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THE REVOLUTION IN DATA GATHERING SYSTEMS

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16. Abstract

A revolution in data gathering systems began in the late 50's because there was; (1) a need for consolidating data from many sources into a single data base, (2) the need for maintaining data integrity and, (3) the need for the experimenter to observe the computed results during an experiment. The advent of the computer introduced stored program concepts to data gathering and raised the qualifications of support personnel by introducing disciplines identified as; the Customer Engineer (CE), the Analyst, and the Programmer. The computer caused a complete cyclic evolution of the data gathering system by transforming the distributed hardware system of the early 1950's to the large central computer system concept of the late 1960's. The central computer system soon produced increasing software costs and unreliable availability to the experimenter, which resulted in the evolution of the distributed computer system concept of the 1970's. The net gain in the evolutionary chain was the common data base, data integrity, experiment control and real time processing.

During the early years dramatic changes evolved slowly. The revolution picked up momentum as computer technology advanced from discrete logic to medium scale integrated circuits (MSI), and finally to large scale integrated circuits (LSI) where many functions could be performed by a single component that took the place of thousands of discrete components filling up several chassis. These advances in the computer industry impacted both the data gathering and the control fields in that it became possible for their functions to be combined. This combination of functions was reinforced by the distributed computer system which allows the experimenter to interact with the experiment to obtain more reliable data.

The revolution is continuing with the coming of the micro-processor and micro-computer. It appears that the micro-processor will become powerful enough to move into many of the system functions presently performed by the minicomputer. The minicomputers in turn are growing in capacity and continue to encroach on the big computer's functions by fulfilling the increased demands placed upon the data gathering systems for real time answers in the fields of dynamics, stability, safety of test and reduced environmental pollution.

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THE REVOLUTION IN DATA GATHERING SYSTEMS

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INTRODUCTION

This paper summarizes data acquisition systems used in NASA's wind tunnels from the 1950's through the present time as a baseline for assessing the impact of minicomputers and microcomputers on data acquisition and data processing. Early data gathering systems were basically distributed systems with data processing almost completely accomplished manually. Data reduction typically took from weeks to months depending on its complexity and the amount of data being processed.

Data gathering systems of the 1960's provided quantum jumps in performance over earlier systems due to the introduction of solid-state components and minicomputer systems to the measurement of DC and low frequency phenomena. Digital systems could provide a five to ten-fold increase in end-to-end data accuracy not possible with FM/FM or other analog data acquisition techniques. A major advance during this period was the introduction of the minicomputer to data processing which significantly shortened data reduction times and reduced costs, resulting in fewer manhours consumed in the data reduction process.

Data systems evolved to basically single media data records (tapes) with processing performed on a central computer. The use of a large central computer for data processing became the by-word in 1968 and was really the beginning of computer controlled data systems. On-line processing and time share terminals at the data system location were introduced in 1969 at Ames, further reducing data turn-around times for quick look decision making. The use of the time share system by the user community however, was unpredictable and computer system overload failures occurred frequently. Therefore, the engineer often reverted to the cumbersome process of manually processing data for real time analyses.

Other than the minicomputer, significant advances in data gathering during the 60's were primarily front-end related. The minicomputer added nothing to the accuracy of acquired data. However, the introduction of the high quality, wideband differential DC amplifier produced greater dynamic analog signal conditioning accuracies than the earlier chopper amplifiers. Related developments introduced during this period included the autoranging DC amplifier (1964), MOS-FET multiplexers (1966) and MSI logic (1968-70), as well as computer-controlled programmable amplifiers. During this period, data throughput rates were advancing from less than 2000 WPS (the early 1960's) to 125,000 WPS (the early 70's). The hardware advances helped reduce the data system's power, heat and space requirements and increased reliability. The higher word rates, plus more data points per test combined to dictate the use of the digital computer to reduce the massive amounts of data acquired. The negative aspects of the computer related to the software systems explosion in the late 1960's and the start of spiraling software costs. Also during this period some data users lacked confidence in some of the data because they did not (or were not able to) participate in the software development.

The late 60's and early 1970's saw the introduction of the advancement of several concepts; (1) the use of solid-state remote multiplexing, (2) the integration of signal conditioning with the PCM encoder and (3) the computer-controlled data gathering system. Proliferation of minicomputers in data systems resulted in a trend towards decentralization of the computer function so that today (1975) the distributed systems with potentially more than one minicomputer per system are on the drawing boards.

The introduction of the microprocessor and the projected lower costs of micro's coupled with currently tumbling costs for mini's coupled with spiraling software costs is reinforcing the trend towards distributed systems. It is safe to say that by 1980 multiple microprocessors will be used in a single system for dedicated hardware type tasks so that the minicomputer (which is growing in power) can be dedicated to more sophisticated real time data processing tasks.

SYSTEMS OF THE 1950's

Data gathering systems can be linked to the beginning of man and can be traced historically along with man's technological advancements. Those systems form the prime elements used in observational research. Edwin P. Hartman, in his book "Adventures in Research" says "Experiment might be thought of as a form of observational research such as that used in astronomy, but instead of waiting for nature to speak in her own good time and place, we ask her questions and deliberately force her to speak at a time and place of our choosing. She withholds nothing from those clever enough to ask the right questions. Our questions are asked by confronting her with a cunningly devised situation or mechanism to which she must react." Some of the devices and mechanism referred to by Dr. Hartman are Wind Tunnel Facilities used in aeronautical research.

The early wind tunnel data systems (prior to 1950) used in these facilities were a conglomeration of analog instruments, each measuring a specific parameter. There were manometer boards for measuring pressures (refer to Figure 1), panel meters for measuring temperatures/power/positions, induction type transducers for measuring angular rotation, shadow-graph and Scheleran systems for measuring aero-dynamic air flow, and Toledo scales for measuring aero-dynamic forces. The experimenter, was part and parcel of this data gathering system which provided the control function, as well as the recording function by taking photographs of the manometers and aerodynamic flow as well as manually recording the readings of the scales and meters. During this period data was reduced by a team of mathematicians using mechanical calculators. The processing of data for some tests could take as long as 6 months. In tests that required measuring many parameters, engineering teams (as many as 15 engineers) were required to monitor the various displays and recorded results. Few reports were produced as the product of these experiments because of the long time required to reduce the data.

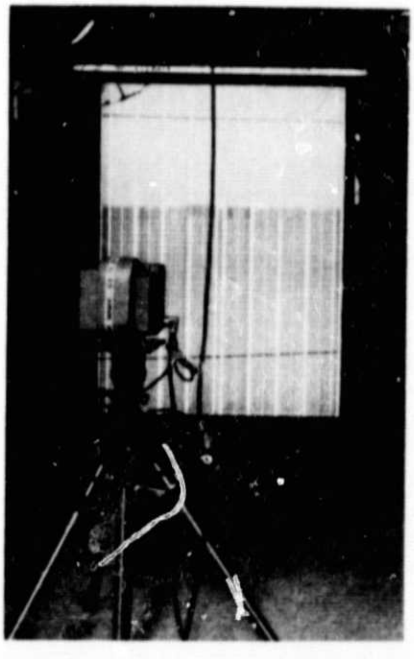

Figure 1

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At the beginning of the 1950's, jet propulsion, rocket propulsion vehicles and air foil testing spirited the perfection of strain gage transducers (resistance elements). These transducers were employed in ingenious devices for measuring pressures and forces. Since the output of a strain gage is an analog voltage proportional to the resistance change, recording and display devices such as oscillographs, oscilloscopes and strip chart recorders were added to the growing number of instruments used in aeronautical vehicle testing. Further, since these transducers were small, larger numbers were used in each experiment. This further increased the complexity of data gathering and processing as well as the cost for each experiment.

By the middle of the 1950's, the increase in jet, rocket vehicle as well as air foil testing placed a great demand for measuring more parameters with a higher degree of accuracy. There was also a demand for faster processing of data, and for consolidating the data on various media to one common data base. These needs, gave rise to the era of automatic digital data gathering systems, and were the beginning of the revolution in data collection. Up to this point in time, improvements in measurement technology and data collection systems were slow in maturing. However, during the next fifteen years advances in device technology permitted vast improvements in data collection systems.

Automatic digital data acquisition systems emerged by 1958, as transducers were mounted on the model and peripheral instrumentation was added for monitoring special tunnel parameters. The basic elements of data gathering systems of this period were: (1) a conditioning element consisting of a number of presample filters and amplifiers, (2) a measurement element consisting of a stepping switch scanner that scans the output of the amplifiers and sequentially connects each to an analog-to-digital converter (ADC) that converts the analog signal to an equivalent digital value and, (3) a control element that initiated the measurement cycle upon command and recorded the digitized results on IBM cards or paper tape as well as listing the data on keyboard printers. This type of data system is depicted on Figure 2, a block diagram of typical hardwired data acquisition systems of the late 1950's.

Data reduction was performed at a separate computer facility. The computers operated on data from either punch cards or paper tape and provided as results lists of data values. By 1958, some forward thinking institutions hardwired a number of the data gathering systems to the facility's central computer; thereby allowing the computer to bypass the card or paper tape media and to process the data as it was digitized. This was called "on-line processing". The results were transmitted over long lines to a keyboard printer and a plotter used for monitoring computer results. The plotters used were the analog type that had internal logic which converted the computer output to plotter drive signals.

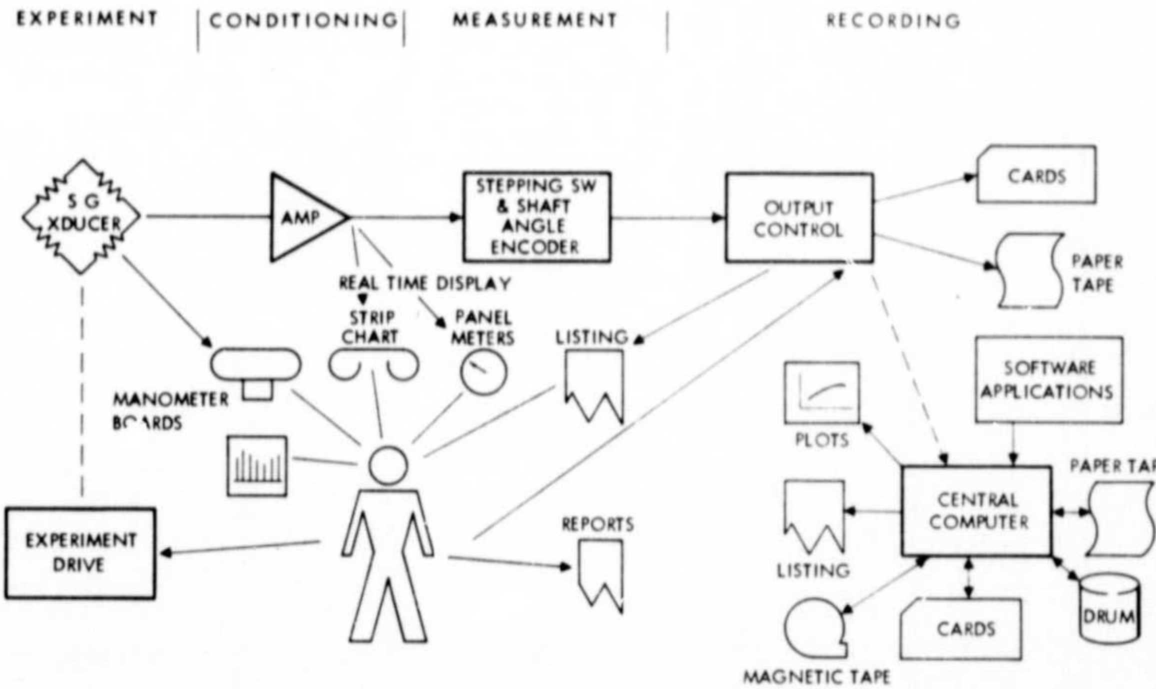

Figure 2

Ames Research Center was one of the many organizations that purchased and implemented a system similar to that depicted on Figure 2. However, the first hardwired link to the central computer was not successful so a paper tape link was used until 1970. The early systems employed one of two commonly used measuring systems; the first was a null balancing potentiometer type using a shaft angle for digitizing, the second was an electronic tube design that used a time varying reference to convert a voltage signal into a proportional time signal. (1)

The data system procured by Ames in the late 1950's for the unitary transonic wind tunnel was a sequential digital recorder made by the Austin Company of New York. A photograph of the Austin System is presented in Figure 3. The system consisted of a program board; a multiplexer composed of a 100 point stepping switch and relay logic; a measuring circuit consisting of a null balance potentiometer and a shaft angle digital converter; and a keyboard printer with the appropriate control and storage logic. A functional block diagram of the Austin System is shown in Figure 4. This system was capable of scanning up to 100 analog voltage sources at a rate of about 4 channels per second. It had the following electrical characteristics:

- Range ± 3mV to ±30mV in 20 steps
- Automatic zero suppression
- Resolution of ±1 part in 10,000
- Accuracy .25% of Full Scale

Figure 3

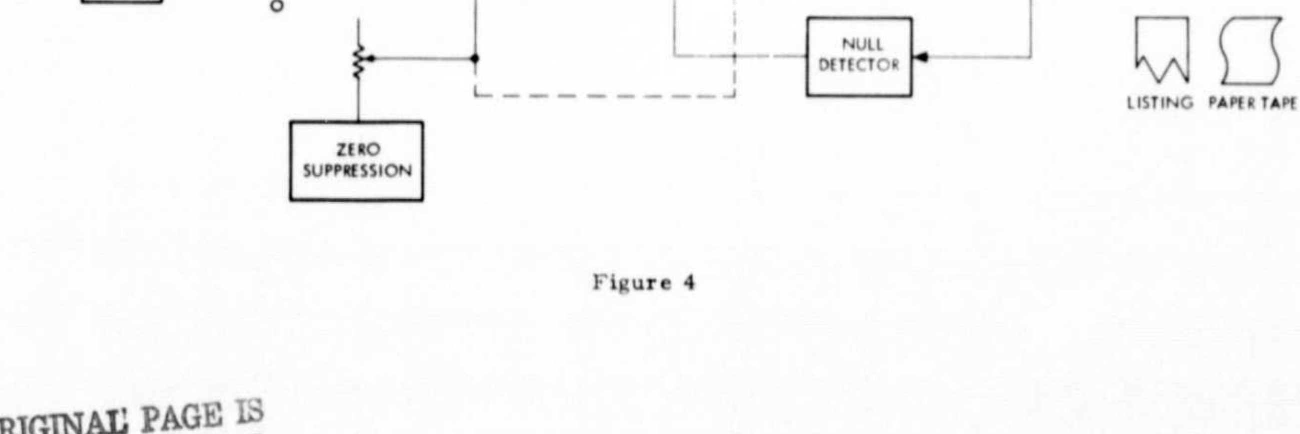

Figure 4

The apparent discrepancy between the accuracy and resolution was justified by the claim that 0.12% Full Scale absolute accuracy was not the goal. However, repeatablity of each measurement was required to about 0.03% Full Scale. This requirement lead to an error budgeting type of hardware specificatior (e.g., the accuracy was specified as DC plus the offset errors, plus linearity errors, plus noise errors, plus digitizing errors). This method of specifying accuracy is a misnomer since it specifies the maximum tolerable errors; in spite of this fact the practice of specifying worst case, root mean square errors or average errors in this way continues to this day.

SYSTEMS OF THE EARLY 1960's

The systems of the early 60's were a large improvement over the hand recordings, photographs, and manual measurement techniques of the 1950's, but they still had major draw-backs. They provided little or no common mode rejection, narrow bandwidth, low slewing rate and they were not reliable. Since these systems were characterized as DC measuring systems, dynamic data (2Hz to about 10Hz) during this period was recorded on oscillographs and later was digitized and reduced off-line.

During the early part of the 1960's (1961 to 1964) research provided advancements in common mode rejection, amplifier slewing rate, matched filter response and grounding techniques. Systems employing all solid state design were appearing in the market place. These first solid state systems used discrete transistors in a number of new circuits. From this time on, the advancements in the semiconductor field forced rapid changes to occur in data gathering systems as well as in the computer industry.

One of the first solid state systems employed by NASA was purchased from Beckman by Langley Research Center. Two years later Ames Research Center procured a similar system (the Beckman 210 System) employing a sophisticated potentiometric amplifier design and a state-of-the-art analog-to-digital converter system made by Packard Bell Corporation.

The High Speed Beckman 210 System was installed in the newly constructed 3.5 Ft. Hypersonic Wind Tunnel (HWT). It was a second generation system whose performance characteristics were tailored to the transducers used in the wind tunnel and to the functional requirements of the experimenter. This system uses an amplifier per channel. It has a 100 channel input capacity (expandable to 400 channels through stepper switches) with a fixed sample rate of 2.5 KSPS. It has 0.01% Full Scale (F.S.) resolution, provides 120 db Common Mode Rejection from DC to 60Hz and provides data accurate to 0.3% F.S. (worst case) across data bandwidths of DC to 10Hz. Its recording media is digital magnetic tape in a blocked/gapped format compatible with the IBM 704 and 7090 Computer. A photograph of the High Speed Beckman 210 System is shown in Figure 5.

Some of the operational features of the

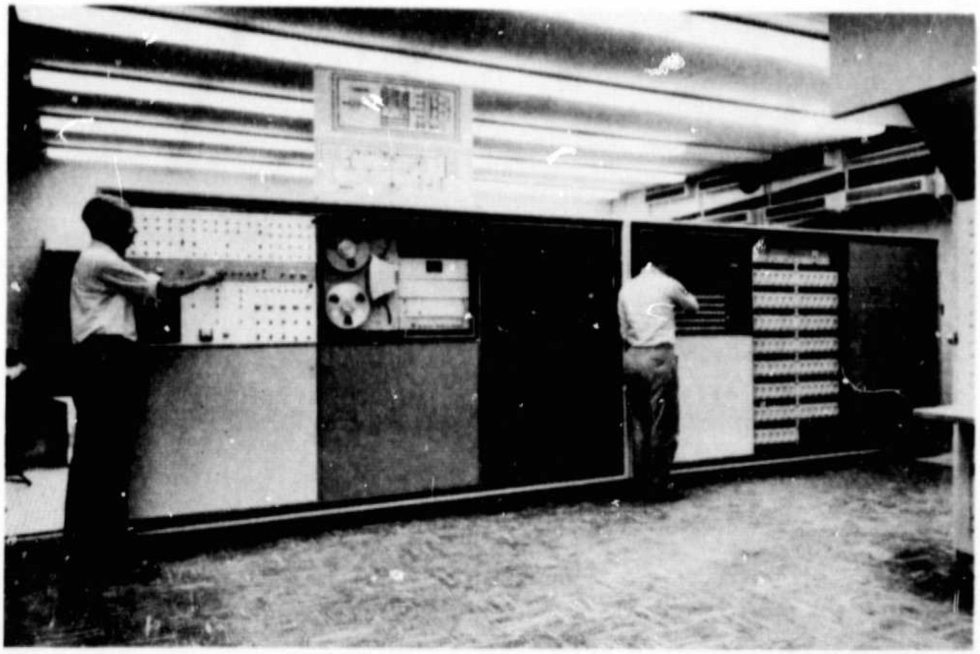

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Figure 5

Beckman System are data display, difference check, limit start, manual start, calibration, error checks, type data and tape playback. A classical display mode is provided where any channel can be selected for continuous data display while the system is recording all data being acquired. The Difference Check feature measures the integrity of the analog front end by verifying the similarities of data on a channel-to-channel comparison. The Difference Check is performed by comparing the first or reference channel to each succeeding channel. Each difference is then compared to a selected digital out-of-tolerance unit value. When an out-of-tolerance occurs an error condition is generated and the data system is halted. This feature is a valuable aid in both maintenance and in real time operation. A simplified block diagram of the Beckman System is presented on Figure 6.

The Limit Start feature starts a data gathering cycle whenever an input function is Equal-To-Or-Less-Than (ETOLT) some predetermined value. This feature is used to complete the loop in a control situation. The Manual Start and Calibrate functions are self-explanatory. In the latter mode, the system automatically checks itself against a known internal standard. This operation is functionally similar to the standardization technique used in counters. The Error Check feature tests the integrity of the digital circuits. In this mode, the system checks for the presence of forbidden digital codes that may be generated during the course of a data gathering cycle. This is essentially a form of parity checking.

The Type mode and Playback mode use an electric typewriter as an output device. In the Type mode, data is transmitted directly to the typewriter for printing. In the Playback mode, data is read from the magnetic tape unit and printed out on the typewriter. Data processing is performed during the Limit and Difference Check mode. The complexity of processing the Beckman System would not be termed processing by today's standards in the light of current computer systems. However, at the time this system was brought on-line, it represented a state-of-the-art system that set trends in the fields of data gathering. Even today, system performance features of the Beckman System are emulated by current data gathering systems.

Another Beckman 210 System was procured and installed in the Unitary Transonic wind tunnels on or about 1964. This system provided a medium speed data recording capability (DC to 2Hz bandwidth). It sampled up to 300 channels of data at a rate of 10 SPS. This system was an offshoot of the Beckman High Speed System and the predecessor of a class of Beckman Systems called DEXTIRS. A photograph and block diagram of the Beckman Medium Speed Data Recorder are shown in Figure 7. This Beckman System had only six (6) amplifiers that were wired to six (6) separate 50-point stepping switches emersed in silicon oil. Each stepper was alternately stepped with the others held stationary, to allow the amplifiers to settle to DC conditions. The procedure was called "leap frogging". Both the High Speed and

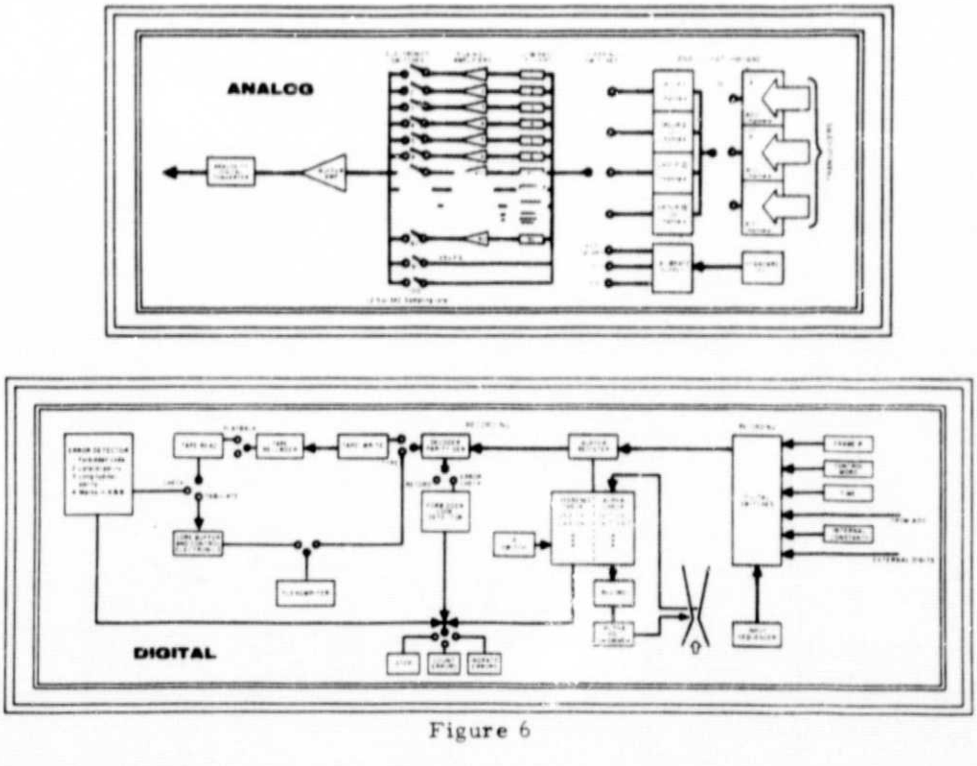

Figure 6

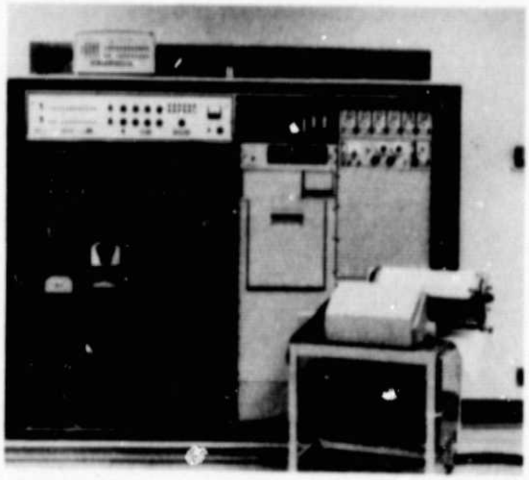

Figure 7a

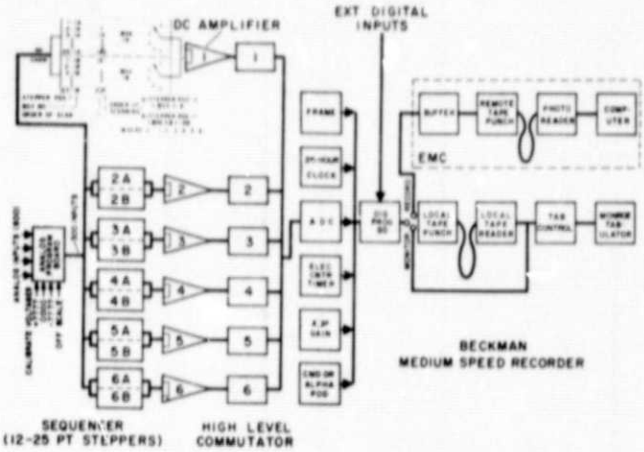

Figure 7b

Medium Speed Beckman systems are representative of the systems in the early 60's.

SYSTEMS OF THE LATE 1960's

About 1964, integrated circuits began to appear in the market place, spurring significant advances in both the data gathering system and the computer system design. The period of 1965 to 1970 was a dynamic period for the electronic industry. Integrated circuits evolved from Resistance Coupled (RTL), to Transistor-Diode Coupled (TTL) logic. Each of these circuit concepts obsoleted the previous development. Integrated circuit technology during this period evolved to Medium Scale Integrated (MSI) and finally to Large Scale Integrated (LSI) logic. Rapid changes in integrated circuits as well as software technology obsoleted systems prematurely (in a period of 5 years or less) and the cost of obsolescence was borne by both the user as well as the manufacturer. The technological advancements in the semiconductor field resulted in lower hardware costs, miniaturization of systems and increased capability.

Concurrent with advances in integrated circuits, the minicomputer (computers costing less than $25,000) (2) started to impact the data gathering and measurement field. Minicomputers represented in inexpensive source of logic that permitted data sampling and routing between the central processor and a number of peripheral units such as magnetic tape units, line printers and keyboard entries. The early minicomputer data systems were plagued with hardware failures and they lacked software to support many of the peripherals such as Analog-to-Digital Converters (ADC's), discs, plotters, CRT's, etc., needed to enhance data gathering and processing. They were generally limited to memory size, due to the high cost of the memory. This forced system manufacturers or users to write efficient machine language programs so as to conserve expensive core memory. In spite of these limitations, the minicomputers represent d a cost effective logic element when a number of peripheral units were required. The cost of minicomputer systems normally exceeded $50,000, which generally became the dividing line for computer operated data gathering systems during this early period. Ground based systems costing more than $50,000 were generally implemented with minicomputers while systems costing less were implemented with hardwired controllers.

The advent of minicomputers provided the system manufacturers with the capability of replacing the hardware controller of the data acquisition system with a small computer system or a large scale computer system. This had the net effect of dividing the computer industries into two camps; those who supported a "dedicated minicomputer" for each data acquisition system and those who supported the "big computer" system that would service a number of user applications. By 1968, there was a proliferation of minicomputer manufacturers whose main interest was in selling hardware. They dazzled the user community by publishing many detail hardware performance specifications, suppressing the deficiencies in the system software and idealizing the potentials of a computer system.

The user community, on the other hand, wanted data systems that would have the operational simplicity of the hardwired system, the computing power of the big computer and advertized cost of the minicomputer system. In short, the data gathering community wanted a single system capable of gathering and processing data over the entire spectrum of interest.

The industry responded to user and economic pressures of the times and proceeded to develop data systems with three basic architectures; (1) the hardware (logic) controlled data system, (2) the minicomputer operated data system and (3) the big computer operated data system. The hardware controlled systems employed signal conditioners, a multiplexer and either a conventional (successive approximating type) analog-to-digital converter or the Integrating Digital Volt Meter (IDVM). The latter system found wide spread use in the user community interested in static measurements because of its greater resolution and lower noise susceptability.

Hardware Controlled Data Systems - The hardware controlled IDVM data systems were configured with electromechanical multiplexers; i.e., a stepping switch, reed relay or cross-bar scanner connected to the guarded input of the IDVM. The output of the IDVM was connected to a control unit that interfaced to any one of a number of peripheral controllers such as paper tape or magnetic tape. IDVM systems were pioneered by VIDAR and Hewlett-Packard (HP). They were a great improvement over the systems of the early 1960's because the IDVM's perform pure integration in real time, making them ideal for applications having noisy environments. Since integration takes time, and the scanning rate was slow, systems were implemented with inexpensive electromechanical scanners, which reduced the system cost per channel. The IDVM type of data systems are characterized by their high common mode rejection (140db), high resolution (0.01% F.S.), high accuracy (0.01%) and large channel measuring capacity (up to 2000 channels with slave scanners). In addition, these systems had manually programmable integration periods (by program board) and automatic gain control. Further, the slow data processing speeds of the IDVM and the stepping switch scanners made these systems ideally suited for use as analog linkages to minicomputer and large central computer systems. A photograph of a Vidar IDVM system used in the Ames calibration laboratory is shown on Figure 8.

Minicomputer Operated Data Systems - The second data gathering system architecture used a dedicated minicomputer to provide all the logic necessary to operate the analog linkage system as well as to output to recording devices. The analog system varied from the simple electromechanical scanners connected to separate IDVMS up to sophisticated Amplifier/Filter/Sample-and-Hold per channel data systems with solid state multiplexers coupled to high speed analog-to-digital converters. Sampling rates ranged from 40 SPS for the former to 20,000 SPS for the latter. In addition, these data systems provided real time control of the linkage system controlling gain, integration period, automatic calibration, random selection of channels and measurement functions such as ohms, frequency, voltage, etc.

It was during this period that the user showed increased interest in digitally acquiring dynamic data that was previously acquired through FM analog recording techniques. The user community representing helicopter interests wanted to acquire data having a frequency spectrum from DC to 100Hz. Some members of the space science community wanted to acquire data in a closed loop control mode having a frequency spectrum from DC to 50Hz. On the other hand, the life science community wanted to conduct several experiments at the same time. The needs of the user community at Ames were broad, and therefore, a

Figure 8

number of systems were implemented during the late 60's. A photograph of Ames' first minicomputer operated data acquisition system, driven by a Digital Equipment Corp. Model PDP-5 is shown on Figure 9.

Large Computer Data Systems - The third approach to the data gathering, "the big computer" approach was based on time sharing a large scale computer data processing center with the user community. The large scale computer system was not cost effective when used as a dedicated data gathering system. The payback on a large scale computer system would have to be in the order of a million dollars or more per year for a five to six year period. Therefore, the large scale computer approach to data gathering was to service several wind tunnel facilities on a time share mode. This approach received much greater support by the user community when the naked minicomputer concept was advanced in about 1968 (3). The naked minicomputer concept advanced the idea that a "smart" terminal capable of data gathering linkages could be designed with a minimum instruction set consisting of the following:

- FETCH
- STORE
- INPUT
- OUTPUT
- BRANCH ON ZERO
- BRANCH ON NOT ZERO
- UNCONDITIONAL BRANCH
- BRANCH AND SAVE
- RETURN

In addition, the naked mini would be configured with sufficient memory to store the required number of scans of data prior to transmitting it to the central data processor. This approach showed great promise and as a result, a number of controllers appeared on the market such as the IBM 2780X. About 1970 IBM introduced the System 7 which was designed around the naked mini concept. The philosophy at Ames during this period was to time share the Central Data Processing Center with both the wind tunnel community and the research community at large. As illustrated in Figure 10, a system consisting of Duplex IBM 360-67's were connected to the wind tunnel data gathering units via the data communications unit (composed of a naked mini and a keyboard entry unit). This approach to data gathering was initially attractive to the data user because a large scale computer with powerful operating system software, virtually unlimited memory, and a wide variety of peripherals were made available under his command. The large scale computer system provides more accurate reduced data than a dedicated minicomputer presently provides. It has better editing and reporting facilities and interfaces to the user through a high level language that is easier to understand than machine code. It has a further advantage in that a single vendor can maintain the software and hardware, which is becoming increasingly important with current

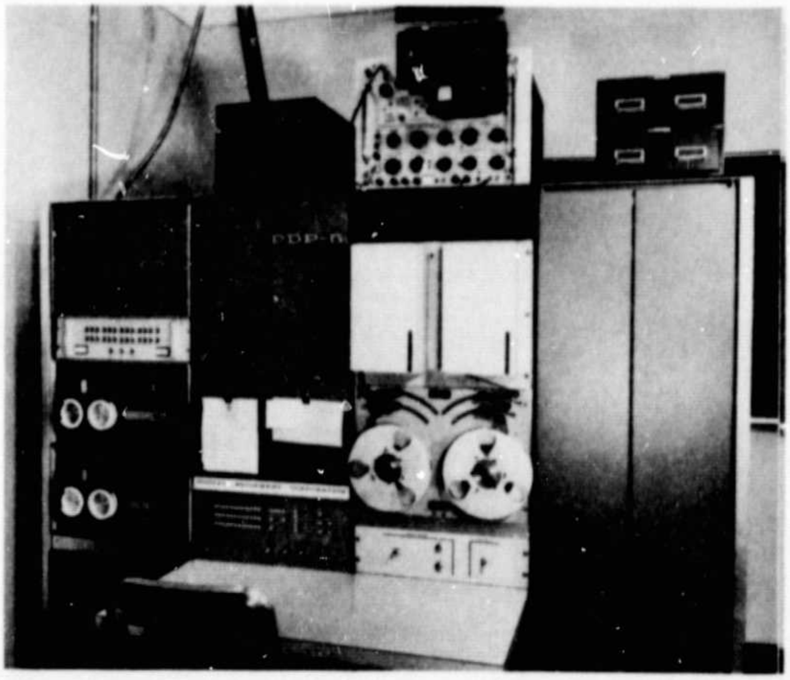

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Figure 9

systems.

There are some major disadvantages to the large scale computer approach to data gathering and real time processing which are a result of the time sharing software systems used to implement them. The Time Share systems are complicated, and therefore are usually operated and maintained by a separate organization other than the data users. Furthermore, complications result from the need for user interaction with the system, which occurs from day-to-day (or from test-to-test). The following is a list of some of the major objections to a large scale computer system functioning in the data acquisition mode:

1. System response to user demands are long on the average.
2. Frequent system down times are experienced as a result of unpredictable user demands.
3. New data acquisition and processing programs and program changes are costly and difficult to implement.
4. System operating costs are higher than those of a distributed system.
5. The large scale computer adds nothing to the accuracy of the acquired data.
6. The system is limited to real time processing of static data and limited control functions.
7. The user is isolated from the process used to obtain the final results.

The response time of a Time Share system is a function of the demands placed on the system by the entire user community having access to the central computer, the computer hardware complement, the operating system software, the priorities of each user and a number of other conditions. However, the effective cycle time on a per user basis is statistical in nature, and depends on community activity, software overhead, and the program that the computer is executing for a given user. In an unconstrained user system (where satisfying the largest user community is most important) the on-line response time can vary from 10 seconds to greater than a few minutes. Even when the priorities of a certain user are high, such as those that might be given to wind tunnels, the system response times can be intolerable when it comes to making real time or near real time decisions. Figure 11 are histograms correlating predicted response to Ames' Time Sharing System, the actual response of Ames' Time Sharing System and the actual response of an older dedicated computer system. These histograms show that the actual performance of a time shared central computer system, an order or two of magnitude more sophisticated than its predecessor, provided less user capacity than predicted and thus lower performance than the dedicated computer it was to replace.

Frequent system down times occur in a Time Share system, since any user can, at times, cause the system to be overloaded. The effects of

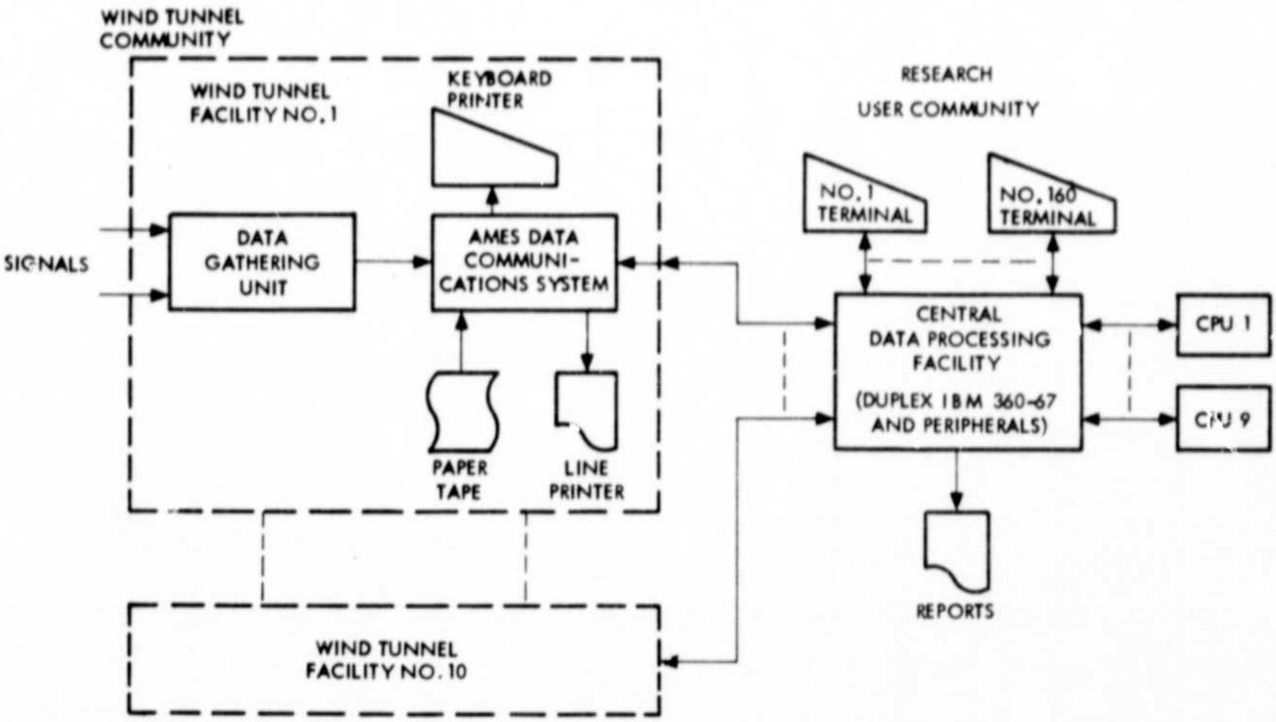

Figure 10

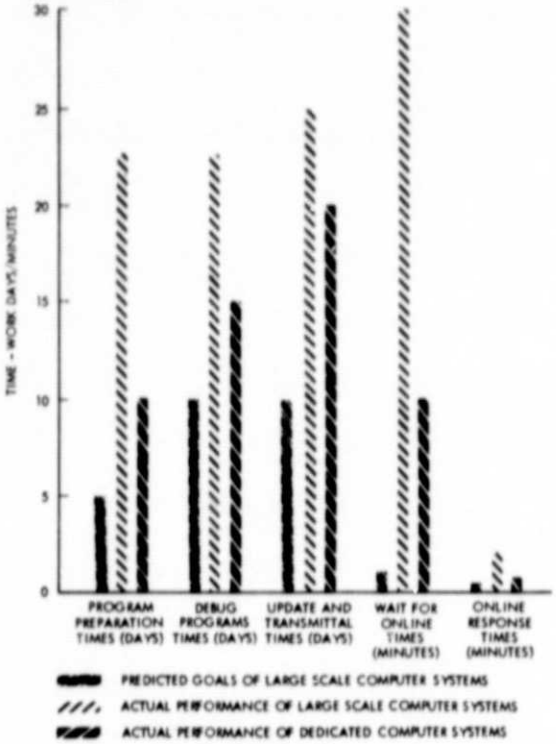

Figure 11

the changing dynamic environment of the central computer as a result of unpredictable user demands add a degree of unreliability to this system's concept. System software changes, that are instituted by the computer operations organization in order to improve the system response, may and can impact other users who were not the direct cause of the change. This, on the average, appears to the user as a random system failure and results as user down time even though the system may be considered to be operating by those charged with system operation responsibilities.

New software programs and program changes can require from weeks to several months of lead time for implementation while debugging these new programs can take an additional month or two. As a result, each new software change must be planned months in advance. This type of planning is difficult as program changes usually involve new ways to display either the raw data, and/or the test results. Planning is further compounded by some additional last minute requirement for calculation of special tunnel parameters. Since the calculation algorithms are usually integrated with the data gathering and control function, the whole data acquisition program must be debugged in order to determine the interactions of the program changes. This causes long software debug times and prevents the fast turn-around time needed by the data user. In addition, the resulting program is in a continuous state of change and, therefore never completely checked out. Programs of this type, that integrate well defined data acquisition requirements with the changing data display requirements of a specific test, usually are translated to unreliable system operation.

System operating costs per hour of large computers are high because of the large capital investment, the manpower required to maintain and operate the computer system and the inefficiency introduced by the overhead software. The penalty of overhead software is inescapable as it results from housekeeping software necessary to service a large user community. The per user price performance ratio of a large computer system is low in comparison to that of a dedicated computer approach. Large Time Share computers have a relatively slow per user response, time on the average which as previously mentioned, is statistical in nature, preventing the user community from acquiring and processing dynamic data in real time. Most Time Share computer data gathering systems were connected to remote data gathering units through voice grade telephone lines having data transfer rates of 2400 to 9600 bits per second (200 to 800 12-bit words/second or 100 to 400 bytes/second). A photograph of the Ames Synchronous Data Communications System Terminal is presented on Figure 12. Aerodynamic stability, flutter and vibration control tests require data rates that exceed 50,000 bytes per second (25,000 WPS) and block sizes of about 500,000 bytes (250,000 words) for a single snapshot recording of the event of interest. Therefore, a 5 minute response time would require transmission rate of 20,000 bits per second. A one minute response time is too long for dynamic

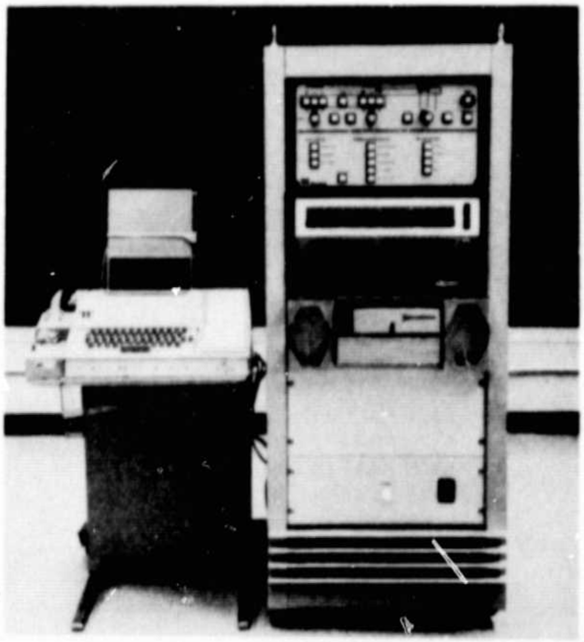

Figure 12

testing which corresponds to a data transmission rate requirement of greater than 60,000 bits per second. For these reasons real time dynamic data gathering has required a dedicated computer approach.

Finally, large computer systems isolate the data user from the processing algorithm. These systems are complicated and require specialized personnel in the field of programming and computer sciences to implement some of the special data processing algorithms. Normal errors in communications between the experimenter and the programmer usually result in programmer innovations caused by a communication gap. The wide span of disciplines between the fields of computer science and the aerodynamic experimenter widen the communications gap between the programmer and the experimenter and the process for computing final results. As a result, the wind tunnel experimenter's support for Time Sharing a large scale computer with the user community at large dwindled. Conversely, the functional capabilities of the large computer systems has continued to set the standards for the dedicated minicomputers used in real time data gathering systems.

The period between 1968 and the early 1970's brought about dramatic changes in real time operating software systems, computing power, and the number and types of low cost peripherals. During this period the experimenters real time requirements continued to expand. The minicomputer continued to encroach on the domain of the large scale computer. Special low cost hardware options such as Floating Point Processors and Fast Fourier Transform Processors gave the minicomputer the capability of performing single and double precision calculations, auto- and cross correlation, spectrum analyses and other correlation functions.

SYSTEMS OF THE EARLY 1970's

The hardware performance characteristics of the minicomputers stirred the imagination of the user as well as the data gathering systems designer. By 1972 the performance characteristics of the minicomputers exceeded some of the performance characteristics of the IBM-360/50. This period (1970 to 1972) was the beginning of the big minicomputer. The wind tunnel experimenter community at Ames saw these minicomputers (at lower prices) as the answer to their data gathering and processing needs as well as the vehicle for deliverance from the problems of the large computer system.

Data gathering and control systems employing minicomputers prior to 1970 were limited in computing power (16 bit single precision), core capacity, operating software and the availability of low cost peripherals. Sixteen bit resolution met the data gathering requirements but fell short of the computing needs for data processing in wind tunnel testing. In the scientific field, floating point calculations were desired. If software floating point routines were used, the throughput rate (input to computed results) was reduced by an order of magnitude. Systems prior to 1970 lacked good operating software and this combined with limited memory compounded the programming efforts. The lack of off-the-shelf software was a major limitation and its development for the data user proved to be a major expense to both the manufacturer of computer data gathering systems and the user of such systems. Software development costs increased with increasing inflation. As the user data system grew to meet new requirements, the software needed to meet those new requirements in heavily utilized minicomputer systems had to be more efficient. Overlays and virtual memory techniques were and are currently used to extend memory. These latter techniques introduce other problems such as time constraints due to inefficiency, and unreliability due to the noisy wind tunnel environment destroying the overlay process. B. W. Boeham (4) addresses this problem in his paper, "Software and Its Impact, Quantative Assessment".

Figure 13 is a graph showing the variation in the percentage of the total system cost attributed to hardware and that attributed to the software (projected to 1985). This curve was based on a study made by the Air Force on several large computer systems. The significant conclusions which may be drawn from this data are that hardware

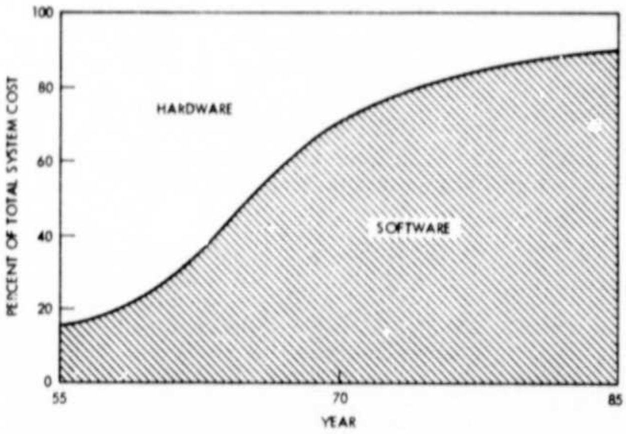

Figure 13

costs are decreasing with the years while the software costs are increasing, and that the hardware costs of the current system are becoming a smaller percentage of the total system costs (Note: These cost figures are not normalized by the inflationary rate). Figure 14 illustrates the impact of software cost on a system with varying degrees of utilization. The curve indicates that the cost of programming increases exponentially as the system capabilities approach full utilization, also implying that a capable programmer reaches programming difficulty at higher utilization than less capable programmers.

Another factor which impacts the current and future costs of the computer controlled data gathering system is the price of installed memory. Installed core memory costs have decreased from $2.50 per byte in 1967 to $0.25 per byte in 1975. This represents more than a ten fold decrease over an eight year period (because they have gone down while inflation drove labor costs upward). Along with these trends of core memory costs, the costs for semiconductor memories have taken even a steeper decline in cost/byte over the recent years. The resultant message presented to the user of a computer controlled data system is:

1. That those computer controlled data systems that exceed about 75% utilization of the CPU and memory will, on the average, cost the user more to program and may not be capable of performing new tasks.
2. That increasing the memory size of heavily utilized systems can significantly decrease the cost of system operation and application program software development.
3. That the user should procure data gathering systems that initially make minimum use of CPU and memory so that unknowns can be accommodated.
4. That the user should shop around for a minicomputer controlled data gathering system that has high performance characteristics and the largest memory expansion capabilities.

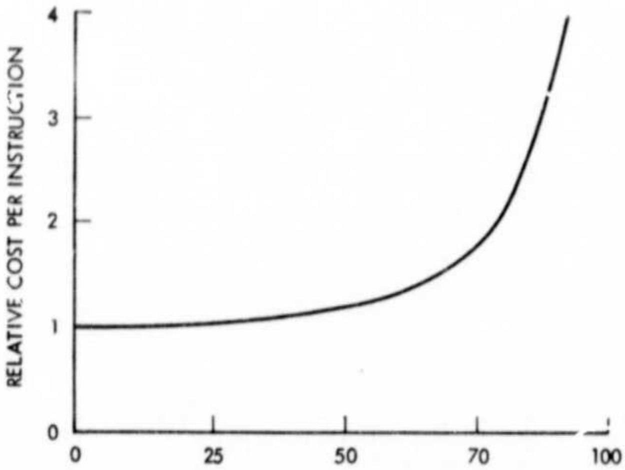

Figure 14

The computer and system manufacturers response to the users requirements, to a large extent, has produced systems designed to have memory expansion capabilities that exceed the addressing ability of the 16 bit word. This memory expansion must operate efficiently and wherever possible, microprocessor and firmware implementation of specific system functions must be used to produce a cost effective system. To this end, distributed computer controlled data systems can be a cost effective and efficient approach to the solution of the data gathering, real time process and control requirements of the experimenter.

Current minicomputers used in data gathering systems provide a definite advantage over previous minicomputer system approaches. Part of these advantages result from technological breakthroughs in computer architecture and part through the evolution of the data gathering system architecture. It is not uncommon, today, to see minicomputers with cache memory, memory capacity of greater than 128K words and systems with a large number of peripherals all of which could only be found in the larger central computer system a few years ago. Some of the major advantages of the more powerful minicomputer systems to the user community are:

1. Low cost performance and modular expandability.
2. Real time control and data processing.
3. Fast computer response times.
4. Systems tailored to the individual task requirements.
5. Systems which are easier to understand and operate.
6. A single system that satisfies a major part of the user data gathering requirements.

Big computer performance for minicomputer prices is a challenge which the minicomputer industry has undertaken while making a deep thrust into the field of data gathering and real time processing. At the present, the minicomputers have a stranglehold in the real time systems. Big computer performance is emulated through the use of high speed peripherals, fast cycle response, cache memory and virtual memory as well as increased memory response. One can equate data gathering capability to the ability of the system to do that extra job beyond the original design criteria. A quantitative estimate of computer capability when normalized to one could be expressed as excess capacity shown mathematically by Equation 1:

$$\text{Capability} \approx (1 - \rho) \qquad \text{Equation 1}$$

where: ρ equates to the data gathering system utilization

In a time sharing or multitasking system, the system utilization is given by Equation 2:

$$\rho = \sum_{n=1}^{N} (\rho_n + \rho_o) \qquad \text{Equation 2}$$

where: N = the number of users currently using the system
ρ_n = the fraction of the system utilization given to User N
ρ_o = the system overhead required to service N users (a fraction of the utilization)

In a time share system where each user is given an equal portion of the system ρ_n is given by Equation 3:

$$\rho_i = \frac{\rho}{N} \qquad \text{Equation 3}$$

But the utilization of any computer data gathering system is a function of its resources. The computer resources are:

1. K_tT = Effective instruction time. ∴ T is the memory cycle time, and K_t is a multiplying factor.
2. K_mM = Maximum computer memory size where K_m is a function of the computer design.
3. K_aA = Type of CPU Arithmetic Unit.
4. P = Type of peripherals.
5. B = Input/Output Bandwidth B which is in terms of total words transferred between user N and the CPU and peripherals.
6. R = The Real Time Operating System.
7. A_{lc} = The analog linkage unit and conditioning.

System utilization quantatively stated is given by Equation 4:

$$\rho \cong kXf\,(K_tT,\ K_mM,\ K_aA,\ B,\ P,\ R,\ A_{lc}) \qquad \text{Equation 4}$$

Some of the terms of equation 4 interact with each other. For example, the terms K_tT, B and A_{lc} all are affected by the number and speed of data paths. Bandwidth B is affected by the memory cycle time as well as the maximum sampling rate of the analog linkage and conditioning unit (A_{lc}). The maximum memory size K_mM and the real time operating system R interact with each other. For example, if the memory size is small, a severe constraint is placed on the operating system features. If the memory is too large, then the operating system becomes very complex because in order to service the large memory the memory addressing requirements are increased in size.

Theoretical examples of systems such as single servers and multiple servers utilizing first-in first-out algorithm has been investigated by James Martin (5). Figure 15 are plots of relative response time (including wait and service time) plotted against capability (C) instead of utilization for a single server-system with a first-in first-out algorithm as the servicing rule. These curves state that for systems with low capability (0.1) the response times can be as high as 10 times the average. The parameters that affect this capability are those that affect utilization.

Those parameters that the current minicomputers have impacted are memory clock time (T), arithmetic units (A), memory (M), peripherals (P) and analog linkage and conditioning (A_{lc}). For example, memory having a 330 nanosecond cycle time, coupled to a 32-bit single precision (64-bit double precision) floating point processor with 300KSPS sampling rates for the A_{lc} are common

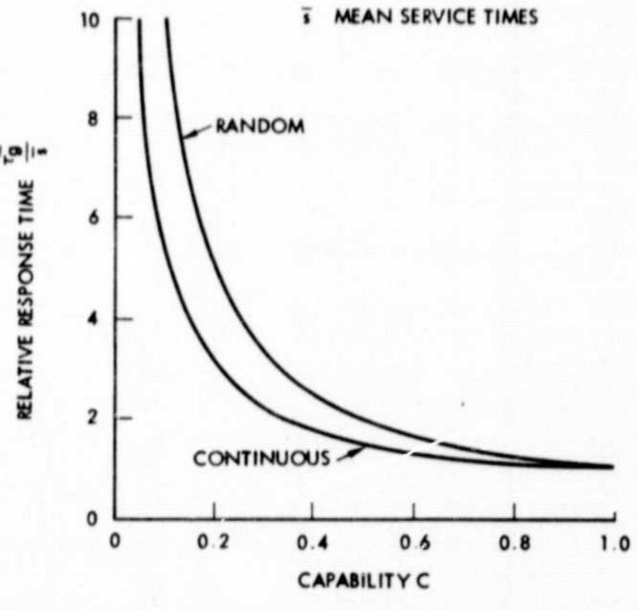

Figure 15

features in minicomputer systems today. Large mass storage devices such as 40 megaword discs are also available for minicomputers. Strongholds, which still remain to be impacted are operating systems and system bandwidths. However, it is safe to predict a significant effort will be made to improve real time operating systems in the future. The system bandwidths depend on a number of items which include data paths and data path widths as well as I/O bus and memory cycle time. For example, multiport memory and discs effectively increase the data paths. Some minicomputers like the PDP-11/70 have memory data widths of 32 bits from several peripherals. The capability per user, that is the Effective Capacity (C_E) is given in Equation 5:

$$C_E = \frac{C}{N} \approx \frac{1-f\,(K_t T,\ K_m M,\ A,\ B,\ P,\ R,\ A_{lc})}{N}$$

In a large scale computer where the capability can be (for example) 1000 times that of minicomputer system the Effective Capacity can be reduced measurably by the number of jobs and design limitations. On the other hand, the capability of minicomputer systems can be increased dramatically by adding another computer subsystem and operating both in a distributed system configuration. The effect is to provide, increased memory capacity and greater bandwidth, resulting in increased capacity for each computer on the average. As capacity decreases, so does the response time to service a user, therefore, it can be seen that the minicomputer is only small in terms of price. It is obvious from Equation 5, that a large computer has a low effective capacity when a large number of users are being serviced, and under these circumstances the large computer exhibits a narrow bandwidth. Real time processing, however, requires wide bandwidths, which in many instances can only be provided by a dedicated computer, or a large scale computer that is underutilized. Another term in real time control and data processing is the power of a computer. L. L. Constantine (6) defined the power of a computer "R" in 1968, as "the processing capability per second divided by the processing requirements per event". Since that time several of the parameters that were used to compute power which included; data paths, data widths, cycle time, instruction set, and types of process, have shown significant improvements. Computer power relates to the ability of process and control functions in real time. Dedicated computer systems can be tailored to the task desired and in some cases, because of the low costs of minicomputers, each task can warrant a standalone computer system. Under these conditions a computer complex can be designed so that each special function is implemented very simply in hardware and software. Examples of these types of systems are the Dynamic Analysis or On-Board Systems of the 40' x 80' wind tunnel complex described later in this paper.

Instrumentation in early years of operation of the 40' x 80' wind tunnel had consisted of a number of small special purpose systems that performed both the dynamic and the static data gathering requirements. The basic requirements of the tunnel were a need for:

- Data Gathering
- Real Time Monitoring - Quick Look of Dynamic Testing
- Data Recovery From Analog Magnetic Tape

In most wind tunnels the user needs a quick look capability where he selects the conditions that he wants and records data. He essentially takes a snapshot of the model conditions and processes this data in real time or near real time. The affect is real time data selection resulting in a reduction of the total data recorded. The system is easy for the user to understand because once the system is set up all the user is required to do is to actuate the record button for the next data picture. The complex provides a single distributed system to perform all the functions. The turnaround time for reporting results can be effectively reduced through the use of special purpose standalone systems, as illustrated by the TMX Report written by Wayne Johnson and Jim Biggers (7) of Ames. A test was conducted in the 40' x 80' Wind Tunnel consisting of random vibration applied to the model with real time data processing performed by the Dynamic Analysis System. The results were displayed in near real time on a CRT and photographed within a few seconds after the data was taken. During this test raw back-up data was recorded on the Wind Tunnel's Dynamic Recording System. All required data was gathered and a test report was published within a one month period.

DISTRIBUTED SYSTEMS OF THE 40' x 80' WIND TUNNEL (1975)

In the latter part of the 1960's Ames recognized the shortcomings of the central computer facility in servicing both wind tunnel facilities and the research user community. The data acquisition system designed for the 40' x 80' wind tunnel as shown in block diagram form on Figure 16 is a distributed, computer controlled system using a medium sized computer as a Master Computer (8). The complete wind tunnel system is composed of six (6) subsystems, five of which interface with the master computer (a unidirectional data path) and three with bidirectional paths which may be controlled by the master computer. Two of these three subsystems; the Dynamic Analysis System, and the On-Board System in turn used minicomputers for subsystem control and communications

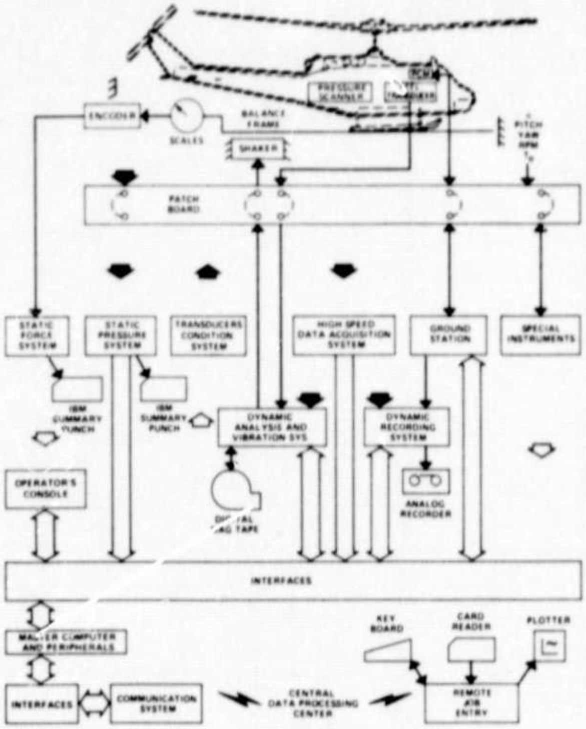

Figure 16

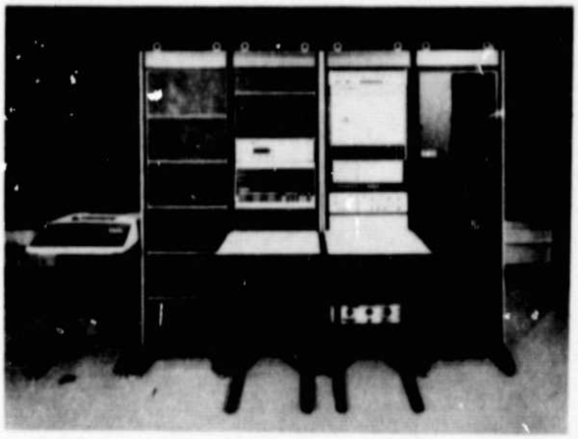

Figure 17

with the master computer. The Dynamic Analysis System processes up to 32 channels of wideband data performing histograms, autocorrelation, cross correlation, impulse responses, Fourier transforms, autospectrums, cross spectrums and can linearly or exponentially average up to 51,200 samples of data displaying the results on a CRT terminal, X-Y Plotter or a printer. The On-Board system monitors the majority of the parameters in the model and architecturally departs from the classical computer operated data systems produced by the minicomputer industry. A photograph and block diagram of the Dynamic Analysis System are presented on Figure 17 and 18 respectively.

NOTE: In an attempt to differentiate the dramatically different architectures between Data Acquisition Systems incorporating minicomputers the authors present the following definitions:

1. A COMPUTER OPERATED DATA SYSTEM is one that uses the CPU's memory for data point address storage and for routing of data to peripheral devices. The computer must be programmed so that the equal time interval equivalency of a hardware timed PCM system is achieved for moving data addresses and data via the CPU's bus system.
2. A COMPUTER CONTROLLED Data System is a multiple bus system that only uses the

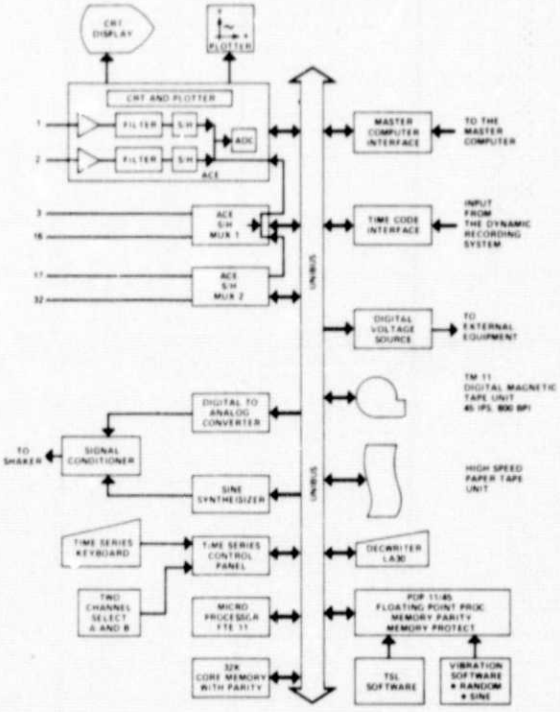

Figure 18

computer to initialize system operation under software control. Once acquisition and routing of data to peripheral destinations is started, the computer only services Data Acquisition Unit failure interrupts leaving it free to perform real time data processing (the computer can be halted without interrupting the data acquisition/ display operation). This type of system has multiple data paths.

Under these definitions the 40' x 80' wind tunnel's On-Board system is an example of a Computer Controlled data system providing a great degree of modular configuration flexibility without systems design modifications. The On-Board System (OBS) developed for Ames by Teledyne Controls provides many features suitable to the user requirements of the 40' x 80' wind tunnel not available from classical instrumentation systems. Significant performance characteristics include:

1. Remote multiplexing with integral signal conditioning and transducer power supplies dramatically reducing sensor cable lengths (and costs) and system noise.
2. An autoranging gain programmable amplifier in the Remote Multiplexer/Demultiplexer Unit (RMDU) which saves data which would be lost due to full scale signal limiting if the model gets out of control or if signal scale factors are understated by the experimenter during system programming.
3. A sophisticated built-in calibration/self-test data cycle capability for dynamic calibration without opening sensor lines (and for remote troubleshooting and diagnosis).
4. Over 2400 linearly programmable sampling rates (50 WPS increments) which permits the user to optimize data bandwidths and reduce the amount of tape consumed for history recordings of a test.
5. A high degree of operations reliability since system can acquire and record (and display) data even though any peripheral device fails, including the computer.
6. A system architecture in both hardware and software where the computer power may be upgraded and the peripheral complement changed by Ames at any future time without system design changes or existing hardware/ software obsolescense.
7. Remote unit architecture which permits instant changeover from ground station control to a firmware controlled IRIG PCM system so the models may be free flight tested with the same data system used when the model is flown in the wind tunnel.
8. A bi-directional data processing architecture in the RMDU which permits it to be included as part of a command/control loop as well as providing the classical data acquisition function.

Due to the wide variety of tests that are performed on a model in the wind tunnel, and the wide spectrum of models tested, OBS must have the ability to readily change data sampling formats (sampling rates), change the display of selected parameters, gather data from multiple sources and operate as a slave or standalone system. These are the typical requirements of current data gathering systems.

The OBS is essentially divided into two major types of hardware; (1) a rack mounted Data Management/Display Subsystem (DMDS) for benign ground based environments and (2) the ruggedized (MIL-E-5400M) RMDU's suitable for the harsh environment of high performance military and research aircraft. Figure 19 is a photograph of the ground station installed in the wind tunnel control room, the miniaturized airborne RMDU's which are installed in the model, and a portable test set for RMDU operation without the DMDS.

The Data Management and Display Subsystem can be operated as a slave to a master computer or as a standalone data system receiving instructions from an operator via data terminal/ keyboard inputs. It is capable of controlling the acquisition of data from up to 27 RMDU's, providing data point capacity in excess of 10,000 channels at software selectable word rates of 250 to 125,000 words per second in increments of 50 words per second. As shown on Figure 20, a block diagram of the OBS, acquired data can be distributed in real time to the master computer, to a bar graph CRT display (up to 128 data points), to a strip chart recorder (up to 32 data points), to one or both of two analog magnetic tape recorders (BIØ-L or DM-M format) or to the DMDS's minicomputer for data processing in real time.

The DMDS can be utilized as a "quick-look" playback facility for preprocessing and display of data previously recorded on magnetic tapes in any of the standard IRIG PCM formats. Initialization information consists of the remote acquisition unit identifier and data point address (card and channel), amplifier gain for each analog channel, each data points required sampling rate and the desired data output (peripheral) destination requirements. This information may be entered locally via punched paper tape or from the master computer. Resident software generates a "master sampling format" with sub-commutation and super-commutation as required. Embedded within the master data cycle are the minor data cycle sampling formats for the individual recorder outputs, complete with software controllable frame synchronization patterns. Conversion of the DMDS from the data acquisition

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Figure 19

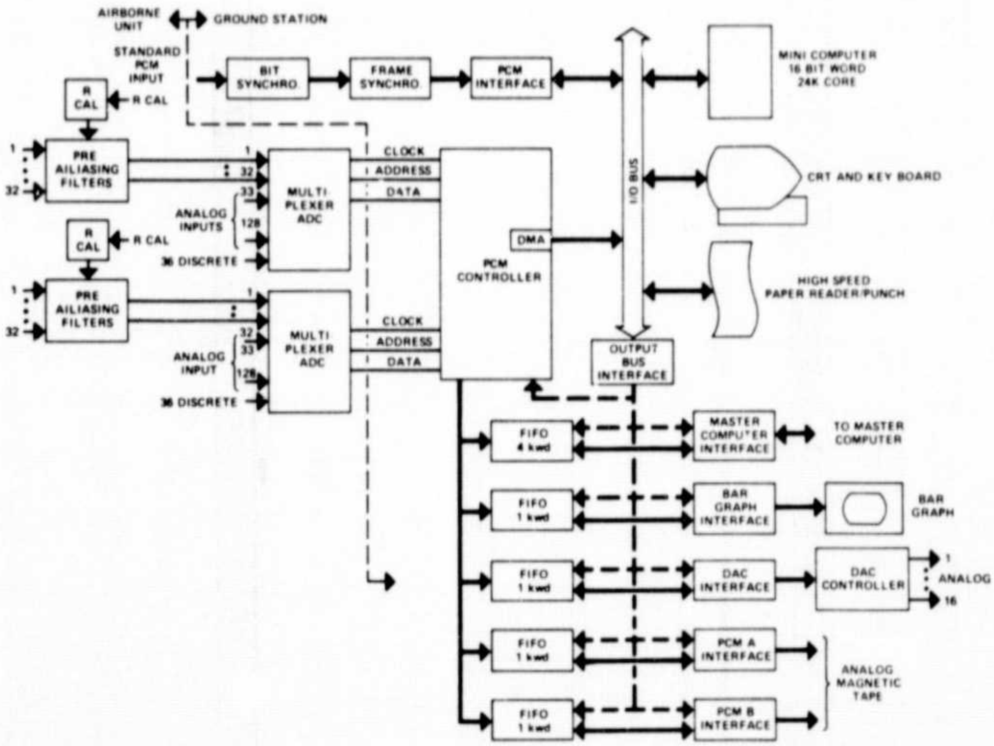

Figure 20

mode to the data playback or data reduction mode can be performed dynamically under interrupt control.

The OBS has two basic modes of system operation; (1) On-Line and (2) Off-Line. In the On-Line mode the DMDS is slaved to the master computer. As a standalone data system in Off-Line mode all machine functions are controlled locally by an operator through an interactive CRT terminal. In either mode of operation, the DMDS controls the acquisition of data from the RMDU(s) or other (foreign) PCM systems in the model and outputs the acquired data to any one (or to all) of six output devices. All key system parameters are under software control of the DMDS's minicomputer. The storage medium for the data acquisition sampling format is a 4096 word x 18 bit semiconductor random access format memory (with parity), while the main memory for the CPU consists of 28K words x 16 bit core RAM supported by a 1.25 megaword disk system. The format memory can accommodate a single data cycle of approximately 2000 data points or multiple data cycles of smaller size. For future expansion, or to satisfy requirements for increased data cycle sizes, the storage capacity of the format memory can be incrementally expanded to 16K words by the addition of up to four standard 4K word memory modules. When multiple sampling formats are stored in the Format Memory, the DMDS can switch formats in less than 80 microseconds by software command from the minicomputer, thus dynamically changing the system configuration to meet changing test conditions. The key feature here is that the OBS is a computer controlled multiple bus system where the CPU is only used for system initialization and real time processing/control functions. During data acquisition and display the CPU can be halted, turned off, or can fail without affecting the data acquisition process. Conversely, by being under CPU control dynamic changes in system configuration can be implemented during a test. Real time data processing is only limited by the power of the minicomputer. The modular expansion capability of OBS and its multiple bus system give it the wide bandwith necessary to apply it to unforseen tasks which may develop as requirements during its life cycle.

Since Ames Research Center has an investment in existing data acquisition equipment, it was necessary for the DMDS to simultaneously accept data from both RMDU's and existing PCM equipment, which may be installed in the models using any one of the standard IRIG formats. To satisfy requirements for widely varying data acquisition rates, the DMDS can provide a master data cycle for data acquisition with minor data cycles imbedded within the master cycle. It has the capability of delivering either the master data cycle and/or minor data cycles at semi-asynchronous word rates to the various destination devices. Master data cycle flexibility is achieved by a software controllable time base generator in the RMDU controller which incorporates "phase-locked-loops" to synthesize asynchronous frequencies for the word rate generators.

A format generation software system assembles a standard PCM sampling format from initialization data consisting of RMDU address, RMDU card select, channel select, amplifier gain, required sampling rate and data destination and produces punched paper tapes of the format memory contents as an archivable record. The sampling format may be stored in both the CPU's core memory and on the disk. During system initialization it is transferred to the format memory section of the DMDS where it is accessed by the RMDU controller for transmission of data point addresses in serial format to the RMDU's, which may be located up to 250 feet away in the model. Additional information stored in format memory consists of output port destination control information and pointers to the next words to be fetched from format memory. Acquired data is routed to any or all of up to eight destination ports (six are presently mechanized). In addition to the real time displays, data can be routed to two different magnetic tape recorders (or parallel tracks of the same recorder) with individually programmable word rate, word length and bit location controls, to the master computer (block transfer), and/or to the minicomputer for real time computation. Data point information routed to the bar graph and strip chart recorder are displayed in real time, and can be changed by the system operator during a test via the CRT/Keyboard terminal.

Either the master data cycle or minor data cycles (or both) can be directed either or both serial tape recorder ports. Each serial recorder port is a software programmable data formatter and timing subsystem which can be programmed to produce a unique IRIG standard PCM minor data cycle which may, or may not be related to the size of the major data cycle of the RMDU controller. Each serial recorder format controller's minor data cycle, however, is synchronized to the RMDU controller master data cycle by its "end of cycle". Thereby, the common time denominator between the RMDU controller and each serial recorder format controller is the master cycle rate of the RMDU controller. The word rates of the serial recorder ports are simply the master "cycle rate" multiplied by the number of words out of the data cycle that are recorded on that recorder track. Either serial recorder format controller can provide subcommutation or supercommutation capability with software programmable frame synchronization patterns. This multiport capability for serial recorder data formatting permits division of the acquired data bandwidth (additional serial recorder format controllers can be added at any future time to supplement the two presently installed) so that longer data recording cycles per reel of tape can be achieved even when using the 125K WPS maximum throughput rate of the system.

OBS software is divided into five basic categories; (1) A Paper Tape Software System, (2) Diagnostic Programs, (3) A Data Acquisition Processor, (4) A Real Time Disc Operating System and (5) A Sampling Format Generation Program. These programs provide a software package which gives the programmer or experimenter the ability to exercise the memory, the computer logic, the digital I/O interface units, and all associated peripheral equipment. The paper Tape Software System allows for software program development and checkout. For program development it provides an assembler, on-line editing and debugging programs, and a dump facility. As previously mentioned, the OBS Data Acquisition Processor software provides for two basic modes of system operation: (1) on-line operation and (2) off-line operation. All software is user oriented and provides an interactive English language dialogue with the CRT/keyboard operator.

Off-Line software permits the OBS operator to set up the system, and to use it in several different standalone modes controlling any of the optional peripherals that are required for a specific test run. When the OBS is used as a ground based PCM decommutation station, the same data acquisition processor software controllable destination (display) capability is provided as when the system is operating in Real Time in the data acquisition mode. Software for the off-line mode of system operation is as modular as the hardware. It presently provides twenty-one different submodes for setup and operation of the system as listed in the following table:

(1) Input PCM Format Tape
(2) Output PCM Format Tape
(3) Input PCM Format Memory Tape
(4) Output PCM Format Memory Tape
(5) Setup RMDU Controller
(6) Setup RMDU Address Words
(7) Change RMDU Destination Bits
(8) Mark RMDU Bad Channels
(9) Setup Bit Synchronizer
(10) Setup Frame Synchronizer
(10A) Setup Subframe Synchronizer
(11) Static Standardization
(12) Static Calibration
(13) Dynamic Calibration
(14) Data Collection
(15) Recorder Playback
(16) Record RMDU Data
(17) Verify RMDU Data
(18) Noise Measurement
(29) Self Test
(30) Debug
(31) Disk Boot

The Real Time Disk Operating System (RTS) also communicates with the user in an interactive mode through the keyboard entry unit (CRT terminal). The RTS resides on the disc, with a small statement core resident, and it services all system peripherals. In addition to the monitor, it contains a Linker, a Librarian, a File Utility Program, an Editor, an Assembler, a Fortran IV Compiler and a real time operating system.

The flexibility of a computer data acquisition system such as OBS produces new operational software requirements that were not present with older data systems having hardware controlled or fixed data cycle sampling formats. The first goal is gather no more data (or use any more channel bandwidth) during a test than absolutely necessary. The second goal is to sample each channel at a rate necessary to faithfully reproduce the raw data bandwidth. In order to accomplish these goals it will be almost mandatory for the test planner to construct a new sampling format data cycle for each test. To minimize data bandwidths each data cycle designed should incorporate supercommutation, subcommutation and sub-subcommutation so as not to sample any channel more often than necessary and thus generate minimum word rate and bulk raw data storage requirements (a full bandwidth raw data tape should be made of each test for archivable reliability even though data compression is applied to real time operations). Developing a new data cycle map for each test could represent a significant software recurring cost if it were done manually as it has been done in the past (when it was a nonrecurring task). In recognition of this potentially significant negative aspect of system flexibility, a software design evolved from the OBS development which should prove quite cost effective as an operational tool.

The OBS format generation software can ultimately reduce the laborious task of writing, programming and documenting a sampling format and producing correlative hardware configuration control documents (down to the level of acquisition hardware pin connections), to the preparation of a simple English language listing composed of a short list of overhead characterists of the test program and a parameter list of the hardware channel identifiers for each parameter and its sampling rate.

The computer organizes all parameters having identical sampling rates into tables in descending order of parameter number. It then processes an algorithm which tests for supercommutation, so as to develop the mainframe rate of the data cycle and determine whether or not the parameter table having the highest sampling rate is processed by supercommutation in the mainframe. If the supercommutation test is not passed, the highest sampling rate will be selected as the mainframe rate for the test. The computer next compares all remaining sampling rate tables whose specified sampling rate is less than the selected mainframe rate against integer submultiples (1/n ratios) of the mainframe rate, so as to assign subframe column depths to the data cycle.

Subsequent iterations produce any necessary upward adjustments in sampling frequency of the remaining sampling rate tables until they match rates which are integer submultiples of the mainframe rate. Once all of the subcommutation rates (subframe column depths) have been established, the computer calculates the number of required subframe columns for each rate (lower than the mainframe rate), computes the mainframe length and develops the hardware word rate requirements. This algorithm accounts for the number of mainframe parameter time slots, the total number of subframe columns, and the number of synchronization/subframe ID counter/overhead words necessary to produce the mainframe length. Calculated word rate requirements not matching software programmable hardware word rates or other hardware restrictions (such as a mainframe length not exceeding IRIG requirements of 2048 bits maximum) result in upward readjustment of all sample rate tables until hardware requirements are satisfied.

Finally, the computer produces paper tapes which can be used to document the sampling format information and to load the DMDS format memory for the test. Typical documentation and listings of the format generation program are presented in Figure 21 (a 3-part figure). The important consideration in this area relates to; (1) the need for rigid configuration control of software controlled variables and, (2) ease in modifying the sampling formats from test to test so that the unforeseen variables and iterations integral to a research program can be accommodated with minimum impact on the total amount of archivable data collected.

SOME STATISTICS OF AMES' DATA SYSTEMS

Data gathering systems at Ames may be classified in three major categories; (1) low speed (1 to 40 SPS), (2) medium speed (40 to 1K SPS), and (3) high speed (above 2K SPS). In addition, these classifications may be further described as non-computer or computer-controlled. Over the period of years (from 1956 to 1975) the cost per channel for these systems have decreased dramatically. Figure 22 presents graphs of the cost per channel for low speed systems (from 1957 to 1975) and for high speed data systems (1960 to 1975).

The low speed Austin system cost about $740 per channel, while the current day equivalent system costs $85 per channel. These systems differ radically, however, in capability and processing power. The Austin system used a stepping switch scanner as a multiplexer, a shaft angle encoder for digitizing, and printed out the data on a keyboard (typewriter) type of printer. The Vidar IDVM system uses a Reed relay scanner, an integrating digital voltmeter, and a micro-processor as a control element. It can support a wide range of peripherals and provide real time linearization and engineering unit conversion of parameters.

The costs per channel for a high speed data system are based on actual dollars paid in 1960 for the Beckman System, which cost four times as much as the current AIFTDS-4000 systems produced by Teledyne Controls. The front end signal conditioning of the Beckman System cost Ames about $1000 per channel while the remaining $3000 per channel is attributed to the cost of the control logic, ADC, input keyboard, recording peripherals and systems engineering. The signal conditioning cost for the current (1975) AIFTDS-4000 hardware is about $500 per channel. The other $500 is attributed to the other components of the system and systems engineering. It is interesting to note that the purchase price per channel for signal conditioning over a fourteen year period decreased by a factor of two in spite of inflation eroding the value of the purchase dollar. During this same period end item hardware costs for control logic and input/output hardware decreased by a factor of six while labor costs increased dramatically. This dichotomy was made possible by MSI and LSI logic which provides orders of magnitude more circuits per production labor dollar.

Figure 23 is a bar graph showing the increased performance in data system sampling rates over the 1960 to 1975 period. In 1960, the sampling rate for "high speed" systems were 2.5K SPS while in 1975 the "high speed" system sampling rates are about 300K SPS. For the same period the signal bandwidths studied were 30Hz maximum in 1960 and 40 KHz for 1974. Digital resolution of systems over this same period remained constant at about one part in 10,000. This means that the design goals and performance increase greatly over the fourteen year period.

Figure 24 is a bar graph showing actual dollars paid at the time of procurement per channel per samples per second. The parameter dollars/channel/sample/second is a measure of system capability. The graph shows that there was about a 10-fold decrease in dollars/channel/sample/second over the first seven years and another decrease of 20-fold for the next seven years, producing a total decrease of 200 times over the fourteen year period starting in 1960. One conclusion which may be drawn from these statistics

GENERAL FORMAT INFORMATION

DC 10 S/N 7065 FLT 3 — 11 NOV 74

MODE: SAT-M SEMIAUTOMATIC

GPA	GAINS:			
		A	HIGHEST	512
		B	"	256
		C	"	128
		D	"	64
		E	"	32
		F	"	8
		G	"	4
		H	"	2
		J	LOWEST	1

SELECTED MAX. WORD RATE	70,000 WPS
TEST OBJECTIVE	FLUTTER
TEST ENGINEER	W. TROVER
RCDR PORT CODE	BI-PHASE M
XMTR PORT CODE	DM-M
AUTORANGE GPA	TES
WORD LENGTH	12 BITS
SYNC CODE	BARKER [illegible]

REQUESTED SAMPLING RATES

NO. CHAN.	SPS
1	2000
4	1000
2	400
4	220
3	150
8	100
5	50
10	10

ACTUAL SAMPLING RATES

NO. CHAN.	SPS
1	2000
5	1000
2	500
8	250
8	125
16	63

FRAME RATE	1000 FPS
FRAME LENGTH	14 WDS
CYCLE DEPTH	16 FRAMES
NO. SUBFRAME COLUMNS	5
WORD RATE	14,000 WPS
WORD RATE SELECTOR	M = 5
SF STEERING MEMORY REQMTS	80 WORDS
DATE CYCLE PERIOD	15.99 MSEC

SUBFRAME PARAMETER LIST

DC 10 S/N 7065 FLT 3 — 11 NOV 74

DATA CYCLE INFORMATION — RMU ADDRESS

LINE	PARA	SPS	MF COL		FRAME NUMBER				CARD	CS	GAIN	CH	NXT	MEM LOC	SF COLUMN
10	2	500	9	1	3	6	9	15	OCB	0	128	1	M	128	
11	7	250	10	1	5	9	13		DSF	2	1	1	SF	129	
12	8	250	11	1	5	9	13		PSF	2	1	2	M	130	
13	11	125	12	1	9				CMR	6	.	1	SF	131	
14	19	63	14	1					PTM	7		1	EOF	132	
15	3	500	9	2	4	6	8	16	DCB	6	128	6	M	133	
16	20	250	10	2	6	10	14		PSF	2	1	3	SF	134	
17	21	250	11	2	6	10	14		PSF	2	1	4	M	135	
18	12	125	12	2	10				PSF	4	2	1	SF	136	
19	22	63	14	2					PTM	7		2	EOF	137	
20	26	250	10	3	7	11	15		OCB	0	64	6	SF	138	
21	34	250	11	3	7	11	15		OCB	0	64	7	M	139	
22	13	125	12	3	11				AMX	3	128	3	SF	140	
23	23	63	14	3					TCMX	1	512	2	EOF	141	
24	27	250	10	4	8	12	16		OCB	0	64	8	SF	142	
25	D	250	11	4	8	12	16		..	.	..	.	M	143	
26	14	125	12	4	12				DCB	0	128	8	SF	144	
27	24	63	14	4					TCMX	1	256	3	EOF	145	
28	15	125	12	5	13				AMX	3	8	4	SF	146	
29	25	63	14	5					TCMX	1	256	4	EOF	147	
30	16	125	12	6	14				AMX	3	32	5	SF	148	
31	28	63	14	6					TCMX	1	512	5	EOF	149	
32	17	125	12	7	15				AMX	3	1	6	SF	150	
33	29	63	14	7					TCMX	1	512	6	EOF	151	
34	18	125	12	8	16				CMR	6		2	SF	152	
35	28	63	14	8					PSF	4	2	33	EOF	153	
36	29	63	14	9					PSF	2	x	33	EOF	154	
37	30	63	14	10					AMX	3	256	33	EOF	155	
38	31	63	14	11					TCMX	1	128	33	EOF	156	
39	32	63	14	12					DCB	0	64	33	EOF	157	
40	33	63	14	13					LPA D	.	512		EOF	158	
41	34	63	14	14					PSB				EOF	159	
42	9	63	14	15					TCMX	1	512	1	EOF	160	
43	D	63	14	16									EOG	161	

DATA CYCLE MAP

DC 10 — S/N 7065 — FLIGHT 3 — 11 NOV 74

MF WORD		1	2	3	4	5	6	7	8	9	10	11	12	13	14
FRAME	1	5	5	10	D	1	4	5	8	2	7	8	1	11	18
	2									3	20	21		12	22
	3										35	36		13	23
	4										37	D		14	24
	5													15	25
	6													16	26
	7													17	27
	8													18	28
	9														29
	10														30
	11														31
	12														32
	13														33
	14														34
	15														9
	16														D

Figure 21

GENERAL FORMAT INFORMATION

DC-10 S/N 7065 FLT 3 — 11 NOV 74

MODE: SAT-M SEMIAUTOMATIC

OPA	GAINS:			
		A	HIGHEST	512
		B	"	256
		C	"	128
		D	"	64
		E	"	32
		F	"	8
		G	"	4
		H	"	2
		J	LOWEST	1

SELECTED MAX. WORD RATE	70,000 WPS
TEST OBJECTIVE	FLUTTER
TEST ENGINEER	W. TROVER
RCDR PORT CODE	BI-PHASE M
XMTR PORT CODE	DM-M
AUTORANGE GPA	YES
WORD LENGTH	12 BITS
SYNC CODE	BARKER 20 BITS

REQUESTED SAMPLING RATES

NO. CHAN.	SPS
1	2000
4	1000
2	400
4	220
3	150
8	100
5	50
10	10

ACTUAL SAMPLING RATES

NO. CHAN.	SPS
1	2000
5	1000
2	500
8	250
8	125
16	63

FRAME RATE	1000 FPS
FRAME LENGTH	14 WDS
CYCLE DEPTH	16 FRAMES
NO. SUBFRAME COLUMNS	5
WORD RATE	14,000 WPS
WORD RATE SELECTOR	M = 5
SF STEERING MEMORY REQMTS	80 WORDS
DATE CYCLE PERIOD	15.99 MSEC

SUBFRAME PARAMETER LIST

DC-10 S/N 7065 FLT 3 — 11 NOV 74

DATA CYCLE INFORMATION									RMDJ ADDRESS						
LINE	PARA	SPS	MF COL	FRAME NUMBER					CARD	CS	GAIN	CH	NXT	MEM LOC	I-O CONN
10	2	500	9	1	3	5	7	15	DCB	5	128	4	M	128	
11	7	250	10	1	5	9	13		DSF	2	1	1	SF	129	
12	8	250	11	1	5	9	13		PSF	2	1	2	M	130	
13	11	125	13	1	9				DMX	6	-	1	SF	131	
14	19	63	14	1					PTM	7	-	1	EOF	132	
15	3	500	9	2	4	6	8	16	DCB	5	128	5	M	133	
16	20	250	10	2	6	10	14		PSF	2	1	3	SF	134	
17	21	250	11	2	6	10	14		PSF	2	1	4	M	135	
18	12	125	13	2	10				PSF	4	2 1	1	SF	136	
19	22	63	14	2					PTM	7	-	2	EOF	137	
20	35	250	10	3	7	11	15		DCB	5	64	6	SF	138	
21	36	250	11	3	7	11	15		DCB	5	64	7	M	139	
22	13	125	13	3	11				AMX	3	128	3	SF	140	
23	23	63	14	3					TCMX	1	512	2	EOF	141	
24	37	250	10	4	8	12	16		DCB	5	64	8	SF	142	
25	D	250	11	4	8	12	16		-	-	-	-	M	143	
26	14	125	13	4	12				DCB	5	128	9	SF	144	
27	24	63	14	4					TCMX	1	256	3	EOF	145	
28	15	125	13	5	13				AMX	3	8	4	SF	146	
29	25	63	14	5					TCMX	1	256	4	EOF	147	
30	16	125	13	6	14				AMX	3	32	5	SF	148	
31	26	63	14	6					TCMX	1	512	5	EOF	149	
32	17	125	13	7	15				AMX	3	1	6	SF	150	
33	27	63	14	7					TCMX	1	512	6	EOF	151	
34	18	125	13	8	16				DMX	6	-	2	SF	152	
35	28	63	14	8					PSF	4	2	33	EOF	153	
36	29	63	14	9					PSF	2	1	33	EOF	154	
37	30	63	14	10					AMX	3	256	33	EOF	155	
38	31	63	14	11					TCMX	1	128	33	EOF	156	
39	32	63	14	12					DCB	5	64	33	EOF	157	
40	33	63	14	13					GPA-O	-	512	-	EOF	158	
41	34	63	14	14					PSB	-	-	-	EOF	159	
42	9	63	14	15					TCMX	1	512	1	EOF	160	
43	D	63	14	16					-	-	-	-	EOC	161	

DATA CYCLE MAP

DC-10 — S/N 7065 — FLIGHT 3 — 11 NOV 74

MF WORD		1	2	3	4	5	6	7	8	9	10	11	12	13	14
FRAME	1	5	5	ID	D	1	4	5	6	2	7	8	1	11	19
	2									3	20	21		12	22
	3										35	36		13	23
	4										37	D		14	24
	5													15	25
	6													16	26
	7													17	27
	8													18	28
	9														29
	10														30
	11														31
	12														32
	13														33
	14														34
	15														9
	16														D

Figure 21

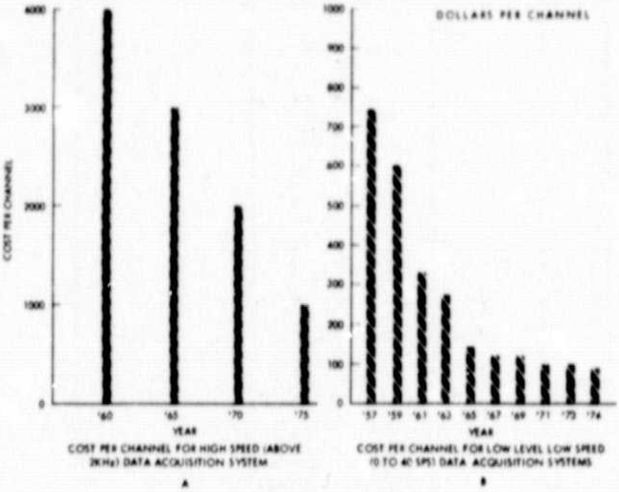

Figure 22

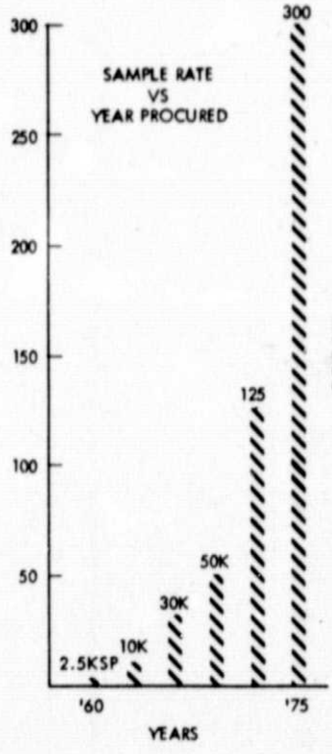

Figure 23

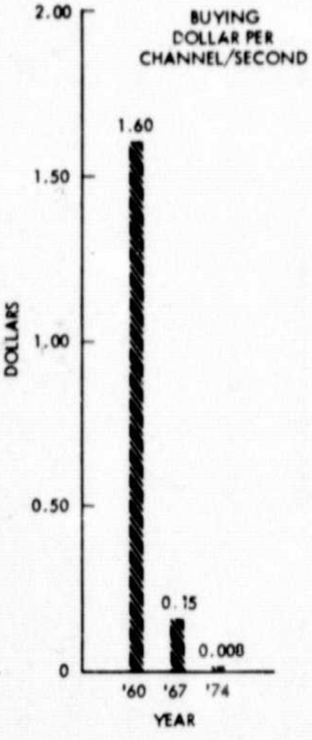

Figure 24

is that the performance of the current data gathering systems represent a quantum change for the buying dollars.

Some other statistics of the revolution in data gathering systems which may be of interest, are those relating to the biannual expenditure of dollars for both the data gathering system and maintenance during the twelve year period spanning 1963 to 1974. Figure 25 presents two graphs showing the total dollars and the running average dollars spent each year by Ames on data gathering systems. The data, averaged over two year intervals to account for late reporting, shows about a 20% rate of increase over the 12 year period. The running average of the yearly expenditures represents the cost averaged over the preceding years. The first six years shows about a 15% increase while the last six years shows about a 6% increase in dollar expenditures. The running average is a lower boundary on the expenditures.

Maintenance costs over the period of 1964 to 1974 are shown by the graphs presented on Figure 26. The dollar expenditure averaged over a two year period, which accounts for late reporting, shows about 15% increase per year from 1965 to 1974. The jump in maintenance costs (about 3 times the 1965 expenditures) was about the time computer data systems were procured. The average dollar expenditures graph shows about an 8% increase per year and places a lower boundary on the expenditures for maintenance. One conclusion which may be drawn from the latter statistics are that computer data gathering systems represent a large investment for the user, and

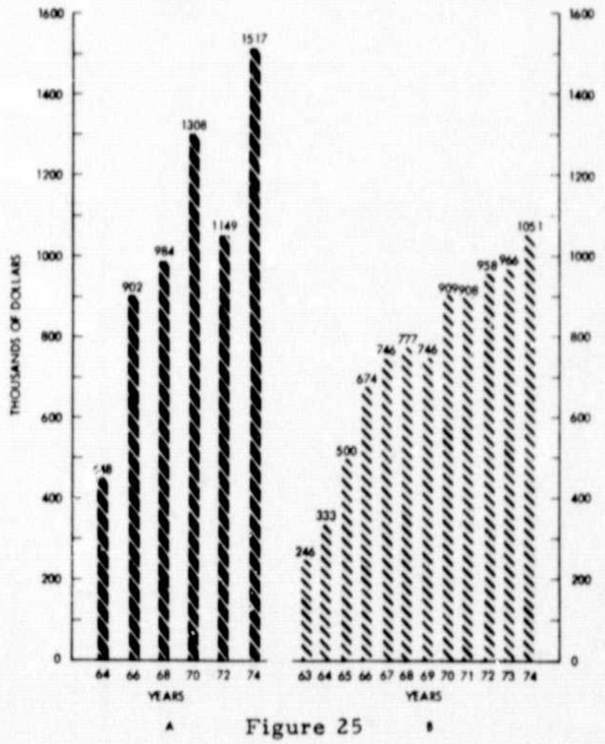

Figure 25

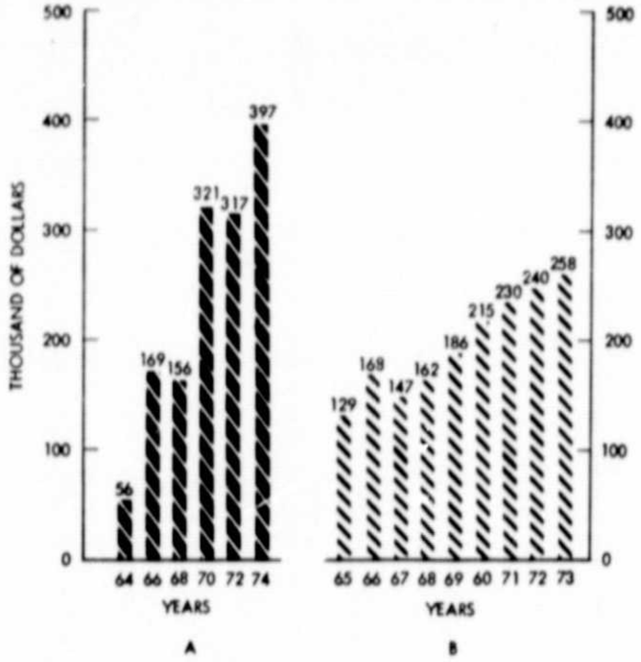

Figure 26

that software costs (as were shown on Figure 13) are a large investment for both the industry and the user. Therefore, it is advantageous to both the industry and the user to make every effort to optimize the dollars spent on data gathering systems. This means that the user community as well as industry should produce a standard software/hardware I/O specification for data systems.

SYSTEMS OF THE 1980's

The distributed systems concept will most certainly spread in acceptability in the next decade. This prediction may be made quite confidently based on two recent events; dramatically reduced costs for core and semiconductor memory and, multiple source introduction of the microprocessor. Along with these major events are the introduction of more powerful minicomputers with high speed multibus architecture.

The microprocessor (μP) with its low cost should cause a revolution in peripheral hardware design, especially those peripherals which require a lot of servicing from the CPU to perform their function. By incorporating the microprocessor and some memory in the peripheral the CPU servicing of hardware can be off-loaded to the peripheral, leaving the minicomputer with more time for the task of number crunching necessary in real time preprocessing and display.

The small size of the μP makes it ideal for incorporation in small remotely located acquisition units. It can off-load the real time tasks of the system's minicomputer (which in this application becomes essentially a dedicated large scale computer system). For example, in the 40' x 80' Wind Tunnel, a μP in one of the On-Board remote units could calculate true airspeed and true angle of attack in real time so that it can be displayed in real time to the experimenter in the control room.

As more confidence is obtained by the data user in the computer controlled data gathering system (by continuous reliable operation), it will evolve that the data gathering system can be used to control wind tunnel performance. The ultimate efficiency of the tunnel will be realized when the model, the model's controls and the tunnel's controls all become integrated as a single system. Distributed dedicated computers (and μP's) will give the system the degree of reliability mandatory for this goal to become a reality.

CONCLUSION

It appears that the most cost effective and reliable data gathering systems are those of the distributed computer concept using multibus, computer controlled architecture. More powerful minicomputers will permit more real time processing and will ultimately permit data reduction to be performed off-line by the data gathering system.

In the area of software it is apparent there is a great need within industry to set standards for the software related structure. This would include:

- Basic Instructions/Addressing
- Monitor Services
- Utility Services
- I/O Driver Standards
- High Level Language Syntax, Compiler and Real Time Operating System
- Minimum On-Line Health Checks
- Minimum Off-Line Diagnostics
- Minimum System Verification Software

All efforts should be made to optimize the high level language, compiler and real time operating system so as to minimize machine language code. In addition, a minimum set of standard diagnostics should be developed by the industry and user community in order to minimize the mean time to repair so that maintenance costs can be reduced. This set of diagnostics may be in the form of real time dynamic execution under the real time operating system. Another set of standard software which should be developed is system verification software package that determines the integrity of the system at a higher level than detail diagnostics. This latter software package should be made part of the real time software.

Finally, another factor of growing concern is that of software documentation and the need to establish some minimum standards for software documentation which will minimize the cost of system evolution. It is essential that software configuration control and documentation be brought up to a quality level commensurate with that achieved by the hardware community. The importance and seriousness of this problem might be best illustrated by relating to Stonehedge as an example of the undocumented computer program.

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