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PROPOSAL FOR A DIRECT NUMERICAL CONTROL SYSTEM

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ABSTRACT

This report describes a Direct Numerical Control (DNC) System proposed for use in the LLL Mechanical Shops. The DNC system includes a small digital computer that will provide the capability to store, manipulate, and distribute parts programs to the various machine tool stations. The system will also provide editing capabilities for parts program development and optimization. Diagnostic routines will be included to provide preventive maintenance. Logging of machine "on" time can be instituted to provide data for improved scheduling and machine tool usage.

INTRODUCTION

Fifteen years ago the laboratory entered into a new era of metal cutting called Numerical Control (N/C). The first N/C Gorton Mill was purchased on the basis that if it ever cut any useful parts it would be considered a bonus.

Computer programs were developed, means of punching and handling the paper tapes were established, and precedures for running the N/C machine were set up. After about six to nine months of dedicated effort, the first part was finally cut. The N/C Gorton Mill then became the most popular machine tool in the Mechanical Shops as it was cutting templates in support of the Plum Bob series of nuclear tests. Today N/C machine tools are recognized as being much more efficient than conventional machine tools.

Now we are at the dawn of another new era. It is similar to N/C in that its effect will be as far-reaching, but it is so different that we should not think of it as just a metal cutting operation but rather a complete manufacturing system. This new era is computer-aided manufacturing.

This proposal is limited to a Direct Numerical Control (DNC) system, which is only one part of computer-aided manufacturing. DNC can improve the "in-the-cut" time of each machine tool by linking together management, planning, the parts programming group, and the machine tool stations through a hierarchy of computers.

It has been recognized by many in industry that computers can aid in manufacturing with the result that many approaches have been developed. But which approach is best? This is a reasonable question to ask, but it is not complete. The question should really be, which approach is best for the Lawrence Livermore Laboratory Mechanical Shops?

At the International Machine Tool Show (Chicago, September 1972), many DNC systems were shown. Most of the systems were designed for companies with limited access to a supporting computer facility. The DNC systems for industry are, in general, designed to process parts programs and distribute the post-processed data to each machine tool on a block-by-block, real-time basis during the actual machining operation. If the central processor fails, all N/C controlled machines come to a grinding halt. This approach is not acceptable in our Mechanical Shops. These two factors, as well as many other requirements, indicate that there are differences here at LLL; therefore, it is necessary that we establish a set of requirements to meet our particular objectives.

The proposed system will use the existing hardwired N/C controllers, most of which are modern and in very good working order. The controllers will continue to operate from paper tapes and paper tape readers exactly as they do now. In addition, they will be connected to a central data director computer. This approach will aid in two ways: (1) the transitional period during the installation of the new computer control system will be easier because the machine tools can continue operating in their old mode, and (2) the paper tape will provide a redundant path for N/C control tape input in case there should be a failure in the new system. Parts programs will still be processed under the control of a sophisticated computer program called APT (Automatically Programmed Tools) and will be post-processed, as before, in the LLL computations computer center.

Each machine tool station will have a "stand alone" capability. This means that once a machine starts cutting a part it will not be interrupted by the failure of any component in the overall system other than its own individual controller. It also means that any single failure in the control system will not cripple the whole shop.

The main objectives that will be accomplished by the addition of the DNC integrated control system include:

- The N/C data will be loaded into a buffer memory at each machine tool station automatically and almost instantly on demand. This will reduce the set-up time and the turn-around time when modifications have to be made to the N/C program.
- N/C data may be modified at the machine statement level, allowing minor changes to be made by parts programmers without requiring the full parts program to be reprocessed by the APT program and then run through the postprocessor again. This will also reduce set-up time.
- A means of monitoring each machine tool on a real-time basis will be provided. If this system is truly to be used to increase productivity while still maintaining excellence in quality, then by definition we must be able to define the areas where productivity is lost. This data can be merged with the data collected by the Singer data collection system, and used to provide reports on a periodic basis to allow studies on how to improve productivity.

- The system should reduce the time that machines are down for maintenance. This can be accomplished by reducing both the number of times that a machine breaks down and the amount of time that it takes to repair it. Historical data collected on each machine can be stored in the data base and used to develop an optimized preventive maintenance schedule. The time to repair a disabled machine can be reduced by storing maintenance diagnostic routines on disc. Once a machine is reported out-of-order the diagnostic routine can be called up to exercise the system and determine which particular electronics circuit board or mechanical subsystem has failed.

This proposal will point out that by the addition of a single minicomputer (the data director), peripherals, and an interface system at each machine tool station, the "in-the-cut" time of each machine can be significantly improved for a very nominal cost. By making some general assumptions with regard to the cost of operating each machine tool, it can be shown that by improving the chip cutting time by less than 1/2 of a percentage point (say from 40% to 40.5%), the increased utilization of the machines will pay for the total DNC system. See Appendix A for a discussion of this cost analysis.

The proposed system will include the CDC 7600 computer center for parts programming and post-processing, a remote job entry terminal (RJET), an intermediate data storage and management center, and a machine tool controller station.

This proposal is organized into three main sections; present system and background, proposed modifications to the present system, and proposed schedule and cost of modification.

PRESENT SYSTEM AND BACKGROUND

The Mechanical Shops Division is presently responsible for 2300 machine tools, 615 of which are in the Machine Shop, Building 321 Complex, and 10 of these are numerical control (N/C) machines. The N/C machine tools are listed in Appendix B. We expect that the number of N/C controlled machines will increase by one per year as part of the machine tool replacement and upgrading plan. The computer aided control system discussed in this proposal will have a useful life expectancy of 10 years; therefore, it will be designed to control at least 20 machine tools.

A parts program may generate one or many separate N/C tapes that are required to completely machine a part. Each N/C tape completes a particular cutting routine and then moves the cutting tool away from the work piece. For example, when a parts program is written to cut a hemisphere, it is broken into three N/C tapes, the first tape is used to machine the vacuum holding fixture, the second tape is used to machine the outer radius contour, and the third is used to machine the inner radius contour.

Approximately 1000 feet of N/C tape is used each day. A random sample was taken of 1/2 of the N/C tapes that were stored in the Mechanical Shops work bins on

December 20, 1972, and the results are shown in Fig. 1. The data excludes the five-axis Sunstrand Mill because its N/C tapes tend to be much longer than the other machine tools. The data points were arrived at by totaling the number of tapes that were 10 to 20 ft, 20 to 30 ft, etc. The distribution clearly indicates that the majority of N/C tapes were less than 100 ft in length. On this particular day, 87.3% were less than 100 ft in length. This point is significant and will be used to determine the size of buffer storage at each machine tool station, with the exception of the five-axis Sunstrand; its buffer storage will be larger.

Figure 2 is a block diagram that shows how the DNC system can integrate into one dynamic system the different areas, such as management and planning, parts programming, and N/C machining. Much attention has already been given to these areas individually. The management system has been augmented by the addition of a computer-based data collection system. The parts programmers make heavy use of the Computations Computer Center in preparing parts programs. We are presently evaluating the potential of computer numerical control (CNC) for existing machine tools that will be replaced or retrofitted in the future. The computer is no stranger in the Mechanical Shops, but the full effectiveness of computer-aided manufacturing cannot be realized until all of these areas are linked together into a single system. Each group should have ready access to the data available to other groups. Fast reaction time is essential in a fast moving, viable and dynamic organization, such as the LLL Mechanical Shops. Management must be able to evaluate rapidly the current status of every vital operation in the shop and then implement decisions and control based on that knowledge.

PROPOSED DIRECT NUMERICAL CONTROL SYSTEM

Figure 2 is a block diagram of the proposed DNC system. The cross-hatched blocks presently exist and are to be tied into an integrated system by the additional blocks that are not cross-hatched. The parts of the system that are to be added include the data director, the disc, the buffer interface at the machine tool station, and the interactive control and communication link to the machine tool station. Each of these parts will be discussed in detail separately.

Data Director

The addition of DNC will include a mini-computer that will interconnect the parts programmers processing system, RJET, the management data collection system, and the machine tools. The mini-computer will be called the data director as it will be the heart of the entire system and will cause all data to be directed to its proper place. Two alternative schemes of coupling the data director to the computation computer center are under consideration: through the RJET, or through the 1-kilobit data-acquisition link. The data director will perform the following functions:

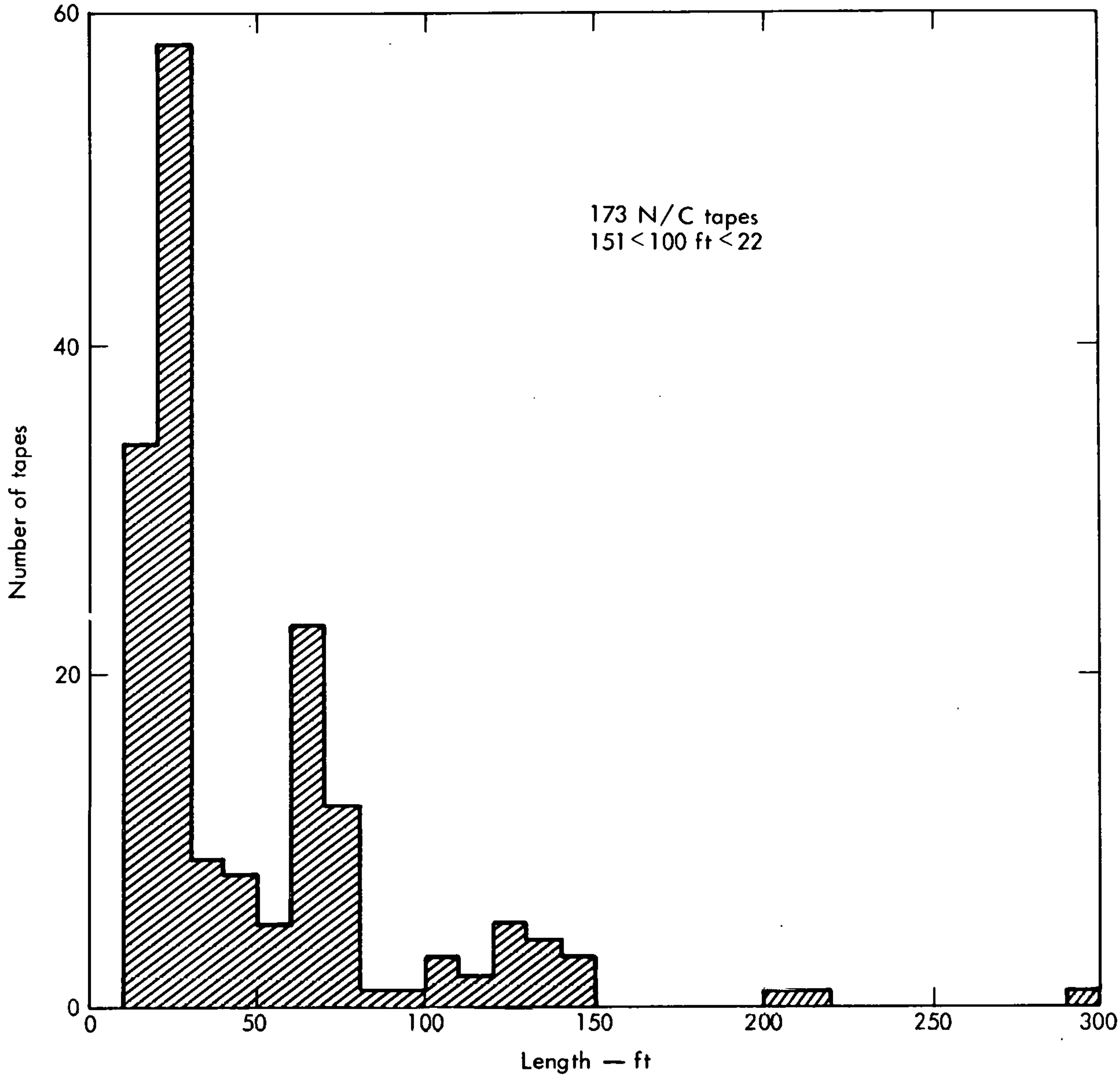

Fig. 1. Lengths of the control tapes (Dec. 20, 1972).

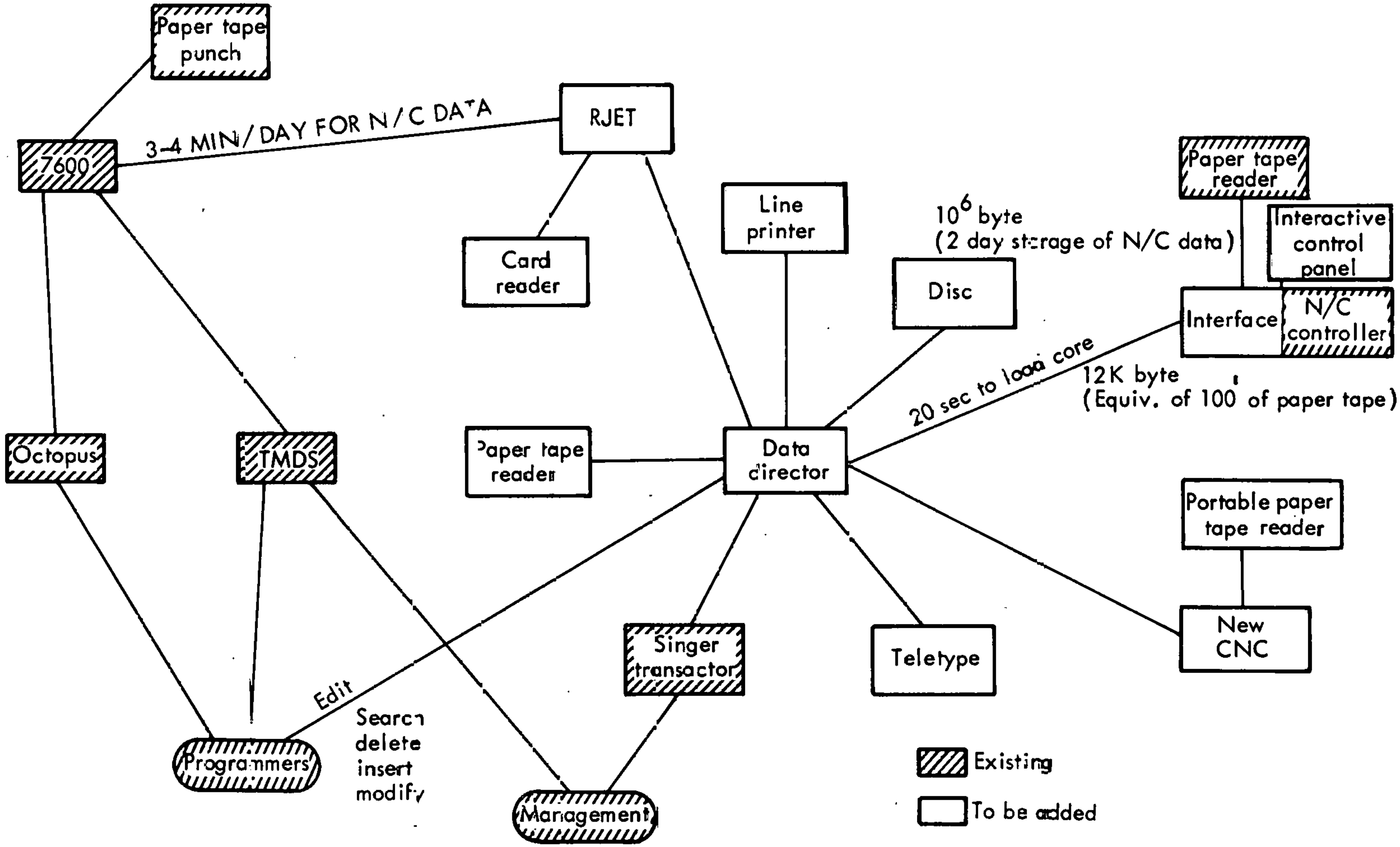

Fig. 2. Machine shop control system.

- Receive and store post-processed parts programs (N/C programs) from the part program processing system.
- Distribute N/C programs to the machine tool stations.
- Provide the ability to edit N/C programs at the machine tool language level.
- Collect run/status data from each N/C machine tool station.
- Provide diagnostic control data to the machine tool station to aid in maintenance.
- Receive and retransmit management data from the Singer data collection system to the data base located in the computation computer center.

The data director must have a disc-oriented operating system, be well documented, and have a direct memory access.

Disc

A disc will be used as a peripheral to the data director to store the N/C programs and system programs. It will also provide temporary storage of management data, diagnostic routines, an edit program, and machine status data. Sufficient N/C programs will be stored on disc so that the machine shop can operate for at least two days without any additions being made. We estimate that a two-platter disc unit with one of the discs removable and a total storage capacity of at least 10^6 words will be adequate.

Interface

The existing hardwired N/C controllers receive their input N/C data from a paper tape reader. The N/C controllers can be integrated into the DNC system by the addition of an electronic interface that will communicate directly with the data director. The controllers will still maintain their present stand-alone capability, i.e., operate from the paper tape reader without any assistance from the data director.

The electronic interface will allow the data director to send a complete or nearly complete N/C program to the machine tool station to be stored in a buffer memory. The transmission will have error check capability. The buffer memory will be able to store 12,000 bytes (8-bit words) of data, the equivalent of 100 ft of paper tape. As shown in Fig. 1, on December 2, 1972, 87% of the N/C tapes were equal to or less than 100 ft in length. Approximately 13% of the time, the N/C programs will be greater in length than can be stored in a single memory buffer. In these cases the first 12,000 bytes of the N/C program will be transferred to the buffer, and checked to determine if there has been any errors in transfer in the same manner as for shorter programs. If there are no errors, the machine tool operator can start the program and the data director will automatically transmit the remaining section of the N/C program into the buffer memory as the N/C program is used up and space becomes available. An alarm will indicate if the transfer cannot be completed successfully.

Interactive Control Link

The control and communication channel will use a small local processor to display alphanumerical messages, parts number, and program status indicators to the machine tool station operator. The operator may communicate with the data director through the use of a set of condition pushbuttons and a numeric keyboard. He can call for particular N/C programs and indicate machine status through coded instructions. Messages that the operator might send to the data director are parts program request, parts program number, and coded status messages. Messages that the data director might send to the machine tool station are parts program ready, parts search in progress, parts program finish, and error.

The operator will also use the control panel for local control to select the point at which the N/C program is to start. He would normally start at the beginning of the program when he is cutting a part, but during the setup procedure he may wish to start or restart the program in the middle of the machining cycle. All of the normal operating controls presently existing on the N/C controller will remain on the original control panel. A switch on the interactive control panel will permit the machine tool operator to select whether to receive the N/C program from the data director or directly from paper tape.

System Operation

N/C programs will be created in the computations computer center under control of the APT program. The parts programmers will continue to use OCTOPUS and TMDS to generate their programs and the data cards will be read into the computer center through the RJET in the Mechanical Shops. The APT processed programs will also be post-processed in the computer center and transmitted to the Mechanical Shops via RJET at a rate of 4800 baud. At that time, the data director will be alerted and will accept the data using a simple handshaking technique. The data director will take the N/C program, create a file, and store it on a rotating disc memory. The name of the file will be added to a directory to be used later by the machine tool station operator. When the machine tool operator is ready to machine a particular part, he identifies the corresponding N/C program by name on the interactive control panel at his station and requests that it be sent to him. One of several messages will be sent back to the operator, depending on the status of the data director and whether the N/C program is on disc. When the N/C program is available on disc, it will be transmitted to the machine tool station at a rate of 4800 baud. The transmission of a program, equivalent in length of 100 ft of paper tape, will take about 20 sec to complete. The speed of transmission is limited only by the 4800 baud cable; therefore the data director is able to service many stations at the same time. This is especially desirable early in the morning when all stations may request programs at the same time.

The transmitted N/C program data will be echoed back to the data director and checked for errors. If there is an error it will be retransmitted at least three times.

If the error still remains, an alarm will occur at both the data director and at the machine tool station and data transmission will cease and await further instructions.

Mechanical Shops management data will be generated and collected in the Singer data collection system. These data are to be complemented with additional machine run time and status data through the machine tool control interface unit. The data director will cause the data from the Singer system to be transmitted directly to the main computations computer center and stored in a data base. The machine tool status data will be collected on disc and sent to the computer center at the appropriate time to be merged into the data base.

The N/C program data flow (described above) will normally be used. However, storage of at least two days of N/C programs on disc will aid in the event there is a disruption of RJET service. The buffer storage at the machine tool station will isolate the station should the data director fail. Inevitably a failure will occur somewhere in the system that cannot be completely taken care of by buffering. Therefore, a redundant path will be placed around each of the critical data paths. This redundant path will be the existing paper tape system plus a paper tape reader/punch tied to the data director. Paper tapes can be punched by the computations computer center. They can be read in or punched out of the data director and also read into the paper tape readers at the machine tool station. By this means, any or all of the system data links can be bypassed.

SCHEDULE AND COSTS

The computer-aided manufacturing system will be developed in four phases.

The first phase will include purchasing the data director computer and a disc to establish a communication link between the computations computer center and the Mechanical Shops. A fast paper tape reader/punch will be added as a peripheral. N/C programs can then be punched at the machine shop, thus eliminating the hand carrying of paper tapes from the computer center.

Phase two will be to set up a single machine tool station (possibly the SLO-SYN index mill) so that it can communicate with the data director. The necessary interfacing and application programs will be completed to demonstrate that a single machine tool can be operated in the mode as outlined in this proposal. The N/C program will be stored on paper tape rather than on a disc and the interactive control will be via a teletype rather than a control panel at the machine tool.

Phase three will introduce the interactive control panel. This will be the prototype channel to be used as a guide to expand the system to the remaining N/C machine tool stations.

Phase four will be the expansion of the system to the remaining stations.

The proposed time schedule of the four-phase plan is shown in Table 1. A breakdown of the equipment cost is shown in Table 2.

Table 1. Proposed time schedule and costs.

Phase		Effort (man-months)	Equipment cost	Completion date
1	On site N/C tape punch system	4	$11,000	6/74
2	Single channel demonstrator	21	4,000	11/74
3	Channel No. 1 complete	8	26,000	11/74
4	Next 9 channels	7	$36,000	5/76

Table 2. Breakdown of equipment costs.

Item	Cost
Computer (data director) 12 K of core	$ 7,000
Teletype	1,500
Paper tape reader/punch	4,000
Machine tool interface to data director	4,000
Disc	12,000
Interactive display and control	12,500
Addition of the remaining machine tool stations	36,000
	$77,000

SUMMARY

This proposal has described a Direct Numerical Control System that will place the Mechanical Shops at the forefront of the N/C field. The center of the system will be a mini-computer data director which will supervise the activities of the system. Together with an RJET it will provide convenient entry and output of parts program and parts control data. A system disc will provide the capability of storing at least two days part control data for the shop, and buffer storage at each machine tool station will provide storage for the bulk of the data needed for any one part. This latter feature will eliminate the need for control tapes except as a backup to the system. A simple interactive control panel will allow the machine tool operator to communicate with the system.

The system will offer a number of opportunities for improving tool utilization. The immediate availability of the control data can reduce set-up time. The presence of the mini-computer on site will make it easy to initiate editing procedures to make minor corrections in the control data or diagnostic program to assist in machine maintenance. Moreover, it will facilitate the collection of additional data on machine operation to help define areas where further productivity increases can be obtained. The key to the system, however, is flexibility. It will provide the capability of implanting a wide variety of system operations under software control, many of which may not be evident until greater experience with this type of operation is achieved.

The cost of obtaining these benefits is quite small. A rudimentary cost analysis (Appendix A) reveals that only a very small improvement in machine tool utilization is needed to pay for the system.

ACKNOWLEDGMENT

Thanks to the many people who have contributed information that has aided in the preparation of this proposal including Ray Spies, Bob Zimmerman, Leo Frick, Al Jensen, Glenn Strahl, Lloyd Newton, and Richard Volz.

APPENDIX A
MACHINE TOOL UTILIZATION

The machine cost per hour is based on depreciation, direct labor, and burden (Table A1). Straight-line depreciation based on a 25-year useful lifetime for the machine tools will be used.

Table A1. Average cost per N/C machine tool station.

Machine tool	Cost
Spherical drill	$ 50,000
Morey mill	80,000
Excello lathe	230,000
LeBlond lathe	160,000
Sunstrand Omni mill	390,000
Cincinnati gilbert	160,000
Bostomatic mill	49,000
Star turn	66,000
20-in. standard engine lathe	80,000
Average cost per machine	$147,000 ≃ $150,000

It is assumed that the machine tools will be operating two shifts per day, five days per week; thus, each machine will be in operation 4000 hr per year.

The average machine cost was determined by taking the average replacement cost of the 10 machine tools that will be initially controlled by the DNC system. For lack of more definitive information it will be assumed that the average cost of the next 10 machines will be the same. (A higher average cost would enhance the desirability of the proposed system.) The average hourly operating cost, based on the above assumptions, is $19.73 per hour as shown in Table A2.

Table A2. Average cost of operating each N/C machine tool.

Tool	Costs	
Average purchase price of an N/C machine tool	$150,000	
Depreciation (25-yr life, st. line, 4000 hr/yr)	6,000/yr	1.50/hr
Direct labor + burden		16.20/hr
Maintenance (a total of 16 hr/day for 8 machines)		2.03/hr (av)
		19.73/hr

The N/C machine tool can be considered to be in one of three states at all times.

- Automatic cycle
  - In-the-cut
  - Traversing (not in-the-cut)
- Active (setup, tear down, maintenance, etc.)
- Inactive (waiting on parts or people).

An increase in the percentage of the time that the machine tool is in automatic cycle and in-the-cut is an increase in the utilization of the machine.

Utilization of a machine tool is based on the amount of time that the tool bit is actually "in-the-cut" and removing metal. Any time the tool bit is cutting air (such as during set-up or traversing back to make another cut) it is not in-the-cut, and thus, is reducing the utilization factor. An optimized N/C program will increase the utilization of a machine tool. The effective cost of machining is also based on the actual time that the machine tool is "in-the-cut" and becomes:

$$\text{Effective cost of machining} = \frac{\text{fixed operating cost}}{\%\ \text{utilization}} .$$

The effective cost of machining as a function of percent utilization is tabulated in Table A3 and plotted in Fig. A1. The slope of the curve in Fig. A1 is the rate of

Table A3. Effective cost of machining.

Utilization (%)	Hours in use	Effective cost of machining time ($/hr)
100	4000	$ 19.73
90	3600	21.92
80	3200	24.66
70	2800	28.18
60	2400	32.88
50	2000	39.46
40	1600	49.32
30	1200	65.77
20	800	98.65
10	400	$197.30

change in the cost per hour to operate the machine tool as a function of the percent utilization. Therefore by differentiating the curve and making the approximation that the ratio of the incremental values of the variables are nearly equal to the derivative, a family of curves is generated as shown in Fig. A2.

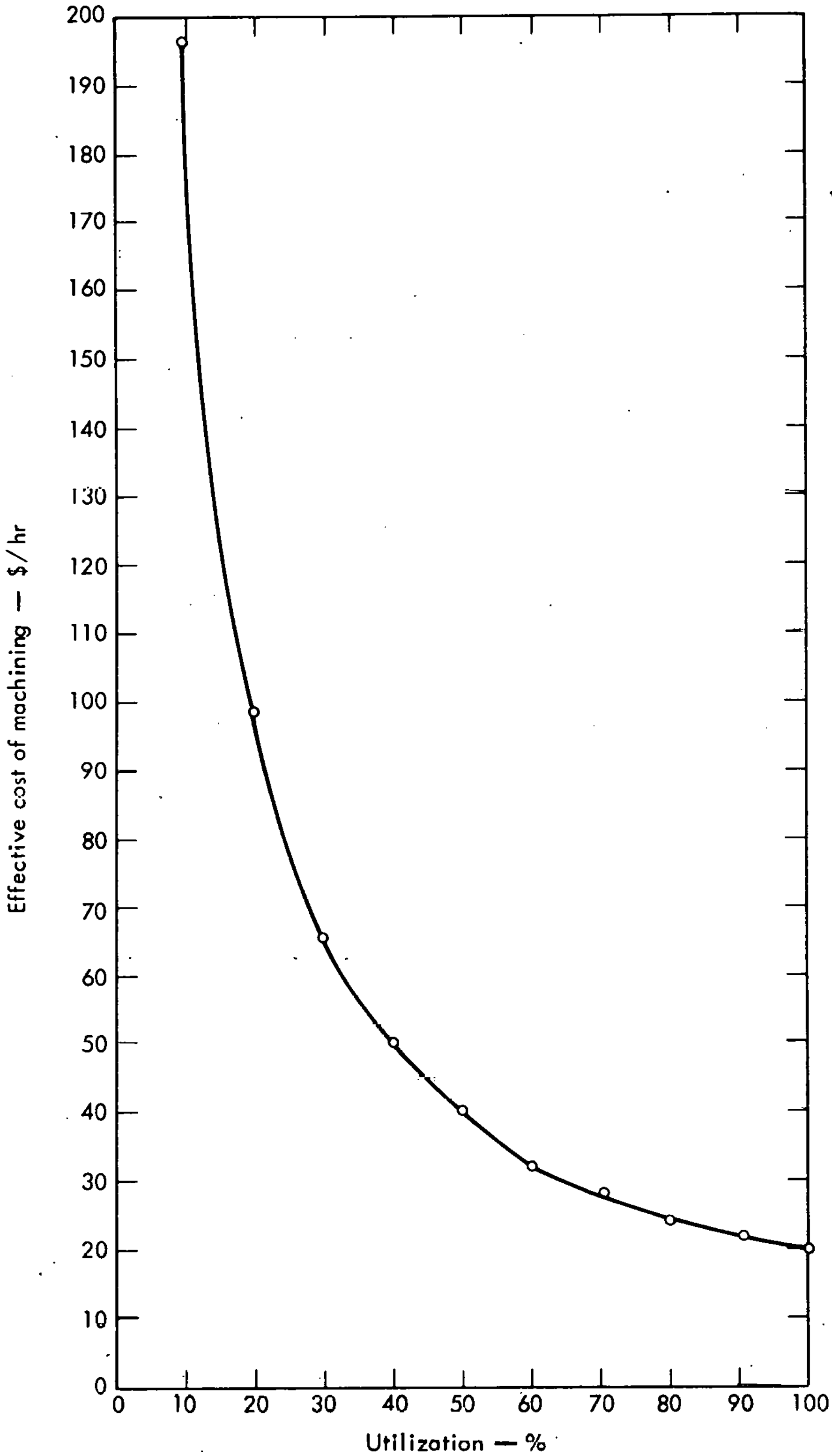

Fig. A1. Effective cost of machining as a function of utilization.

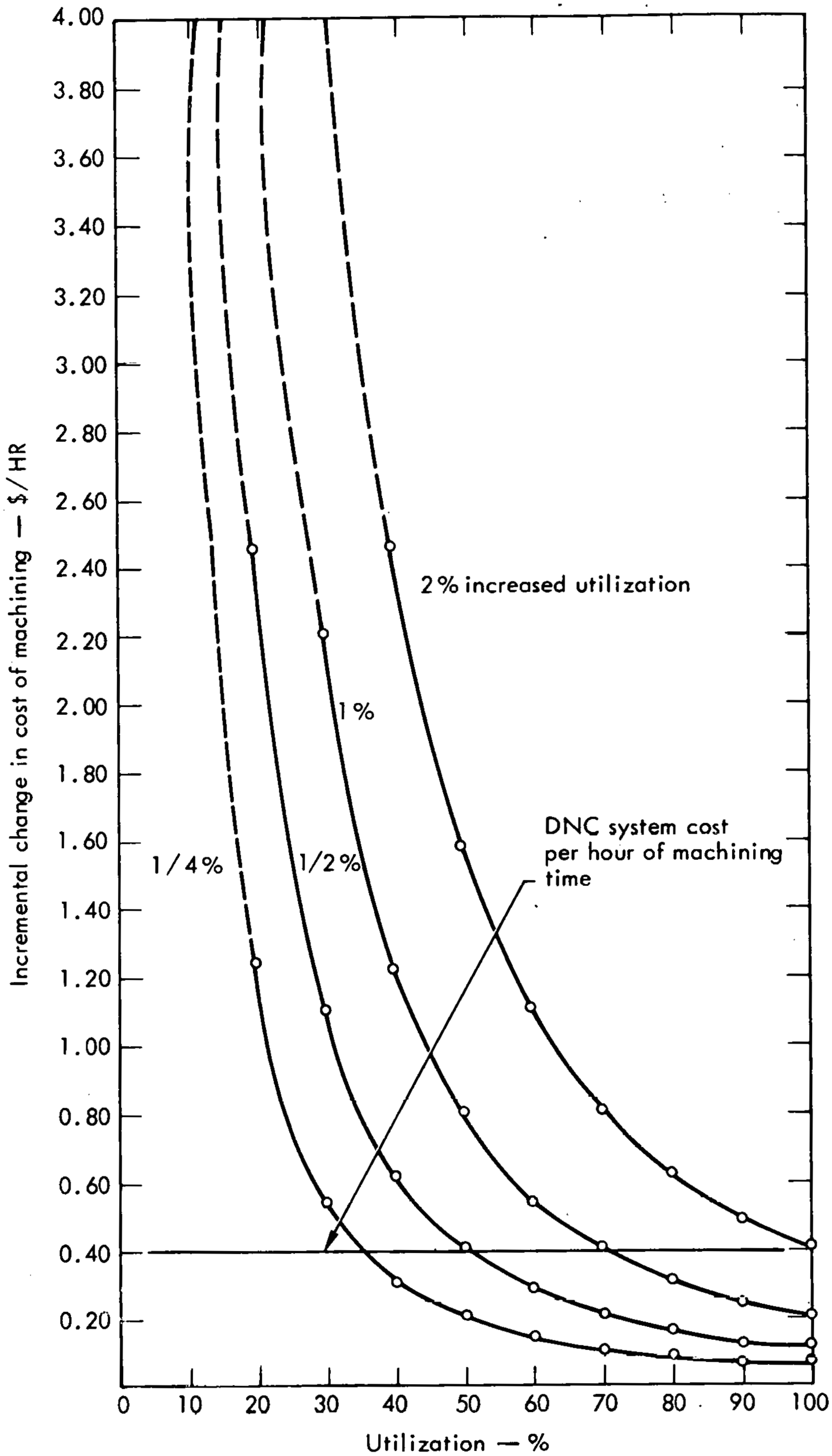

Fig. A2. Incremental change in the cost of machining as a function of increased utilization.

$$y = \frac{z}{x}$$

$$\frac{dy}{dx} = -\frac{y}{x}$$

$$\frac{dy}{dx} = \frac{\text{effective cost of machining}}{\text{utilization of the machine tool in percent}}$$

for small values of Δx

$$\frac{\Delta y}{\Delta x} \simeq \frac{dy}{dx}$$

thus

$$\Delta y \simeq \Delta x \frac{dy}{dx}$$

where

y = effective cost of machining

x = utilization of the machine tool in percent

Δx = small percentage increase in the utilization of the machine tool, i.e. (1/4, 1/2, 1, and 2 percent)

Example: If the machine tools are utilized 40% of the time, then by increasing the utilization 1/2 of one percent the operating cost will be reduced by $0.61 per hour.

It is estimated that the total cost of manpower and capital equipment of the initial DNC system (which will include the control of 10 machine tools) will be $210,000. It is also estimated that ten more machine tools will be added to the system at a rate of 1 per year during the ten-year lifetime of the DNC controller. Many of these controllers will be CNC controllers and can be integrated into the DNC system without the buffer interface. The worst case cost is where all controllers require the interface; therefore, that number will be used for this proposal. The average depreciation on these 10 controllers will be only half of what it would be had they all been purchased the first year rather than 1 per year over the ten-year period.

Amortizing the costs of the DNC system over a ten-year period,(useful lifetime of electronic controls) in the same manner as done for the machine tools, results in an annual cost of $23,914 as shown in Table A4.

The DNC system will initially service 10 machine tools and it is estimated that the number of N/C machine tools in the mechanical shops will increase by one each year over the next ten years. Therefore, the average number of machine tools serviced over the ten-year period will be 15. The cost of the DNC system will be charged

Table A4. Average annual cost of the DNC system.

Item	Cost	
Total cost of initial DNC system (including 10 stations)	$210,000	
Depreciation (10 year life straight line)		21,000/yr
Ten additional interface units purchased at a rate of 1/yr	30,000	
Average depreciation		1,500/yr
Maintenance (2 hr/wk)		1,414/yr
		23,914/yr

equally to all machine tools; thus, the hourly cost of the DNC system per hour of machine tool operation will be:

$$\text{Cost per hour} = \frac{\$23{,}914}{4000 \times 15}$$

$$= \$0.40/\text{hr}$$

Referring this cost back to Fig. A2 it can be seen that if the utilization factor is 40%, the DNC system must improve the utilization factor by less than 1/2% to pay for itself.

APPENDIX B

NUMERICAL CONTROLLED MACHINES THAT WILL INITIALLY BE CONNECTED TO THE DNC SYSTEM

Machine	Function	Control	Type	Location	Resolution	ID number
Spherical drills (five)	2-axis spherical drill	LLL	P-P	Development shop	0.010 in.	SE100/SE212/ SE217/SE236/ SE 223
Morey mill	3-axis mill	Computer Retrofit (Hughes)	Cont.	Development shop Tu/Be	10 μin.	M144
Excello lathe	2-axis lathe	GE Mark Century	Cont.	Tu/Be	10 μin.	L359
Excello lathe	2-axis lathe	Bendix	Cont.	Tu/Be	20 μin.	L435
LeBlond lathe	2-axis lathe	GE Mark	Cont.	Tu/Be	100 μin.	L419
Sunstrand Omni mill	5-axis mill	GE Mark Century	Cont.	Tu/Be	100 μin.	M212
Cincinnati Gilbert	3-axis	GE 7573	P-P	Main bay	0.001 in.	B17
Bostomatic mill	3-axis	BostoMatic	Cont.	Precision	0.001 in.	M220
Star Turn						
20-in. standard engine lathe						