip. The INTEL 8022 is an 8-bit single-chip microcomputer having processor, memory, and two-channel A/D converter all packed into a 40-pin package. The chip includes 2 K bytes of ROM, 64 bytes of RAM, CPU, internal time/event counter, a clock oscillator, a 2-channel 8-bit A/D converter and 26 digital I/O lines. The A/D converter, which requires no external circuitry, has two multiplex 8-bit channels. Conversion is completely hardware-controlled using the successive approximation technique, and occurs in 40 microseconds. For general applications, analog devices, such as temperature sensors and pressure sensors may be directly connected to one of the channels of the A/D converter. The software capability of this single chip microcomputer includes filtering the input analog signal digitally for special purposes. For example, the software can easily be designed to average several input analog readings or to apply different weights to different readings before accepting them. For some applications the 8-bit resolution of the A/D converter may be a limitation. However, future development of the one-chip microcomputer and A/D converter may circumvent this limitation. It appears, in the feedback control application of microprocessors, that the addition of A/D converter is an important milestone in revolutionizing the feedback control methodology.

4. MICROPROCESSOR APPLICATIONS IN BUILDING ENERGY CONSERVATION

4.1 BUILDING ENERGY MANAGEMENT SYSTEMS AND DEVICES

The concern over energy supplies and their cost during recent years has led to the concept of building energy management methodologies, especially in commercial facilities. Any form of depletable prime energy, electrical, natural gas, petroleum, or coal, is under consideration for energy conservation. The benefit of energy management systems, is to minimize, or optimize, energy usage in buildings. The energy management methodologies include considerations of "static" losses, such as building insulation and HVAC system, and "dynamic" losses, such as energy consumption and the rate of energy usage. For large facilities, centralized computer-based automation systems, or distributed control systems can be utilized to optimize energy usage. As for smaller buildings, the microprocessor type programmable controllers in the form of small energy management systems or energy control devices, can be employed to control energy usage.

In the case of electrical energy, more concern will be on peak usage of a facility, because the changes for demand are sometimes higher than for the actual electrical consumption. Hence electrical load shedding is the most common central scheme used in energy management.

The method of load shedding is the practice of reducing electrical loads without adversely affecting comfort, safety, or production and is usually carried out using one of the following control schemes:

- duty-cycle control
- time-of-day control
- demand control.

Duty-cycle control consists of grouping a number of building loads, and, after determining the duration and frequency by which each load can be shed, off/on times for the loads are staggered so that a minimum amount of load is on at any time. The time-of-day control involves turning a load on and off based on a predetermined schedule. Different schedules may be used on weekdays, weekends, and holidays. For example, lights, heating systems, and air conditioning systems may be scheduled to be turned on an hour before a building is occupied and turned off an hour before a building is unoccupied. Demand control, or demand limiting, is a scheme to minimize the demand charge. The actual energy conservation is not significant because the load at peak time is removed and incurred at different non-peak time. The strategy of demand limiting, generally included in most energy management systems, is to minimize the coincident occurrence of large loads.

Energy management systems should include the generation of routine reports which can consist of:

- management reports
- maintenance reports
- summary for failure or alarm reports.

A management report summary showing how a system is performing and how much energy, or manpower is used or saved may be printed out on a daily, weekly, or monthly basis. A maintenance report can be generated to indicate how many times a load has been cycled, and the cycle duration, or the report can describe the operating efficiency of subsystems. The maintenance report could list pieces of equipment that require preventive maintenance, so they can be scheduled for maintenance. A report of the alarm summary could be generated whenever an input or output module of the system failed, or on demand by operator.

A programmable controller can be considered as a special purpose digital computer that can replace hardwire circuits; such as relays, counters or timers. As engineers implement programmable controllers by designing around microprocessors, microprocessors will become powerful devices to handle sophisticated control functions. Having significant advantages of low cost, small size, and low power consumption, microprocessor-based programmable controllers have been applied to stand-alone energy management systems which are usually used in smaller buildings having less than 100 control points. The majority of these energy management systems from the commercial control companies are using general control strategies of demand limiting, duty cycling, time-of-day control, and load shedding with priority levels. The programmable controller also includes manual override, and alarm features for malfunctions. The commonly used demand limiting methods are forecasting and ideal curve [1].

Some manufacturers employ the sliding window method to continuously monitor actual demand, such that current (sliding window) interval energy consumption as well as peak interval energy consumption are retained and automatically updated for each meter input. Some also use the intermittent "sample and hold" technique, with the "hold" being the period between control points at which forecasts are made. These energy management systems usually have battery backup supply to ensure that power failure will not destroy memory. Access code is also used to prevent tampering. There are systems with additional environmental temperature control capabilities to adjust the cycling strategies, such as increasing the air conditioning off time if the outside air temperature falls.

Another important feature for some portable energy management systems is their use for distributed systems of a host computer. That means they have the flexibility to be extended whenever the facility needs to be enlarged or improved. For example, systems IM-1 and IM-2, PT-1 and PT-2, and AC-1 have the capabilities to be interfaced to central computers.

- MC-1 -- In addition to the peak control, MC-1 is also designed to be adaptable for control of other forms of energy, such as gas, oil, steam, etc.

- AC-1 -- Permits the introduction of a supplementary or alternative energy source. Off-peak power usage and solar heating can be optimized by the system. It is also capable of performing enthalpy control. If more controlled points are required, several AC-1 systems can be connected serially.

- IM-1 -- Is capable of performing nine energy functions by monitoring sensing points in a building. It can perform surveillance of security, fire, flood, sump-pump, etc.

- PT-1 -- There is an input for a photocell so exterior lights will go on only if it is dark outside. It can override the programmed timer for these lights.

- C-7 -- Has up to 55 points capability using special sensors named accensors. This is an "intelligent" sensor which "remembers" its own address, type, and scaling factor. A custom LSI chip is used for the addressing and point characteristic identification. These sensors can be wired in a serial manner because of their intelligence. The term accensor stands for access and sensor, and is a unique feature with this manufacturer.

- AT-1 -- Is a microprocessor-based system designed to reduce electric energy cost in a hotel/motel environment. It provides monitoring of occupied and unoccupied rooms for the desk clerk. It is possible for the desk clerk to control room air conditioning and heating systems remotely from a central location. A natural extension of this capability is to provide an indication on a central panel when a room has been cleaned.

- RC-1 -- Is a microprocessor-based programmable controller for use with HVAC systems of various solar-assisted facilities. It has the capability to accept different types of inputs such as temperature, pressure, flow and others. After input signals are converted to engineering units, customized control equations can be solved for outputs. In such a manner, the HVAC system will perform according to individual control function requirements. For example, the controller can turn on appropriate pumps by monitoring differential temperature measurements, or turn on the backup system in the event that solar radiation is not sufficient.

Because it is inexpensive, flexible, and small, the microprocessor has played an important role in programmable controllers in feedback controls. The building control industry has employed microprocessors in the application of energy conservation devices such as temperature controllers, and special timers for home and commercial users. In general, the microprocessor based temperature controllers, or thermostats, are designed around a microprocessor chip to give the user choice of temperature and scheduling controls via simple programming for the purpose of energy conservation. They usually provide the capability to have more than one temperature setting in the 24-hour period. Some have battery backup power systems to maintain continuous temperature control. Manual overriding features are usually provided to handle any unusual circumstances. The following are some of the examples of the programmable temperature controllers.

- CP-1 -- A temperature controller built from a single chip microcomputer, INTEL 8049. It can accommodate up to six changes per day in two different 24-hour schedules, including weekday and weekend. There is also an outdoor temperature sensor that allows the user to see the outdoor temperature display on the device.

- PC-1 -- The thermostat utilizes mercury sensor technology to avoid drift from the temperature setting. It is also a microprocessor-based temperature controller providing four temperature settings, proof of heating, and proof of cooling.

- RT-1 -- The thermostat includes a clock in the unit with a 3-way switch to offer time indication only, or temperature indication only, or both, alternating every 5 seconds. The clock does not contain a battery, and it is supplied from the same two wires that power the thermostat. This microprocessor-based thermostat has two settings for temperature control.

- TC-2 -- Is a programmable timer for special applications to be used as a multi-load, and multi-function time clock. TC-2 is also a microprocessor-based controller with software capability to provide time-based scheduling and cycling of electric loads. Up to 16 loads can be controlled by this programmable timer. A unique control plan for each of the 7 weekdays plus special holidays could be set up for individual loads. Manual override and battery backup are provided.

4.2 RESIDENTIAL BUILDINGS

As the cost of utilities continues to rise, homeowners have become concerned about energy conservation in their houses. Builders and owners have been addressing this problem by increasing insulation, reducing air infiltration, and decreasing thermostat control settings. Sophisticated control strategies for residences has not yet been feasible; and the only control in most residences has been limited to the temperature control, or thermostat. With the advent of microprocessors and their supporting chips, numerous energy control strategies have been developed for home applications. However, products to implement the strategies are new entries to the market and there is insufficient data for analyzing the payback period required for the justification of the initial cost. An example of an available product is an interactive computerized control system built around the INTEL 8085 microprocessor by manufacturer H and installed in a $350,000 home [5]. Six months after installation, the energy savings was estimated to be about 50%. This microcomputer unit has the capability to open and close a sunshade using a time control unit, which also has priority scheduling for other appliances. The unit also has a theft security system and connects to the smoke detector for fire protection. The system shuts down all appliances if an emergency occurs. Water conservation via lawn watering control using a sensor in the lawn is also provided by the system. Although the manufacturer claims that this interactive microcomputer unit will soon become standard in new homes, further evaluation is necessary before any conclusion can be made.

Another example of a home energy management and control system is a microcomputer system designed for use in buildings under renovation, or in new buildings [6]. This system is installed in facilities with a solar energy system consisting of "active windows" of double-pane glass on the south walls. This microcomputer energy management system has the capability to close the shutters of active windows automatically when night-sky cooling or solar heating systems are not in operation. It also monitors the air quality, control relative humidity and utilizes ultrasonic motion sensors to monitor occupant activities for ventilation control programs.

Residential energy control management systems have some drawbacks, such as climatic dependence and lack of local maintenance facilities. Standard hardware and software are difficult to apply in some areas since the building situation and climate conditions will make a big difference in system design.

4.3 LOCAL-LOOP ENERGY CONTROL DEVICES

Some control system components may be located in the general area of the equipment or space being controlled, and these are referred to as local-loop devices. Although a large number of microprocessor-based building energy management systems are in use, the number of microprocessor-based local-loop energy conservation devices is somewhat limited, with the exception of the demand-limiting device. The main reason for the wide acceptance of the demand limiter is the demand charge penalty. The penalty for exceeding the demand limit is to pay a demand charge for a period of several months following the establishment of the new peak. Building automation systems have adapted a variety of optimization schedules for energy conservation (section 2.2). With the concept of distributed control systems using microprocessors, each local loop can continue to be functional even when the central computer is off line for service. Apparently, the energy optimization schemes of the EMCS can be replaced by microprocessor-based stand-alone devices. The most probable developments by the control manufacturers are the energy conservation devices such as enthalpy optimizer, chilled water optimizer, secondary-loop optimizer, and start-up controllers. However, in some cases, the potential return of these devices may not be as high as for the demand limiter.

As microelectronics devices become relatively inexpensive, it is anticipated that these control devices could be designed around microprocessors with the advantage of small size, flexibility, and low cost; or even become "off the shelf" items for standard HVAC systems in the future. Furthermore, the application of microprocessor-based control devices would not only be limited in large building automation systems but include residential facilities as well. For example, a microprocessor-based temperature controller could include several sensors to indicate temperature readings in different locations. The control logic of a single zone system, may be designed in a variety of ways. It may be based on either "most occupant" or "scheduled" logic. The "most occupant" logic requires some sensing means of occupancy within the zone. The controlled variable is the space temperature of the "most occupant" space. If no occupant is present, the space temperature will be controlled at minimum energy level. As for the "scheduled" logic, one could select family room sensor as evening temperature, bedroom sensors as night temperature, dining room sensor as dinner time temperature, etc.

It follows that many other generic ideas may be developed for energy conservation application, even though such control devices might be costly at the present. However, the consideration of this and similar apparatus for residential controls should not be overlooked as the high performance microprocessor becomes more capable, reliable and inexpensive.

4.4 SOLAR ENERGY APPLICATIONS

Since the Arab oil embargo and the resulting rise in the cost of energy, energy conservation has played a key role in building automation systems. In many conventional controls, the individual control loop is an independent feedback control system, although the control variables in the loop are frequently related to other control loops.* The application of adaptive controls in energy conservation requires the analysis of the entire system so that dynamic relationships between subsystems can be taken into account. The complexity of system optimization increases if the control system includes many subsystems. Thus, the control logic under such circumstances requires the capability of microprocessors and microcomputers. Recently, new control methodologies have been investigated, especially in the area of solar energy controls.

There are numerous projects sponsored by Federal agencies and private industry to develop microprocessor-based adaptive controllers and control algorithms for solar energy homes. The purpose of these projects is to evaluate the cost effectiveness of certain controllers and to explore a variety of control strategies. For example, from the same manufacturer of the RC-1 programmable controller, a microprocessor-based programmable data acquisition system (PDAS) has been developed to be custom-programmed for three solar energy conservation houses to monitor all energy-related parameters [7]. The information from the subsystems is to be used for energy-related engineering studies for the Pacific Gas and Electric Company.

Another project, developed by Middlebury College, Vermont, is to compare different control strategies for two solar hot water collector systems interfaced to a microprocessor-controlled data acquisition system. These identical systems are being operated simultaneously under the same load and environment conditions, but different control strategies will be used for the purpose of energy conservation testing.

4.5 CHILLER CONTROL METHODOLOGY WITH MICROPROCESSORS

The microprocessor control of a chiller plant is a new concept in building controls. This section of the report will demonstrate a generalized chiller control logic, designed to be usable in centrifugal chiller plants. The control logic must be tested by simulation and actual field conditions before final programming can be completed.

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* In adaptive controls, the control process enables the controller to improve its decision-making ability and the system performance on the basis of its experience and to adapt itself to its environment.

Many conventional controls in chiller plants may be replaced with microprocessors. These microprocessors can be programmed so that more sophisticated control logic and algorithms will be incorporated for energy conservation and safety controls. In building complexes with EMCS and distributed control systems, chiller control microprocessors may also be used to communicate with the central minicomputer.

One microprocessor is sufficient to control all of the variables in a chiller. Each chiller microprocessor needs an independent timer for self-clocking, in order to determine the chiller's availability for start-up when it is off-line. For a multi-chiller cooling system under a central EMCS an interface microprocessor is required to act as a concentrator for communication between the central minicomputer and the microprocessor-controlled chillers. The chiller microprocessors mush be bit-synchronized to communicate with each other when an "interrupt" signal is generated by the building control minicomputer. Thus, all microprocessors can function as either receivers or tranmitters to complete the communication link. The interface microprocessor maintains a transaction directory of the status of each chiller for the purpose of reporting to the minicomputer. The microprocessor must be equipped with full battery back-up systems so that, in case of power failure, the microprocessor can still keep the central computer informed of the status of each chiller.

A central minicomputer may be programmed to optimize the chilled water temperature and chiller loading. After the minicomputer receives the status information of all chillers, it may give commands to the concentrator to take proper actions. A printer is generally used to keep a log about the chiller status and/or error/alarm conditions. Figure 9 illustrates the transmission links of the microprocessors with the minicomputer.

Basic chiller operation requires a number of safety controls to protect the equipment against potential damage. The chiller microprocessor continuously scans the status of each chiller operation and uses one of two possible status flags, "ready" or "error," to indicate status.

For the common operation of chillers, four subroutines are constructed to carry out the process of the "turn on" command. After the execution of each subroutine, either the "error" flag or "ready" flag will be set to identify the status of the chiller. In case an "error" flag is set by any of these subroutines, sensing inputs of the chiller should indicate the nature of malfunctioning. Then, besides turning the chiller off, the microprocessor will inform the central minicomputer about the situation so necessary action can be taken to protect the equipment accordingly.

Figures 10 to 13 show the generalized chiller control logic with microprocessors. The general description of each subroutine is as follows:

- Status Subroutine (Figure 10):

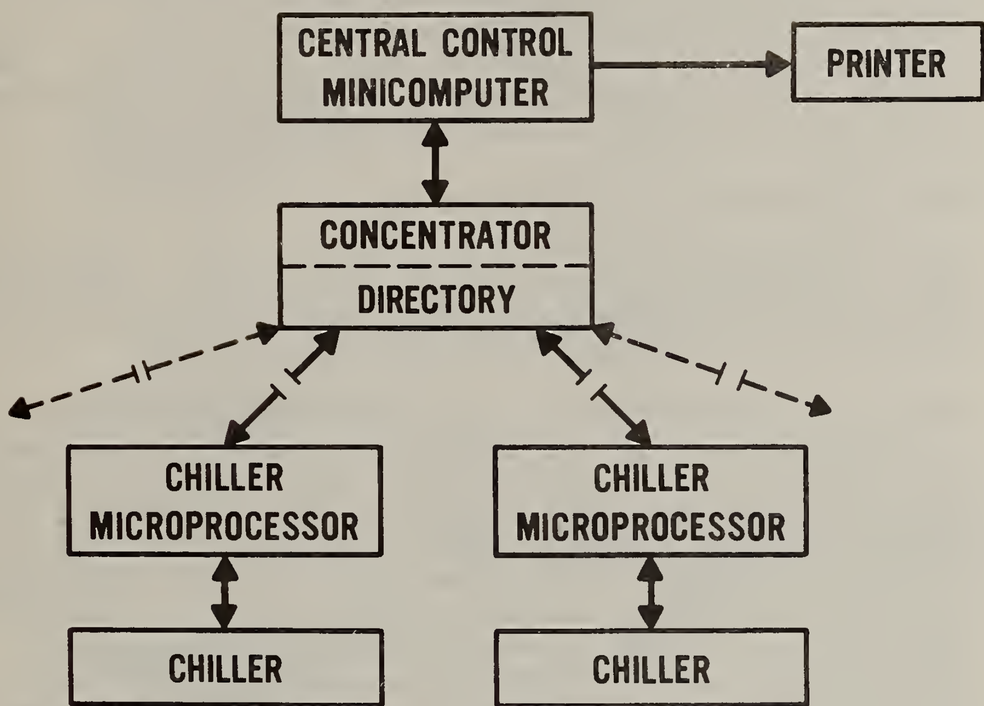

Figure 9 General Layout of Chiller Control Microprocessor with Minicomputer

This subroutine is mainly used to determine the chiller availability for start-up when it is off-line. Continuous scanning within this subroutine is necessary. If the chiller has been stopped under normal operation, a normal status will be required to restart the chiller. Figure 10 demonstrates some significant variables, as examples, to be monitored; other variables could be added if desired.

o Pre-Start Subroutine (Figure 11):

This subroutine is to check the conditions of all the variables prior to start-up. If the status is normal, this subroutine will turn on the oil pump and monitor the oil pressure before starting the condensing water and chilled water pumps. (Normally these two pumps are interlocked for starting). When the flow switches in both condensed and chilled water circuits are closed, the chiller is ready for start-up.

o Start Subroutine (Figure 12):

This subroutine is employed to start up the chiller initially. After the chiller is on-line and the chilled water temperature has reached the set point temperature, this subroutine will be phased out until the chiller is required to restart.

Prior to the dynamic starting of the chiller, it is necessary to determine the preset and additional increments of vane positions according to the chilled water return temperature (T_{CHR}), and chilled water set point temperature (T_{SP}) in order to set the proper chiller capacity. The latter can be read from the building minicomputer if the building EMCS and the optimization routine are available. Otherwise, table look-up is required to find this value. Once the vane positions are obtained, the chiller can be started by opening the vane position according to the preset value. Afterward, the minimum load limitation will be monitored and the vane position will be adjusted, enabling the chilled water temperature to reach the set point. Then, the ready flag will be set to indicate a normal status for the run time load control subroutine to begin.

This subroutine utilizes much of the capability of a microprocessor when it is used as a controller and overcomes the many drawbacks in conventional controllers. For example, the minimum load limitation in chiller control is one of the many advantages in using microprocessors. In conventional controls, the chiller is shut down whenever the electric current consumption drops below a minimum level. The minimum load limitation prevents the compressor from being operated with low efficiency for energy saving purpose. However, in the microprocessor control, the nuisance of shut-down and restart by the motor-winding high temperature cutoff can be avoided, because the vane may be

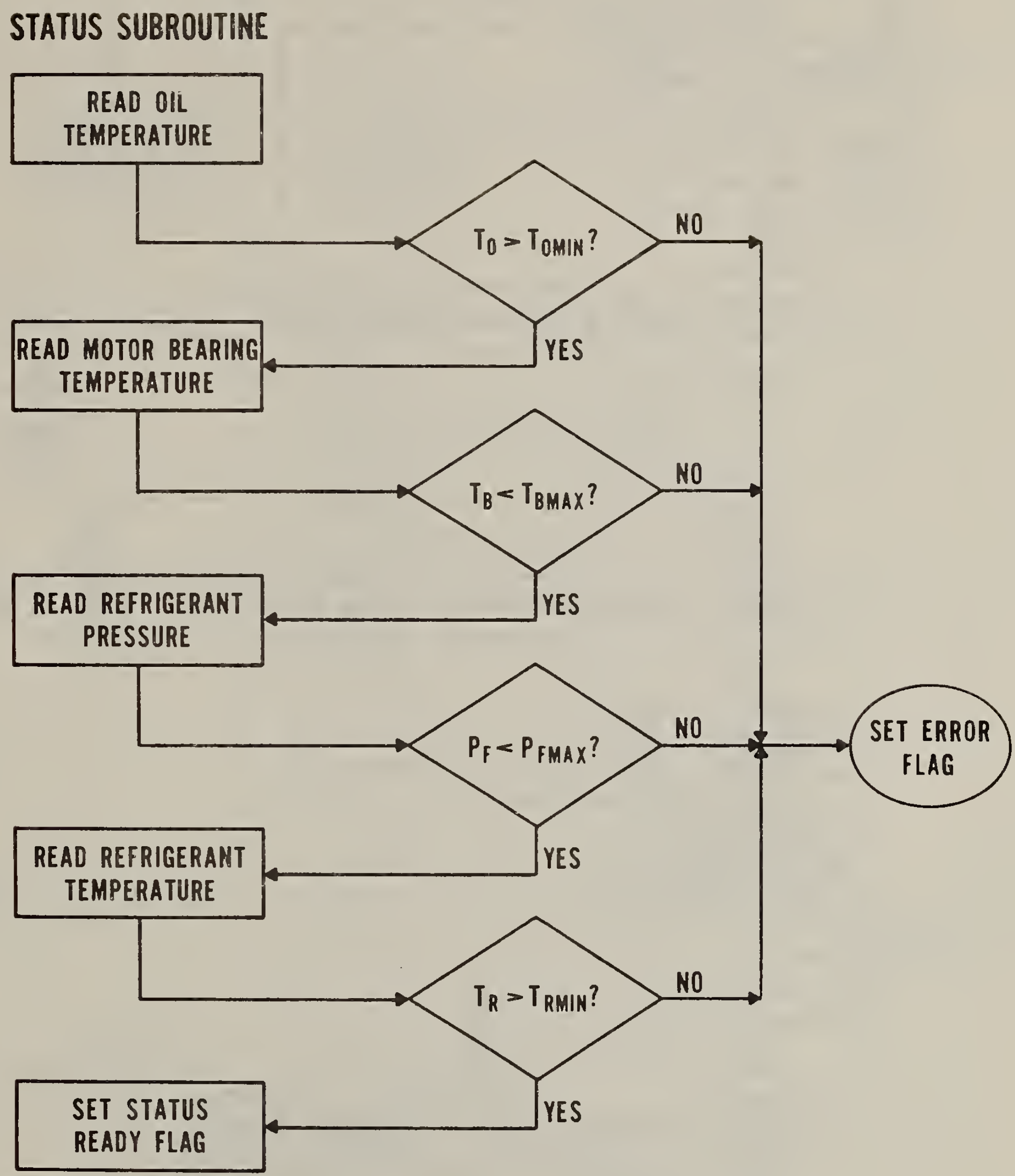

Figure 10 Generalized Chiller Control Logic with Microprocessor-STATUS

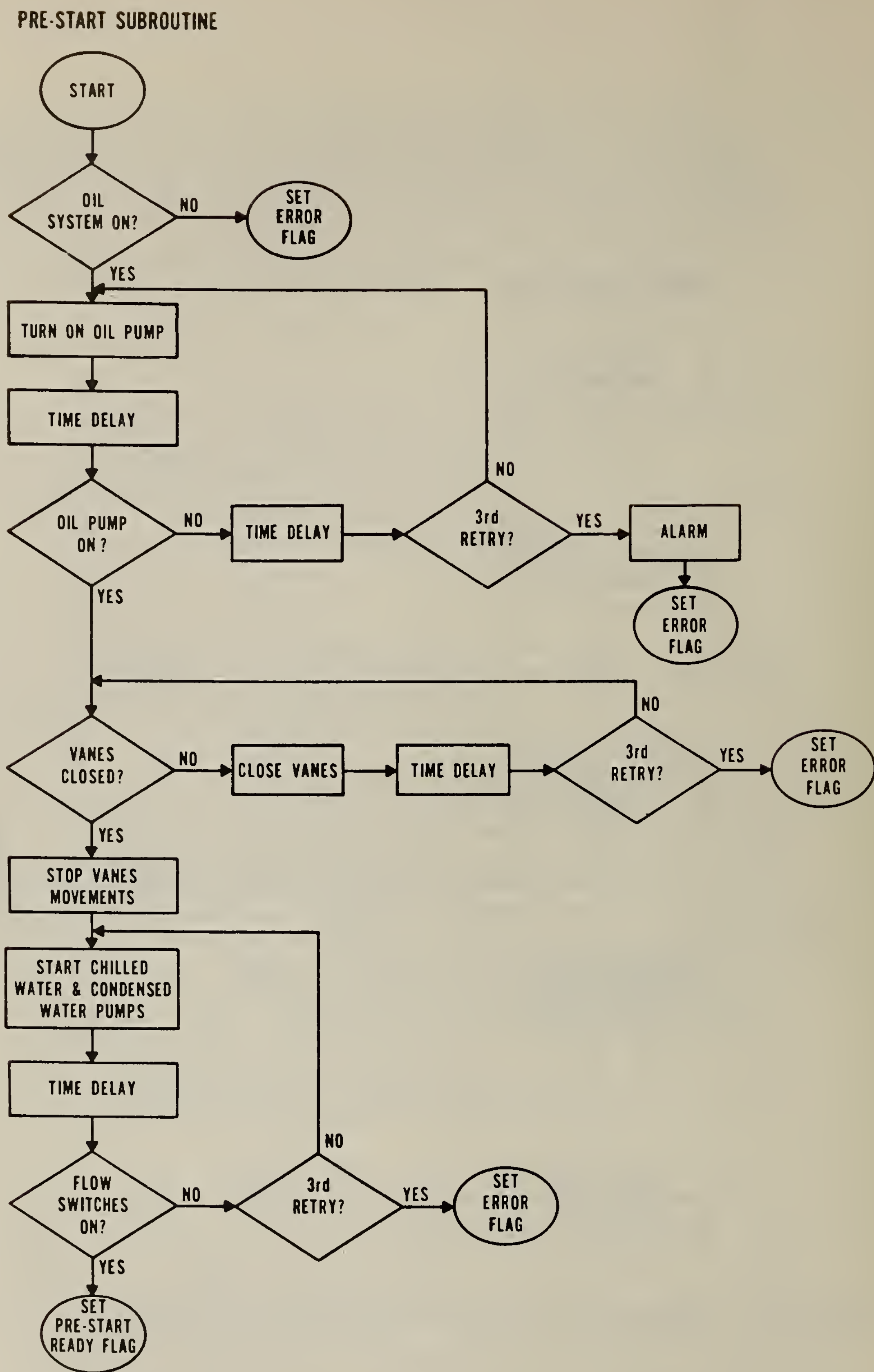

Figure 11 Generalized Chiller Control Logic with Microprocessor- PRE-START

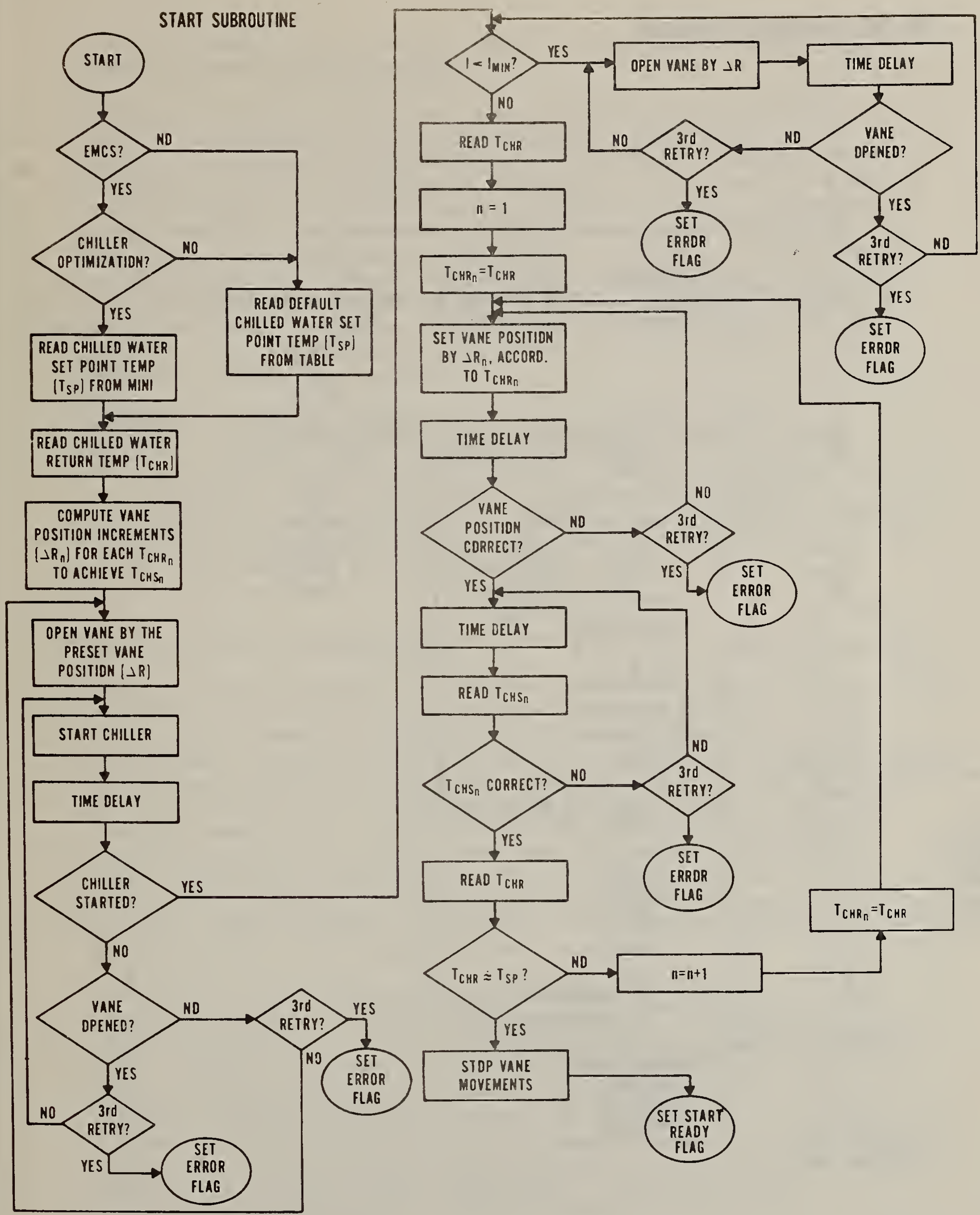

Figure 12 Generalized Chiller Control Logic with Microprocessor-START

RUN TIME LOAD CONTROL SUBROUTINE

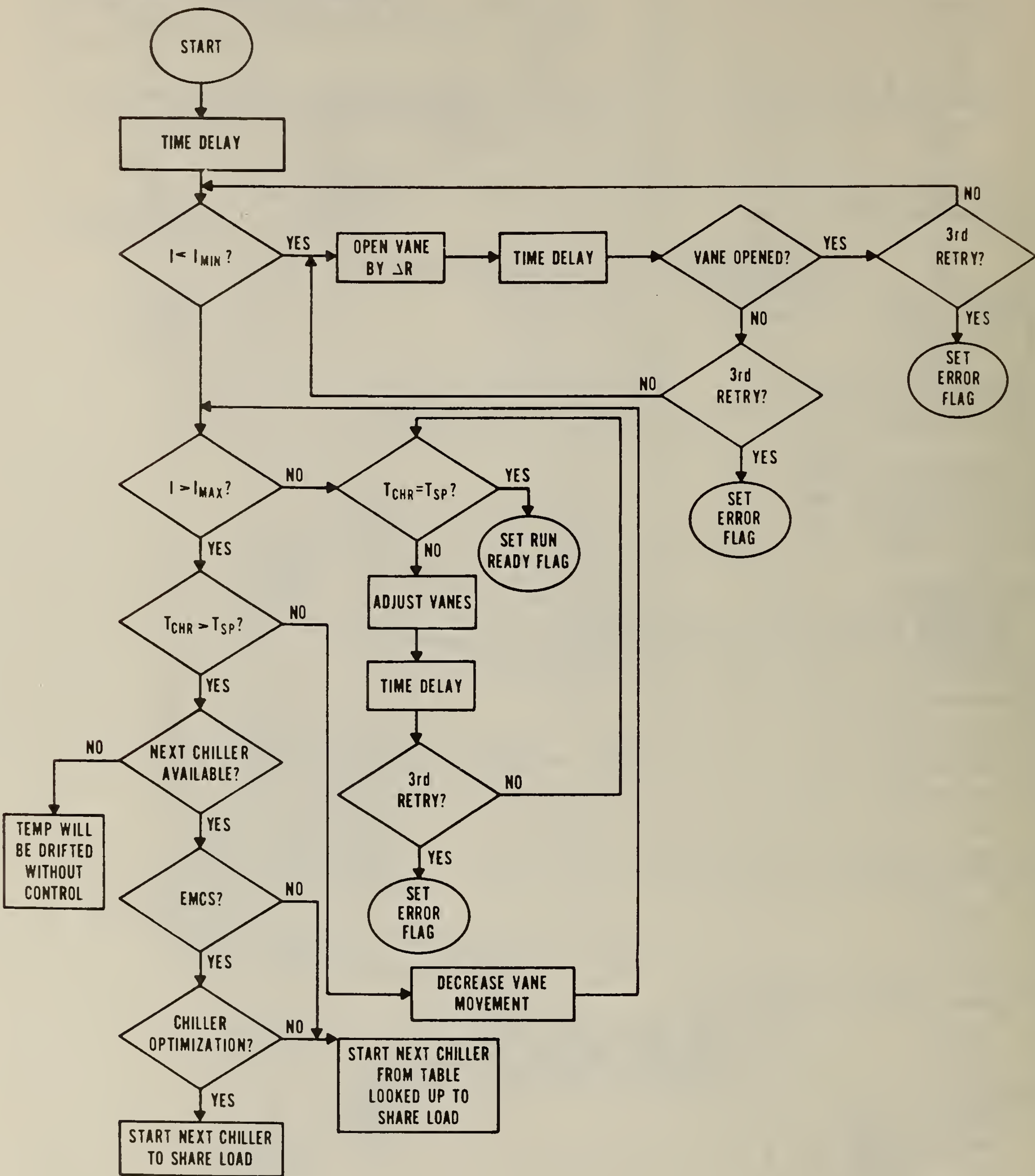

Figure 13 Generalized Chiller Control Logic with Microprocessor-RUN TIME LOAD CONTROL

opened so that a load is always created to exceed the minimum-load requirements of the chiller.

Another advantage of the microprocessor control is preload control of the chillers. With the conventional proportional control, during startup of the chillers vanes are wide open, and therefore, a drastic overshoot in the response of the chiller-controlled variable, chilled-water temperature, occurs. In contrast, the time response during preload of the microprocessor control is always in an overdamped fashion, because the microprocessor holds the vanes at a fixed angle without allowing them to reach wide-open position during the time response. It usually takes many small increments, such as one Fahrenheit degree step, to reach the desired control point. By preventing the overshoot, energy is conserved.

An additional energy-saving factor is the stability of the control. The conventional strategy for controlling the chilled water temperature is proportional control. Due to the high gain requirement, the system tends to be highly underdamped and oscillation has been frequently observed. As a result of the microprocessor control, the system always responds to any step change in an overdamped fashion because of the small step increment.

- Run Time Load Control Subroutine (Figure 13):

This subroutine is used to control the chiller load during run time by continuously monitoring the minimum load limitation, electric demand, and chilled water return temperature. The minimum load limitation check will be performed here as in the start subroutine. If demand limiting routine exists in the building EMCS, no controlling is required for the electric demand, since any overload will be shed automatically by the demand limiter. In the case that an overload condition causes the chilled water temperature to rise above the set point, it is necessary to seek help from the next chiller if there is one available. Otherwise, the chilled water temperature will drift upward without control.

When there is more than one chiller available in the cooling system, each chiller control microprocessor will remain in stable operation at a certain chilled water supply temperature (T_{CHS}) and a certain chilled water return temperature (T_{CHR}). As the need arises to start up a second chiller, the same algorithm shall be followed. If the EMCS and chiller optimization route are available, the percentage load shared among chillers will be determined and automatically performed by the building EMCS. Otherwise, table look-up is required to start the next chiller, in order to share the chiller load.

There are many ways of utilizing microprocessor in building EMCS. This microprocessor chiller control algorithm merely demonstrates one of the many applications of microprocessors in building controls. It is recommended that the control logic be tested on a computer-simulated system and the hardware/software be field tested under the actual building conditions before any "generalized" package is used in building EMCS.

5. MICROPROCESSORS IN ENERGY MONITORING AND CONTROL SYSTEMS (EMCS) -- CASE STUDIES

5.1 MINICOMPUTER CONTROL SYSTEMS

A computer system was installed at the Earle Cabell Federal Building (ECFB) in Dallas, Texas in 1976 for the purpose of controlling and monitoring the building's heating and air conditioning systems.* Prior to the decision to utilize a computer control system, an attempt was made to conserve energy by reducing lighting levels, shutting down unnecessary equipment and running only minimal equipment during non-working hours. However, in order to increase operation efficiency, additional operating engineer manhours were required. The building was operated as designed until 1974, with the following profile:

- Electric demand: 87,086 kW/year
- Electrical consumption: 31,902,159 kWh/year
- Required operating engineer manhours: 5,592.

By 1975, with efforts toward energy reduction, the operating profile of the building was as follows:

- Demand: 56,525 kWh/year
- Consumption: 22,292,516 kWh/year
- Required operating engineer manhours: 8,760.

This state of affairs represented the limit for energy conservation with the existing control systems and available human resources; any additional improvements without increasing operating manhours would require computer control. In February, 1975, a decision was made by the Building Management Division, General Services Administration to purchase an integrated minicomputer system to control the environmental system of the ECFB, which had a floor area of over one million square feet (92903 m^2), 2,460 tons (8659 kW) of air conditioning capacity and 32,775 pounds per hour (14866.5 kg/h) of steam heating capacity. The minicomputer was to be utilized as a control device to operate the heating and air conditioning systems. In the process of controlling the building environment the system was to perform control functions such as start/stop, reduce

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*Information was provided by the Assistant Building Manager, Dallas, GSA Region 7, and their internal reports.

electrical demand and consumption through load-shedding techniques, reduce operating manpower, maximize efficiency of boiler and chiller operation, and provide capability for additional functions. The computer system was on-line in December, 1975. After a trial period, the system was found to be realiable and the third and weekend shifts of the building operators were reduced. At mid-1977, the building energy profile was as follows:

- Demand: 42,124 kW/year
- Consumption: 15,325,492 kWh/year
- Required operating engineer manhours: 260.

The reductions were not all the results of the computer system, as the building was partially vacated. Taking into account an approximate adjustment for vacancies of 120,000 kWh/month consumption, and 500 kW/month of demand, the reductions of building energy and manpower by the computer system during the first seven months of 1976, as compared to the first seven months of 1975, were as follows:

- Demand reduced: 543 kW/month
- Consumption reduced: 174,986 kWh/month
- Required operator reduced: 556 manhours/month.

5.2 DISTRIBUTED MICROPROCESSOR SYSTEMS

During the period of system installation and debugging for computer system at the ECFB, distributed control systems were being developed using microprocessors. The decision was made to expand the existing system to monitor another facility remotely via telephone lines. The second building, a 50,000 square foot (4645 m^2) underground federal building in Denton, Texas, is the Region 5 Headquarters for the Defense Civil Preparedness Agency. The security activities and the equipment installed in this underground facility require the building to be monitored 24 hours per day, seven days per week. The agency responsible for providing on-site security, fire, and equipment alarm monitoring was to eliminate their non-working hour shifts on August 1, 1976. Thus, if the building was to be operated as required, an alternative approach was to provide remote monitoring.

In late 1976, a multiple microcomputer control system was installed at the Denton Federal Center in Denton, Texas to reduce building security cost, control HVAC equipment, and provide smoke and fire detection. It was a distributed energy management and security system, fully standalone and able to communicate with another environmental computer control system in the ECFB located in Dallas, 40 miles away. From January through May, 1977 the savings over the previous year from the microprocessor-controlled system in the Denton facility were reported to be 33% for electric demand, 45% for electric consumption and the elimination of three previously needed additional employees. The major impact of the computer systems on the two facilities, beside savings of energy, was the reduction of operating manpower as all 2nd, 3rd and weekend shifts were removed.

Five microprocessors have been employed to perform supervisory control, as well as other functions. One battery backup microcomputer performs all supervisory functions for the system; two other microprocessors monitor both electrical demand and consumption, sense building temperatures, operate heating, ventilating and air conditioning (HVAC) equipment, detect smoke and fire, and provide security; a fourth unit controls a local status printer; and a fifth serves as a telephone line communications controller to link the system with the other building forty miles away. These five microprocessors make up a distributed system with preset priority levels; the entire system may either function in unison or each microcomputer may function in a stand-alone fashion. Furthermore, the microprocessors are programmed so that they may diagnose each other continuously. The microcomputer system in this building monitors all the control functions independently during office hours and reports all security and safety alarms, and equipment malfunctions to a host minicomputer, in the Dallas building during non-working hours. The manpower for security is drastically reduced in this building during unoccupied hours.

Another example of a distributed microprocessor system consists of two control systems for two buildings in Louisville, Kentucky. The Federal Office Building, FOB, and the Louisville Post Office, LPO, with a total floor area of approximately 1.2 million square feet (1 million square meter), are separated by a distance of one city block, and connected by a shielded 300 conductor underground electrical cable. The control center in the FOB performs monitoring and controlling functions for the system in the FOB as well as for the LPO system. In the LPO, there is a microprocessor designed to obtain a stable reading of various space temperatures; these temperatures can be read by the control center in the FOB.

6. CONSIDERATIONS FOR DESIGN OF MICROPROCESSOR CONTROLLED EMCS

The evolution in computerized building control systems has been dramatic in the past decade. With the recent development of microprocessors, these systems can have total stand-alone capability and provide distributed intelligence. Currently, a total system approach to EMCS will require the system to provide efficient utilization of energy and operating manpower, to provide life safety and property protection, to record factual operating data for building manager's decisions, and to maintain environmental conditions for the specific activity or work function of the building.

To design an EMCS for an existing building, personnel with background in HVAC system, computer, and applied mathematics will be needed. Building management also plays an important role in decision-making. From the standpoint of systems analysis, the HVAC system is considered to be a complex system in the sense that it is non-linear, time-variant, and nondeterministic, which implies that techniques from statistics, decision theory, and game theory will have to be applied. At the beginning of EMCS design, the HVAC system will be analyzed theoretically. Concurrently, decisions will have to be made to determine whether the analytical approach will achieve the target by optimization of system operation. After the installation of EMCS computer system, its software will be employed to perform analysis on a set of system performance criteria with strategies determined by the building manager. The strategies, which are suitably weighted by parameters beyond the control of the data environment, (e.g. temperature, humidity, etc.) are then correlated with the target. The performance of each strategy is then evaluated in terms of its ability to reach desirable targets. A particular strategy, which most closely approximates the initially chosen performance criteria, is selected as "optimized". With the help of the building manager, variables and parameters of the problem are isolated to make decisions in order to achieve the optimization. For example, the following shows some of the parameters that can be chosen for optimizing:

- latest morning start up
- earliest evening shut-down
- maximum efficiency of existing HVAC equipment
- psychological factors (e.g., after turning an air handler off, regardless of comfort levels, occupants will notice and begin to complain about the lack of air movement)
- most optimal interactional effects (e.g., which combinations of equipment turned off at which time of the day will produce the most desirable effects)
- number of fans and fan speed of cooling towers operating as a function of external temperature, humidity, and chiller load
- morning start-up sequence (e.g., as a function of ambient temperature during the weekend, it is more desirable to bring equipment on at 2 am and slowly set the building under control, as opposed to starting the equipment at 6 am, which is the normal operating procedure).

Initially, the methodology of optimization will be to study the overall problem in a localized sense to select one parameter at a time for a hypothetical test. For each parameter, different strategies are tested in order to select the most suitable strategy to meet the performance criteria, and this strategy will become the initial hypothesis of the interactive process among parameters. After all parameters have been exhausted, higher order effects will be studied by changing more than one parameter. The EMCS computer system will be set up deliberately as a learning instrument to permit sequential and interactive interplay between an operator and the machine from the set of performance criteria in such a way that the building operation can eventually be totally optimized. As far as the software is concerned, it should contain sufficient mathematical sophistication in performing predictor/corrector analysis, autocross correlation analysis, and weighted analysis of variances, in order to avoid such errors as a hypothesis accepted as being valid when it should have been rejected and vice versa.

In a complex installation of EMCS, functionally decentralizing the data environment is a helpful way to understand the operation of HVAC equipments. Accordingly, the idea of the microprocessor approach will be adapted successfully with the following examples:

- Installation, debugging, and maintenance will be simplified by the substructure of the data environment. Specifically, without worrying about any sophisticated analytical algorithms, the microprocessor can be validated locally and debugged. Once it is thought functional, the only remaining task is the communication with the central computer.

- The distributed hierarchy will leave the option of performing routine data acquisition and preprocessing in the microprocessors. The minicomputer can use statistically robust data for calculations immediately.

- Interactional effects among all the multitude of equipment will be difficult to determine, assess, and debug within the central system. Therefore, for ease of comprehension and experimentation, most stand-alone microprocessors would be structured to interface with various signals from specific HVAC systems.

- If further signals or controls have to be added, it can be done easily.

7. CONCLUSIONS

The advancement of microelectronics technology has enabled building controls to become highly sophisticated systems. Microprocessors have helped to improve the feasibility of distributed control systems and could also replace the traditional controllers. By designing programmable controllers around a microprocessor, controllers may be given computer-like capabilities such as signal converting, data storing, and data analyzing.

Because of the concern with energy shortages and the rise of energy costs, building controls have been an important investment, together with building envelope design, for depletable resources conservation as well as for energy cost reduction. A microprocessor-based programmable controller in the form of an energy management system or an energy control device is capable of controlling energy usage in small buildings. For larger facilities it will be necessary to employ microcomputers in building automation systems that require greater sophistication including extensive computation, data storage, printouts, displays, and interfacing. The enhancement of microprocessors will make progress in improving the performance of energy conserving equipment, such as boilers and chillers, desirable and will allow development of local loop control of this equipment. It is anticipated that direct digital controls will be ultimately adapted in building automation systems. With the advantages of versatility and low cost, the microprocessor may be used in a tremendous number of applications in control systems as well as in other areas. Microprocessors are capable of being utilized in controllers, communication links, signal conditioners, actuators, sensors, and even in operation of central minicomputers as display terminals and keyboards.

Due to the high demand and low cost of silicon chips the semiconductor industry is likely to produce so called firmware, which is a variety of packaged programs on ROM. The enhancement of the firmware, instead of the software, allows the end-users to link the miniprocessor to the outside world by mere interfacing. Thus, sophisticated control system design may be accomplished without complicated software development and program debugging. Furthermore, new advances are being made in semiconductor process technology to achieve the package density needed for future applications. Due to the rapid growth of today's technology it is not unrealistic to predict that the 32-bit microprocessor will be available from manufacturers in the next few years.

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15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A well insulated building may be considered a thermally efficient building. However, the systems and controls within the building must also be energy efficient in order to conserve energy. Thus, building controls is an important subject in energy conservation. In recent years, building control engineers have been developing energy conserving control methodologies. The availability of microprocessors and minicomputers has made it possible to apply many control strategies requiring extensive computations. Since a large segment of energy is consumed in buildings, the enhancement of control methodologies will help achieve national energy goals. This report is mainly to investigate the capabilities of microprocessors in building control applications so that requirements to expedite these applications may be developed. Microprocessor applications in both conventional control systems and in local-loop energy conservation devices are examined. In addition, special applications of microprocessors in buildings are explored. The development of microprocessor technology is also discussed.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Building automation; building energy management systems; building controls; chiller controls; distributed control systems; energy conservation; energy conservation devices; microcomputers and minicomputers; microprocessor applications; programmable controllers.

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