A MICROPROCESSOR CONTROLLED PHYSICAL SIMULATOR:

AN AID TO MANUFACTURING EDUCATION

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PREFACE

Current interest in the Industrial Engineering profession of modeling automated manufacturing systems has increased the need to educate graduates accordingly. This report presents a reasonable approach to such instruction obtainable through the use of microprocessor controlled physical simulation. Physical simulators, herein described, are operational iconic models of manufacturing equipment that can provide students with the opportunity to obtain hands-on experience in real-time manipulation and control of manufacturing system components. Comprehensive details of a physical simulator component design, its fabrication, interfacing, and system testing are included. Applications in the area of machine tools is the prime interest.

I wish to express my appreciation to Dr. John W. Nazemetz as report adviser for his guidance, assistance and valuable suggestions throughout this study. I would also like to acknowledge and thank Eduardo Martinez for his valued contribution in programming software development and Gary Gerber for his indispensable efforts in the electronic interfacing. I am also thankful to Charlene Fries for typing this report.

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CHAPTER I

INTRODUCTION

The complexity of the modern manufacturing environment has led to the implementation of sophisticated technology to control manufacturing operations. Microcomputer technology in particular has been effectively applied to the engineering problems confronting this area. This microprocessor-based technology is being used to control manufacturing processes, as well as acquire data for production control activities and for other related functions.

It is apparent, therefore, that Industrial Engineering students must be familiar with this vital and growing component of the manufacturing environment. They must be acquainted with and appreciate its use or at least its effect upon the design and content of manufacturing operations. The formal education of the industrial engineer should include exposure to microprocessor-based manufacturing control and data collection in as realistic a fashion as possible. Since most universities lack full scale manufacturing facilities and do not have sufficient funds to acquire microprocessor-controlled equipment, plant tours and field trips are used to provide an element of realism. However, this lacks the ingredient of hands-on learning which provide for a clearer comprehension of the concepts involved in the automatic control of systems.

CHAPTER II

USE OF MODELS IN MANUFACTURING EDUCATION

Many students coming into manufacturing curriculums lack familiarity with the industrial environment and in particular with the operations of manufacturing systems. The increasing complexity of modern microprocessor-based manufacturing require effective teaching tools to enhance the learning experience. Conceptualizing these often complex systems becomes an issue. Few educators, such as Dr. Gus Olling of Bradley University, enjoy the benefits of having a full scale system with which to teach manufacturing concepts. Short of this, most educators are faced with implementing alternate methods for providing as much realism as practical to the students.

The classic approach generally taken to teaching the design and control of manufacturing systems is that of modeling. System modeling enables full scale complex, inaccessible or economically unattainable systems to be studied in some detail. Practitioners are often faced with making decisions with respect to system development and will rely on modeling techniques to aid in this decision process. Such techniques allow a proposed system to be developed in model form, i.e., mathematically modeled and simulated, then manipulated to test the impact of changes in one or more components of the model. System parameters thus tested can then be well defined or modified to produce the desired outcome prior to large investments of both time and money.

There are three fundamental model classifications: iconic, analog, and symbolic[9]. The iconic model closely maintains the visual effect of the situation under consideration (e.g., a scale model). In the analog model a set of system properties or parameters is substituted by analogous properties (e.g., activating a light to indicate a process or operation). The symbolic model is an analytical and abstract representation of a system (e.g., equation of a line, y = m x tb). Each model type obviously has its advantages and disadvantages which will not be discussed herein. Suffice it to say that the iconic model most closely physically represents or simulates a system or component and lends itself well to microprocessor control.

The current interest in the industrial engineering profession of modeling automated manufacturing systems has increased the need to educate graduates accordingly. It is the purpose of this paper to provide the School of Industrial Engineering at Oklahoma State University with a usable guide for implementing manufacturing systems modeling via physical simulator, i.e., the iconic model. This will be accomplished by gathering data which will be useful in determining the direction with which to pursue physical simulation.

The procedure commenced with a comprehensive review of that is currently being done by educators in the area of physical simulation. Next, based upon those results, an outline for development of physical simulation implementation will be presented. Then, details are presented for the design and construction of a modular component of a manufacturing system. Finally, recommendations are made for further studies.

CHAPTER III

PHYSICAL SIMULATOR STATUS

In order to determine what is currently being done by educators/ industrialists, with respect to physical simulators, a literature search was conducted. This was accomplished via three thrusts: scanning periodicals, using a computer literature search, and a telephone survey.

A thorough scanning of current periodicals revealed a small number of useful articles[2,6]. Therefore, in order to increase coverage, a library on-line computer search was conducted. Again, only a small amount of information surfaced with respect to physical simulator use. Most of the findings were regarding computer simulation, i.e., symbolic models. The most comprehensive studies uncovered at this point were those conducted at Purdue[1]. Since the desired data were not forthcoming, the direct contact route was taken. This involved data gathering by a thorough telephone campaign. The procedure was that various educators were telephoned, solicited as to their views on physical simulators, and asked for any other contacts/leads of persons involved with physical simulators. Each lead was followed in turn until all leads were exhausted. This iterative approach proved to be the most successful in terms of information gathering. Twenty telephone conversations were carefully transcribed and edited in order to present the information effectively. A list of those individuals contacted is presented in Appendix A.

Telephone Survey

A summary of these transcriptions is now in order. What precipitated from these conversations was not a clearly singular consensus, as might be expected. Instead, a trident of philosophies emerged as to what should be done by educators to aid in the teaching of microprocessor-based manufacturing systems via physical simulators.

One philosophy maintains that physical simulators be constructed from reusable materials. The Fischer-Wenke Company of West Germany manufactures such a set of modular reusable component building blocks. Marketed under the name of Fischer-Technik, these kits are comprised of basic structural and mechanical building elements as well as electrical and electromechanical devices for power and control. The basic elements of these kits are plastic injection molded precision parts. They allow construction into functional assemblies by sliding, twisting, or snapping various pieces together.

Similar in concept to the toy Erector Sets manufactured in the United States, the Fischer-Technique kits are often called sophisticated toys. Their precision and versatility facilitate construction of bridges, towers, conveyors, and many other types of mechanical and electromechanical devices. In the hands of creative student engineers, these kits can be used to build models of various physical systems.

Several manufacturing educators are using Fischer-Techniks to model manufacturing systems. Meier and Nof of Purdue and Deisenroth of Michigan State[6] have done some pioneering work with physical stimulators built from Fischer-Technik kits. Others are implementing and/or expanding this usage. For instance, at Oklahoma State University, Mike Sales (an Industrial Engineering graduate student) successfully constructed and operationalized a Fischer-Technik conveyor system patterned after the Purdue work. What seems to be lacking, however, is detailed, comprehensive documentation of how to replicate a particular system. When the researcher leaves, often the source of system information is in absentia.

While Fischer-Technik kits are popular and versatile, they are somewhat expensive. They are sufficient for sophisticated iconic model building but lack rigidity and cause some problems during activation (e.g., sticking and wear yields ineffective sliding motion). Such a model has realism but lacks the practicality of material removal. Also, all components of these kits are seldom completely used and spare parts inventory can become a matter to be solved.

A second philosophy favors converting small bench top conventional machine tools into numerical control machines. This is accomplished by retrofitting the conventionally controlled (manual) machine tool, making it into a microprocessor-controlled machine. D.C. stepper motors are generally fitted in place of the manual hand wheel controls. Interfaced with a microprocessor, these steppers provide for automated control of the basic machine tool functions, such as activation of cross slide or spindle. Other peripheral functions of turning on relays, monitoring sensing devices, etc. can be likewise be accomplished. The resulting dedicated equipment is capable of machining and fabricating parts. Of course, this requires the acquisition of the original machine tool, which in itself is not inexpensive. These machines are, however, much larger and more robust than the Fischer-Technik physical simulators.

Several manufacturing educators are either doing or are considering doing retrofitting. Biegel of Kansas State University has successfully retrofitted both a milling machine and an engine lathe[4,5]. At Wayne State

University, Lamberson[16] is using a retrofitted bench top milling machine in his computer-aided manufacturing laboratory. Most of those not involved with retrofitting think the major drawback is in the cost of the basic machine tool and the cost of the more robust retrofitting necessary, i.e., higher motor horsepower, more voltage, and current required, etc. The last philosophy takes the middle road and incorporates features from each of the other two philosophies. Here the idea is to build a working scale model of a particular type of production equipment capable of material removal. This model could represent one component of a manufacturing system. In size it would be close to the Fischer-Technik models; however, in rigidity, accuracy, and repeatability, it would be more like the retrofitted machines. The procedure is to manufacture or purchase only those items necessary for the fabrication of the model. Assembly would then be much like using the Fischer-Technik except that a stouter, more robust model would result.

Not many educators are implementing this concept. This may be due to lack of facilities, available talent, or interest. A preponderance of educators opt for the Fischer-Technik type of physical simulators. One of the exceptions, Wisk[16] at Virginia Polytechnic Institute, has developed an automated manufacturing cell which includes machine tools that were built in-house. The three- and four-axis milling machines are identical replicas of production equipment in terms of operation. These model machine tools are constructed of aluminum and capable of machining soft materials (polymers and nonferrous metals).

Interestingly, some educators, like Kimbler[16] of the University of Southern Florida, are using Fischer-Techniks as prototypes to a scaled permanent working model. After construction of a Fischer-Technik physical simulator, the design is lifted and transformed into a "hard copy" of the system component.

Another example of this type of modeling used to teach the concepts of microprocessor control is the automatic storage and retrieval system (ASRS) modeled by Bedford and Sobczak at Arizona State University[8] and again at Oklahoma State University by Wolf. This scale model automated three-dimensional warehouse allows students to have interactive control over optimization of random storage and retrieval functions. It has been "extremely worthwhile" as a hands-on aid to the learning of inventory control concepts.

Outcome of Survey

After reviewing this information, it was determined that the best direction would be to apply the latter philosophy. This would be to build a small scale model capable of simulating the physical aspects of a manufacturing system as well as actually preforming the system function, e.g., material removal. Furthermore, it was decided that a prototype of a standard machine tool (lathe, drill press, mill, saw) be modeled. Subsequent machine tools could be patterned after this one. Also, design and fabrication aspects of construction would be documented so that a complete manufacturing cell or system could be eventually be developed and constructed.

This type of model would incorporate in its construction and operation the interdisciplinary concept which in itself will simulate the real world of manufacturing applications. It would require the use of mechanical aspects of design, electrical power considerations, electronic interfacing, and programming. As other models of this type are constructed, the team approach will provide an additional benefit for those students involved with the actual fabrication.

Once the necessary machines of sufficient number have been modeled and operationalized, the modular units would accommodate hands-on instruction in several manufacturing related areas. In particular, those areas which are closely associated with the microprocessor-based technology incorporated in today's modern manufacturing facilities can be emphasized, such as flexible manufacturing systems, plant layout, optimization of production processes, material handling, group technology, etc.

CHAPTER IV

DESIGN OF SIMULATOR

The analysis of the previously mentioned survey resulted in establishing a direction for modeling manufacturing systems. In order to build a small component of such a system many design aspects must be considered and implemented. The design phase consists of several steps: (1) a statement and analysis of the problem; (2) an outline of principle requirements; (3) gathering data or available materials, equipment, parts, etc.; and (4) preparing details for fabrication.

Definition and Analysis of Problem

An effective design sequence begins with a concise and precise statement of the goal or problem. In this case the goal is to build a small scale model component of a manufacturing system that is capable of simulating actual system functions. Analysis of this very broad area resulted in a refinement to the specific area of machine tools. A further distillation requires a decision as to which machine tool to model.

Since this was a prototyping activity, it was decided to design a basic building block from which other machine tools would be developed. Construction of a simple X-Y table was determined to be the logical first step. This mechanism could be manufactured in such a way as to simulate, by appropriate modifications, various machine tools, e.g., drill, mill, tap, grind, etc.

The X-Y table shown in Figure 1 consists of two orthogonal axes residing in a horizontal plane. Each axis would be capable of independent motion in either direction along its axis. This fundamental motion, of mutually perpendicular movement, is used in all classes of machine tools. It is upon this table that either a workpiece or tool could be situated to facilitate the necessary material removal function.

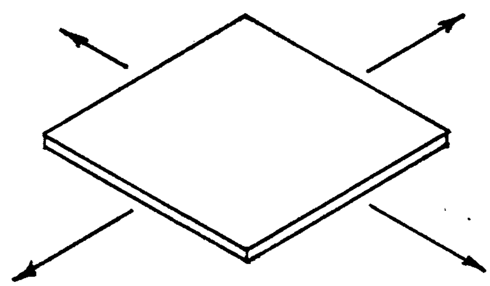


Figure 1. X-Y Table

Specification of Requirements

Based upon the overall function of the model, the specification phase of design involves determining the principle operating requirements for the X-Y table. Features to be considered include cost of table, its function in terms of motion, and power and drive requirements.

Cost Factor

The cost was to be kept considerably lower than the estimated cost of a comparable Fischer-Technik model or retrofitted machine, specifically targeted to be less than $300. The physical size of the prototype would to a large degree control the cost factor of the hardware portion of the model. Therefore, a work envelope of approximately 4 in. x 4 in. was considered to be adequate for simulation purposes and was chosen as a design constraint.

Functional Attributes

Since it is intended that the model be capable of cutting material, it should be rugged enough to function appropriately. Parameters of this feature include functional rigidity (in terms of deflection), positional accuracy of $\pm$0.001 in., and repeatability to within 0.005 in. nonaccumulative. These are qualities innate to the method of motion and drive that are implemented, e.g., resolution of motor and drive train components.

The primary motion of the X-Y table could be effectively accomplished by one of two methods: dovetail slide or rod and linear bearing slide. The dovetail would require a significant manufacturing effort but would provide for a rigid and smooth action. On the other hand, the rod and bearing configuration would need only a moderate amount of manufacturing by comparison and would supply the sufficient rigidity. Both of these mechanisms are available commercially, but it was decided to manufacture as many of the components of the prototype model as possible. A number of items for the table were, however, purchased, such as shafts, rods, bearings, and drive mechanism components. What was to be manufactured were those parts which would hold, align, and eventually integrate the parts into a completed assembly. Then a cost comparison could be made between strictly buying and assembling versus manufacturing plus purchase and then assembly. Additional benefits could be gained by the students in the actual machining and fabrication of the various parts.

Two fundamental rotational to linear mechanical actuators were considered as drive mechanisms: the rack and pinion and the lead screw. Both were equally attractive mechanically. Again, the decision of which to use was made based upon judgment as to ease of manufacture. It was estimated that a rack and pinion would take two to three times as long to fabricate and be more difficult to adapt. The lead screw was chosen on this criteria and the fact that backlash in the lead screw would be easier to control (see Figure 2). This backlash control would enhance attainment of the specified design goal of ±0.001 in. positional accuracy.

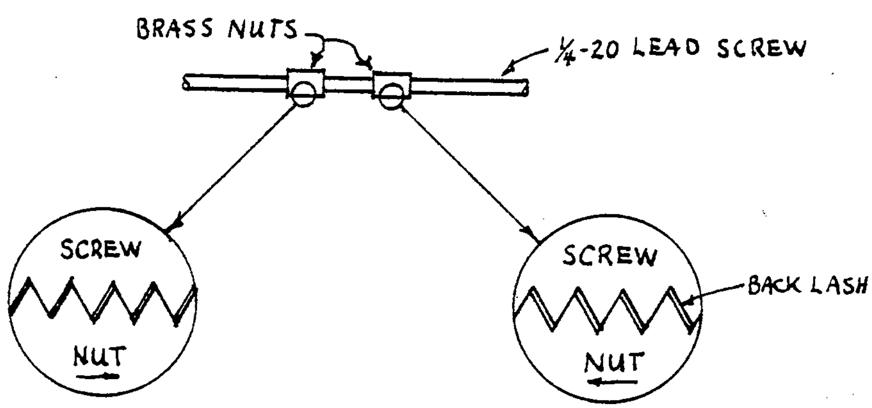


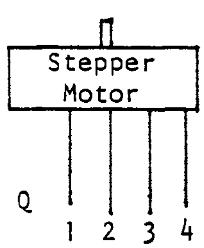
Figure 2. Lead Screw (Double Nut)

Power and Drive Train

The most convenient and easily interfaced power source is electricity. Other sources such as the areas of pneumatics, i.e., compressed air, and hydraulics were rejected due to the bulk of the actuators and the pressure supply units. Most of the commercial units use electric motors for power and it would seem reasonable to go directly to this source. There are two basic types of electrical motors which would be appropriate for this application: AC reversible and DC stepper. The AC motor was dismissed because of the interface control problems posed. Thus, by elimination the DC stepper is chosen. It is also directly compatible with microprocessor control.

It is necessary at this point to discuss basically how the stepper motor activates. The motor operates by interaction between a permanent magnetic fluxfield of the rotor and the electromagnetically induced fluxfield generated by applying direct current to the stator windings. The proper switching sequence of the coils will control stator flux and cause clockwise or counterclockwise stepping to occur.

As graphically depicted in Figure 3, a step will occur when coil windings are simultaneously activated or not activated and set in a particular on-off order. For instance, to make a second clockwise step, from step 1 to step 2, coils Q1 and Q2 settings remain unchanged while coils Q3 and Q4 settings are reversed, i.e., made to go from on to off for Q3 and off to on for Q4. This switching sequence is controlled by the logic in the motor drive and control system circuitry.



CW	Unipolar Windings				CCW
Step	Q_1	Q_2	Q_3	Q_4	Step
1	On	Off	On	Off	4
2	On	Off	Off	On	3
3	Off	On	Off	On	2
4	Off	On	On	Off	1

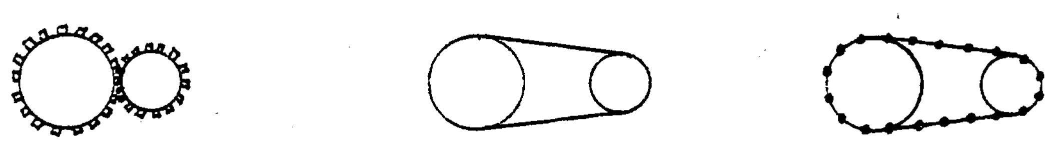
Figure 3. Normal Four-Step Sequence

Of the various stepper motor types[13], the permanent magnet type is considered the most economical with good accuracy and long life. Complete details of the stepper motor operations can be found in Reference 10.

Drive Train

The coupling between the lead screw and stepper motor shaft was not to be accomplished directly by a positive mechanical connection. Instead, coupling was to be through a reducer drive mechanism, e.g., either a gear set or belt and pulley or pin belt and sprocket. Versatility would be thus present in this feature as it would allow the student to vary the drive ratios by changing gear, pulley, or sprocket sizes.

Each of these drives has its advantages and disadvantages. The gear set inherently has a backlash problem but provides for positive drive. The belt drive does not pose a backlash problem, but can slip and cause positional errors. The pin belt drive combines the advantages of the other drives--that of a positive, no backlash drive (see Figure 4). More information on selection of pin belt drives will be discussed in design details. This occurs directly after the next section covering availiability of resources.



Geared | Pulley and Belt | Sprocket and Pinned Belt

Figure 4. Coupling Types

Resource Availability

To implement the design and begin construction of the model, it is necessary that essential resources be readily attainable. Availability of manufacturing equipment and materials, controller motors and components are considered the pertinent resource categories.

Facilities

The School of Industrial Engineering at Oklahoma State University does not have its own direct resources for manufacturing the needed components. However, the academic environment at Oklahoma State University is such that cooperation is encouraged among the various schools within the College of Engineering. Since the School of Technology has the necessary manufacturing capability, and Industrial Engineering and Manufacturing Technology had previously developed a satisfactory relationship with respect to mutual use of facilities, an agreement culminated to allow the use of Technology's machineshop for fabrication of this prototype. Some of the materials needed in this fabrication could be acquired through Technology's stock. They would be subsequently reimbursed for all consumable materials used. Other materials would be obtained via purchase from local suppliers.

Controller

The microprocessor used as the control device was the PET Commodore 2001. The PET, Personnel Electronic Translator, 2001 is an MSC 6502 microprocessor programmable in Basic Language. Of its several peripheral interface connections, the parallel user Port J2 is applicable to the

X-Y table use. Some consideration was also given to the Radio Shack TRS-80, Model III, but technical information was not present as to peripheral interfacing; therefore, its use was not further pursued.

Motors and Components

A number of motor and precision component manufacturers were helpful in supplying catalogs and technical literature. This material was obtained and reviewed so that judicious selections could be made regarding which items would best suit the design parameters. Some decision criteria follow next in the section on design details.

Design Details

The final step prior to the actual manufacturing and assembly was to "spec" out all the necessary components of the model. The proper choice of motor was to be considered, as well as its driver and control circuits. The motor to drive coupling mechanism was to be finalized. Then the physical dimensions of the various components, purchased or manufactured, were to be determined and engineering drawings made for construction. These features were all incorporated in the details of design.

Motor Selection

The choice of stepper motor depends upon several factors such as cost, both initial and interface, resolution, torque, and physical size. The cost factor dictated that the torque producing ability of the motor be adequate but not extravagant.

The resolution of the X-Y table depends on the pitch of the lead screw and the step angle of the motor. The pitch is the distance, or lead in a single lead thread, which the table would travel per revolution of the screw. The pitch is determined by the number of threads cut per inch on the screw. The step angle is the normal angle that the motor shaft rotates for each winding polarity change. Table 1 is a matrix showing the various outcomes of available stepper-lead screw combinations.

TABLE 1. X-Y TABLE RESOLUTION

Step Angle		7.5°	15°	18°
Steps/Rev.		48	24	20
N	P	Resolution		
18	.055	.00115	.00230	.00275
20	.050	.00104	.00208	.00250
24	.042	.00086	.00170	.00208
28	.036	.00075	.00150	.00180
32	.031	.00065	.00130	.00156

N = number of threads per inch.

P = 1/N, lead.

Since the desirable functional characteristics included an accuracy goal of ±0.001 in., the combination yielding the closest resolution was chosen. Therefore, it was decided to use the smallest motor step angle of 7.5 and a lead screw with 20 threads per inch, resulting in a resolution of .00104 in. per step, closest to the targeted .001 inch per step. The fact that it is not an exact increment could be accounted for in the control program software.

Stepper motor manufacture's speed-torque characteristic curves were next consulted to select the correct motor for the particular application.

It was then necessary to specify the speed and torque requirements for the model.

The speed of the motor shaft will determine the rate at which the lead screw turns and subsequently the rate at which the table moves or feeds. Since the optimum rate of feed is a function of work material, cutter material, number of cutter teeth, and cutter speed, it would require a range of operating speeds, dependent upon the particular machine tool and operation performed, i.e., milling, turning, boring, etc. However, a feed rate for an X-Y table used for drilling would not need a range but could be operated at system drive capacity; in other words, move from position to position as quickly as possible. In either case the translation rate could be varied via appropriate software. The upper limit on this range is determined by the motor output torque.

Steppers manufactured by Airpax[10] have a wide range of torque to steps per second. System torque requirement will be used to specify the motor and thus the speed range. The exact torque magnitude was difficult to derive because the required data were not available. That is, some components had not been sized. The closest estimate of torque was made by calculations using the following formula[14]

$$T_f = \frac{Fd}{2}\,\frac{\ell + \pi\mu d}{\pi d - \mu\ell} \qquad (1)$$

where

d = mean diameter = 1/4 in.;

μ = coefficient of friction = 0.05;

ℓ = lead = 1/20 in.; and

F = force estimated at 5 lb.

$$T_f = 0.5 \text{ oz in.}$$

Other factors difficult to estimate, e.g., bearing friction, drag of drive train, etc., warrant the use of a high safety factor. A factor of 4.0 would yield an estimated safe torque of 2 ounce inches.

The stepper motor manufacturers have a torque formula that considers some finer aspects of torque imposition, primarily inertial loads[10]. Such a formula follows:

Total torque = torque due to mass moment of inertia

+ torque to move 5 lb load

$$T_{total} = (J_m + J_s + J_r)\alpha + T_f \tag{2}$$

J_m = motor rotor moment of inertia

$= \text{given } \underline{3.1 \times 10^{-3}\ g\cdot m^2}$

J_s = screw moment of inertia

$= D^4 \times 7.7 \times 10^3$

where: D = 0.25 in., screw diameter

ℓ = 9 in., screw length

$= \underline{2.86 \times 10^{-6}\ g\cdot m^2}$

J_r = reflected moment of inertia

$= ML^2 \times 0.025$

where: M = mass, 5 lb

L = lead, 0.05 in.

$= \underline{7.2\ g\cdot m^2}$

α = acceleration

$$= \frac{\Delta V\ \pi}{\text{no. steps/rev}}$$

where: ΔV = 100 steps, est. steps/rev = 48

$$= \underline{2.08 \text{ rad/sec}^2}$$

$$T_f = \underline{0.5 \text{ oz in.}}, \text{ from Equation (1)}$$

$$T_t = (3.1 \times 10^{-3} + 2.86 \times 10^{-6} + 7.2)\ 2.08/7.06 + 0.5$$

$$= \underline{2.62 \text{ oz in.}}$$

A more modest safety factor of 2.0 can now be used, yielding a 5.2 ounce inch total system torque requirement. An Airpax stepping motor having a running torque with this magnitude and a step angle of 7.5 degrees was considered. The operating characteristic curve for the unipolar K 82701-P2 stepper is shown in Figure 5. It represents the maximum output torque produced at a given step rate. In this case, at about 5.2 ounce inch the step rate will be approximately 100 steps per second. It remains only to determine if a maximum step rate of 100/sec is adequate. With a lead screw pitch of 0.050 in. per revolution and a motor with 48 steps per maximum revolution at 100 steps per seconds, a 100/48 (0.050) = 0.104 per second maximum feed rate is attainable. This equates to approximately 6 in./min when direct motor coupling is used.

Drive Coupling

The coupling between the lead screw and motor shaft was to be accomplished through a reducer, either a set of gears, belt and pulley, or belt and sprocket drives. Sources for these components were consulted and an assessment made of adequacy and flexibility. Berg Inc.[11] manufactures a belt and sprocket drive system which was deemed to be ideal for this application. The Min-E-Pitch® belt drive system, as it is called, is a set of specially cogged sprockets that mesh with a matching toothed

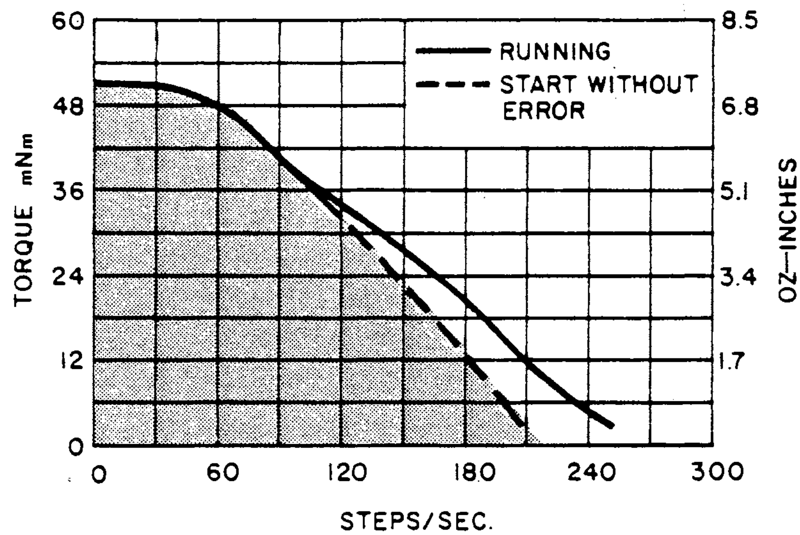


Figure 5. Torque Versus Drive Rate[10]

belt. The belt is comprised of a stainless steel cable and polyurethane teeth which combine to form a strong flexible, quite, lube-free drive. It also has zero backlash for positive drive and can be used in high speed applications.

Various sprocket diameters and belt lengths are available which would lend a degree of versatility in the coupling by adjusting the drive ratio. A ratio of 2:1 was judged sufficient for speed and torque requirements. As a result the feed of the table per step of motor would be reduced by one-half, thus increasing positional accuracy. The apparent motor torque output would be doubled, that is, twice the torque can be handled. However, if the needed torque remains unchanged as calculated, this increased motor torque could accommodate the safety factor of 2.0 in the design.

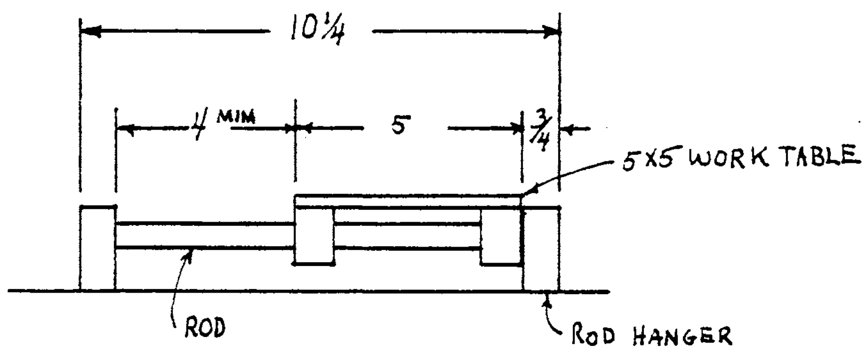


Figure 6. Y-Axis Rod Length

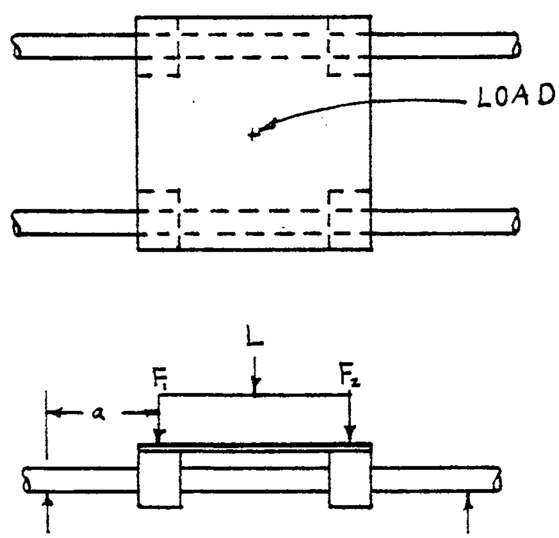


Figure 7. Y-Axis Rod Loading

Sizing Components

Determining the configuration of the various structural members was an iterative process. For instance, it would begin by choosing a key component, sizing it, and then continuing to size the attaching parts until a constraint is encountered, i.e., lack of clearance between parts. After correcting the problem, it would then be necessary to work backwards until the key component was confronted. At this point the design was checked against the specified goals. If satisfied, the process would continue on the next component; if not, another iteration was performed, and so on.

In this way each component was designed. An example of this is the sizing of the shafts or rods. The rod length was determined by the previously determined size of work table, 5 in. x 5 in., and the fact that a 4-inch travel was specified. Additionally, the rod ends must be supported and allowance was made for the grip length of rod hangers or supports. The overall length for the Y axis was therefore established at a minimum of 10¼ in., as shown in Figure 6. The rod diameter was determined by the applied load of table, work, and drill thrust. The criterion here is that a minimum of deflection would be tolerated. Calculation of deflection was based upon a simply supported beam with twin loads, as depicted in Figure 7.

Since beam deflection is load dependent, the load must be estimated. This begins with drill thrust and then work and table weight is added for total applied load.

Drill thrust calculation[15]:

$$T_d = (2\,k\,f^{0.8}\,d^{0.8}\,B) + k\,d^2\,E \qquad (3)$$

where

T = thrust in lbs;

k = 7000;

B = 1.355;

E = 0.03;

f = drill feed/revolution; and

d = drill diameter.

Aluminum work piece, standard drill point

$$T_d = 18970\ f^{0.8}\ d^{0.8} + 210\ d^2$$

Thus the thrust is of function of drill diameter (d) and feed per revolution (f). Table 2 shows pounds of thrust at various diameter and feed combinations.

TABLE 2. DRILL THRUST IN POUNDS

f \ d	1/8"	1/4"	3/8"
.001	17	38	63
.002	28	56	84
.004	46	88	134
.006	63	118	174

It was arbitrarily specified that the table and work weights should not exceed 5 pounds. Therefore, another calculation is needed to determine deflections based on the following formula[14]:

Maximum deflection for twin loaded beams:

$$D_{max} = \frac{F_a}{24EI} (3\ell^2 - 4_a^2) \quad (4)$$

where

F = force, load/4;

a = 2.5 in.;

ℓ = 10 in.;

$I = d^4\pi/64$, d = rod diameter; and

E = modulus of elasticity, 30×10^6 psi.

This formula can best be solved for a particular force given a maximum allowable deflection and a rod size. The major consideration of deflection is obviously not to exceed a deflection which would cause permanent deformation in the rod. Well within this range, in the elastic region, the consideration is directed towards accuracy of machining. For the drilling operation an accuracy of ±1/64 in. is satisfactory. Therefore, the total load, thrust plus work and table weight, should not exceed that which will cause a deflection of 1/64 in., about 015 in., say 0.010 in.

Applicable rod size is restricted to commercially available 1/2 in. or 3/4 in. diameters. The 1/2 in. shaft diameter at a deflection of ≤0.010 in. will be used in determining the allowable drill thrust.

Solving for F:

$$F \leq D_{max} \frac{24EI}{a(3\ell^2 - 4a^2)}$$

$$F \leq 33.3$$

Solving for T_d, when $F = \frac{T_d + 5}{4}$:

$$T_d \leq 4F - 5$$

$$T_d \leq 128$$

Based upon these calculations, this limits the drill size and feed per revolution. An applicable constraint would be that of ≤3/8 in. at 0.002 in. per revolution or ≤1/4 in. at 0.006 in. per revolution. It must be realized that these calculations are based upon estimated thrust loads applied at the center of the work table when drilling aluminum.

If drilling takes place at other positions on the table, deflections will be altered. For instance, if drilling directly over one rod the load will be doubled. Therefore, if the upper limit of drill parameters is approached, drilling should be conducted closest to the center of the table so as to distribute the thrust load.

When softer, easier machined materials such as polymers are used, less thrust will be developed and larger drill sizes and/or feed are possible.

Engineering Drawings

Rough sketches of sized components were made during this phase of design from which working drawings were finally developed. Appendix C contains all the drawings necessary for manufacture of the basic model.

CHAPTER V

FABRICATION

Manufacturing commenced when working drawings were completed and parts were specified. The basic machine tools used to manufacture these components were a Bridgeport Series I, model 2J, vertical milling machine, a Southbend 13" x 13" engine lathe, and DoAll band saw. Various tools were also used such as drills, reamers, taps, boringhead, end mills, counter bores, etc., all of which are specified in the operation sheets.

This one-of-a-kind prototype machine work often poses problems for flow charting, as most parts are manufactured on one machine and assembly takes place as parts are completed. An example of a component's development can be seen in the following operation sheet. The remaining operation sheets are presented in Appendix B.

Assembly

The content pages of Appendix B, operation sheets, and photographs in Appendix G are to be used in lieu of any assembly drawings as an aid to putting together the separate pieces. It is suggested that parts be manufactured in order of appearance (as shown in Appendix C) and be subassembled as they complete manufacturing operations. The existing model can also provide a guide for assembly (see Appendix G).

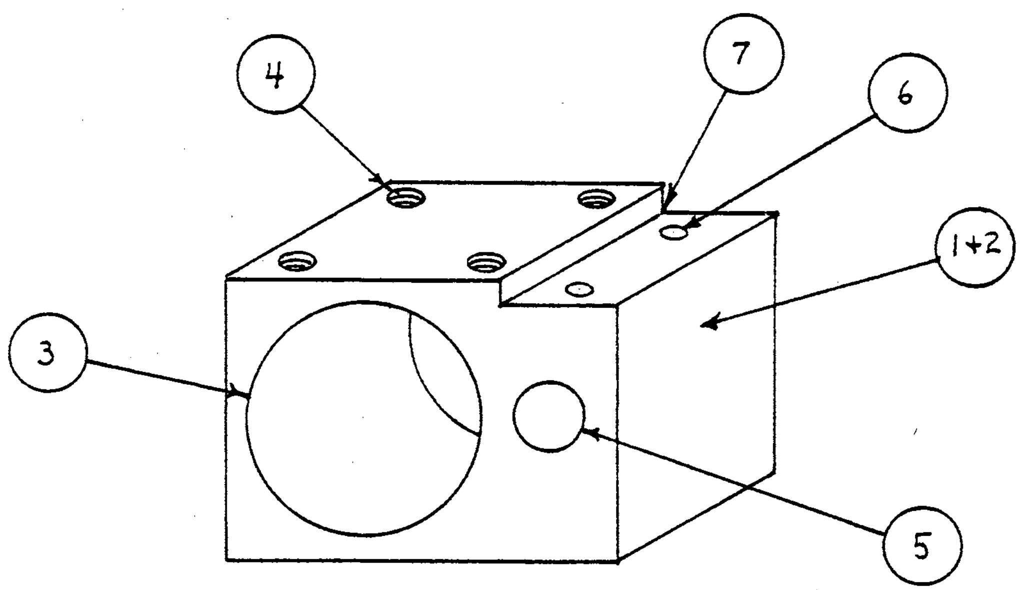
TABLE 3. OPERATION SHEET

PART: D, 3/4 IN. BEARING SUPPORT

OP No.	OP Description	Tool Equipment
1	Rough cut Allow for cleanup	S, Combination Square, scribe
2	Face mill all sides flat and square	M, 2 in. flycutter, Vernier calipers
3	Drill and through bore Bearing hole	M, #3CD, 1/2 in. drill, Boring head
4	Drill and tap hole pattern	M, #3CD, #20 drill, 10-32 HSS plug tap
5	Drill and ream for nut	M, #3CD, 23/64 in drill, 3/8 in. reamer
6	Drill and tap for nut	M, #2CD, #30 drill, 8-32 HSS plug tap
7	Mill clearance step	M, 3/4 in. HSS end Mill
8	Deburr and clean	File, burr knife, Parts washer

Estimated completion time, 3.5 hr.

S = saw; M = mill.



CHAPTER VI

SYSTEM CONTROL

Interfacing

In order to control each step of the rotor by a pulsed input to a drive circuit, it was first necessary to design that circuit. Data for this were obtained from the stepper motor manufacturer's handbook, which gives the stepper motor electrical requirements. Since the 12 VDC motors were chosen for the output torque, the first prerequisite was to obtain a 12V power supply which would be necessary to accommodate the motor and drive circuit. Such an adequate power supply was available in the School of Industrial Engineering at Oklahoma State University. The block diagram in Figure 8 shows the configuration of the control/drive system.

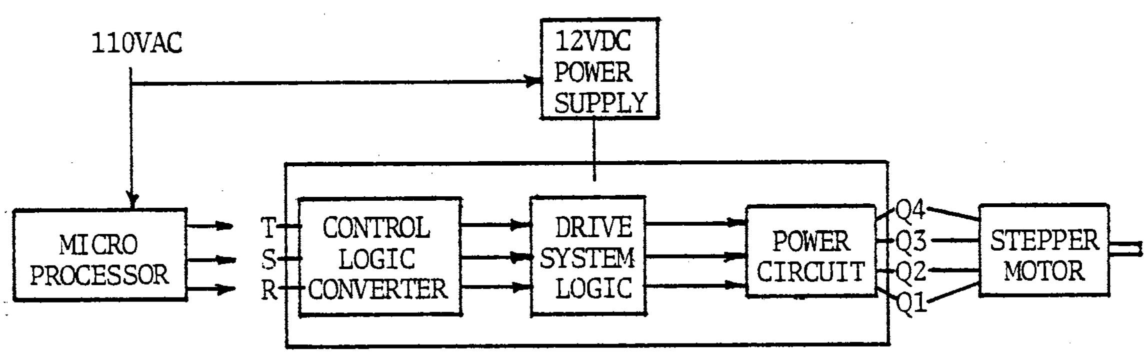


Figure 8. Block Diagram of Motor Drive and Control System

Next, the appropriate resistors and power transistors were sized in order to accommodate both the motor drive and the microprocessor interface control. It was necessary to design a circuit which would be triggered by a 5VDC input control signal and provide an output pulse of 12VDC. This required the addition of a converter circuit which would not have been necessary if the input control signal voltage was compatible with drive voltage. The complete drive and control system diagram is schematically represented in Appendix D.

Before programming of the microprocessor could begin, a clear understanding of the stepper motor drive requirements is essential. The control input to the driver circuitry, i.e., the output from microprocessor I/O port, necessitates a voltage of 0 or 5VDC, low or high, respectively. Three inputs to each motor driver circuit consists of a trigger, set, and rotation signals. The trigger, which is used to pulse or step the motor, is normally high, i.e., has 5VDC applied to it, so that a change to low and then back to high will trigger the control circuit to activate the motor one step. The motor therefore steps on the output of the positive going edge, as shown in Figure 9. The set allows for initializing the logic state of the motor windings to be on, off, on, off, Q1 through Q4, respectively. Rotation determines the direction the rotor will turn: if the signal remains high, the motor will step counterclockwise and vice versa for low.

To simplify matters, it was determined empirically that set input did not affect the operation stepper motors and was not considered in the following development. Therefore, what is needed from the program is to output a signal from the microprocessor to change direction of motor rotation and vary the duration of a fixed pulse rate. A maximum pulse rate

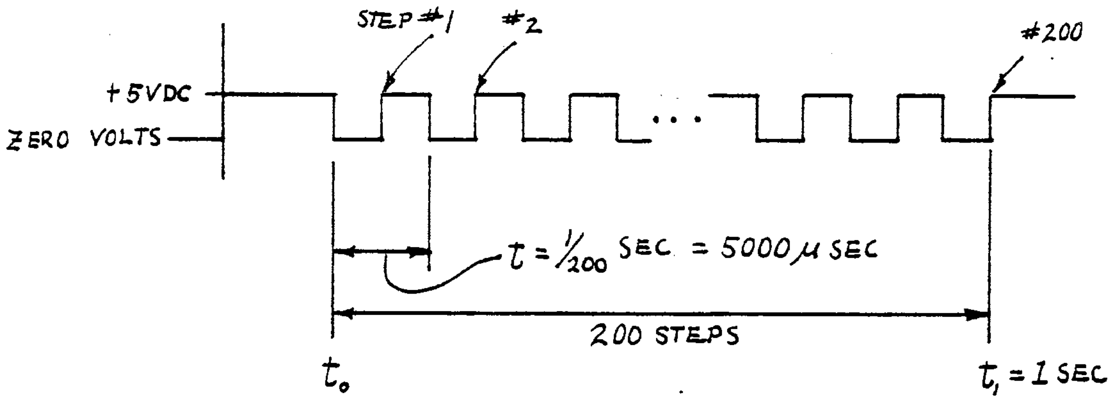


Figure 9. Square Wave Pulse at System Capacity (200 Steps/ Sec)

of 200 Hz was empirically determined by varying a 5VDC pulse rate using a square wave generator. At this rate the 48 steps per second motors will rotate approximately four revolutions in one second. With a drive output ratio of 2:1, the lead screw will rotate two revolutions per second, and at a lead of .050 in. per revolution the table will translate .100 in. per second, approximately one inch in ten seconds or six inches per minute.

In order to effect a move at this rate, the pulses must be timed and as shown in Figure 9 the off and on interval is 2500 microseconds. Now it is a matter of programming the trigger input to be on or off for this short time interval and then to vary the time during which this cycle occurs to determine how far the table travels. Some accommodation is, of course, necessary in order to activate each axis motor drive individually and simultaneously.

Programming

Once the control system requirements have been ascertained, the appropriate programming strategy can be established. This is often conveniently accomplished by using a pictorial representation, the flow chart. The flow chart helps to organize and visually display the logic of the required program. For this application a flow chart was developed and is shown in Figure 10. The actual control program is contained in Appendix F.

The programming port J2 is a 12 position, 24 contact edge connector of which 8 I/O lines are available for control. These data lines, numbered PAO through PA7, are independently programmable for either output or input. A POKE 59459 software command is used to place a number into the data direction register. This initiation determines which lines are to be used as input and which as output. For example, POKE 59459,255 labels all lines as output. A POKE 59471 can then be used to drive the appropriately defined output pin(s). If input lines are used, a PEEK 59471 statement will allow pins to be read. The following pin-control configuration was used: PAØ(C)--Trigger X, PA1(D)--Set X, PA2(E)--Rotation X, PA3(F)--Trigger Y, PA4(H)--Set Y, and PA5(J)--Rotation Y.

The program for the X-Y table is basically composed of two parts, a dual axis motion and a single axis motion. Both of these are in an interactive mode. The machine operator is asked if the move is to be dual axis. If so, then branching takes the program to the dual section; otherwise, the program continues by default to the single axis motion.

In the single axis mode, the operator is asked distance, rotation, and axis information. Distance is the magnitude given in one-thousandth of an inch increments.

A zero indicates a rotation such that table motion is toward the driving motor, and a one translates the table away from the motor. For

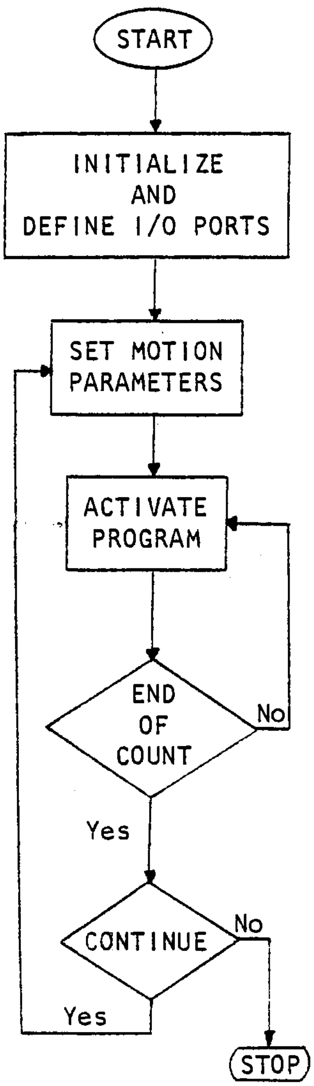


Figure 10. Flow Chart

the axis a one signifies the X axis (3/4 in. rod) while a zero signifies the Y axis (1/2 in. rod). Each individual move along a given axis from point to point is done by specifying this information. At the completion of each move the program continues to repeat the same interactive query sequence until the operator exits by terminating the program.

The dual axis motion portion is a convenience feature allowing other than only a single axis motion to be made with single data entry. For instance, if a relative move requires both X and Y, this program will initiate X axis motion first. When the X move is complete, the Y move immediately commences without operator interaction. A more complex program could have been developed to move both X and Y simultaneously. However, it would be no more efficient than what is in the current program. This is because of the method used to generate the output pulse, a function of the time it takes to POKE low, then POKE high, decrement, and check counter. (See steps 100-140, Appendix F.) (In the interactive section of the dual axis segment, a negative direction is taken to be away from the driving motor. The logic of the IF THEN statements can be altered to change this direction notation.)

The program was tested as to table function. Direction of notation was set to be positive toward the drive motor. Adjustments to the program, the logic of the IF THEN statements, can be made to change the direction notation relative to the spindle as appropriate. It is also possible to fine tune the accuracy of any axis move by altering the denominator in the count step of the program, e.g., 100 N = INT(D/.000522), from .000522 to .00055. As it is presently programmed, the accuracy is ±.001 per inch of table travel.

While backlash is within specifications, it can be reduced by judicious data entry for distance. Empirically determined, the X axis backlash is .0035 in. and the Y is .001 in. If the appropriate backlash is added to the dimension when a change of direction is forthcoming, the magnitude of backlash can be tightly controlled, if not eliminated.

Some manual functions could be incorporated in a more sophisiticated program which Industrial Engineering students could develop. Two such features could be to automatically compensate for backlash during directional changes and to provide for batch loading of positional data. If accomplished by the Industrial Engineering student, such programming would allow them to apply their skills to a real world application.

Testing

The X-Y table parameters were tested by securely placing a dial indicator in such an attitude that it is activated by the table movement. Maximum measurable discrimination of the indicator used was plus or minus one ten-thousandth of an inch, ±.0001 in. A square wave, five-volt signal generator was attached to the driver circuit and a pulse rate of about one per four seconds applied (adjusted for reading response time). The dial indicator face was observed and a reading taken at each pulse of the motor. Readings were recorded until sufficient data were obtained.

The statistics in Table 4 show that each test resulted in a tight average incremental movement of about .0005 in. This is twice the precision requirement, specified at ±.001 in. There were some isolated motor steps which resulted in an increment as high as .0007 in. and one at .0008 in. was recorded. However, this indicates that the precision range was still less than the upper limit specification.

TABLE 4. PRECISION TABLE PLACEMENT IN 10^{-4} IN.

Step No.	3/4 In. Rod Axis Test 1 A	I	Test 2 A	I	Test 3 A	I	1/2 In. Rod Axis Test 1 A	I	Test 2 A	I	Test 3 A	I
0	0		0		0		0		0		0	
1	5	5	5	5	3	7	7	7	1	1	5	5
2	10	5	10	5	7	4	10	3	6	5	11	6
3	15	5	15	5	14	7	19	8	13	7	15	4
4	20	5	19	4	18	4	20	1	17	4	22	7
5	26	6	25	6	26	8	29	9	23	6	28	6
6	31	5	28	3	29	3	31	2	28	5	34	6
7	37	6	35	7	36	7	40	9	34	6	38	4
8	41	3	39	4	39	3	42	2	38	4	45	7
9	48	7	44	5	46	7	50	8	44	6	49	4
10	52	4	49	5	50	4	51	1	48	4	55	6
11	58	6	56	7	55	5	60	9	55	7	59	4
12	63	5	60	4	60	5	62	2	59	4	65	6
13	68	5	66	6	67	7	70	8	65	6	69	4
14	74	6	70	4	R=3.8		72	2	68	3	75	6
15	79	5	75	5	M=5.15		80	8	75	7	80	5
16	85	6	79	4	S=1.81		82	2	79	4	86	6
17	91	6	85	6			91	9	86	7	90	4
18	96	5	90	5			94	3	89	3	96	6
19	102	6	96	6			102	8	97	8	R=4.7	
20	107	5	100	4			105	3	R=1.8		M=5.3	
21	113	6	R=3.7				112	7	M=5.1		S=1.08	
22	118	5	M=5.0				116	4	S=1.79			
23	123	5	S=1.07				123	7				
24	128	5					126	3				
25	134	6					133	7				
26	140	6					136	3				
27	146	6					143	7				
28	151	5					147	4				
29	157	6					152	5				
30	162	5					157	4				
31	167	5					163	6				
32	172	5					167	4				
33	178	6					173	6				
34	183	5					177	4				
35	189	6					184	7				
36	194	5					188	4				
37	200	6					195	7				
38	R=3.7						199	4				
	M=5.3						205	6				
	S=1.02						R=1.7					
							M=5.39					
							S=2.5					

A, accumulative; I, incremental; R, range; M, mean; S, standard deviation.

Possible reasons for parameter deviation in the incremental movements are that the lead screw pitch may vary slightly, that the inherent ±1/2 degree motor step angle accuracy may be active, or that the pulse of the motor caused the table to be accelerated at such a rate that deviations are a result of table momentum.

The magnitude of the backlash was determined by a similar setup. The table was activated in one direction for a short distance, then pin R of the drive board was controlled to reverse motor rotation. This involved either removing or applying five volts to pin R depending on its previous state, high or low. As soon as this activity was initiated, the number of audible steps were counted until the dial indicator began to register a movement of the table in the opposite direction to the previous motion. Each axis was thus tested and backlash results are tabulated in Table 5. The largest magnitude of backlash, .004 in., was in the 3/4 in. rod axis, which is within the specified parameter of .005 in.

The actual table displacement recorded during testing is compared to the expected value of displacement, as indicated in Table 6. The significance of these data are that there is apparently some accumulated error in individual tests, but that in other tests the error is nullified. Further testing of the system is required to determine the extent of any positive accumulation. It is perceived that any appreciable accumulated table displacement be accounted for in control system software development.

TABLE 5. X-Y TABLE BACKLASH

Trial No.	1/2 In. Rod		3/4 In. Rod	
	No. Steps	Inches of Backlash[1]	No. Steps	Inches of Backlash[1]
1	2	0.0010	6	0.0030
2	3	0.0015	8	0.0040
3	3	0.0015	7	0.0035
4	2	0.0010	7	0.0035
5	2	0.0010	6	0.0030

[1]At 0.0005 in. per step.

TABLE 6. COMPARISON OF ACTUAL TO EXPECTED TABLE DISPLACEMENT IN INCHES

Test	(Rod)	Inches of Displacement		
		Actual	Expected[1]	Difference[2]
1	(3/4)	0.0200	0.0193	0.0007
2	(3/4)	0.0100	0.0104	-0.0004
3	(3/4)	0.0067	0.0067	0.0000
1	(1/2)	0.0205	0.0203	0.0002
2	(1/2)	0.0097	0.0099	-0.0002
3	(1/2)	0.0096	0.0094	0.0002

[1]Expected value calculation:

No. of steps at actual displacement times 0.050/96
where: 96 = no. of motor steps per lead screw revolution; and
.050 = pitch of lead screw.

[2]Difference = Actual - Expected.

CHAPTER VII

CONCLUSION

This study began with the goal of determining the proper course to follow in implementing physical simulators in manufacturing education. The literature search combined with a telephone survey uncovered how prominent educators viewed physical simulation.

Three philosophies emerged in this regard. One philosophy inclines toward the use of Fischer-Technik precision plastic components to fabricate simulators. These models are iconic in nature but are not capable of adequate material removal, as in the case of machine tool applications. Another philosophy supports the retrofitting of conventional bench top machine tools with microprocessor control enabling them to fabricate parts, similar in operation to numerical control machines. The last philosophy adopts the idea of developing a scale model of a machine tool (e.g., a miniature milling machine) capable of actual material removal.

All three approaches have their merits; however, the last philosophy marries the other two into a project that has additional benefit aside from the fact that a working model is developed. Designed for students to build, a major portion of the construction of this type of model would utilize manufacturing operations which can enhance the student's understanding of manufacturing as a discipline.

By actually performing manually some of those operations which might be microprocessor-controlled in the working model, the student will begin to appreciate the role of the microprocessor in manufacturing operations. Additionally, the building of this type model will give the students involved an opportunity to work together as a team. Engineering team effort is essential to the growth of productivity in all areas of manufacturing, in terms of getting the most out of every resource. It is human nature that people have different skills, mental abilities, and levels of competency and motivation at their disposal. These attributes need to be exercised to the fullest in order to accomplish actitivies and achieve the objectives of the engineering goal.

Aside from the benefit the student will receive in the actual manufacturing, there is the exposure to the multidisciplinary feature of such a project. The mechanical and electrical design and manufacture, and the microprocessor interfacing and programming represent those areas which the student will become cognizant of and understand their interaction.

There is a final benefit derived by hands-on utilization of the completed model. This would focus on the strict manufacturing discipline of the model in question. For example, in using a model milling machine it would be necessary to determine such parameters as speed, feed, depth of cut, etc. This would be incorporated into the control aspects, i.e., software programming and the microprocessor interaction, used with the working model.

Implementation of Physical Simulators

It is therefore suggested that the Industrial Engineering department at Oklahoma State University consider further development of the herein designed model. This report, serving as a basic design document, can be utilized to manufacture as many fundamental machine tools as necessary to be used in a computer-aided manufacturing laboratory. The expansion of this area should include at least the concepts of the basic lathe and milling machine, in addition to the conversion of the X-Y table to a drill press. Other machines could be developed as the need arises.

Each machine tool, considered as a modular unit, could be incorporated into a group of like machines or those machines necessary to produce a class of parts. The latter is the machining or manufacturing cell concept. Such a machining cell, comprised of the fundamental tools, could be fed raw material by conveyor from a warehouse and be loaded and unloaded by a robot, all of which are controlled via microprocessor technology. A production system thus physically simulated could effectively be used for hands-on teaching both of undergraduates and graduates in the burgeoning area of computer-aided manufacture.

If, as suggested, several model machine tools are constructed, the concepts of job shop operations could be pursued. Since these machines are small and portable, they would lend themselves well to development of layout schemes to optimize the flow of work through a manufacturing cell. Flexible manufacturing systems could then be studied in real time. The system could be further expanded, as previously mentioned, by coupling material handling, robotic manipulators, conveyors, and storage systems, together with the actual manufacturing operations. This total system concept would provide a real-time control application which would allow the Industrial Engineering student hands-on experience in exercising of the fundamentals learned in their discipline, such as: industrial processes, numerical control, production planning, facilities layout, material handling systems, manufacturing systems design, project management, etc.

Development of this model can be described in summary as being effectively designed and built within the actual design criteria. The total cost, from Appendix B, Bill of Materials, was approximately $350, which represents a cost overrun of about $50. Even at that the project was considered successful. Functional characteristics were satisfactorily within the specified guidelines of accuracy, repeatability, and rigidity as just discussed. There were approximately 15 to 20 hours in conception and design of the model, 48 hours in the manufacturing of parts, 9 hours of assembly and fitting, and 28 hours of electronic interfacing and programming. This represents close to 4 man-weeks which were spread out over a 5-month period.

Thus it is possible to design and build a microprocessor controlled physical simulator of a manufacturing component. With only a modest investment, a functional machine tool model can be constructed by students within a semester's time.

Suggestions for Improvement

Mechanical Design

Several small difficulties in manufacturing and operation of the X-Y table were encountered due to shortsightedness during early phases of design. Such are expected in most projects of any size, particularly when prototyping. The following are some suggestions which will improve the operational and manufacturing efficiency of subsequent models of this design.

Lead Screw. A larger diameter lead screw would enhance the coupling to the drive mechanism. The lead screw ends could then be turned to a shoulder and OD which would fit the drive sprocket and bearings. This would eliminate the coupler and precision shafting altogether.

Nut. The double nut arrangement for reducing backlash is effective, but in this application is cumbersome to disassemble and adjust, as well as time consuming to manufacture. A split nut which attaches to the side of the bearing block would reduce these problems. The adjustment for backlash reduction can be made by tightening the split nut to a desired setting. This would be the best approach short of ball lead screws which are prohibitively expensive.

Rod Hanger. The spacing between the rod support hole and the lead screw will require an adjustment if the preceding suggestions are implemented. Should the originally designed smaller lead screw and coupling arrangement continue to be used, more space will still be needed for adequate clearance between the lead screw coupler and the bearing support. Also, the coupler set screws have a tendency to loosen. A solution would be to either LOCTITE® the screws or use spring pins to mechanically connect the coupler, lead screw, and precision shafting.

Electrical Control

In the interest of time this X-Y table control system was designed in an open loop. A better design would incorporate closed loop control. Microswitches could be placed at the limits of each table travel for feedback and beginning positional information. A fully closed loop control system should implement an encoder on the shaft of the lead screw, since positive displacement occurs whenever the lead screw turns.

A final suggestion is that the retrofitting of a hobby lathe be investigated as a possible addition to the manufacturing system. The purchase of a hobby lathe and the steppers to drive it would reduce the manufacturing effort and focus on interfacing.

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16. Telephone Conversations with individuals listed in Appendix A.

APPENDIX A

LIST OF INDIVIDUALS CONTACTED

DURING TELEPHONE SURVEY

Name	School
Bob Young	Texas A&M
Rick Wisk	VIP
M. P. Deisenroth	Mich. Tech.
Randy Sadowsky	Purdue
Del Kimbler	Univ. So. Florida
L. Lamberson	Wayne State
W. Meier	Purdue
W. E. Biles	Penn. State
R. C. Wilson	Univ. of Mich.
Collin Moodie	Purdue
Tom Hogston	Univ. of Florida
D. Bedworth	Arkansas State
Bob McGowan	Memphis State
John Priest	Univ. of Arkansas
Unny Mennon	Cal. Pol. St. Univ.
Bill Moore	Western Kent. Univ.
Henry Popkin	Louis Tech. Univ.
G. Olling	Bradley Univ.
Mackulak	Arkansas State Univ.
J. Riggs	Oregon State Univ.

APPENDIX B

ISOMETRIC DRAWING AND OPERATION SHEETS

B.1 Isometric Drawing

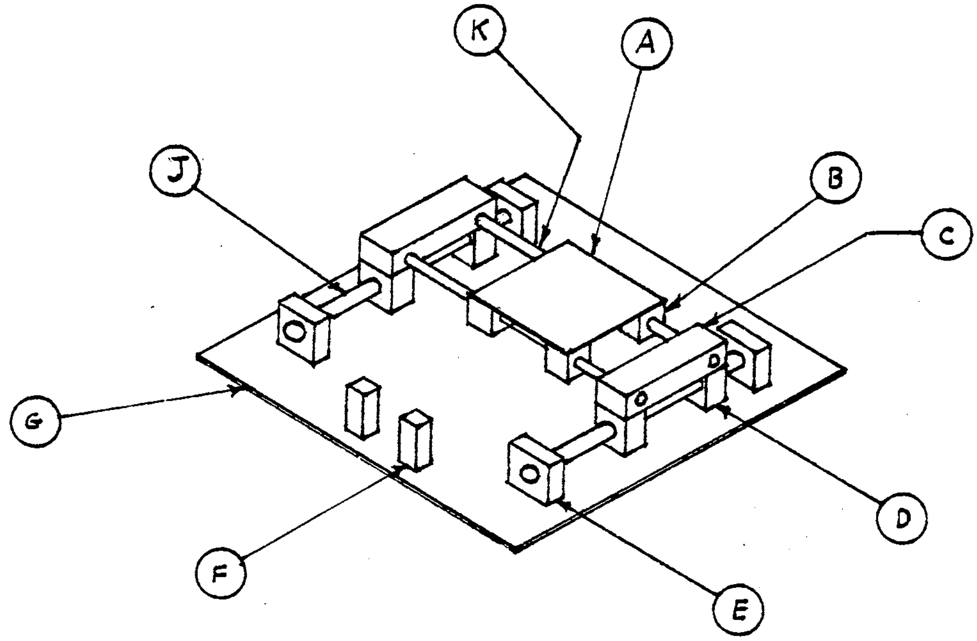


Figure 11. Isometric Drawing of the X-Y Table

TABLE 7. ITEM DESCRIPTION OF PARTS

Manufactured	Purchased
A Work Table	J 3/4 in. Rod
B 1/2 in. Bearing Support	K 1/2 in. Rod
C 1/2 in. Rod Holder and Bearing Support	L 1/4-20 Lead Screw
	M 1/4 in. Coupler
D 3/4 in. Bearing Support	N Base Feet
E 3/4 in. Rod and Lead Screw Hanger	O 3/4 in. Bearing
	P 1/2 in. Bearing
F Motor Standards	Q 20T and 40T Sprocket
G Machine Base	R Pinned Belt
H Motor Supports	S Stepper Motor
I Lead Screw Nut	T 1/4 in. Precision Shaft
	U Various Hardware--screws, etc.

B.2 Operations Sheets

The following operations sheets describe steps to be performed on each manufactured part and which machine, tool, etc. are necessary for the completion of that operation. These sheets are in order listed in Appendix B.1, Item Description of Manufactured Parts. The corresponding sheet should be referred to when duplicating any part listed in Appendix C, Engineering Drawings.

TABLE 8. OPERATIONS SHEETS

PART A: WORKTABLE

Oper. No.	Operation Description	Tools and Equipment Used
1	Rough-cut 5x5x1/4 aluminum Allow material for cleanup	S, Combination Square and Scribe
2	End mill edges square	3/4" HSS End Mill 4 Flutted, Vernier
3	Drill and tap 4x4 holddown matrix	13/64" Drill, 1/4-20 Plug Top, #3 C.D.
4	Drill, then counterbore bolt pattern for bearing and nut supports	#10 Drill, 5/16 counterbore, #2 CD
5	Deburr and clean	File, Parts Washer

Estimated completion time: 2½ hrs

Code: S, bandsaw; M, milling machine; L, engine lathe; CD, center drill.

TABLE 8. (Continued)

PART A: 1/2 IN. BEARING SUPPORT

Oper. No.	Operation Description	Tools and Equipment Used
1	Rough-cut Al blocks Allow for cleanup	S, combination Square and Scribe
2	Face Mill all sides flat and square	M, Flycutter, Vernier
3	Drill and bore bearing hole	M, #3 CD, 1/2" Drill, Boring Head
4	Drill and tap hole pattern	M, #3 CD, #20 Drill, 10-32 HSS Plug Tap
5	Deburr and clean	File, Parts Washer

Estimated completion time: 1½ hrs

Code: S, bandsaw; M, milling machine.

TABLE 8. (Continued)

PART C: 1/2 ROD HOLDER AND BEARING SUPPORT

Oper. No.	Operation Description	Tools and Equipment Used
1	Rough-cut Allow for cleanup	S, Combination Square and Scribe
2	Face mill all sides flat and square	M, 2" Flycutter, Vernier
3	Deburr--break all edges	File
4	Drill and ream through for 1/2 rods	M, #3 CD, 31/64" Drill, 1/2 Reamer
5	Drill and bore through for ball bearing housing	M, #3 CD, 1/2 Drill, Boring Head
6	Drill, then counterbore hole pattern for 3/4" bearing support	M, #3 CD, #10 Drill, 5/16 Counterbore
7	Drill and top setscrew hole	M, #3 CD, 31/64" Drill, 1/4-20 NC Plug Top
8	Deburr holes and clean	

Estimated completion time: 2½ hrs

Code: S, bandsaw; M, milling machine.

TABLE 8. (Continued)

PART E: 3/4 ROD AND LEAD SCREW HANGER

Oper. No.	Operation Description	Tools and Equipment Used
1	Rough-cut Al block Allow for cleanup	S, Combination Square and Scribe
2	Face mill all sides Flat and square	M, 2" Flycutter, Vernier
3	Drill and bore through holes for 3/4" rod and 5/8" bearing	M, #3 CD, 1/2" Drill, Boring Head
4	Drill and tap set screw holes	M, #3 CD, 31/64" Drill, 1/4-20 NC Plug Tap
5	Drill and tap bottom hole pattern	M, #3 CD, 31/64" Drill, 1/4-20 NC Plug Tap

Estimated completion time: 3 hrs

Code: S, bandsaw; M, milling machine.

TABLE 8. (Continued)

PART F: BASE

Oper. No.	Operation Description	Tools and Equipment Used
1	Rough-cut 16x16x3/8 Al plate. Allow for cleanup	S, Combination Square and Scribe
2	End mill edges square	M, 3/4" HSS End Mill
3	Drill and ream dowel alinement holes	M, #3 CD, 15/64" Drill, 1/4" Reamer, 12" Sq.
4	Drill and counterbore, from bottom, rod support hole pattern	M, #3 CD, 1/4" Drill, 7/16" Counterbore
5	Drill and counterbore, from bottom side, motor support holes	M, #3 CD, #10 Drill, 5/16" Counterbore
6	Deburr and clean	File, Burr Knife

Estimated completion time: 3 hrs

Code: S, bandsaw; M, milling machine.

TABLE 8. (Continued)

PART G: MOTOR SUPPORT BRACKET STATIONARY

Oper. No.	Operation Definition	Tools and Equipment Used
1	Rough-cut Al plate Allow for clearance	S, Combination Square and Scribe
2	Face mill all sides flat and square	M, 3/4" HSS End Mill
3	Drill and tap for motor flange	M, #2 CD, #28 Drill, 8-36 NF Plug Tap
4	Drill and tap support bottom	M, #3 CD, #20 Drill, 10-32 HSS Plug Tap
5	Deburr and clean	File, Parts Washer

Estimated completion time: 1½ hrs

Code: S, bandsaw; M, milling machine.

TABLE 8. (Continued)

PART H: MOTOR SUPPORT BRACKET TRAVELING

Oper. No.	Operation Definition	Tools and Equipment Used
1	Rough-cut 1/2x1/2x2 Al stock Allow for cleanup	S, Combination Square and Scribe
2	Face mill all sides Flat and square	M, 3/4 End Mill, Vernier
3	Drill and tap for motor flange	M, #2 CD, #28 Drill, 8-36 NF Plug Tap
4	Drill and counterbore support side	M, #3 CD, #10 Drill, 5/16" Counterbore
5	Deburr and clean	File, washer

Estimated completion time: 1 hr

Code: S, bandsaw; M, milling machine.

TABLE 8. (Continued)

PART I: LEAD SCREW NUT

Oper. No.	Operation Definition	Tools and Equipment Used
1	Rough turn OD of brass nut	E, Turning Tool 1" Micrometer
2	Face end square	E, Facing Tool
3	Drill and tap for lead screw	E, Drill Chuck, #3 CD, 1/4"-20 Plug Tap
4	Finish turn OD	E, Turning Tool 1" Micrometer
5	Knurl	E, Med. Diagonal Knurling Tool
6	Chamfer and cutoff	E, File, Hacksaw
7	Face end square and chamfer	E, Facing Tool, File
8	Clean	Parts Washer

Estimated completion time: 3/4 hr

Code: E,

APPENDIX C

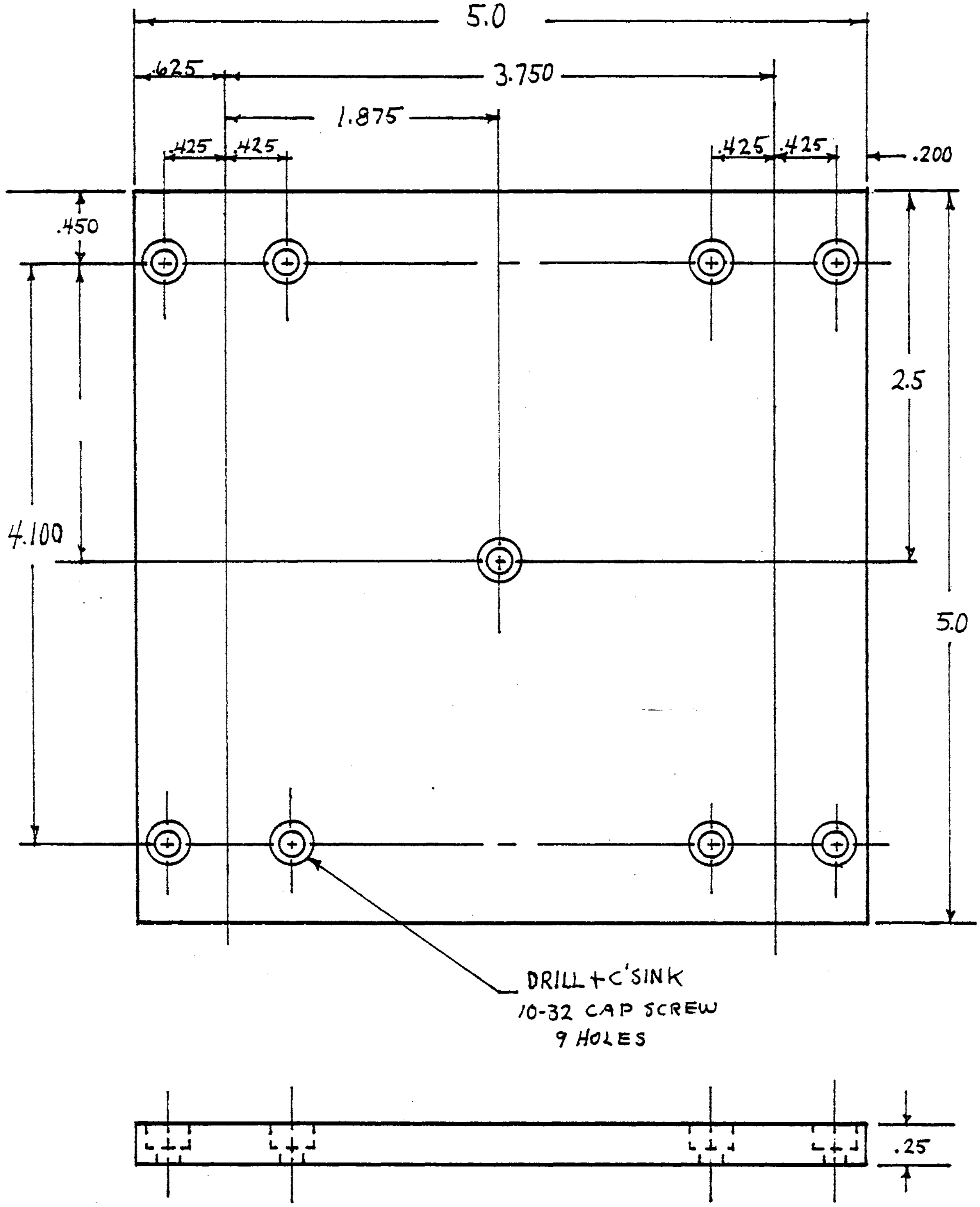
ENGINEERING DRAWINGS

The following drawings appear in order of listing in Appendix B1, Item Description of Manufactured Parts, and Appendix B2, Operations Sheets.

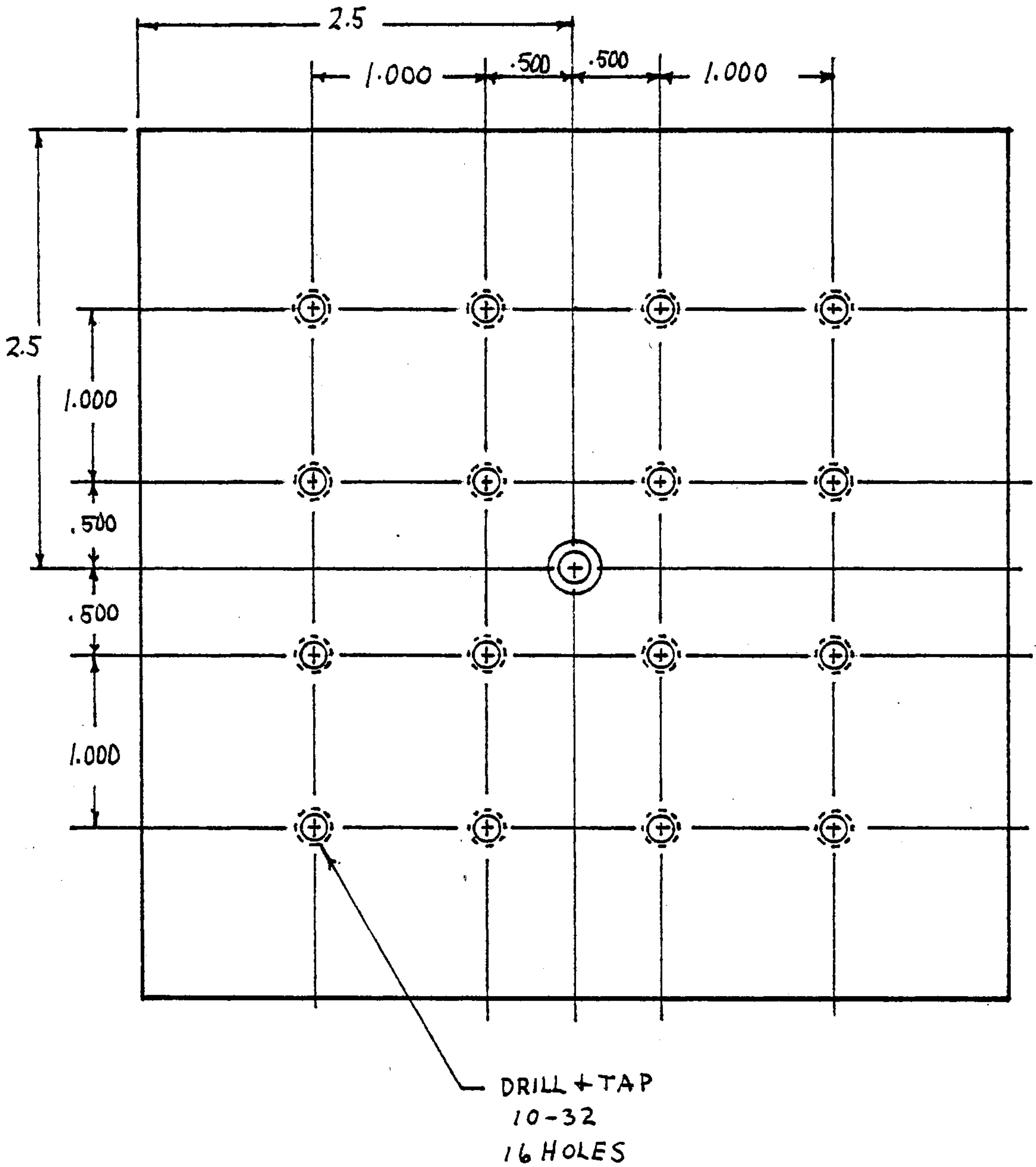
In these drawings all dimensions are in inches with tolerances as listed below, unless otherwise indicated:

Tolerances	.xxx	±0.001 in.
	.xx	±0.005 in.
	.x	±0.01 in.

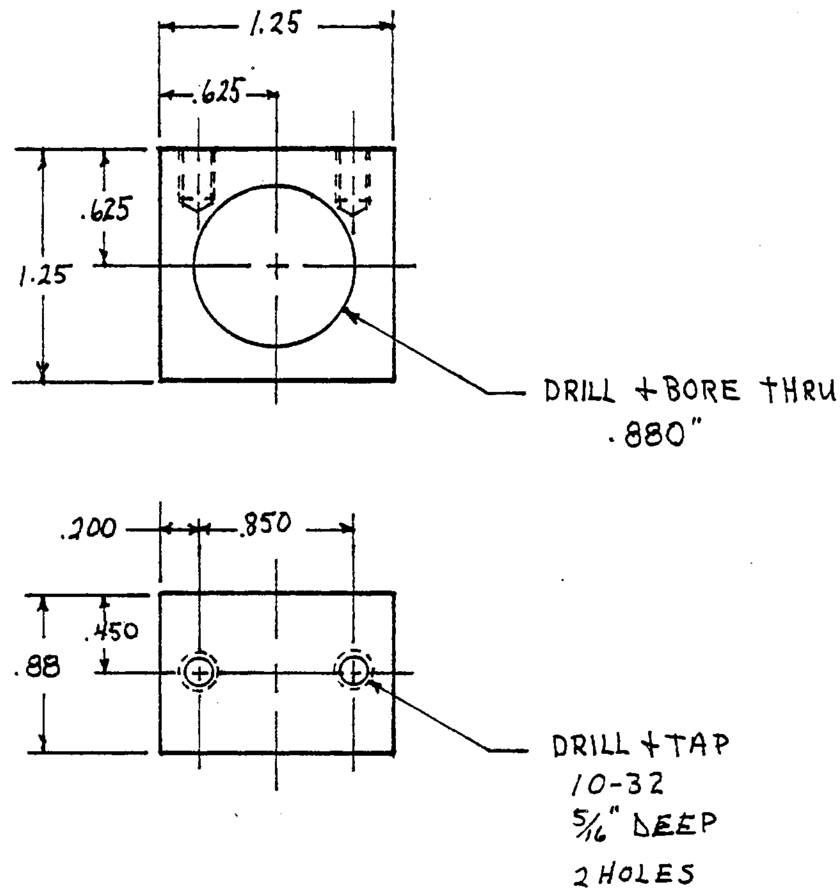
All drawings are to full scale unless noted.



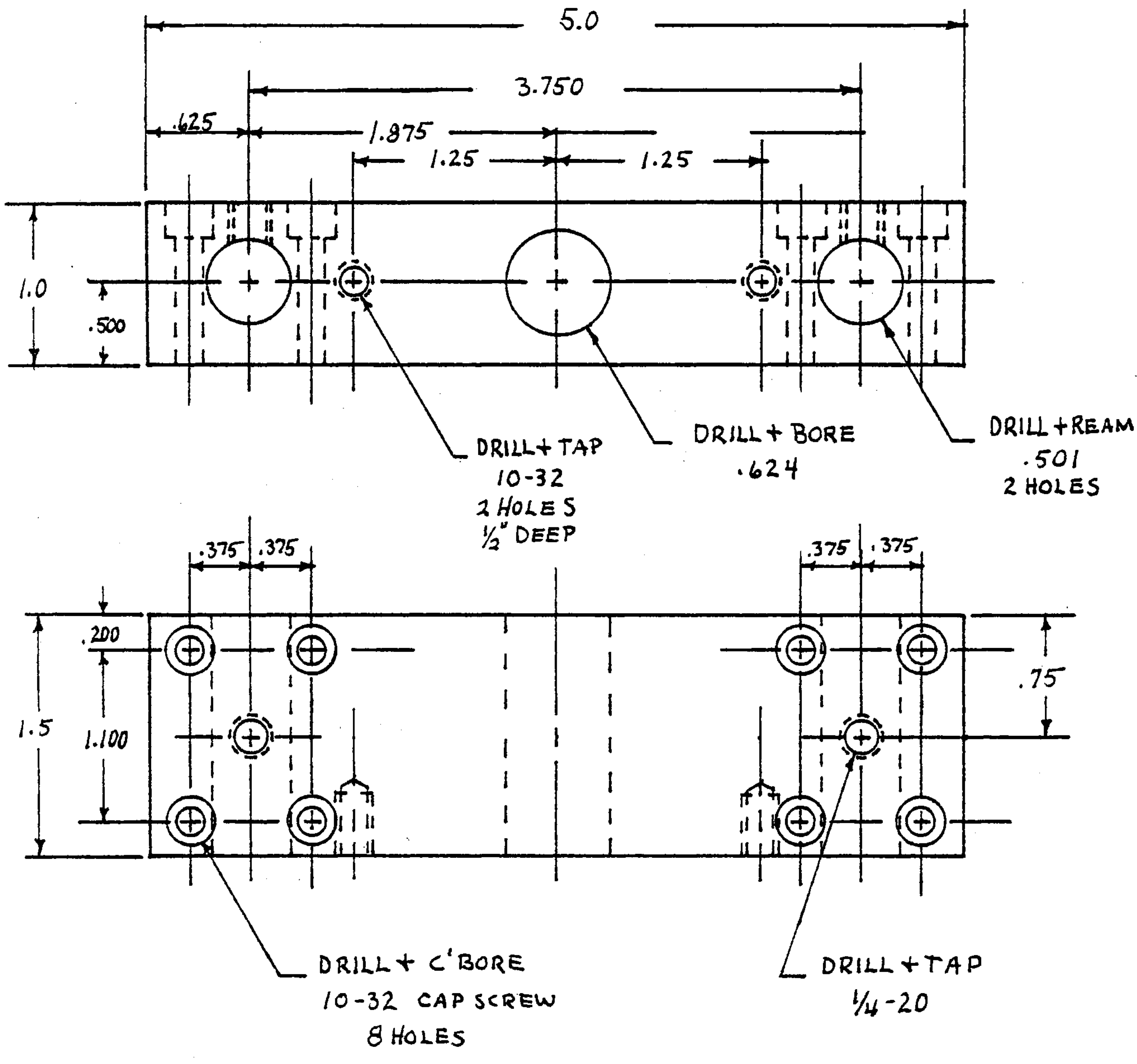
PART A - WORK TABLE



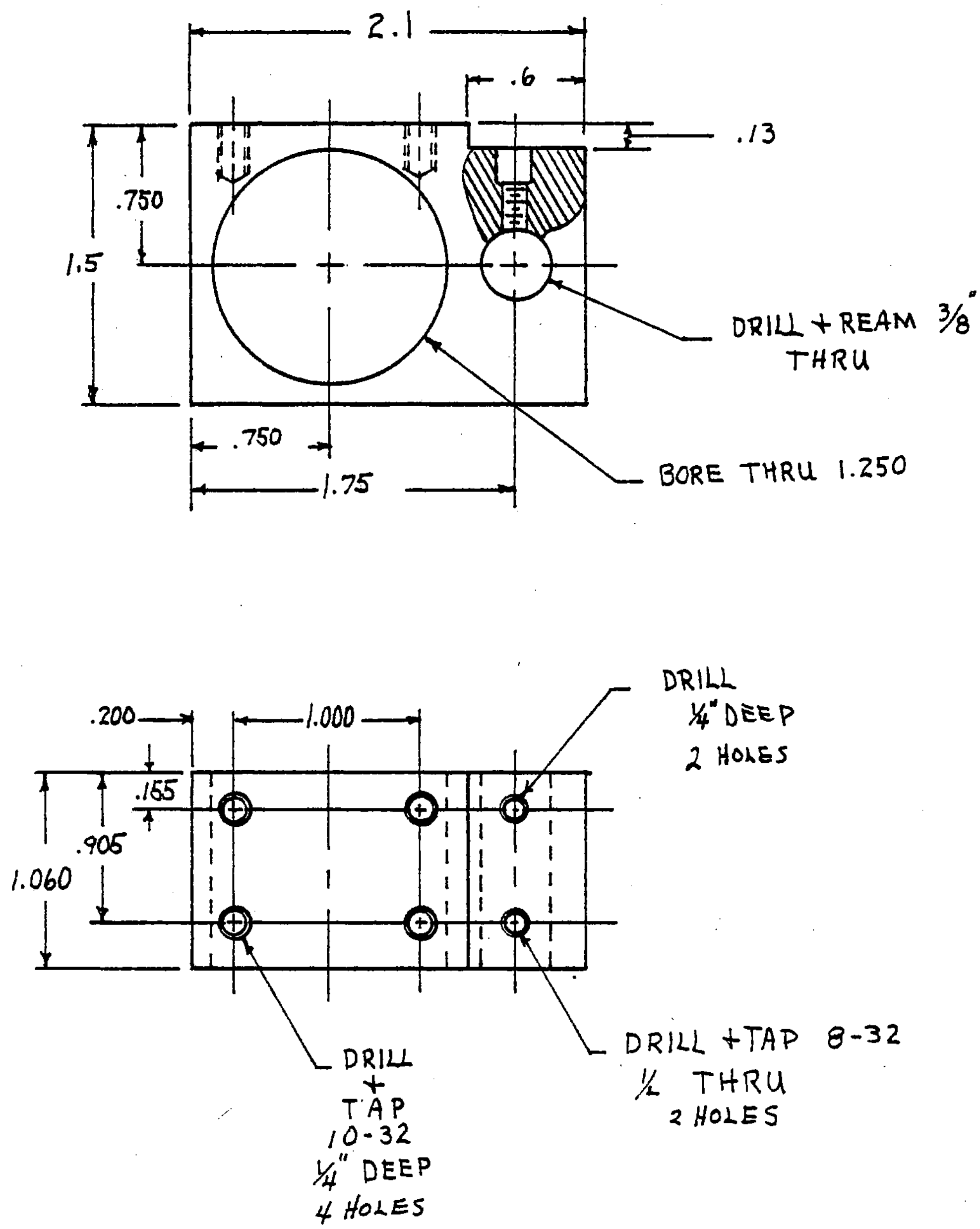
WORKTABLE HOLD DOWN PATTERN



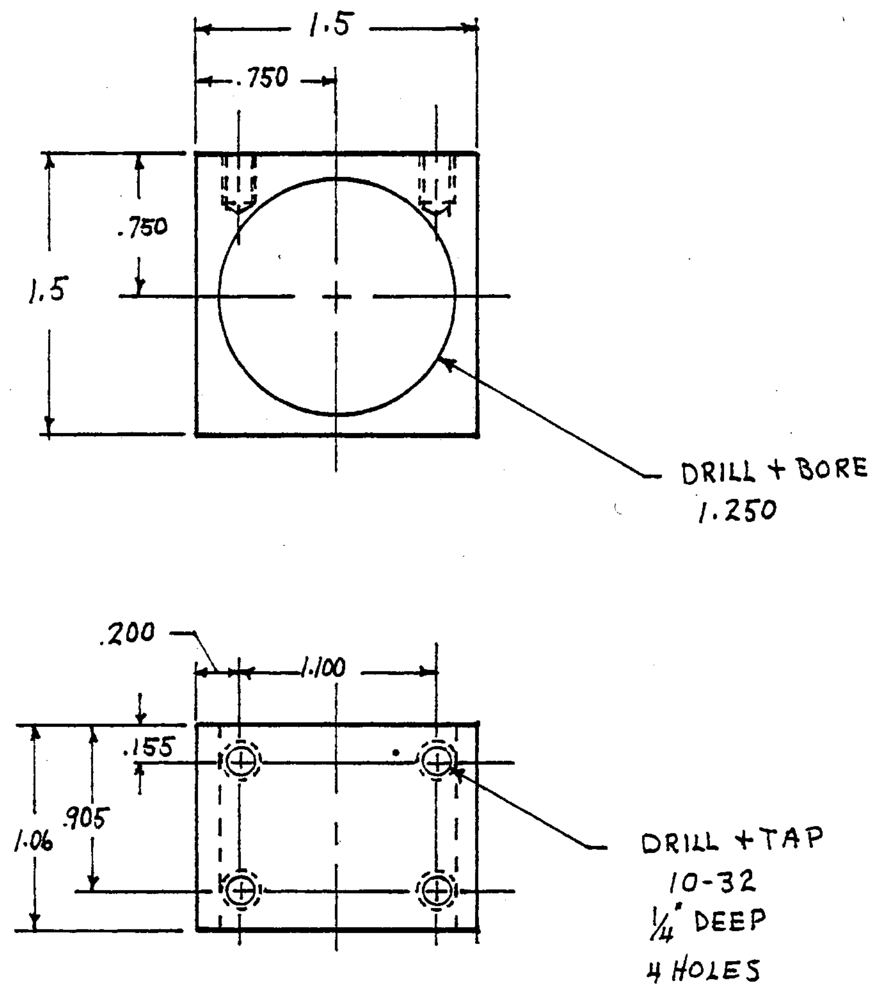
PART B - 1/2" BEARING SUPPORT



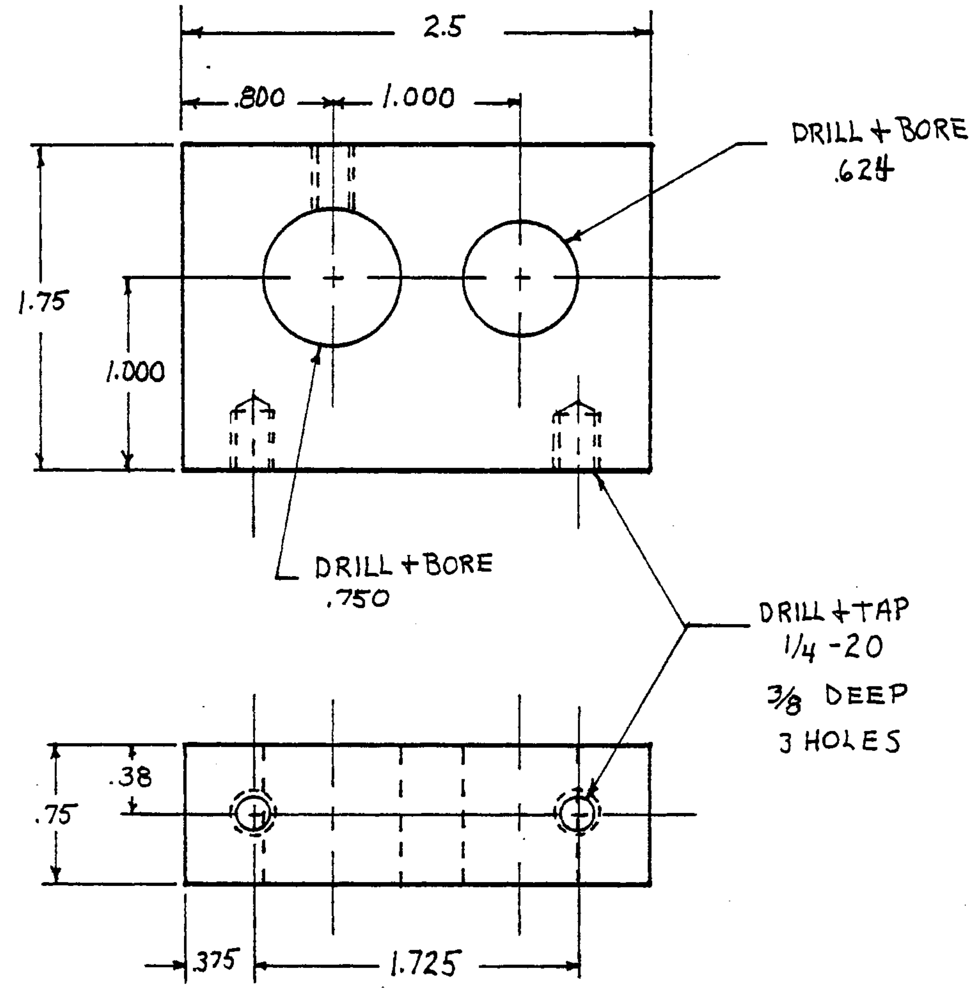
PART C - ½" ROD HOLDER



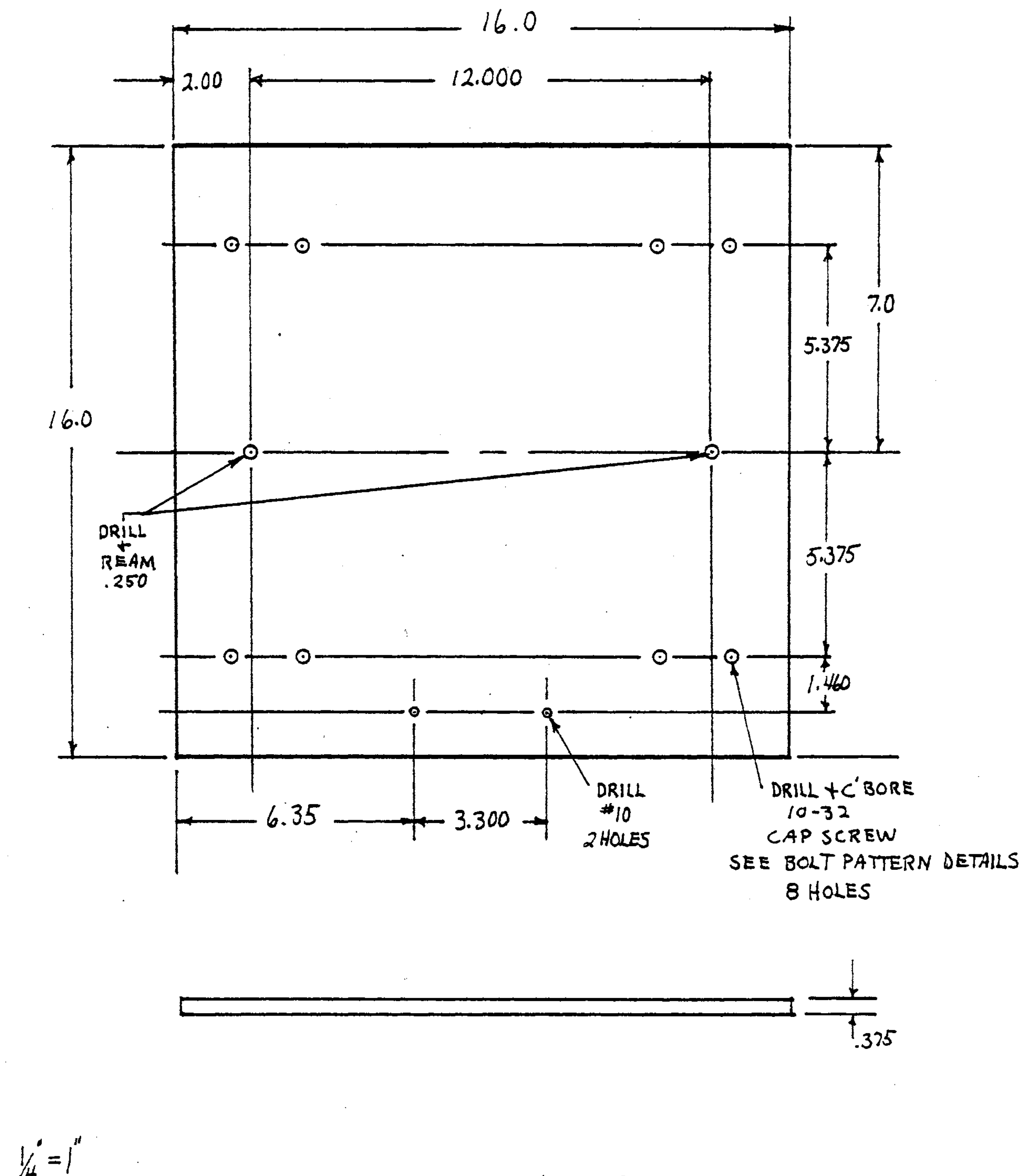
PART D - 3/4" BEARING SUPPORT



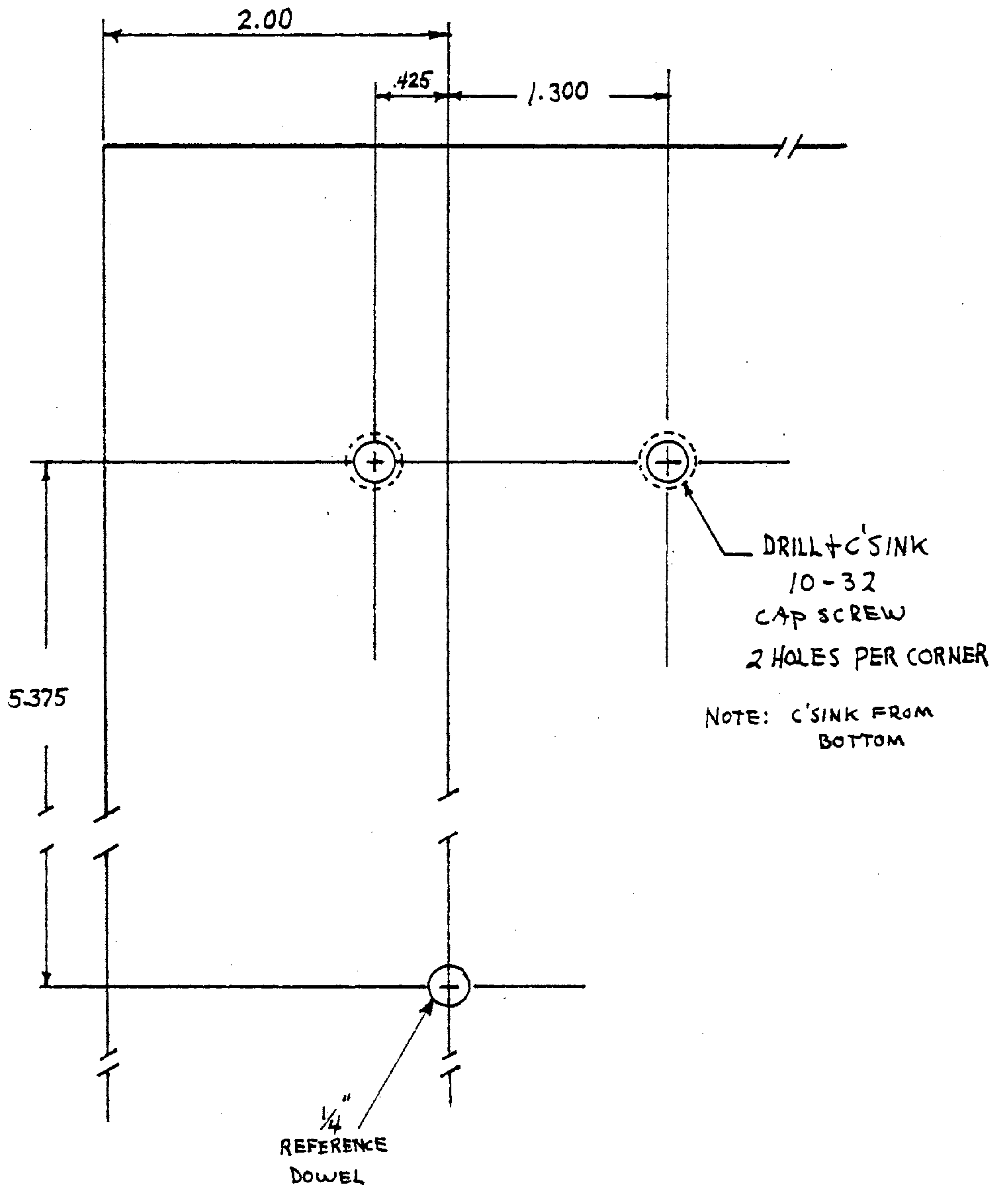
PART D - 3/4" BEARING SUPPORT



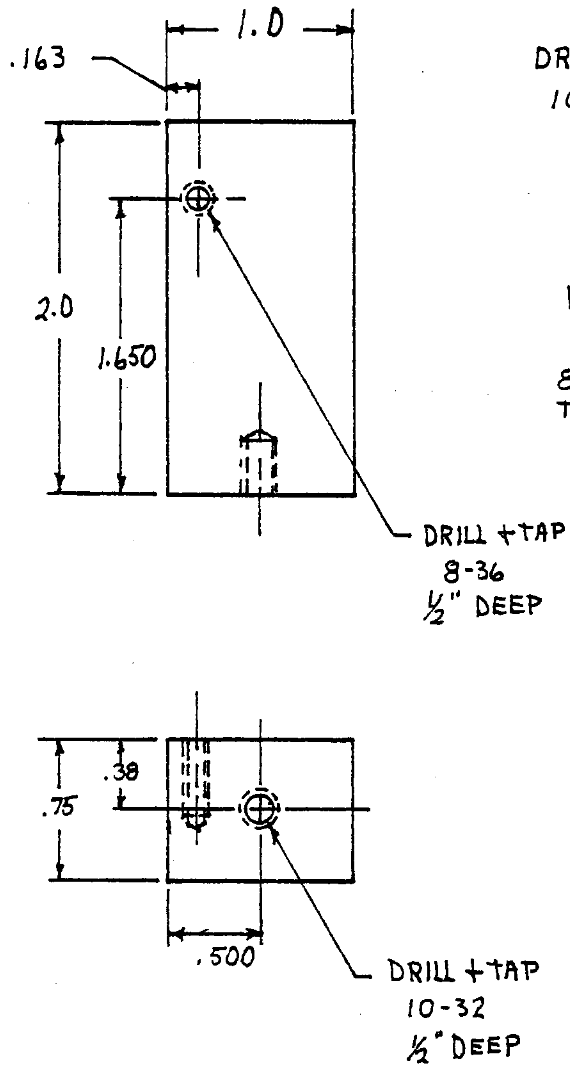
PART E - 3/4" Rod Hanger



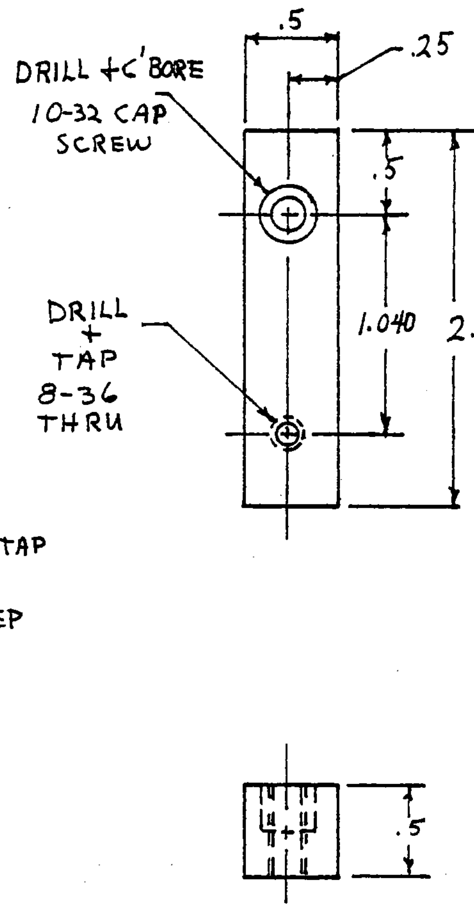
PART G - MACHINE BASE



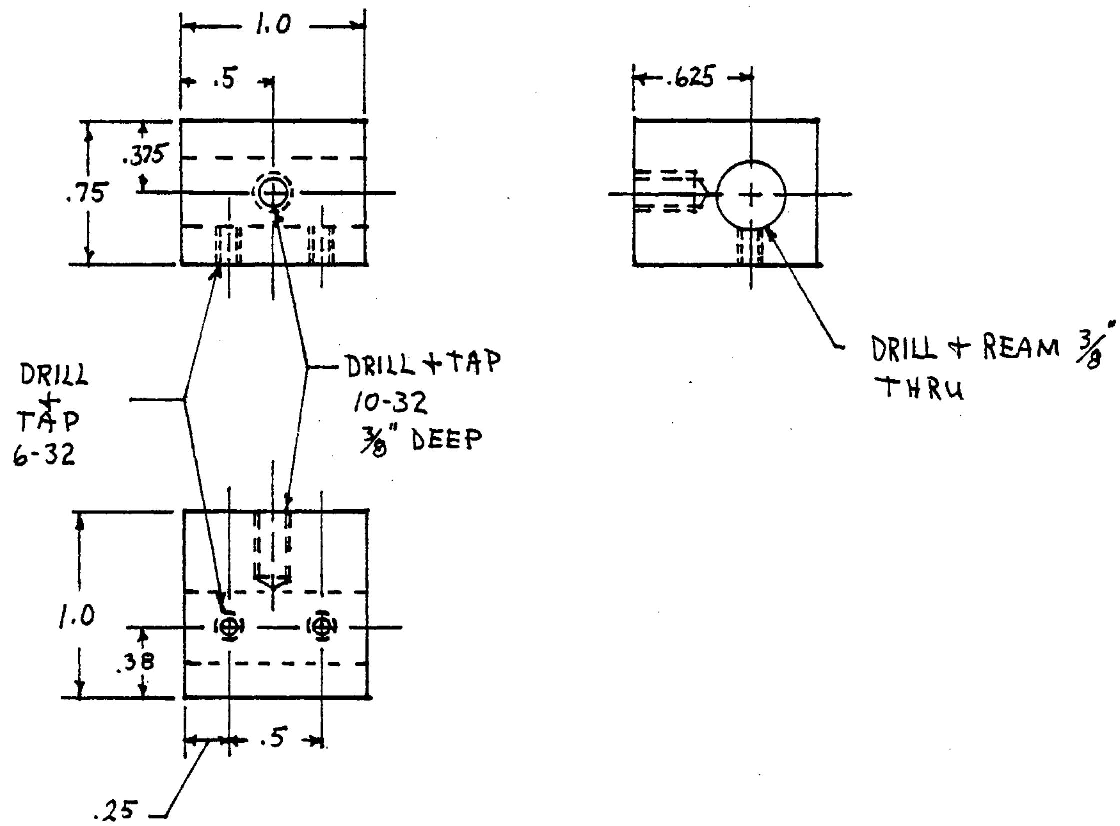
DETAILS - CORNER OF MACHINE BASE



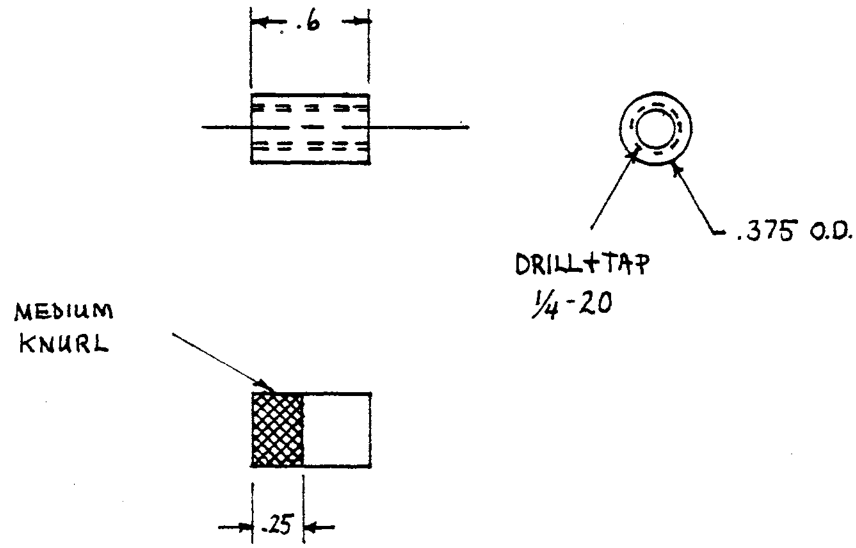
PART F - MOTOR STANDARD



PART H - MOTOR SUPPORTS



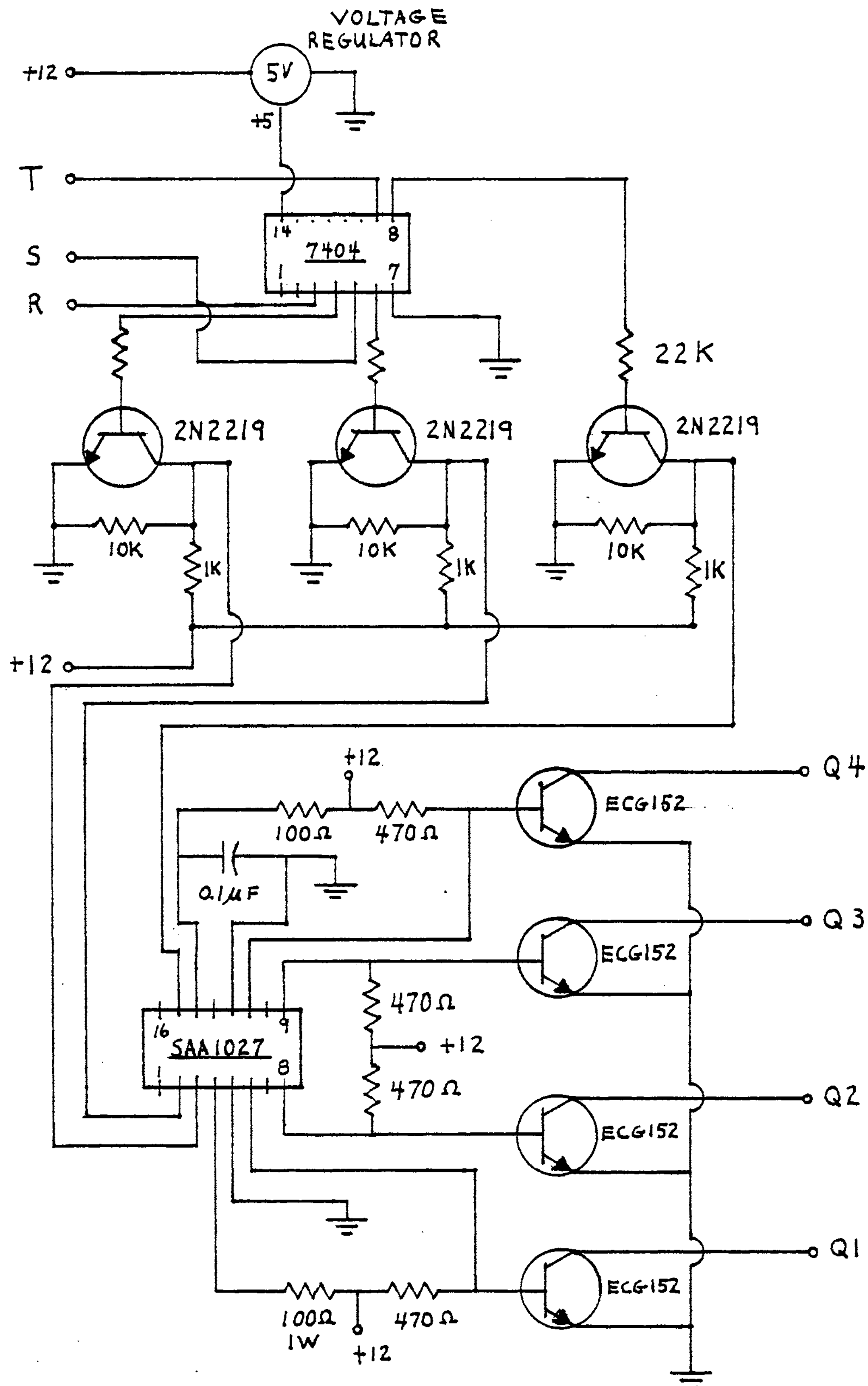
PART I - LEAD SCREW NUT SUPPORT
FOR
WORK TABLE

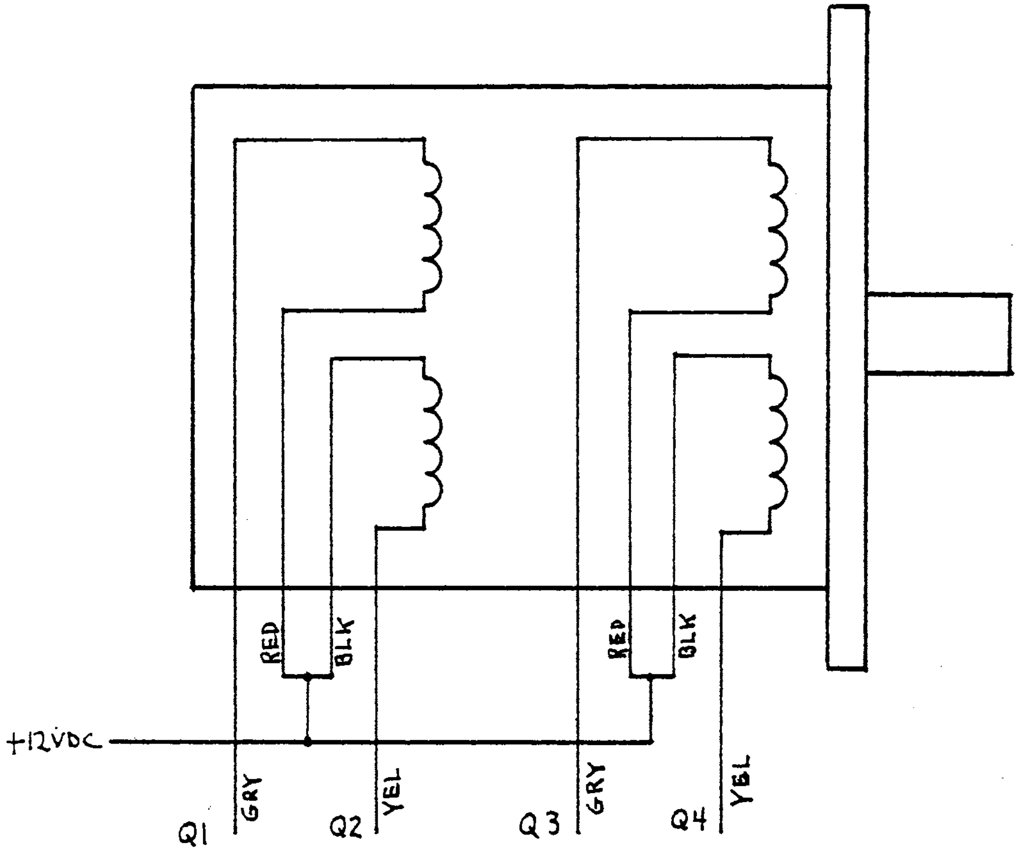


LEAD SCREW NUTS

APPENDIX D

ELECTRICAL SCHEMATIC DRIVE CIRCUIT


VOLTAGE REGULATOR
5V
+12
+5
T
S
R
14
8
7404
1
7
22K
2N2219
2N2219
2N2219
10K
10K
10K
1K
1K
1K
+12
+12
100Ω
470Ω
0.1μF
ECG152
ECG152
ECG152
ECG152
Q4
Q3
Q2
Q1
470Ω
+12
470Ω
16
SAA1027
9
1
8
100Ω
1W
+12
470Ω



MOTOR WINDINGS

APPENDIX E

BILL OF MATERIALS FOR X-Y TABLE

TABLE 9. BILL OF MATERIALS FOR X-Y TABLE

No.	Item	Part No.	Supplier[1]	Amount	Cost/Item	Total
1	1/2 in. Ground Shaft	S8-140	B	2	$ 7.44	$14.88
2	1/4-20 Lead Screw	TI 7	B	2	3.97	7.94
3	3/4 in. Ground Shaft	S20-8	B	2	9.37	18.74
4	1/2 I.D. Linear Bearing	LMN-3	B	4	3.85	15.21
5	3/4 I.D. Linear Bearing	LMN-4	B	4	5.68	22.72
6	LMN-3 Retainer Ring	Q2-87-CP	B	10	.44	4.40
7	LMN-4 Retainer Ring	Q2-125-CP	B	10	.64	6.40
8	Pinned Belt Sprocket	GP31A28-20	B	3	6.94	20.82
9	Pinned Belt Sprocket	GP31A28-40	B	3	7.70	23.10
10	Pinned Drive Belt	31GBF240E	B	1		
11	Pinned Drive Belt	31GBF90E	B	1	1.98	1.98
12	Ground Shaft	54-17	B	3	.64	1.92
13	Ground Shaft	54-10	B	1	.64	.64
14	Ground Shaft	54-12	B	3	.64	1.92
15	Ground Shaft	54-25	B	1	.64	.64
16	Sleeve Coupling	CT-3	B	6	2.65	15.90
17	Ball Bearing	B11-8	B	12	2.32	27.84
18	Stepper Motor	K82701-P2	P	2	26.00	52.00
19	Unipolar I.C. Driver	SAA 1027	P	2	17.25	34.50
20	Transistor	276-2048	R	8	1.79	14.32
21	5 Volt Regulator, POS		L	2	1.56	3.12
22	Ribbon Cable	278-770	R	1	3.95	3.95

Table 9. (Continued)

No.	Item	Part No.	Supplier[1]	Amount	Cost/Item	Total
23	Transistor	2N2219	L	6		
24	Capacitor	0.1 Micro F	L	2		
25	Resistor	100 OHM	L	4		
26	Resistor	470 OHM	L	8		
27	Resistor	1K OHM	L	6		
28	Resistor	10K OHM	L	6		
29	Resistor	22K OHM	L	6		
30	12 Volt Power Supply		L		N.C.	
31	Cop Screw, 1/4-20	3/8"	L	8	.31	2.48
32	Set Screw, 1/4-20	1/4"	L	4	.18	.72
33	Cop Screw, 10-32	1"	L	16	.35	5.60
34	Cop Screw, 10-32	1/4"	L	9	.29	2.61
35	Cop Screw, 8-32	1/2"	L	4	.24	.96
36	Set Screw, 8-32	1/4"	L	6	.15	.90
37	Cop Screw, 8-36	1/4"	L	4	.24	.96
38	Aluminum Sheet 2024-T341	5"x5"x1/4"	L	1	1.56[2]	1.56
39	Aluminum Sheet	16"x16"x3/8"	L	1	24.00	24.00
40	Aluminum Plate	1"x1½"x15"	L	1	5.63	5.63
41	Aluminum Bar	1¼"x1½"x8"	L	1	3.75	3.75

[1] Supplier Code: B, Berg Inc.; P, Philips Control Corp.; L, Local; R, Radio Shack.

[2] At $2.50 per pound.

APPENDIX F

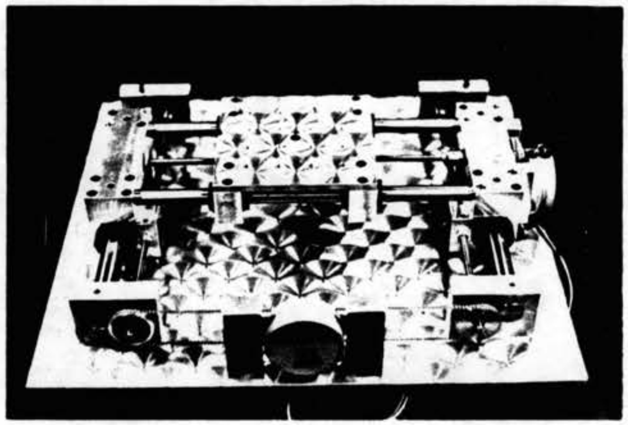
X-Y MICROPROCESSOR PROGRAM

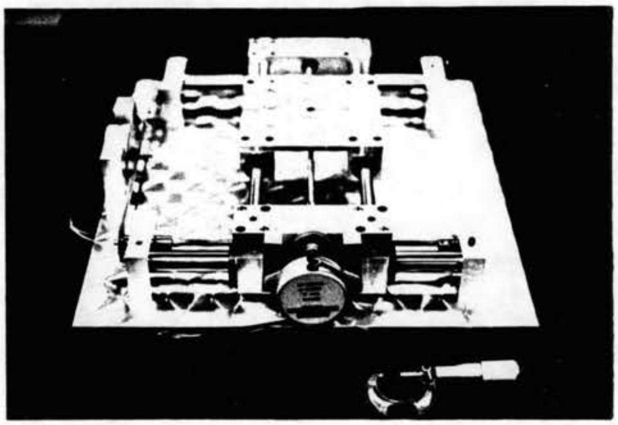
```
READY.

 5 REM            X-Y TABLE PRGM
 10 POKE 59457,255
 12 PRINT"WILL THIS BE A DUAL AXIS MOVE?  Y OR N";
 14 INPUT DA$
 16 IF DA$="Y" GOTO 345
 20 PRINT"DISTANCE?";
 30 INPUT D
 40 PRINT"ROTATION?";
 50 INPUT R
 60 PRINT"AXIS?";
 70 INPUT A
 80 IF A=0 THEN 220
 90 IF R=1 THEN 160
 100 N=INT(D/.000522)
 110 POKE 59471,2:REM                    +X
 120 POKE 59471,3
 130 N=N-1
 140 IF N<>0 THEN 110
 150 GOTO 12
 160 N=INT(D/.000522)
 170 POKE 59471,6:REM                    -X
 180 POKE 59471,7
 190 N=N-1
 200 IF N<>0 THEN 170
 210 GOTO 12
 220 IF R=0 THEN 290
 230 N=INT(D/.000522)
 240 POKE 59471,18:REM                   -Y
 250 POKE 59471,26
 260 N=N-1
 270 IF N<>0 THEN 240
 280 GOTO 12
 290 N=INT(D/.000522)
 300 POKE 59471,48:REM                   +Y
 310 POKE 59471,56
 320 N=N-1
 330 IF N<>0 THEN 300
 340 GOTO 12
 345 PRINT"IS X DIRECTION NEGATIVE? Y OR N";
 350 INPUT X$
 360 PRINT"X DISTANCE";
 370 INPUT XD
 380 PRINT"IS Y DIRECTION NEGATIVE? Y OR N";
 390 INPUT Y$
 400 PRINT"Y DISTANCE";
 410 INPUT YD
 420 N=INT(XD/.000522)
 430 K=INT(YD/.000522)
 440 IF X$="N" THEN 560
 450 IF Y$="Y" THEN 670
 470 POKE 59471,2:REM          +X
 480 POKE 59471,3
 490 N=N-1
 500 IF N<>0 THEN 470
 510 POKE 59471,18:REM         -Y
```

```
520 POKE 59471,26
530 K=K-1
540 IF K<>0 THEN 510
550 GOTO 12
560 IF Y$="Y" THEN 750
570 N=INT(XD/.000522)
580 K=INT(YD/.000522)
590 POKE 59741,6:REM          -X
600 POKE 59471,7
610 N=N-1
620 IF N<>0 THEN 590
630 POKE 59471,18:REM         +Y
640 POKE 59471,26
650 K=K-1
660 IF K<>0 THEN 630
665 GOTO 12
670 POKE 59471,2:REM           +X
680 POKE 59471,3
690 N=N-1
700 IF N<>0 THEN 670
710 POKE 59471,48:REM          +Y
720 POKE 59471,56
730 K=K-1
740 IF K<>0 THEN 710
745 GOTO 12
750 POKE 59471,6:REM           -X
760 POKE 59471,7
770 N=N-1
780 IF N<>0 THEN 750
790 POKE 59471,48:REM          +Y
800 POKE 59471,56
810 K=K-1
820 IF K<>0 THEN 790
830 GOTO 12
840 END
READY.
```

APPENDIX G

PHOTOGRAPHS OF MODEL





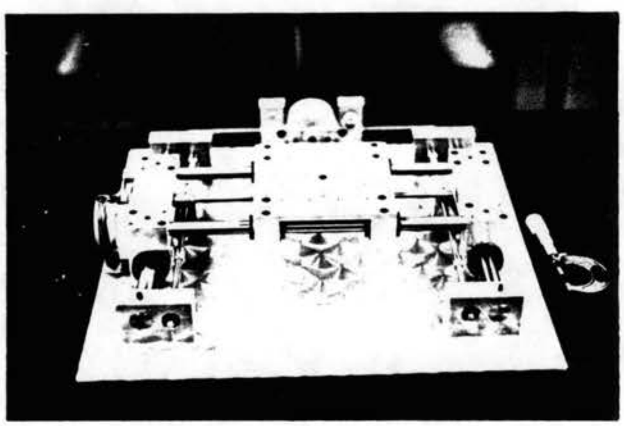
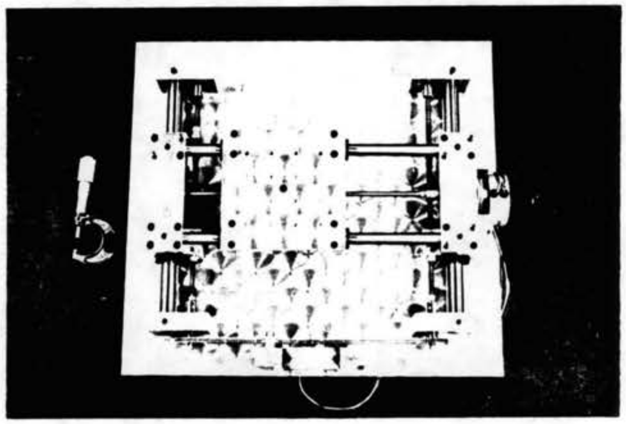
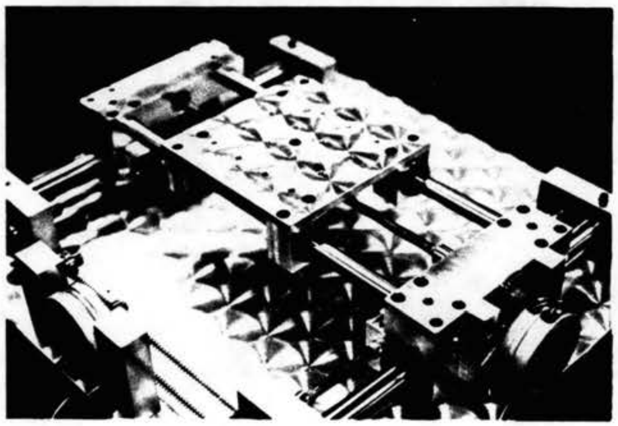


PLATE I





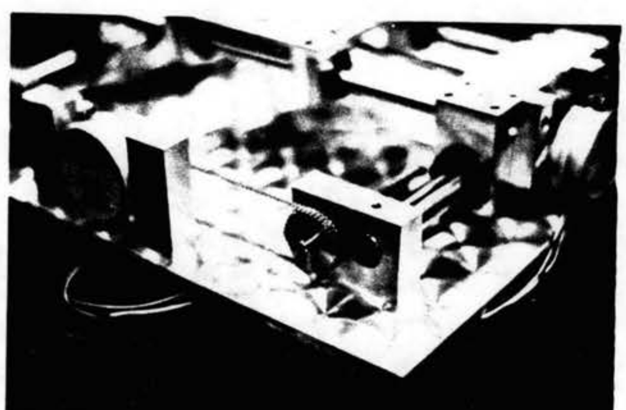


PLATE II