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A MINICOMPUTER CONTROL SYSTEM FOR AN
ULTRAPRECISION TURNING MACHINE

R. R. Burleson

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OAK RIDGE Y-12 PLANT
OAK RIDGE, TENNESSEE

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Y-12 Development Division

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ABSTRACT

An ultraprecision machining capability is needed to meet the requirements for aspherical, optical-quality surfaces for the laser-fusion program. A minicomputer-based control system was developed for use on a Moore Number 3 measuring machine which was transformed into a very accurate contouring machine tool. A 15-inch-diameter by 2-inch-thick copper-plated aluminum disc was machined to a 600-inch-radius spherical contour to determine the viability of the system. The surface finish was 50 nm, peak to valley, with a contour error of less than 2500 nm.

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SUMMARY

An ultraprecision machining capability is needed to meet the requirements for highly aspherical, optical-quality surfaces for the laser-fusion program. A minicomputer-based control system was developed for use on a Moore Number 3 measuring machine which was transformed into a very accurate contouring machine tool. The objectives of this project were: to attain an optimum marriage between hardware and software, to use the Electronic Industries Association (EIA) Standard RS-274-B numerical control (NC) tape service, to use open-loop control for driving three-axis motors with a positioning resolution of $0.25 \mu\text{in}$ on the X and Y axes and $31.25 \mu^\circ$ on the C axis, to drive the X and Y axis motors at a velocity of 0.45 in/min, and to minimize the possibility of tape-reader errors.

Since the very fine pulse resolution called for fast pulse rates, a high-speed interpolator was needed to drive the motors. Therefore, a hardwired version of the digital differential analyzer (DDA) was selected over software techniques. Also, as a result of the ultrafine pulse resolution, a part description tape in excess of 457 m (1500 ft) is possible. To minimize the Mylar tape handling problem, a magnetic-tape cassette unit was installed to store part description data. Software converts a standard NC tape into a stacked binary data format and stores it on a cassette. By storing these data in a stacked binary format, a three-to-one reduction in required storage is realized. The machining software acts upon the stored part description data to generate the defined X, Y, and C axes movements. Manual controls were installed to provide all of the features available on a standard NC unit.

In an effort to obtain the best possible performance, several motors were evaluated and the final choice was narrowed down to one motor that was capable of running at 0.30 in/min. Results of vibration analyses showed that the surface finish on the test part compared favorably with finishes obtained using the d-c torque motors (used for setting up the axes)—less than 25 nm. A 15-inch-diameter by 2-inch-thick copper-plated aluminum disc was machined to a 600-inch-radius spherical contour to determine the viability of the system. The surface finish was 50 nm, peak to valley, with a contour error of less than 2500 nm. Based on the results obtained, a second control system has been assembled to handle production work with only minor changes from the original system.

INTRODUCTION

An ultraprecision machining capability is needed for the laser-fusion program. For this work, a precision air-bearing spindle has been mounted horizontally on a modified vertical column of a Moore Number 3 measuring machine base located in a development laboratory at the Oak Ridge Y-12 Plant.^(a) Inherent accuracy of the machine base is required to fabricate optical-quality components. However, to meet the requirements for aspherical surfaces, a continuous-path control system was required to turn virtually any shape which is symmetric about an axis of revolution.

Two machine tool control systems, employing minicomputers as the central element, have been installed—one in a production shop on an Ex-Cell-O two-axis turning machine⁽¹⁾ and another in the specimen shop on a Monarch lathe.⁽²⁾ Due to the success and versatility of these developments, it was decided to use a minicomputer on this project. The Moore machine tool control system incorporates technology learned on these projects, thereby resulting in an improved system.

One of the main objectives of this project was to use open-loop (stepping motor) control on a precision machine tool. One problem encountered concerned the trade off between pulse resolution and maximum velocity for an axis. Pulse resolution for the Moore machine is so fine that, in order to attain reasonable machining rates, the motors must operate in excess of 6000 rpm. Another problem generated by the ultrafine pulse resolution is that some part description tapes are as long as 457 m (1500 ft). In order to minimize tape handling, the standard EIA RS-274-B NC part description data tapes are converted into a stacked binary data format by the minicomputer and stored on a magnetic-tape cassette unit. The machine operating software package uses the binary data on the cassette to generate the defined X, Y, and C axes movements required to machine optical-quality components.

(a) Operated by Union Carbide Corporation's Nuclear Division for the US Atomic Energy Commission.

MACHINE TOOL CONTROL SYSTEM

SYSTEM DESCRIPTION

The Moore machine tool is a three-axis turning machine. A block diagram of the control system is given in Figure 1 and a view of the machine is provided in Figure 2. Command pulses can be generated manually from the preset indexer or jog logic. Computer-controlled command pulses are generated by the DDA.⁽²⁾ The command pulses then enter the steering logic where either the manual or computer-controlled pulses are selected. These pulses are routed to the position displays and to the translators which cause the motors to move the slides in the required direction at the specified feedrate. A view of the electric stepping motors is provided in Figure 3.

Part description data are stacked in a block, as illustrated in Figure 4, and stored on cassette. By storing stacked binary data instead of the EIA-formatted data, storage requirements are cut by two thirds. To initiate a machining cycle, a cassette with the part description data is loaded into a tape transport. The operator is then given the option of doing a sequence search before machining. After using the manual controls for setting up the tool, a multi-axis machining pass is performed in the automatic mode with an optical-quality component as the end result.

HARDWARE

Hardwired Interpolator

Due to the requirement for very high pulse rates to the motors [30 000 pulses per second (pps) which yield a 0.45 in/min feedrate], the pure hardware DDA (diagrammed in Figure 5) was used. Using this technique as opposed to a software technique, the speed of an axis is limited only by the responsiveness of the motor used and not by the interpolation time. First, the X, Y, and C distance registers are loaded with the binary representation of the number of motor pulses needed to move the required distance. Secondly, the clock register is loaded with a binary value (CLKSTR) which is based on the time allowed for the tool travel corresponding to the given X, Y, and C distance values. Thirdly, the DDA integrates the distance registers using serial hardware addition and provides overflows for motor command pulses.⁽²⁾ The cycle is repeated for each block of part description data.

A common problem that is encountered when attempting to drive stepping motors directly from a DDA is the inherent pulse repetition rate variations in the output pulse train. To correct this problem, accelerator/decelerator circuitry⁽¹⁾ was added. In addition to handling extreme velocity variations, it smoothes the pulse spacing to an acceptable level for the stepping motors.

Manual Controls

The manual control features, shown in Figures 6 and 7, are:

1. Axis Displays - The X- and Y-axis displays show the position of their respective axis (± 19.9999995 in). The C-axis display shows its position ($\pm 199.999975^\circ$). All position indicators are referenced to the part tape setup point.

Figure 1. BLOCK DIAGRAM OF THE MOORE TURNING MACHINE CONTROL SYSTEM.

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Figure 2. MOORE TURNING MACHINE AND CONTROLLER.

2. Feedrate Control - This feature allows the operator to vary the tool velocity with respect to the part surface, but not the tool path during a machining pass.
3. Preset Indexer - A preset number of command pulses can be generated on any axis by setting the number of pulses in the thumb-wheel switches and then selecting the appropriate axis "index" push-button switch. The direction is also controlled by the preset indexer. The pulses are generated at a constant frequency of 1200 pps.
4. Cycle Start - This feature resets all logic in preparing a machining cycle.
5. Initiate Machining - Through the use of this feature, or by using the system Teletype, a machining cycle is initiated.
6. Auto/Manual Switch - The command pulses that are to drive the motors are selected by this switch. In the auto position, only pulses from the DDA are accepted; while in the manual position, only commands from the preset indexer and jog logic are routed to the motors.

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Figure 3. VIEW OF THE ELECTRIC STEPPING MOTOR USED TO DRIVE THE X, Y, AND C AXES SLIDES.

Figure 4. STACKED PART DESCRIPTION DATA FORMAT.

7. Sequence Search - A part program is broken down into various machining processes which are identified by separate sequence numbers. In this manner, any particular process can be accessed by setting the appropriate sequence number into the thumbwheel switches (or by entering it through the system Teletype) and then actuating the "start-search" button.

Figure 5. HARDWARE DIGITAL DIFFERENTIAL ANALYZER.

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Figure 6. RACK-MOUNTED MANUAL CONTROLS.

8. Jog - This feature allows the operator to move each axis in either direction and is used for setting up the X, Y, and C axes. The pulses are generated at a constant frequency of 1200 pps.

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Figure 7. PEDESTAL-MOUNTED MANUAL CONTROL PANEL.

9. Emergency Stop - This control immediately stops all slide motion. After this button has been activated, the machining cycle must be restarted. This function can also be initiated by typing a CTRL P on the system Teletype.
10. Optional Stop - At various times during the machining process it may be advantageous to stop the cycle. Certain points in the part tape contain optional stops. Through the use of this feature, the operator has the option to stop at these points. This feature is available through the use of the system Teletype.
11. Step/Slue Switch - This switch engages either the electric stepping motor or the d-c torque motor. The d-c torque motor is primarily used in rapid traverse moves since it can reach speeds in excess of 10 in/min.

The remaining controls (Figure 7) are the speed controls for the d-c torque motor.

Position Displays

The Moore machine tool, as originally set up, had a resolution of $0.25 \mu\text{in}$ on the X and Y axes and $31.25 \mu\text{in}$ on the C axis. Because of the ultrafine resolution, available displays could not be used. A custom readout using light-emitting diodes was fabricated to match specific requirements. A stumbling block was encountered due to the odd resolution of the C axis. A method was needed to count with a base of 31.25. It was decided to use a programmable read-only memory (PROM) for the job. The PROM was programmed so that each successive location is 31.25 larger than the previous location, with an overflow being generated at 1000.00 (32×31.25). A counter is used to address the PROM, with its input being the command pulse train, as illustrated in Figure 8. The "clear" of the counter is connected to the "overflow" of the PROM, thereby bringing the count back to zero after the PROM has reached its maximum up count (1000). The overflow of the PROM is also connected to a binary-coded decimal counter which is used on the remaining digits. This arrangement has proven to be a highly efficient means of counting by a number that would normally require a very complex logic.

The Engineering drawings of the hardware system can be found in Appendix A.

Figure 8. BLOCK DIAGRAM OF THE C-AXIS POSITION INDICATOR.

SOFTWARE

Data Conversion Routine

The convert software (COVT) performs the conversion of a standard EIA RS-274-B NC machining tape into a binary data format. Due to the ultrafine resolution of this machine tool, an EIA tape in excess of 457 m (1500 ft) is possible. Therefore, the tape-handling problem is greatly amplified. In a standard NC unit, a tape read-in error could cause a part to be killed since the tape reader must function simultaneously with the machining cycle. Therefore, a better scheme was needed.

To minimize the Mylar tape-handling problem, a magnetic-tape cassette unit was installed to store part description data. Routine COVT reads in the EIA tape, block by block, and converts it into a stacked binary format. These data are then stored in a buffer in core. When the buffer is full, data are written on a cassette for future use. The data format of the cassette, which is also used to store system programs, is shown in Figure 9. If an error is

*Cyclic redundancy check.

Figure 9. CASSETTE MAGNETIC TAPE FORMAT.

made while reading the EIA tape, it is possible to backspace the tape to the previous data block and the program can be continued from that point rather than restarting the entire program. Since a magnetic-tape cassette system is much more reliable than Mylar or paper tape, many of the problems associated with tape handling have been eliminated. By storing the EIA data in stacked binary format (Figure 4), a three-to-one reduction in required storage is obtained. The flow charts and operating instructions for program COVT can be found in Appendix B.

Machining Routine

The machining software (MACH) acts upon the stored part description data to generate the defined X, Y, and C movements. This routine reads in stored-part description data from the cassette and outputs the required parameters to the UDA. A timing problem was

encountered when calling on the minicomputer to output data to the DDA's while it was simultaneously reading data from the cassette. To eliminate this problem, data were stored on the cassette in 4096-byte (8-bit) blocks. Initially, two buffers (4096 byte) are filled with data, as illustrated in the software flow chart in Figure 10. When all of the data in the first

Figure 10. BUFFERED-DATA SOFTWARE FLOW CHART.

buffer has been outputted to the DDA's, the software switches to the second buffer for DDA data while the first buffer is reloaded from the cassette. It takes approximately 5 seconds to fill one of the buffers and at least 10 minutes to empty one. Consequently, the next buffer is completely loaded before the present one can empty its data. Outputting a block of data to the DDA takes only 30 microseconds and reading a byte of data from the cassette takes 1.8 milliseconds. Therefore, by giving the DDA the highest priority on the computer, data can be outputted while the cassette is in a "read" cycle.

Sequence search and optional stop are also included in the MACH routine. Optional stop is available in software through the use of the system Teletype. The flow charts and operating instructions for program MACH can be found in Appendix C and the operating instructions for the loading system programs can be found in Appendix D.

SYSTEM EVALUATION

Motor Selection

The translator for the Slo-Syn Model M062 stepping motors, which were initially installed on the Moore machine, offered a $0.5\text{-}\mu\text{in}$ pulse resolution and were capable of speeds up to 5000 pps. At this speed, an average cutting pass requires 80 minutes. Since this time period was determined to be too slow, a new translator was designed. This translator, used in conjunction with available gearing, provides a $0.25\text{-}\mu\text{in}$ pulse resolution, and allows the motors to be stepped at rates in excess of 12 000 pps. The higher speed and smaller pulse value resulted in less vibration and smoother transitions through the resonance frequencies of the motors. In an effort to increase the speed, a larger set of Slo-Syn Model M063 stepping motors was installed. These motors had the same resolution but could be stepped at speeds up to 15 000 pps. Their response was very similar to the original motors. Vibration analyses were run on these motors (the data can be found in Appendix E) with the result being a 250-nm peak-to-valley error on a 6-inch-diameter flat copper disc test part.

In an effort to obtain better performance, other motors were evaluated. The first were Icon Model 109 motors which appeared to run much smoother and at higher speeds. However, these motors became very warm when operating at speeds above 5000 pps, thereby introducing a thermal error. Tests were also run on Vickers Model EPM-0 pulse motors which ran even smoother than the Icon Model 109 motors and can operate at speeds in excess of 20 000 pps. These motors also operate with a minimal increase in temperature. The Vickers motors were installed on the machine tool, and the vibration analysis was run again. Results showed that the surface finish on a test part compared favorably with finishes obtained using the d-c torque motors ($< 25\text{ nm}$).

Mechanical Analysis

The next step was to evaluate the Moore machine tool for positioning accuracy and repeatability. The dynamic-error measuring system⁽³⁾ was set up on the machine to obtain a plot of the commanded versus actual slide travel as obtained by comparing the command pulse train against the laser interferometric distance measurements. The X axis has a cyclic error of 1778 nm ($70\text{ }\mu\text{in}$) at a period of once every revolution of the leadscrew. A $20\text{-}\mu\text{in}$

error at a frequency of 40 times per revolution of the leadscrew was also seen. The Y axis displayed very similar results, but with error amplitudes approximately double those found on the X axis. The charts of the dynamic error plots can be found in Appendix F. The lower-frequency error appeared to cause a contour error, while the effect of the higher-frequency error was to mar the surface finish. The leadscrew and gearbox on the Y axis were reworked and are now comparable to the X axis.

RESULTS

Three test parts were cut to determine the viability of the system. Several machining cuts on a parabolic mirror blank were made. A surface finish of better than 200-nm, peak to valley, was obtained. The next part machined was an aluminum test part which consisted of several segments: an outside diameter, 45° angle, a flat surface, and a 6-inch-radius inside-contour spherical segment. All single-axis operations (the outside diameter, the flat surface, and the 6-inch-radius inside contour) were machined to a surface finish of 25-nm, peak to valley. The 45° angle, which is a two-axis operation, was machined to a surface finish of 75-nm, peak to valley, and showed a contour error of almost 1500-nm.

The final part to be machined was a 15-inch-diameter by 2-inch-thick copper-plated aluminum disc, machined to a 600-inch-radius spherical contour. The finish was inspected on an interferometric microscope, which revealed a peak-to-valley roughness of 125-nm. The contour was measured to deviate from a true radius by 2500-nm. The motors were then mechanically isolated from the machine and the part was remachined. The surface finish was better than 50-nm, peak to valley.

CONCLUSIONS AND RECOMMENDATIONS

One of the primary objectives was to use open-loop control on a precision machine tool. Based on the results obtained, open-loop computer control is a viable method of control. A second Moore machine tool control system has been assembled for production, with only minor changes from the original system.

Using the minicomputer as the system controller permits certain adaptive control features to be incorporated into the system in the future. A laser interferometer could be used to dynamically determine the slide positioning error; and, before each block of data is outputted to the DDA, the minicomputer could correct the distance values. This type of adaptive control would be useful in minimizing contour errors.

Through the use of higher-order interpolators (such as parabolic,⁽⁴⁾ circular, or cubic), tapes could be shortened and surface finishes could be improved. The surface finish can also be improved by mechanically isolating the motors from the machine tool and by reworking the gearboxes.

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ENGINEERING DRAWINGS

APPENDIX A

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Figure A-1. MOORE MACHINE TOOL CONTROL I (Pedestal-Mounted Manual Control Panel).

NOTES:
1-LOCATED IN BOX #2.

Figure A-4. MOORE MACHINE TOOL CONTROL I (Cable Receiving Schematic).

Figure A-5. MOORE MACHINE TOOL CONTROL I (Component Control Panel).

Figure A-6. MOORE MACHINE TOOL CONTROL I (Pedestal Manual Control Panel Schematic).

Figure A-7. MOORE MACHINE TOOL CONTROL I (Pulse Train and Signal Logic Diagram)

Figure A-8. MOORE MACHINE TOOL CONTROL I (Computer Interface Logic Diagram).

NOTE:
1-LOCATED IN BOX #2.

Figure A-9. MOORE MACHINE TOOL CONTROL I (Display Logic Diagram, Sheets 1 and 2).

Notes:
1-LOCATED IN BOX #2.

Figure A-9. (continued)

NOTES:
1-LOCATED IN 30 X 2.

Figure A-10. MOORE MACHINE TOOL CONTROL I (Preset-Indexer Logic Diagram).

Notes:
1-MOUNTED ON FRONT PANEL.

Figure A-11. MOORE MACHINE TOOL CONTROL I (Front Panel Logic Diagram).

Figure A-12. MOORE MACHINE TOOL CONTROL I (Motor Drive System Diagram).

Figure A-15. MOORE MACHINE TOOL CONTROL I (Timing and Add Command Generator Schematic).

Figure A-16. MOORE MACHINE TOOL CONTROL I (Command Pulse Generator Schematic).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	667	668	669	670	671	672	673	674	675	676	677	678	679	680	681	682	683	684	685	686	687	688	689	690	691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708	709	710	711	712	713	714	715	716	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760	761	762	763	764	765	766	767	768	769	770	771	772	773	774	775	776	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799	800	801	802	803	804	805	806	807	808	809	810	811	812	813	814	815	816	817	818	819	820	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864	865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900	901	902	903	904	905	906	907	908	909	910	911	912	913	914	915	916	917	918	919	920	921	922	923	924	925	926	927	928	929	930	931	932	933	934	935	936	937	938	939	940	941	942	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959	960	961	962	963	964	965	966	967	968	969	970	971	972	973	974	975	976	977	978	979	980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	998	999	1000
Y	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																										

MODULE UTILIZATION
MOORE I
BOX #1

[illegible]

MODULE UTILIZATION
MOORE I
BOY = 2

SLO-SYN MOTOR DRIVERS	COMPUTER WITH MANUAL CONTROL
'X'-AXIS VICKERS MOTOR TRANSLATOR	PANEL
PAPER TAPE READER	BLANK
TABLE TOP	DUAL CASSETTE SYSTEM
'Y'-AXIS VICKERS MOTOR TRANSLATOR	UNICOMPUTER
'C'-AXIS VICKERS MOTOR TRANSLATOR	COMPUTER INTERFACE
BLANK	BLANK
	SLO-SYN MOTOR POWER SUPPLY
	BLANK

MOORE I
CABINET ASSEMBLY
SYSTEM LAYOUT
4.4.5.

Figure A-17: MOORE MACHINE TOOL CONTROL I (Module Utilization and Cabinet Assembly).

APPENDIX B

SOFTWARE FOR CONVERTING AN ELECTRONIC INDUSTRIES ASSOCIATION STANDARD RS-274-B TAPE TO A STACKED BINARY FORMAT

Introduction

This software performs the conversion from an EIA Standard RS-274-B tape to a stacked binary format on a cassette. The software flow chart (Figure B-1) and operating instructions are included. Requirements of the EIA tape are also given. The stacked binary format is shown in Figure 4; the format of the data on the cassette is shown in Figure 8.

Operation

Steps in converting an EIA tape to a stacked binary format are as follows:

1. Insert the blank cassette into the Tape Transport Unit 1.
2. Place an EIA tape into the paper tape reader.
3. Set the computer console switch register to 001000 and depress the "load add" and "start" buttons.
4. Type a carriage return on the Teletype when ready to convert a tape.
5. If an error is encountered while reading the tape, the error type is printed on the Teletype. Backspace the tape to the previous block (a 00 001 010 on the tape) and type a CTRL P on the Teletype to continue.
6. When the end of the EIA tape is reached, the system will ask for more tape. If another tape is required, load the tape in the reader, and type a "Y" and a "carriage return" to continue processing. If no more tape is required, type an "N" and a "carriage return" to halt.
7. When the conversion is finished, write "lock the cassette".

Requirements for EIA Tapes

Position: X and Y pulse resolution = $0.25 \mu\text{in.}$

C pulse resolution = $31.25 \mu\text{in.}$

Present data incrementally.

Drop leading zeros.

DX max = DY max = maximum slide movement in one data block =
1.04857575 in.

DC max = 131.07196875°.

Figure B-1. CONVERT SOFTWARE (COVT) FLOW CHART.

Feedrate: Present data as inverse time $[F = 1/T \text{ (minutes)}]$.

$$953 \text{ E-06} \leq F \leq 1.0 \text{ E+06}.$$

F format shall always be 6.4.

$$0.001 \leq \text{ipm} \leq 0.45.$$

Maximum change in ipm per data block is $\Delta \text{ipm} = 0.0225$; and, in addition, this change must be followed by 30 milliseconds of constant ipm.

G Codes: G01 Linear interpolation.

M Codes: M00 Program stop.

M01 Optional stop.

M02 End of program.

N Codes: The block sequence number address "N" followed by 3 digits shall be the first word in a block.

APPENDIX C

SOFTWARE FOR OPERATING THE MACHINE TOOL CONTROL SYSTEM

Introduction

This software package controls the machining process. Operation instructions and software flow charts (Figures C-1 through C-3) are included.

Operation

Steps in operating the machine tool control system are as follows:

1. Load the cassette with the part description into Tape Transport Unit 1.
2. Set the computer console switch register to 001000 and depress the "load add" and "start" buttons.
3. If an optional stop is needed, type a "Y" and a "carriage return" on the Teletype; otherwise, type an "N" and a "carriage return".
4. If a sequence search is needed, type a "Y" and a "carriage return", then type in the sequence number followed by a "carriage return". If a sequence search is not needed, type an "N" and a "carriage return".
5. When ready to machine, push the "cycle start" button and type a "carriage return" on the Teletype.
6. If, at any time, the system needs to be restarted, type a "CTRL P" on the Teletype.

Figure C-1. MACHINING SOFTWARE (MACH) FLOW CHART.

Figure C-2. CASSETTE INTERRUPT ROUTINE.

Figure C-3. DIGITAL DIFFERENTIAL ANALYZER INTERRUPT ROUTINE.

APPENDIX D

SOFTWARE FOR LOADING THE SYSTEM PROGRAMS

Introduction

This group of programs is used to load the system programs from the cassette. The operating instructions are included in the following section and the cassette format for systems programs is illustrated in Figure 8.

Operation

Steps in loading the systems programs are as follows:

1. Load the systems program cassette into Tape Transport Unit 0.
2. Set the computer switch register to 173000 and depress the "load add" and "start" buttons.
3. When the tape has stopped moving, the absolute loader has been loaded. Set the computer switch register to 037000 and depress the "load add" button. To load COVT, set the switch register to 000001; to load MACH, set the switch register to 000002. Depress the "start" button. When the tape has stopped moving, the program has been loaded and is ready to run. Refer to the appropriate Appendix (either Appendix C or D) for the program operating instructions.

APPENDIX E

STEPPING MOTOR COMPARISON

A series of tests were made on various stepping motors. Motor specifications are summarized in Table E-1 and surface finishes obtained with corresponding motors are illustrated in Figures E-1 through E-3.

Table E-1
MOTOR SPECIFICATIONS

Item/Motor Type	Slo-Syn M062	Slo-Syn M063	Icon 109	Vickers EPM 0
Step Angle				
Degrees	0.9	0.9	2.25	1.2
Radian	0.016	0.016	0.039	0.021
Maximum Pulse Rate (pps)	20 000	20 000	30 000	40 000
	<u>At 200 pps</u>			
	65 (4.7)	100 (7.2)	38 (2.7)	35 (2.5)
	<u>At 8 000 pps</u>			
Output Torque oz-in (kg-cm)			46 (3.3)	48 (3.5)
	<u>At 16 000 pps</u>			
				35 (2.5)
Stop/Start Rate (pps)	1 000	1 000	2 000	2 000
Rotational Accuracy Step	± 0.03	± 0.03	± 0.03	± 0.02

(a) Vickers Model EPMO at 20 kpps.

(b) Vickers Model EPMO at 8 kpps.

(c) Slo-Syn Model 06 at 10 kpps.

(d) Slo-Syn Model 06 at 10 kpps. (broader fringes)

(e) DC Sluing Motor.

Figure E-1. SURFACE FINISH OF A DIAMOND-MACHINED COPPER DISC (All Interferographs were Made on a Leitz Interference Microscope; 51X)

Figure E-2. PARABOLIC SURFACE CUT WITH THE X-Y-C PROGRAM USING THE SLO-SYN MODEL M062 STEPPING MOTORS. (8X)

Aluminum Disc: 15-in Diameter, 600-in Radius

(a) Perpendicular to the Feed Direction.

(b) Parallel to the Feed Direction.

Flat Copper-Plated Disc:
1.25-in Diameter

(a) Perpendicular to the Feed Direction.

Figure E-3. COMPARISON OF THE SURFACE QUALITY ON CURVED AND FLAT SURFACES USING VICKERS STEPPING MOTORS (Interferographs Made with a Leitz Surface Finish Microscope; 51X).

APPENDIX F

MACHINE EVALUATION

An evaluation of the Moore machine was made using the dynamic-error measuring system. A laser interferometer was used with the remote interferometer mounted on the axis gearbox. The charts obtained are illustrated in Figures F-1 and F-2.

Figure F-1. DYNAMIC ERROR MONITOR PLOT OF THE Y AXIS, MOVING IN AT 0.1 IPM.

Figure F-2. DYNAMIC ERROR MONITOR PLOT OF THE X AXIS, MOVING LEFT AT 0.1 IPM.

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