THE DESIGN OF A MANUAL NUMERICAL-CONTROL CIRCUIT FOR STEPPING MOTORS

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ABSTRACT:

The successful application of a stepping motor to drive an indexing or positioning machine depends on the accurate knowledge of the machines components, resolutions and dynamic behaviour. This paper describes the design of an electronic numerical control system used to measure the necessary mechanical characteristics of a machine tool prior to its being retrofitted with stepping motor drives. This design enables the manual selection of the axis to be driven and the axis displacement after which motion on the axis is automatically halted. Using this design a machine resolution (accuracy) of 0.00254mm (0.0001 in) was achieved on the machine tool used in this investigation.

NOTATION

$i(t)$ = variable winding current
L = external inductance
L_m = motor winding inductance
I_o = constant supply current
N= number of position steps to be executed by the stepping motor
R = external resistance connected to the motor
R_m = inherent resistance of motor windings
r_m = the machine resolution (single axis accuracy)
T = time constant for current building
TR = power transistor
t = time
V_S = a constant supply voltage
X = linear displacement of the positioning axis
α = step angle characteristic of the stepping motor

1. INTRODUCTION

The special attribute of stepping motor control of machines is the rare combination of accuracy, versatility and simplicity of control. Machine tool control systems employing stepping motors are among the simplest and cheapest to design. The Journal of the British Numerical Control Society, BNCS [1], describes Bridgeport Milling machines (based on stepping motor control) as "the finest money can buy". This is a result of the fact that stepping motors provide very effective -(general) machine control at low cost. Now that Nigeria has got the steel industry and is in the process of negotiations for the acquisition of the technology of machine tools, efforts have to be made to steer a reasonable course in the quality of this technology for the sake of competitiveness. Care should be taken to prevent the transfer of out-dated machine tool control technology in the name of a so-called "appropriate technology" claimed to be suitable for developing countries [2].

One of the steps in the proper direction would be the acquisition of stepping motor based machine tools. Nigerias technical institutions of electronics, mechanical and production engineering studies and research organizations have the opportunity now to lead the way

In the design of stepping motor

control systems the initial problem is the design of stepping motor control the determination of the mechanical characteristics (machine resolutions transmission accuracies and dynamic responses) of the machine tool. This paper describes the electronic control circuitries which were designed, built and successfully applied to measure the drive characteristics of a hydraulically powered milling machine using stepping motor actuated servo-systems.

2. STEPPING MOTOR CONTROL THEORY:

Stepping motors are digital control actuators because their motion is a response to a series of electronic pulses (Fig.1.) For each pulse the motor moves one step and the commonest resolution for-commercial stepping motors is 200 steps per revolution, giving a "step angle" of 1.8°. The accuracy of a stepping motor can be as good as 3% of a single step (i.e an error of 0.054° o· y) and this error is non-cumulative, remaining constant for any number of steps. The potential advantages of using stepping motor control systems in open loop are the relative ease of design implementation, the control flexibility, the low general costs including maintenance and the high positioning accuracies with direct machine federate control involving few systems components. The extent to which these benefits are realised depends very much on the quality and type of control strategy and its overall installation.

Fig. 2 shows the four-phase stepping motor drive circuitry used in this design. M1 is a pulse generator. M2 and M3 are 4-bit.shift registers which distribute the pulses sequentially to switch on the drive translators TR2, TR3, TR4, and TR5. D4, D5, D6 and D7 are power suppression (or "catching") diodes and the circled numbers 10/11, 12/12, 14/15 and 16/17 are points connected to the four motor phases (inductances). To turn a motor phase on (Fig.3) the pulse signal from the sequencing logics (i.e. shift registers) first switches on the drive transistor, say TR2, which in turn switches on the power (V_s) transistor TR6. This closes the circuit (Fig.4) from the supply voltage, V_s through the motor phase, the series resistor R, and the power transistor (which is now conducting).

A transient current which now builds up can be deduced from the equation

$$V_S = (R+R_m)i + L\frac{di}{dt} + \frac{dL_m}{d\theta}\left(\frac{d\theta}{dt}\right)i \ldots\ldots\ldots(1)$$

The term $\frac{dLm}{d\theta}\left(\frac{d\theta}{dt}\right)i$ represents the back emf offered by the motor inductance. This emf is usually very small for practical purposes and when neglected,

the value of the current resulting from a constant supply voltage is given by

$$i(t) = \frac{V_S}{R+R_m} - \left(\frac{V_s}{R+R_M} - I_0\right)^{e^{\frac{-t}{T}}} \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

The time constant, T for the motor phase current build-up is

$$T = \frac{L_m}{R+R_m} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

In this design, this time constant is in the order of milliseconds. Equation (3) shows that the operation of the stepping motor at fast stepping rates is limited by the inductance of the motor (stator) windings. It inhibits the build-up of current in the winding during the period of energization and thus tends to reduce the torque developed by the motor. This problem is solved by increasing the value of R (series registor) to a reasonable level such that the total circuit current is not serverely reduced in the process. A more expensive but surer solution is the use of two voltage values at different periods of phase energization. The higher voltage is applied at the beginning of the energization and the lower voltage takes over when the current reaches a predetermined value; Lawrenson, at al [3] offers a good reference for this method. For the purposes of machine tool control an optimum acceleration and declaration strategy has been developed by Maginot and Oliver [4].

3.THE STEPPING MOTOR MANUAL NUHERICAL CONTROL

The direct digital control of the direction of rotation (clockwise or counter-clockwise) of the stepping

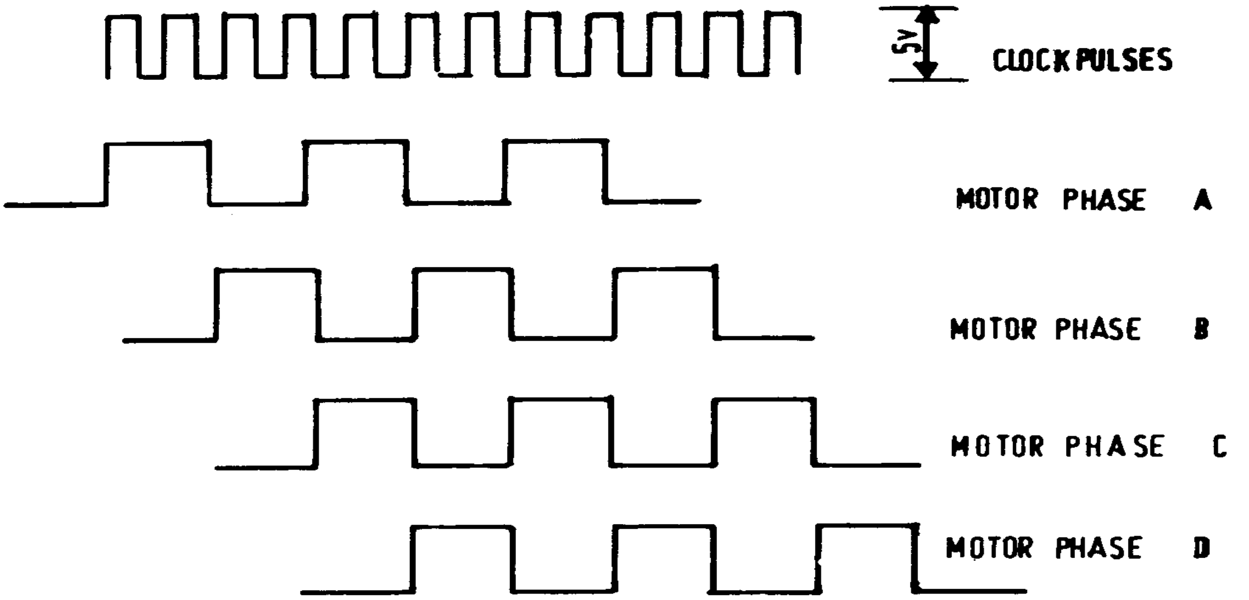
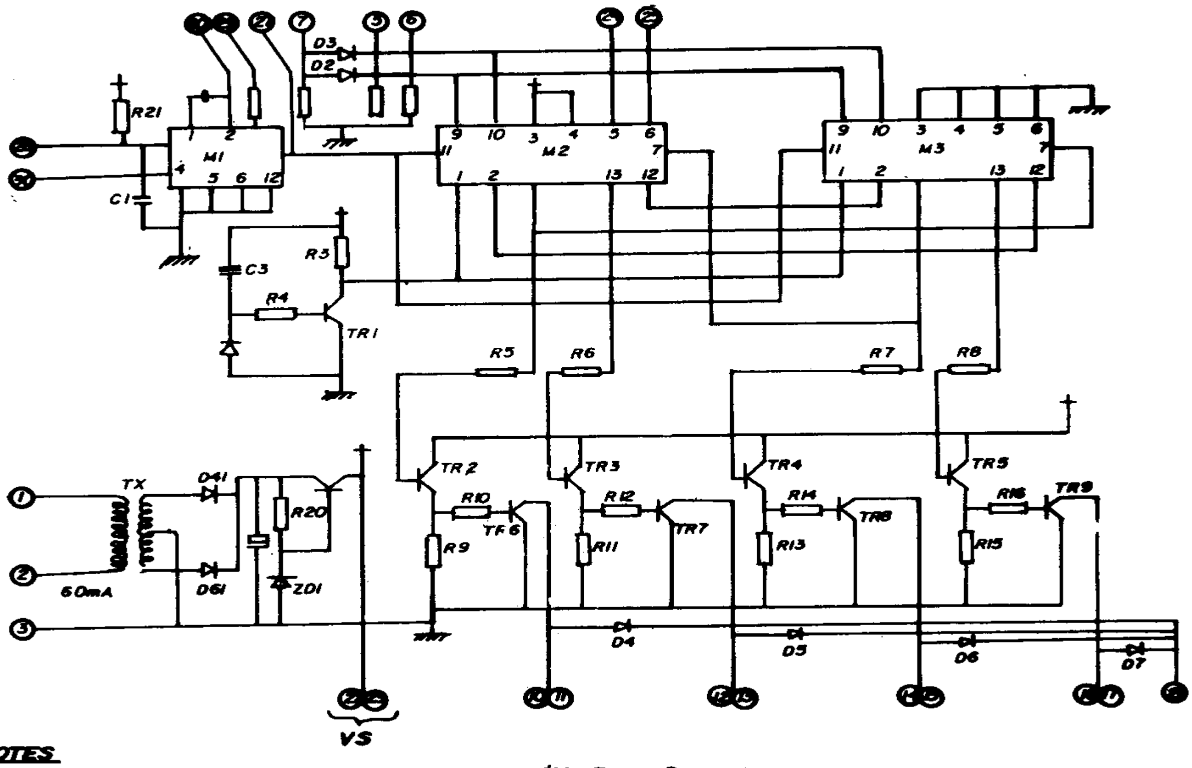


FIG 1 CLOCK PULSES DRIVING A FOUR PHASE MOTOR



NOTES

1. Nos. Thus (5) Indicate Edge Connection

M1 = Pulse Generator

M2 = 4-Bit Shift Register

FIG. 2 THE STEPPING MOTOR DRIVE CIRCUITRY

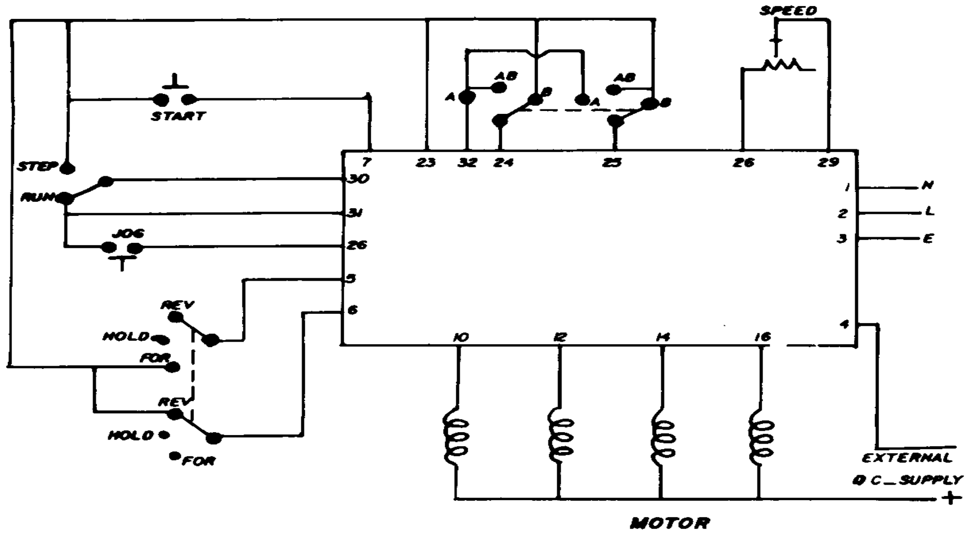


FIG.3 THE OUTLINE OF SWITCHES FOR EDGE CONNECTIONS IN FIG.2

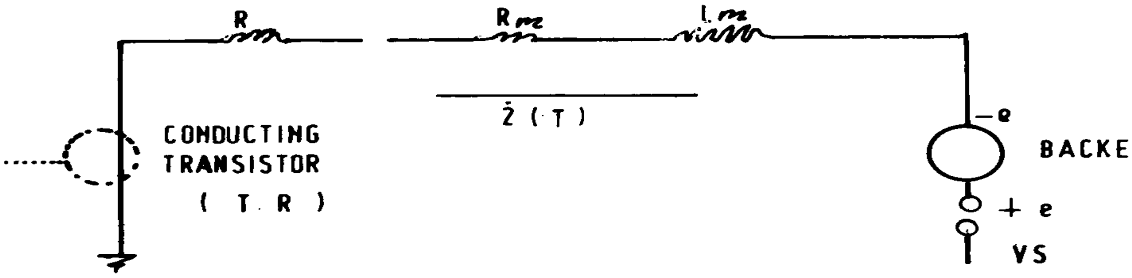


FIG 4 EQUIVALENT CIRCUIT FOR CHARGING A MOTOR PHASE.

motor and the speed of rotation are achieved by imposing the appropriate logic levels (1 or 0) on pins 5, 6 (figs. 2 and 3) and by the rate of pulse generation respectively from an external digital processor e.g. Ml For the purposes of the machine tool tests envisaged in this project it 1s necessary to be able to preselect both the direction and speed of rotation by analogue methods using Manual Switches external to the control "black box"

A rotary potentiometer is connected to points 28 and 29 (figs 2 and 3) to give the speed control and an ordinary two-pole three-way switch is connected to points 5 and 6 to give the FORWARD, REVERSE OR HOLD (no motion) directions of rotation of rotation of the motor. The general outline of the board and pin connections are as follows [5):

Pin	1)	240V neutral
"	2)	240V line
"	3,4	Earth
"	5,6)	Forward, reverse hold
"	7)	Initialise mode
"	8,9)	Not used
"	10,11)	Motor drive, phase 1
"	12,13)	Motor drive, phase 2
"	14,15)	Motor drive, phase 3
"	16,17)	Motor drive, phase 4
"	18,19,20)	Not used
"	21)	Suppression diodes
"	22,23)	Logic 12v supply (v_s)
"	24,25)	Stepping mode
"	26)	Single step input
"	27)	Frequency (speed) monitor
"	28,29)	Frequency (speed) control
"	30)	Step/Run control
"	31,32)	Earth (ov)

the diodes connected together at pin 21 (fig.2) are used to suppress high transient voltages that may develop when used to control a highly inductive motor.

4. THE POSITION AND FEEDRATE COMMAND DESIGN FOR THE MACHINE TOOL

For this machine tool application the drive unit for a stepping motor must be able to receive and "obey" commands for position and speed. The pulse repetition rate determines the motor speed. The pulse repetition rate determines the motor speed, i.e. machine feedreate. The required speed is set by the frequency control of the pulse generator using the rotary potentiometer mentioned earlier, (connected to pins 28 and 29 in figs. 2 and 3)

4.1. Position Commands

For the purposes of position command and its monitoring the crucial elaborate logic circuit shown in fig. 5 was designed to enable the pre-setting, storage and visual display of the up dated position on the machine tool axis. For absolute position command the total number of pulses required to attain a given distance is stored in six cascaded pulse counters using six pre-settable "Binary Coded decimal" thumbwheel switches each with a selection of numbers ranging From 0 to 9. On counting the last motion pulse, the stepping motor is automatically stopped.

In this design, six decade counters, SN74192, were cascaded in counting down mode as illustrated in fig. 5. This affords a maximum decimal number of 999999 which can be stored. Pin 13 of each decade counter is a "BORROW" pin.
To enable the counting in the "Binary Coded Decimal" (BCD) "BORROW lines" are created by connecting pin 13 of each of the first five higher-significant decades to the count-down pin of the adjacent lower significant decade counter. The "BORROW" pin of the sixth counter (least significant decade) is then connected to one of the inputs of the flip-flop, the output of which is used to configure the logic for the automatic stop signal via the NAND gate, G3.

4.2 The Automatic Stop Signal

The stepping motor driving pulses are rounted from the pulse generator (M 1) through the 4. 7V "Zener" diode (to stabilize the pulse level to 4.7V) before they are passed through one of the inputs of the NAND gate, G3. The other input of this gate is the output from the flip-flop formed with NAND gates G1 and G2, One of the two inputs of the gate, G1, is connected permanently to the "BORROW" pin of the "Least - significant" decade of the counter system and that the "BORROW" pin of each of the other counters is linked to the "COUNT-DOWN" pin of the preceding counter.

If, for example, 13924 pulses are required to be counted down through the decade counter system, the digits *0,1,3,9,2,4, are* preset on the six thumbwheel switches SW1 to sw6 respectively (with "0" set on SW1, the "most significant decade). To load the number "013924" into the counters, the load line (connection all pin 11s of the counters) is momentarily brought to logic zero (OV) using the push-button switch shown in fig. 5 The six seven-segment Light emitting diodes, LEDI to LED6 connected to the decade counters via the visual display decoder/drivers",SN7447A,will immediately display the number "013924", thus confirming that this number has been loaded into the six-decade counter system.

To start the counting down of this number, the other push-button switch connected to the flip-flop (Gl & G2) is used to bring one of the inputs of G2 to logic zerio momentarily thus making the G2 output a logic 1 (5V), G1 is also "Enabled" to allow pulses from the "Zener" diode to pass through the six counters, to the "BORROW" pin of the least-significant counter and through the flip-flop before the pulses are routed to M2, the stepping motor driver shift register.

As the number is counted down the LEDs visually display the remainder continuously, thus monitoring the up-dated count. After the number has been counted down completely the counters will momentarily tend to "BORROW" "One" from the preceding decade in the usual counting manner. Then as the least significant decade is being "Borrowed" from, it also tends to "BORROW" finally from the input of gate, G1. A low level logic therefore appears at this input. This gives rise to a high output at gate, G1, and therefore a low output, G2. As a result a high output permanently appears at G3, thus inhibiting the entrance of further pulses to M2. Since no pulses now reach M2, the stepping motor stops automatically, under full "holding" torque. In this design this state of affairs is indicated by a simultaneous display of the number "000000". Fig. 6 shows the numerical control "Black Box" which houses all the drive and control circuitries (fig. 2, 3 and 5) and external switches. The BC 108 Transistor circuit in fig. 5 is an interface circuit to convert the 12V logic employed for the pulse generator (M1) to the 5v logic used for the counter system.

4.3 Determination of the Machine Axis characteristic

4.3.1 Transient response

The "Black Box" includes single step logic which is externally controlled using push-button (JOG) and toggle switches. When the toggle switch is placed in the "STEP" position, the drive logics output only a single pulse to the stepping motor each time the "JOG" push-button switch is pressed and released. The movement of the machine tool axis being tested is monitored with a precise position transducer the signals of which are recorded using a standard ultraviolet, "uv" recorder. Thus the transient response of the axis to a step input from the motor is determined practically on the hardware drives to ensure axis stability.

4.3.2 Machine Axis Resolution

The axis (X, Y, or Z) resolution is the displacement in the axis which is equivalent to one pulse reaching the stepping motor actuating the movement of that axis. Again a precise position transducer together with "dial gauges" are independently used to record the precise (in order of 10^{-6}m) displacements of the axis in response to a fixed number of pulses preset in the position command (counter) logics using the thumbwheel switches and confirmed by the display LEDs. The machine resolution, r_{mx} on the x-axis for example, is calculated thus

$$r_{mx} = \frac{x}{N}\left(\frac{mm}{step}\right) \ldots\ldots\ldots\ldots\ldots (4)$$

The machine resolutions for all the axes on the machine tool are similarly measured. These resolutions depend on both the mechanical hardware constituting the axis drives and the stepping

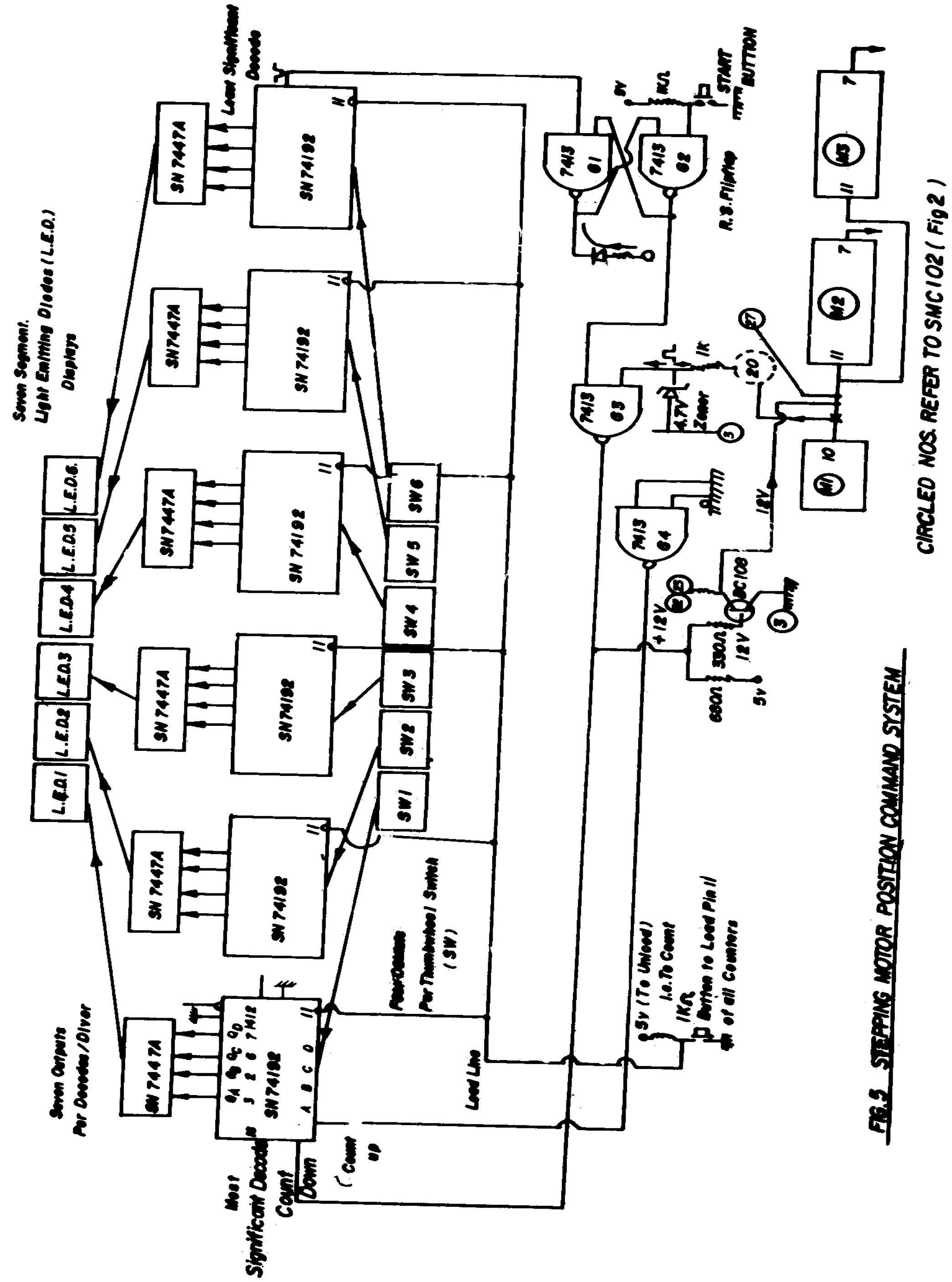


FIG.5 STEPPING MOTOR POSITION COMMAND SYSTEM.

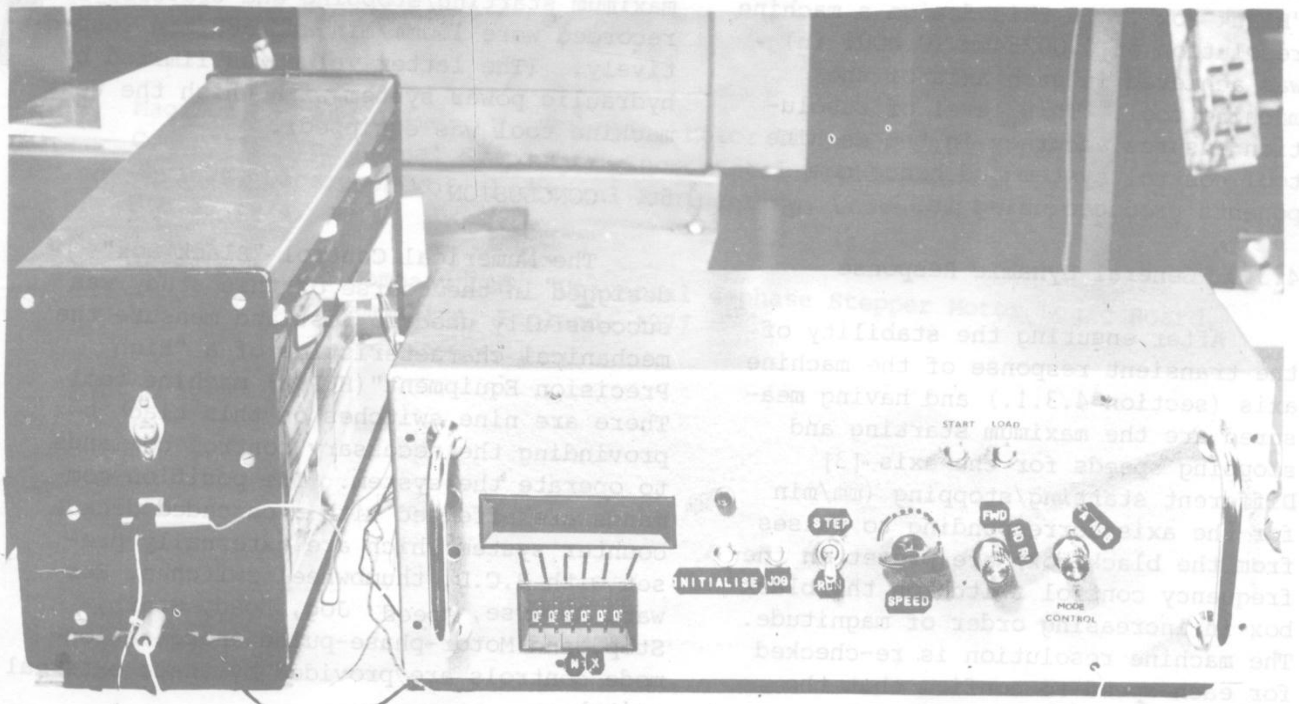


Fig. 6(a) the assmble black box

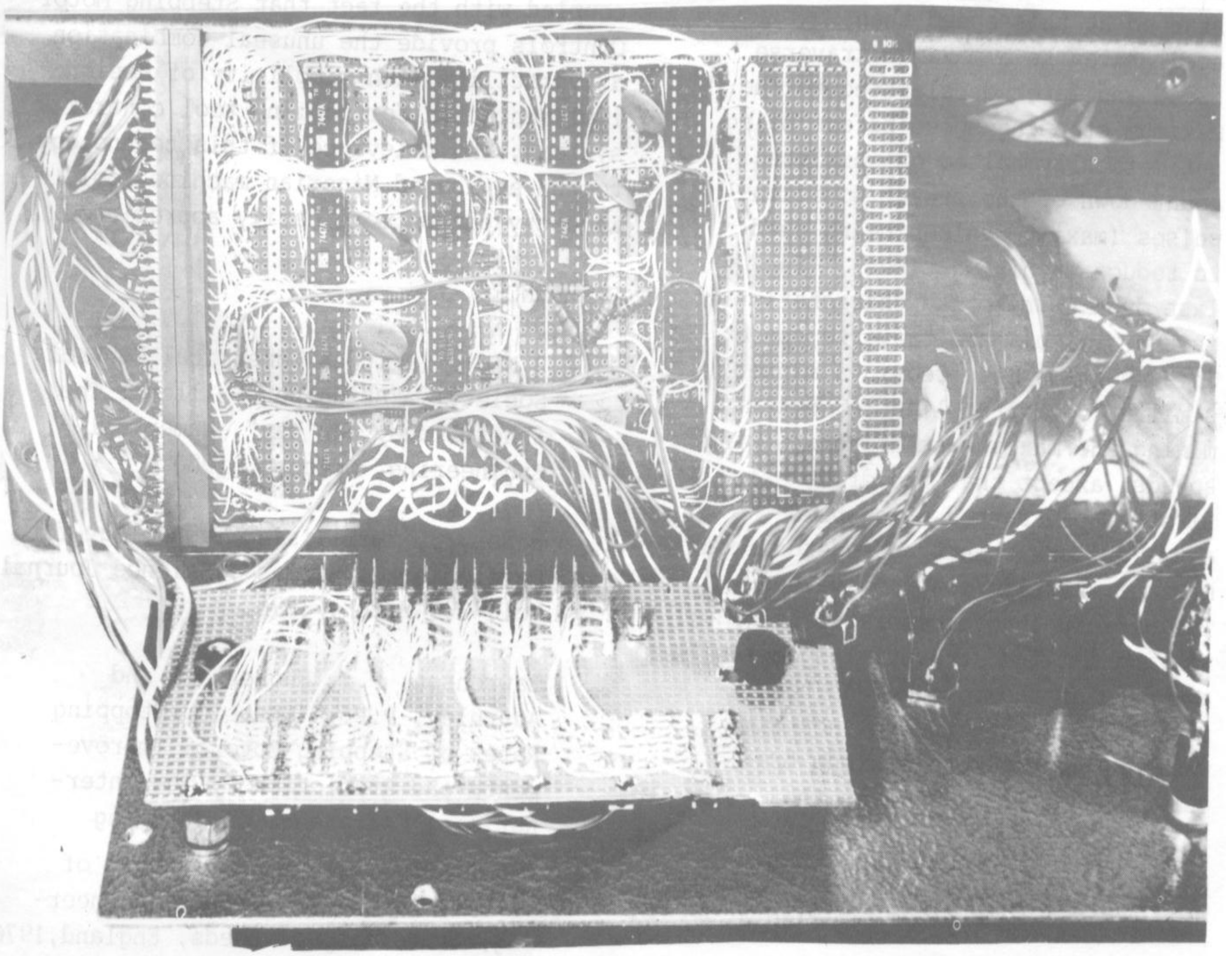


Fig. 6(b) the position command logic box and control switches the black box

motor command logics enclosed in the "Black Box". In this design a machine resolution of0.00254mm (0.0001 in) was achieved in each axis of the machine tool. This level of resolution ensures accuracy in the machine tool control system and hence components produced using it.

4.3.3 General Dynamic Response

After ensuring the stability of the transient response of the machine axis (section 4.3.1.) and having measured are the maximum starting and stopping speeds for the axis-[3] Different starting/stopping (mm/min for the axis corresponding to pulses from the black box) are preset on the frequency control switch on the black box in increasing order of magnitude. The machine resolution is re-checked for each speed to confirm that the resolution is constant (i.e. no pulses have been lost by the drive) until a certain approximate maximum speed consistent with this accuracy is reached. This will then become the maximum starting and stepping speed tolerated by the drive. The machine axis can (in future) be started at this speed then accelerated to a maximum traverse speed and later decelerated to the maximum stopping speed before being automatically halted on complete count down of the preset position pulses (maximum values being used to reduce machining times), The last dynamic response characteristic is the maximum axis traverse speed. This is again measured in a manner similar to that applied for determining the maximum starting/stopping speeds, except that the drive has first to be started at a speed equal or less than the predetermined maximum starting/stopping values. The axis is then accelerated to varying maximum (traverse) speeds and decelerated to stop and the resolution is re-checked each time until an approximate maximum traverse speed that maintains the resolution is reached. In this design the maximum starting/stopping and traverse speeds recorded were 150mm/min and 380/min respectively. (The latter value. was limited by hydraulic power system with which the test machine tool was equipped).

5. CONCLUSION

The Numerical Control "Black Box" designed in the course of this study was successfully used to test and measure the mechanical characteristics of a "High Precision Equipment"(H.P.E) machine tool. There are nine switches on this black box providing the necessary control commands to operate the system. The position commands are affected with cascaded decade counter systems which are externally preset with B.C.D. thumbwheel switches. Forward Reverse, speed, Jog, Load, Start, Step, and Motor-phase-pulse-energisation- mode controls are provided by these external switches.

The total cost of bought items used to manufacture the "Black Box" is estimated at less than N400. 00. With the down-ward trend in the cost of electronic components this cost would be considerably lower in future years. When this is coupled with the fact that Stepping Motor Controls provide the unusual combination of verstility with simplicity of design implementation for machine tool control systems, the relevance of this technology to the envisaged Nigerian machine tool industry can be more easily appreciated.

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