SRC TR 87-129

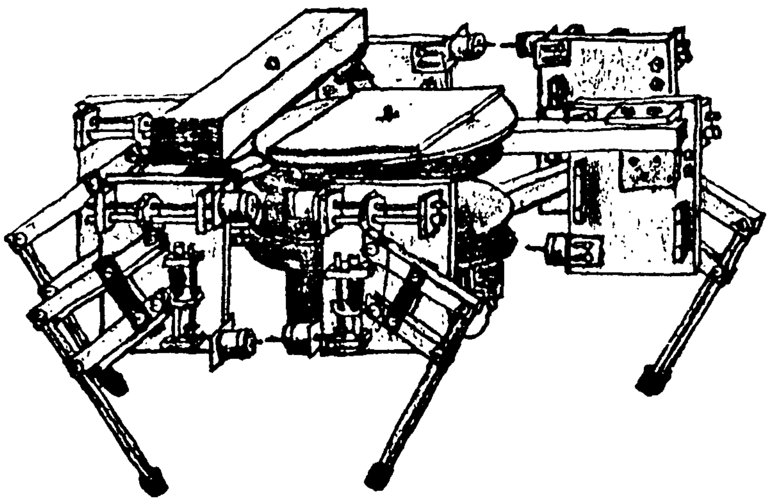
Walking Robot (Terrapin 1)

by

S. Azarm, R. J. Chen, and L. W. Tsai

WALKING ROBOT

(TERRAPIN 1)



A Senior Student Design Project
Directed by

Drs. S. Azarm, R. J. Chen, and L. W. Tsai

Department of Mechanical Engineering
and
Systems Research Center
The University of Maryland
College Park, Maryland 20742

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ABSTRACT

The University of Maryland's entry to the walking robot competition is composed of three parts: body, leg, and control. The body is a tripod design in which one of the two sets of three legs is always on the ground. Each leg is mounted at the corner of one of two triangles which are stacked and able to rotate one relative to the other. The legs are modelled after a pantograph and are driven by "acme" screws in both the horizontal and vertical directions. The robot is controlled by a system that employs both integrated circuits with pulse-width modulation and "class-b" transistors, amplifiers, and relays.

1. INTRODUCTION

The design process generally consists of conception, invention, analysis, fabrication, and finally testing and refinement. The University of Maryland's undergraduate group, composed of ten students, followed this procedure to arrive at their final design for the walking robot. First, the group was divided into two sub-groups and each one was to return with a design that they thought was feasible. This was the conception and invention phase as each student "conceived" of a general idea and then met with his peers to "brainstorm" until a suitable design was found.

The two sub-groups then presented their proposals to the entire group, each one being critiqued for both its strengths and weaknesses. In the final part of the invention stage, the class took the best features from the two presentations and combined them, producing a workable outline in which the three major parts: the body, the legs, and the control systems, could be easily separated and defined.

The "analysis" part was accomplished through a "divide and conquer" process, where three or four students were assigned to one of the three subdivisions of the robot. Again, each group met on its own during the week to discuss the details of its assignment, then at the end of every seven-day period the whole group would reconvene to examine and critique what the other sub-groups had developed. This continued until all three sub-groups were ready to order parts and start assembling their specific component. In the end, some shifting of resources, namely manpower, from one sub-group to the other was necessary when it became evident that some elements, the leg in particular, was demanding more time than four students could offer.

The last part of the development of this walking robot was the testing and continued refinements, as a whole. From the outset, the design was changed to accommodate unforeseen obstacles such as increased power requirements and unanticipated forces that caused binding in the leg mechanisms. In each case, these problems were addressed and alleviated with proper adjustments.

In this paper, the robot will be presented much as it was invented, in three parts: Body, Leg, and Control. The first section discusses size, stability, turning ability, and other attributes of the body. This is followed by an examination of the leg, both in a force analysis of its joints and a presentation of the horizontal and vertical drive systems. Finally, the control systems and power requirements are introduced and high-lighted by flow charts and diagrams.

2. BODY

In designing the body of the walking machine it was first necessary to define the appropriate design parameters which the body had to meet. These included:

Size- According to the contest rules, the machine has to be able to walk through a one by one meter square hoop.

Stability- The machine has to remain upright as it walks, turns, accelerates, and decelerates, or if it is disturbed. This requires that a vector, representing gravity and the forces due to acceleration, drawn from the instantaneous center of gravity, always pass through the support area defined by the legs on the ground. This is the primary reason for the usage of six legs; a six legged design is inherently more stable than a four legged one because the support area is much larger and does not change shape as the robot goes through its stride. In addition to the difficulties of stabilizing the machine by itself, on level two of the competition, the walking machine must carry one gallon of water in a half full container. This greatly complicates the forces which could overturn the robot as the water is free to slosh from one end of its container to the other.

It was decided that we would utilize a tripod design in which the machine would stand on three legs at all times (Fig.1). Therefore, the only stability question was how large to make the equilateral triangle created by the legs contacting the ground. Because of the size restrictions placed on us by the rules of the competition, and our original specifications that the top triangle be able to pivot 30 degrees relative to the bottom one, a balance had to be reached so the robot could fit through the one x one meter square and yet still maintain our desired turning ratio and acceleration requirements.

It was recognized that a top view static stability triangle could be constructed by connecting the points where the legs contact the ground. The interior of this imaginary triangle represents the possible stable locations of the walking machine's overall center of gravity (including water). If the C.G. is ever located outside the stability triangle, the machine may overturn.

To determine the necessary dimensions of the stability triangle, a horizontal stability analysis was performed for dynamic motion. This analysis consisted of summing the moments due to forces acting at the C.G. about the point where the leg contacts the ground. The forces considered were due to gravity of the entire machine and water, due to acceleration of the machine, and due to the water which is displaced during acceleration. This analysis assumed an acceleration/deceleration of 2 ft/s/s, a total weight of 60 lbs and a maximum of 2 lbs water displaced.

It was determined that the most unstable circumstance would be when the robot was at its peak rate of acceleration, and the back most legs (B and C, Fig. 1) were on the ground and in their forward position. So the stability triangle was designed to contain the machine's C.G. during this worst case situation.

Stiffness- Excessive deflections in the body would make the device unstable and difficult to control and would cause it to consume more energy. However it must also be noted that for a given geometry there is a trade-off between stiffness and weight. Therefore we chose to use a box beam pylon assembly with central supporting plates for our frame shown in Fig.s 1 and 2.

Turning Ability- The design must also navigate a prescribed course with a reasonable turning radius and the ability to precisely control its direction. Most fixed body designs would require a change in gate, stride length, stride angle and a horizontal circular motion of the legs in order to turn without dragging the legs through some portion of their travel. This substantially complicates the leg design. By using a two-part vertically stacked body with a central pivot, shown in Fig. 2 we were able to allow the usage of legs with a simple linear motion. However the use of a central pivot did require a bearing and shaft assembly and a motor with gears to control the turning of the device. In addition, because the turning requires the pivoting of the entire body assembly it was necessary to minimize the moment of inertia and to ensure that the center of gravity of each section fell as close to the central pivot as possible to avoid laterally unstabilizing forces while turning.

Lightweight- The weight of the vehicle bears directly on its energy consumption and turning rate. In addition to being strong, the box beam pylon construction technique chosen is relatively lightweight. Aluminum is used extensively as the primary construction material because of its high strength to weight ratio.

Interface with other components- Constant coordination with other design groups working on the project was necessary to ensure that the body design was able to accommodate the design requirements of the leg and electronics systems, especially in the areas of mounting and clearance.

Water container- Level 2 competition requires the placement of a container of water on the machine. This required accommodation in terms of space and also in terms of a reduction in stability due to free surface effects as mentioned before.

Battery mounting- The walking machine is powered by batteries which are relatively heavy and bulky. It was necessary to provide a mounting system that is both strong and located such that the batteries are as low as possible in order to keep the center of gravity low.

3. LEG

Leg Joints

Having chosen the pantograph (Waldron and Waldron, 1987) design for its efficient transmission of forces and unique characteristic that the foot parallels the motion of the drive, it was necessary to reduce the weight of the leg while maintaining it's structural integrity. A bending and tension/compression analysis was performed for each link. It was determined that stock, one x one square aluminum tubing would be effective for the upper and lower thigh links (Fig. 3a). To carry the load between joint 2 and joint P, two one x one quarter inch aluminum plates were used, and a solid one half x three quarter inch aluminum shaft would be utilized for the shank link. All of the leg link materials were chosen for their strength to weight characteristics along with availability and ease of construction.

The next task was to design a joint which would minimize frictional effects and be adaptive to each of the five joints per leg (Figure 3b). Since cost was also an important factor, bronze bushings were used rather than ball bearings in all thirty joints. Each joint consists of a fixed 3/16" circular steel shaft. All attached links rotate about this shaft by way of press-fit flange bushings. Teflon washers act as spacers between the links while the unit is externally retained by "E" clips. All the joints are based on the same principles. To enable the joints to rotate through their full range of motion, the aluminum on the sides of the 1" x 1" tubing that were not supporting the link were cut back from one to one and one half inches depending on the joint.

Force Analysis on the Leg Joints

All variables for the force analysis are in reference to the free body diagram (Figure 4). Neglecting the forces due to inertia and friction, and assuming that each leg should sustain a 30 lb. normal force (total weight of robot is 90 lbs.) at the contact point: The static equilibrium force equations can be formulated as follows:

$$F_{3x} = F_{6x} + F_{54}\cos\theta_1$$

$$F_{3z} = F_{6z} - F_{54}\sin\theta_1$$

$$F_{54} = \frac{k\ (F_{6x}\sin\theta_2 + F_{6z}\cos\theta_2)}{\sin\ (\theta_1 - \theta_2)}$$

$$F_{1x} = -(k - 1)\ F_{6x}$$

$$P_x = -kF_{6x}$$

$$F_{1z} = F_{3z} + F_{52}\sin\theta_2$$

$$F_{52} = \frac{-k\ (F_{3x}\sin\theta_1 + F_{3z}\cos\theta_1)}{\sin\ ({}_2 - {}_1)}$$

$$P_z = F_{54}\sin\theta_1 - F_{52}\sin\theta_2$$

Also by vector analysis, the relationship between the length of the leg and the angle of the knee can be found to be as follows:

The horizontal drive is what makes the robot move forward or backward (Fig. 5). The requirements placed on it were that the robot have an acceleration of at least 2 ft/sec/sec and reach a velocity of 4.5 in/sec, or 30 full steps in a minute. In doing so, the motor must not draw more than four amps or the electrical system would overheat. Taking all these aspects into consideration the students arrived at the lead screw and linear bearing design pictured in Fig. 5.

For the horizontal drive, the 90 lb normal force created by the geometry of the pantigraph when the 30 lb vertical load is placed on it, is taken up by the hardened steel shaft and the linear bearing. Without the shaft, all of the weight would have to be supported by a much larger screw, making it more likely that the nut would bind because of the closing of threads due to deflection. Both the shaft and the screw are mounted between two aluminum housings that are bolted to the plate. For both the drives, the screws are held by thrust bearings on their ends so they are allowed to rotate freely. The motor, for the horizontal drive, is connected to the screw by a flexible coupling so that any errors in alignment would be corrected.

The vertical drive differs only in its length and the manner in which the motor is connected (Figure 6). Because the leg needs only to lift three quarters of an inch, and because of the magnification property of the pantograph design, the nut needs only to move one quarter of an inch, enabling the shaft and screw to be much shorter. To make up for the increased force involved with lifting the entire weight of the robot, the motor is attached to the screw with a worm and worm gear that gives a reduction of fifteen to one. Using a screw was beneficial in both its reduction of power and in its inherent self-locking properties.

4. CONTROL AND ELECTRONICS

Since it was decided in the early stages of design that only two levels of competition were to be attempted, the requirement of the controls and electronics was to insure timing between both the upper (odd) and lower (even) sets of legs during walking and walking/turning operations. Both of these types of operations would be performed at various speeds. In addition, an automatic start-up routine involving raising and lowering of the body and flexing the legs, was needed to meet the requirements of the competition.

In order to meet the contest criteria, continuous feedback from the legs was not necessary. The only information the controller needs to know is when the legs have reached their extreme positions, easily provided by limit switches placed on the drive mechanism; each leg would have four: up, down, forward, and back. Additional switches indicating right and left turn limits would be used as feedback from the body to the turning portion of the control circuit.

With this feedback system established, the first circuit considered utilized "class-B" transistor amplifiers, and relays. The transistor amplifiers were to be used to develop a voltage level that could be adjusted by the operator in order to control the leg speed and the turning motion, but because of the cost and power consumption of the high current relays and transistors this made the controller very inefficient.

Changes in the projected current requirements of the leg drive motors allowed more efficient circuits to be considered. At the beginning, it was determined that two amperes at twelve volts D.C. (Direct Current) would be sufficient to drive both the vertical and horizontal drive motors. With this low current requirement, a pulse-width modulated system using integrated circuit servo-amplifiers could be considered (Robillard). Pulse-width modulation is a concept where the signal to the motor is either on or off, but the percentage of the time the signal is on can be varied. This is done by varying the width of the pulses, while holding the time period between the pulses constant. The duty cycle, which is the percent of time the pulse is on, is used to calculate the average motor voltage.

A second circuit was designed and a single test circuit built using TTL (Transistor-Transistor Logic) and two Sprague chips. This test circuit was used to establish the mechanical soundness of the leg design, and to determine if the integrated circuits could handle the required loads. The test results showed that when the leg was given a load of thirty pounds, comparable to the actual case, there was extreme binding in the screws of both the horizontal and the vertical drive, making the current requirements well above the capabilities of the integrated circuits.

A new control circuit had to be designed, but because the Sprague UDN-2954W operated extremely well at low loads during the test of the circuit, it seemed inopportune not to use them. In addition, the chip also had a brake function that would protect the motor drive circuit from back EMF (Electromagnetic Force), cause by reversing the motor directions in high inertia conditions such as this. These considerations led to the development of a hybrid circuit that combines the high power transistors and relays of the first circuit with the logic and chips of the second.

The final control circuit consists of five separate circuits, which are shown schematically in Fig. 7 through Fig. 11. Fig. 7 includes: the initialization clocks, the pulse-width modulator, the start-up routine circuit, and the 18 volt power relay. Fig. 8 is the schematic for the Master Control Circuit which operates the timing between the two sets of legs, as well as the turning circuit. Fig. 9 is the circuit for each separate leg; this circuit is repeated six times in the controller. The Leg Power Circuit, which is also repeated six times, is shown in Fig. 10. Fig. 11 is the schematic representation of the turning circuit.

5. CONCLUSION

The objective of this project was to make a walking machine that fit the requirements of the contest rules and stayed within the budget limits set for this project (see appendix). Within these constraints, the undergraduates were free to pursue any idea for the design of the walking robot they might have.

The overall design of the machine seems quite promising, as the turning is basically independent of the forward motion, and the speed is limited only by the power that is available. The body is very stable because most of the weight, the batteries and turning mechanism, is located at the very center of the robot. The body was also easy to construct because, except for cutting and drilling the plates and tubing, the only machining required was turning a shaft and housing for the bearings. In addition, the pantograph design allows that the mass center of the whole robot be maintained at a fixed height while walking, making it less likely to malfunction due to vibration of the electronics. Finally, the box beam pylon assembly is not confined by size as the strength and weight of aluminum would permit the manufacture of a much larger body.

In the future, there are several areas which should be given greater consideration, most importantly, that of the design process. Before construction begins on the next robot, a more thorough study of each component: the body, legs, and control systems, should be attempted. In each case, emphasis should be placed not only on a design that works well, but also on one that is easy to manufacture. The robot built this year often required parts that were difficult and time consuming to make. Computer studies of the motion and force analysis and use of microprocessors to control the robot should also be investigated, so higher levels of competition can be attained.

6. ACKNOWLEDGEMENT

Financial support for the project was provided by the Department of Mechanical Engineering, the Dean's office of the College of Engineering, and Systems Research Center at the University of Maryland. In particular, we would like to extend our appreciation to Dr. William L. Fourney for constant support during the course of the project.

7. REFERENCES

Robillard, M. J., Microprocessor Based Robotics, Howard W. Sams and Company, Inc., Indianapolis, Indiana. 1983.

Waldron, K. J. and M. J. Waldron, "A Retrospective Study of a Complex Mechanical System Design," Proceedings of an SF Workshop in Design Theory, Oakland, California, Feb. 1987.

APPENDIX

PARTS AND COSTS

American Bearing and Power Transmission, Inc.

Angular Contact Bearing	2 @ $15.12	30.24
YA40-3/4" 40-Tooth Gear	1 @ $14.19	14.19
YA80 80-Tooth Gear	1 @ $19.19	19.19
Hardened Steel Shafts 7.5"	6 @ $ 2.61	15.66
Hardened Steel Shafts 5.0"	6 @ $ 1.45	8.70
Cutting Charge		15.00

AST/Servo Systems, Inc.

DM-378 D. C. Motor	14 $ 8.50	119.00

Winfred M. Berg, Inc.

W48B29-F40 Worm Gear	7 @ $ 9.22	64.54
W58S-2F Worm	7 @ $ 9.50	66.50
LMB-3 Linear Bearing	14 @ $10.87	152.18
B4-8 Oil-less Bearings	80 @ $ 2.46	196.80
CD8-3 Teflon Thrust Washers	80 @ $ .53	39.43
CD1-2-SS Hardened and Ground Stainless Thrust Washers	30 @ $ .70	20.16
Flexible Couplings	6 @ $ 7.95	47.70
Flanged Ball Bearings	15 @ $ 5.70	85.50
W48b29-F60 Worm Gear	7 @ $10.80	75.60
Discount	@ $13.78	-13.78

Collins Brothers Electronics, Inc

I.C. Chips		40.00
Micro Switches	23 @ $ 2.25	51.75
Miscellaneous Electronics		44.44

Electronics PLus

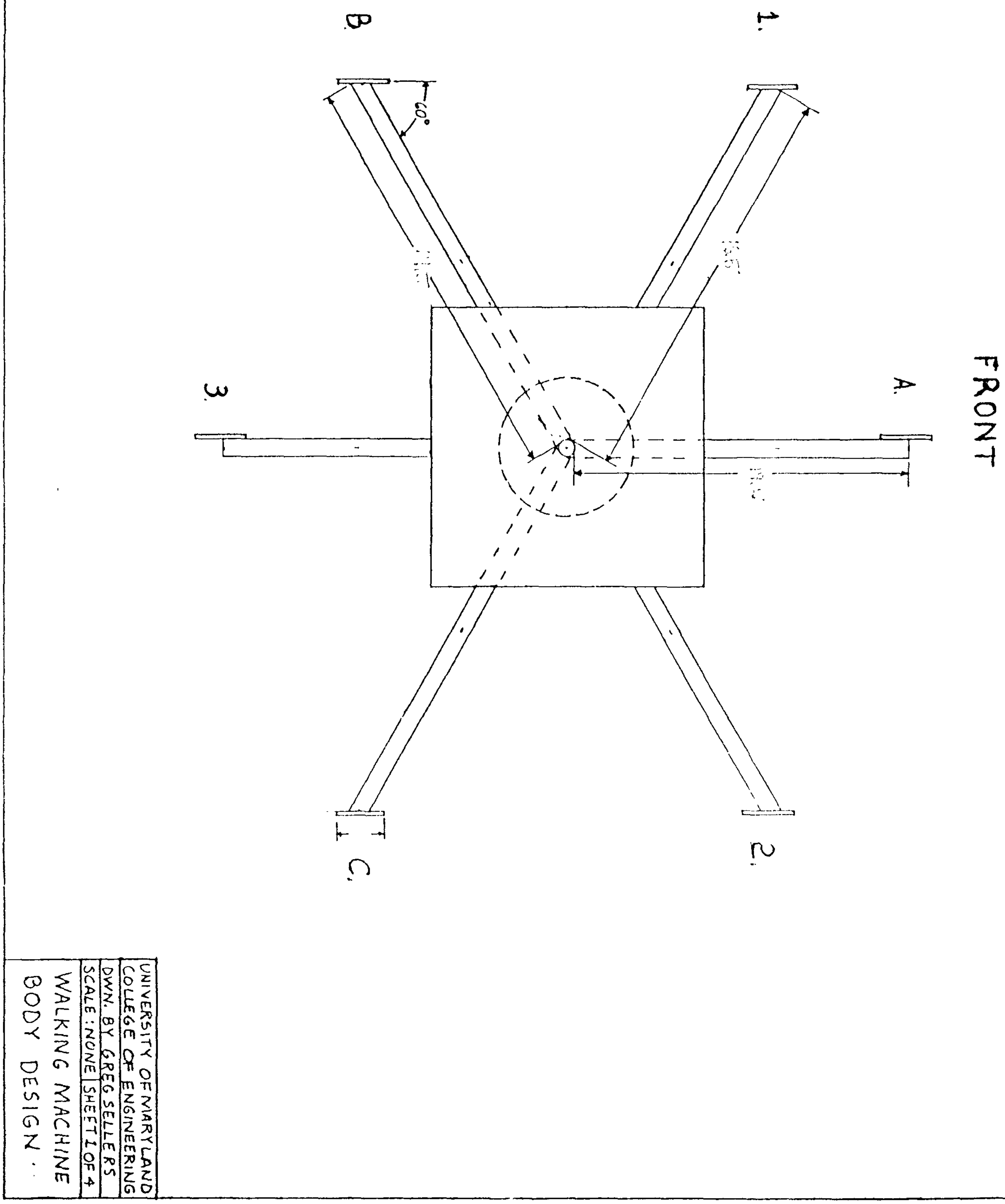
2-gaug. pot	2 @ $ 2.00	4.00
Quad Analog Switch	3 @ $ 3.00	9.00
Assorted Chips	4 @ $ 2.00	8.00
Panel Mount Pot	1 @ $ 2.00	2.00

W.W. Grainger, Inc.

42480 12 VDC Gearmotor	1 @ $31.87	31.87

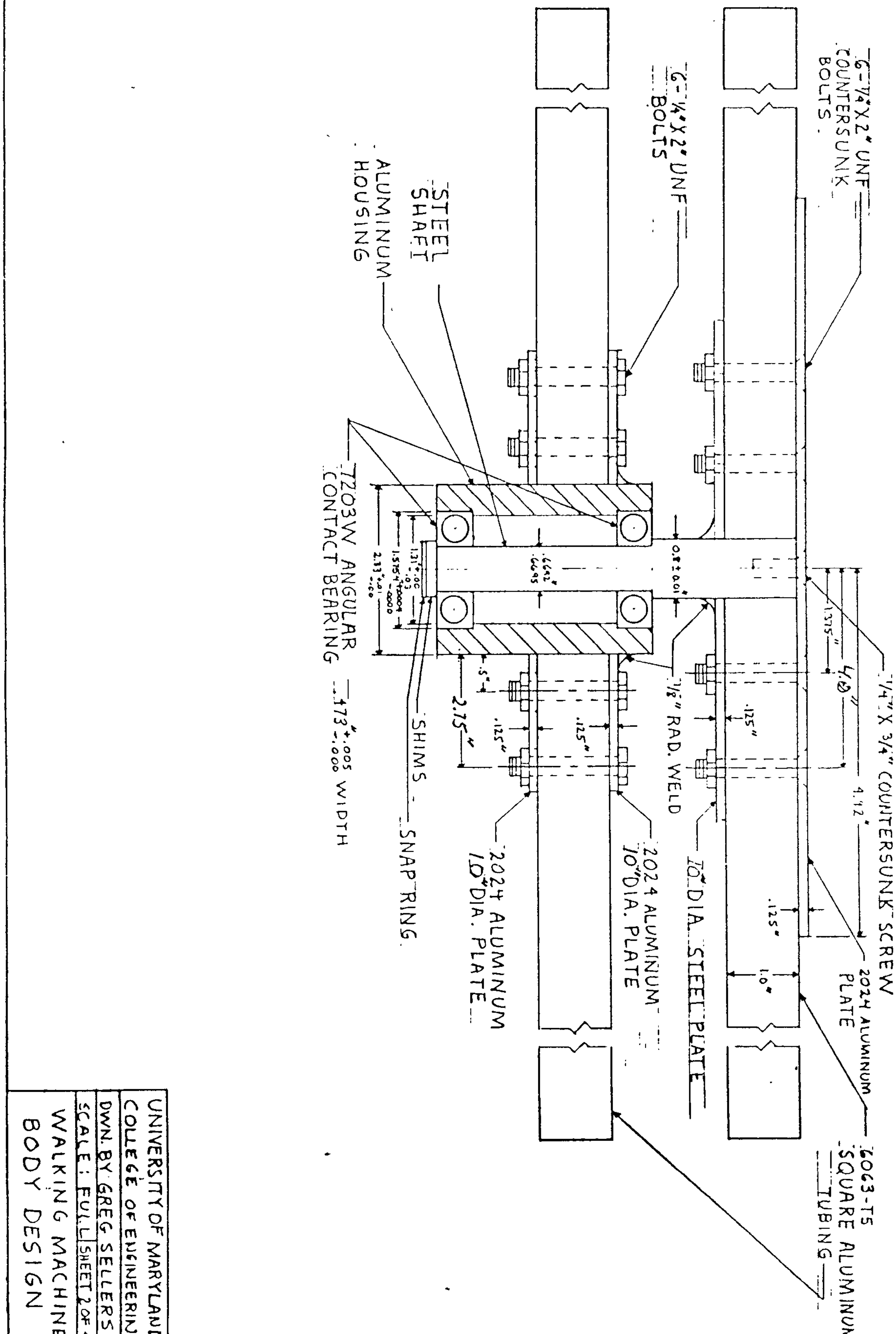
Motion Specialties, Inc.		
KP3A Ball Bearings	12 @ $ 8.80	105.60
Nook Industries		
RH11032 Acme Screws	3 @ $ 8.10	24.30
RH20032 Bronzac Nut	6 @ $11.55	69.30
RH30032 Plastic Nut	6 @ $11.35	68.10
Radio Shack		
Miscellaneous Supplies		9.77
DPDT relay	3 @ $ 2.45	7.35
1N270 Diodes	2 @ $ 1.00	2.00
SPDT Microswitches	6 @ $ 2.19	13.14
University of Maryland Physics Store		
1" x 1" Aluminum Tubing		24.00
1/4" inch Aluminum Plates		5.00
Miscellaneous Electronics		
Relays		
Chips		
Transistors, Wire, etc.		500.00
		+
Total Cost		$ 1985.61

Figure 1.



FRONT
A.
1.
B.
60°
3.
C.
2.
UNIVERSITY OF MARYLAND
COLLEGE OF ENGINEERING
DWN. BY GREG SELLERS
SCALE: NONE
SHEET 1 OF 4
WALKING MACHINE
BODY DESIGN.

Figure 2.


6-1/4"X2" UNF COUNTERSUNK BOLTS
6-1/4"X2" UNF BOLTS
STEEL SHAFT
ALUMINUM HOUSING
7203W ANGULAR CONTACT BEARING
.173"+.005 -.000 WIDTH
SHIMS
SNAP RING
2024 ALUMINUM 10" DIA. PLATE
2024 ALUMINUM 10" DIA. PLATE
10" DIA. STEEL PLATE
1/8" RAD. WELD
1/4" X 3/4" COUNTERSUNK SCREW
2024 ALUMINUM PLATE
6063-T5 SQUARE ALUMINUM TUBING
2.15"
.5"
.125"
1.375"
4.0"
4.12"
1.0"
UNIVERSITY OF MARYLAND
COLLEGE OF ENGINEERING
DWN. BY GREG SELLERS
SCALE: FULL
SHEET 2 OF 4
WALKING MACHINE
BODY DESIGN

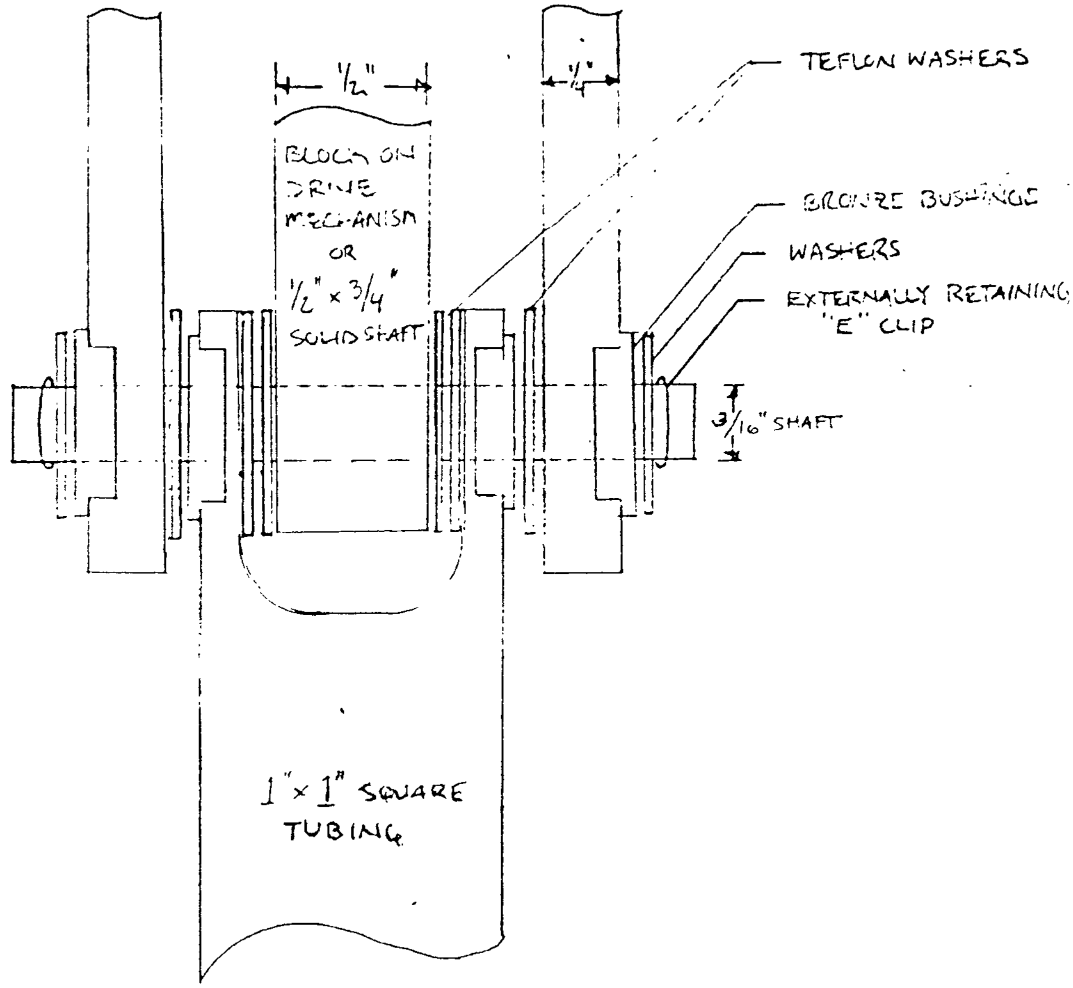


Figure 3a..

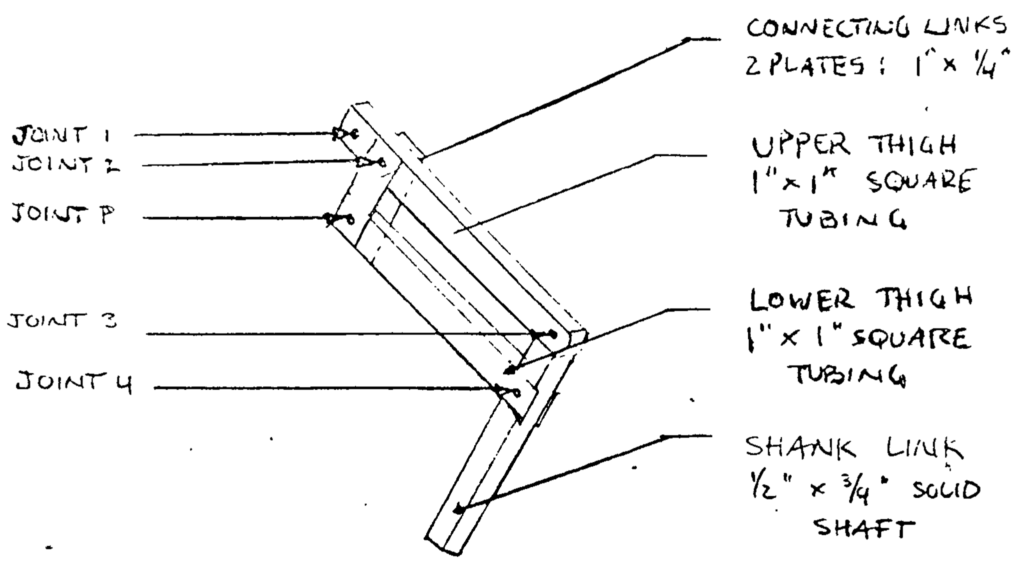
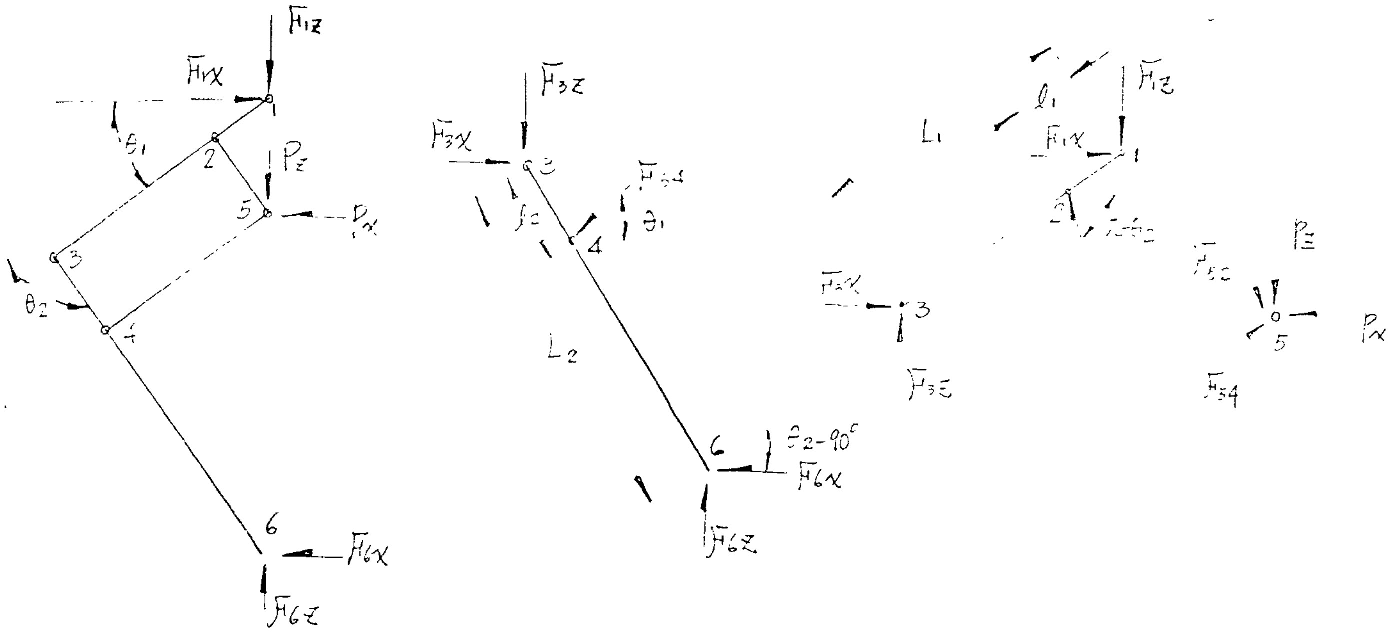


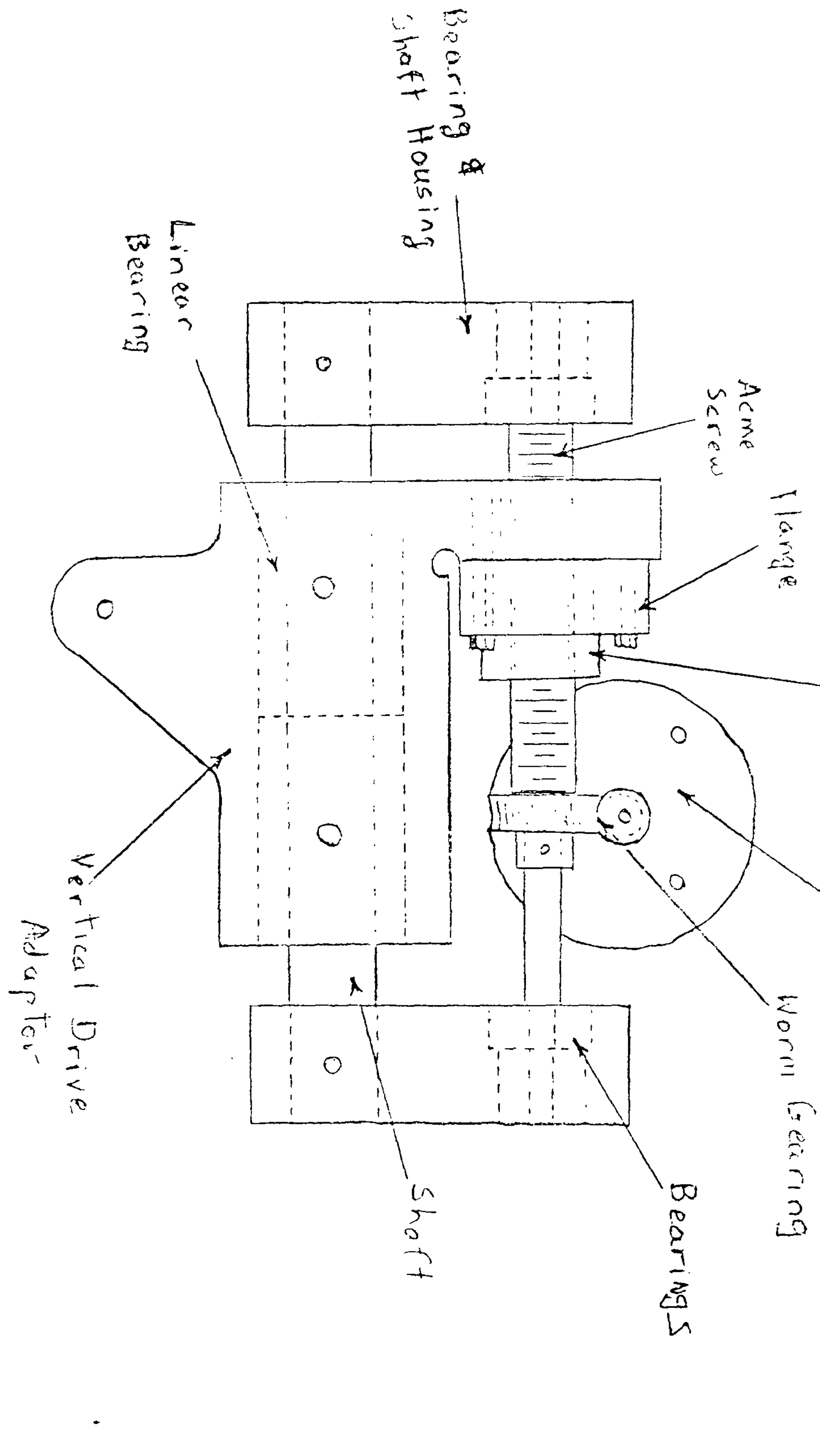
Figure 3b.

Figure 4.



F1z
F1x
θ1
Pz
Px
θ2
F6x
F6z
F3z
F3x
θ1
L2
θ2-90°
F6x
F6z
L1
F1z
F1x
Pz
F3x
F3z
F54
Px

Figure 6.



Bearing & Shaft Housing
Linear Bearing
Acme Screw
Flange
Acme Nut
Motor
Worm Gearing
Bearings
Shaft
Vertical Drive Adapter

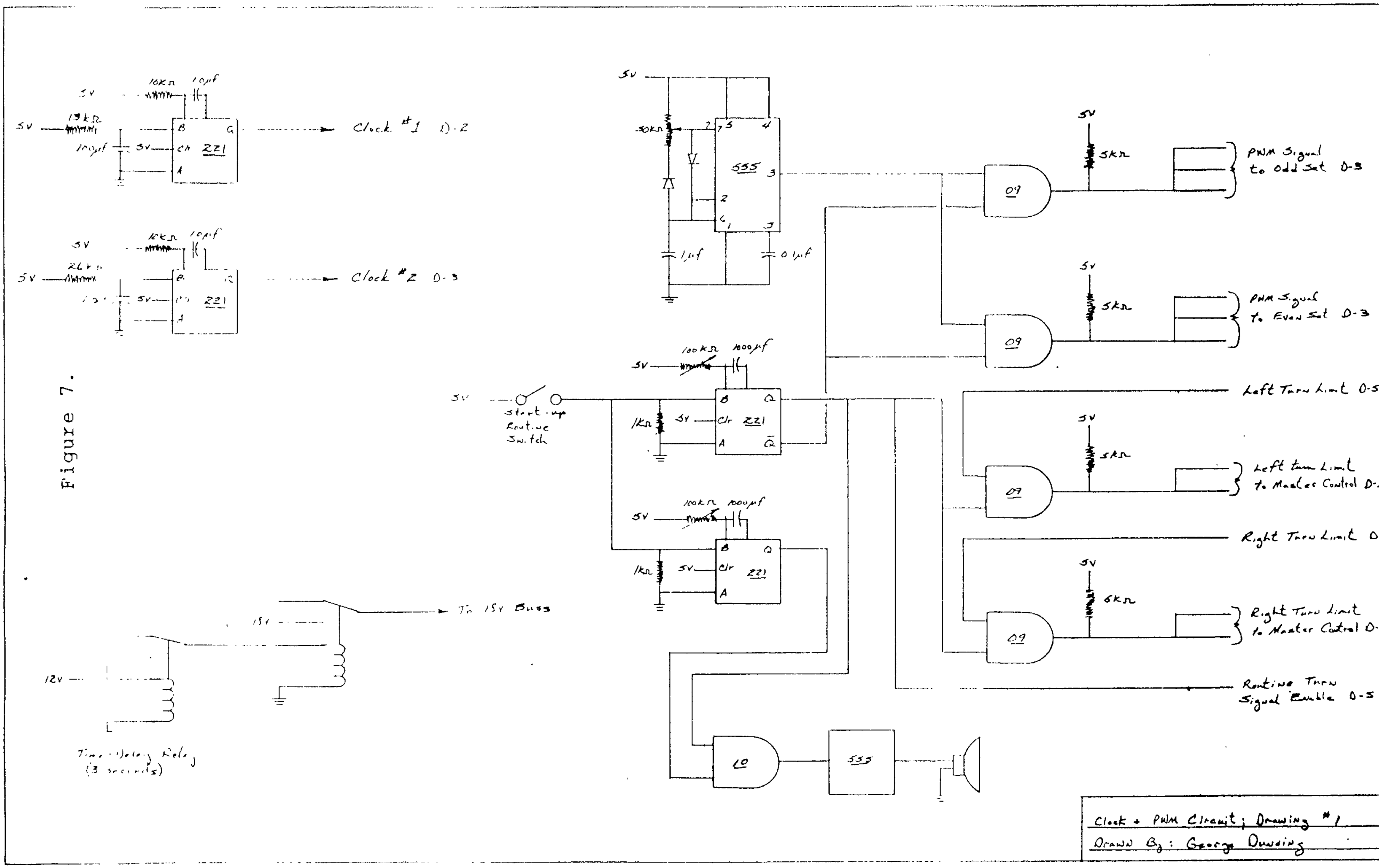

5V
13kΩ
10kΩ
10μf
ZZ1
Clock #1 D-2
Clock #2 D-3
5V
Start-up Routine Switch
100kΩ
1000μf
1kΩ
555
.50kΩ
1μf
0.1μf
09
5kΩ
PWM Signal to Odd Set D-3
PWM Signal to Even Set D-3
Left Turn Limit D-5
Left turn Limit to Master Control D-2
Right Turn Limit D-5
Right Turn Limit to Master Control D-2
Routine Turn Signal Enable D-5
12V
15V
To 15V Buss
Time-Delay Relay (3 seconds)
Clock + PWM Circuit; Drawing #1
Drawn By: George Downing

Figure 7.

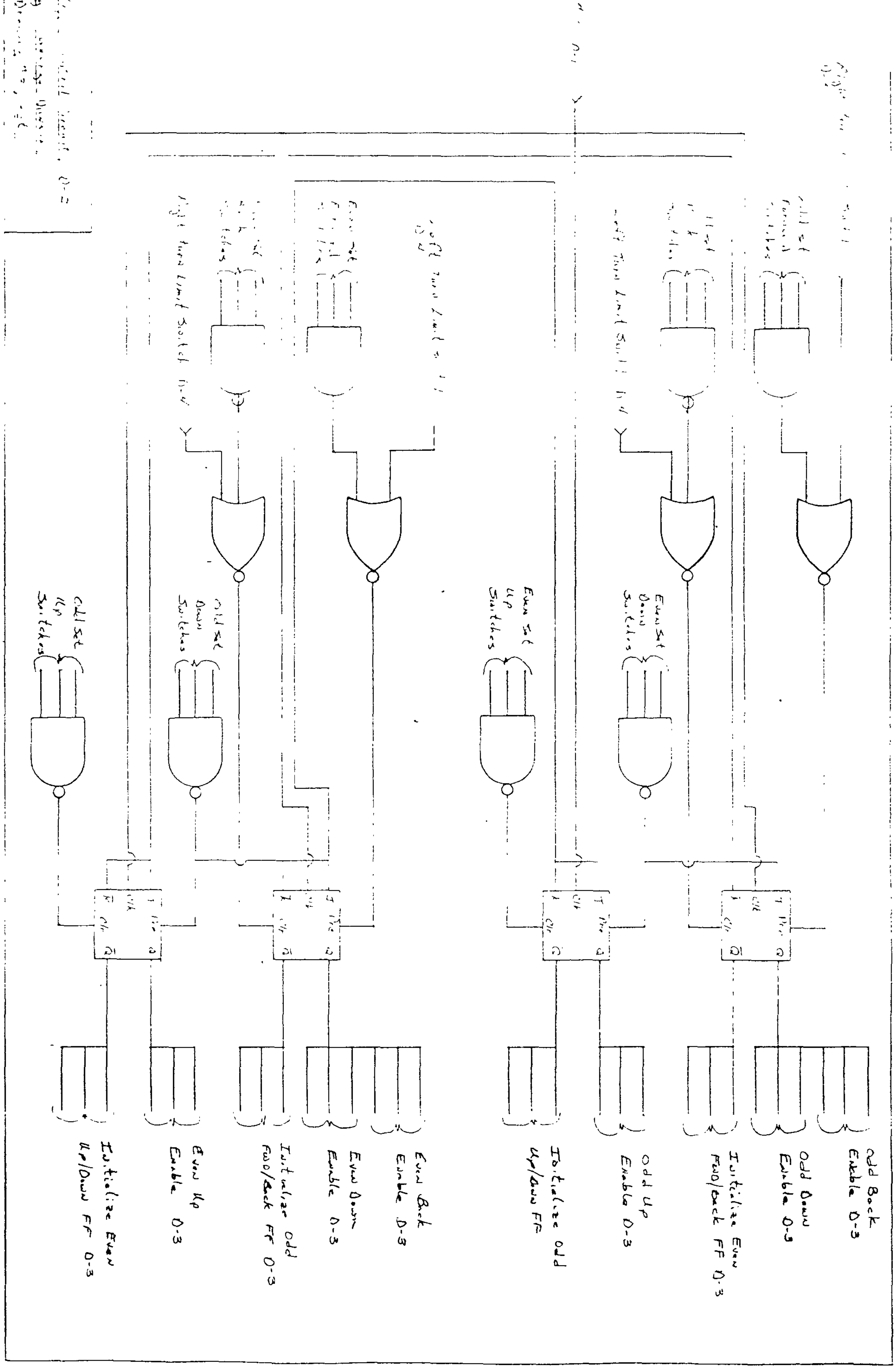

Odd Set Up Switches
Odd Set Down Switches
Even Set Up Switches
Even Set Down Switches
Initialize Even Up/Down FF 0-3
Even Up Enable 0-3
Initialize Odd Fwd/Back FF 0-3
Even Down Enable 0-3
Even Back Enable 0-3
Initialize Odd Up/Down FF
Odd Up Enable 0-3
Initialize Even Fwd/Back FF 0-3
Odd Down Enable 0-3
Odd Back Enable 0-3

Figure 8.

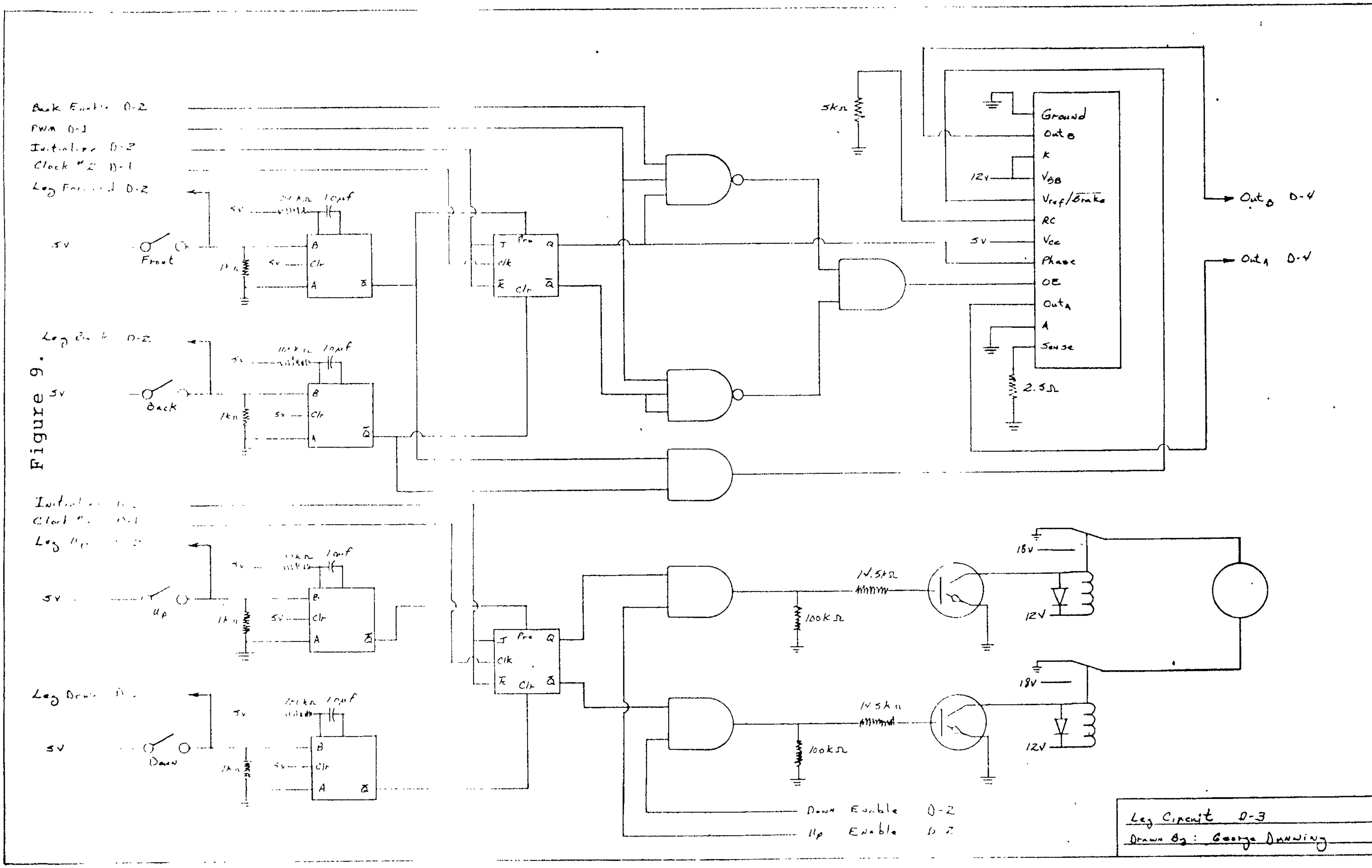
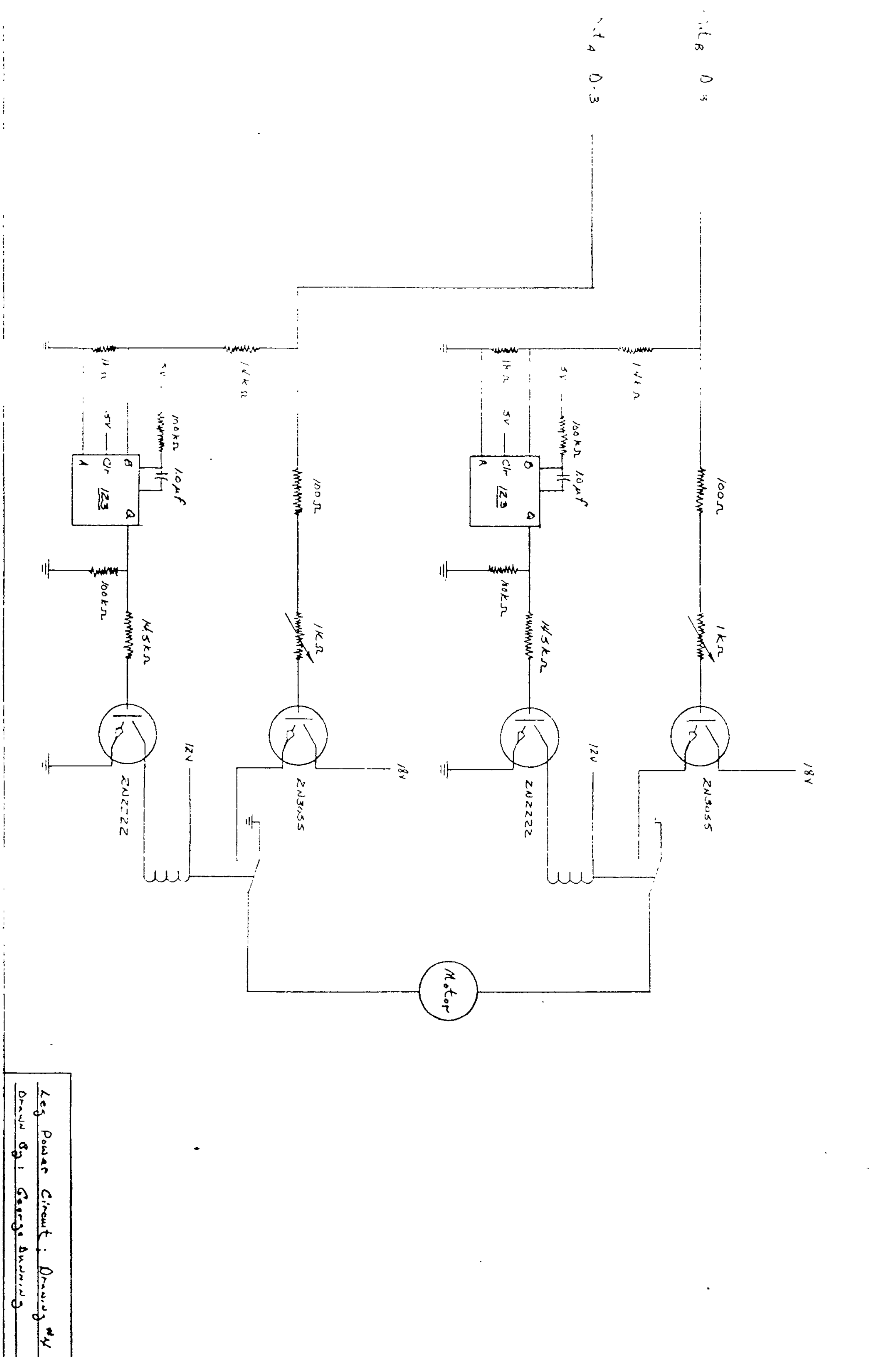
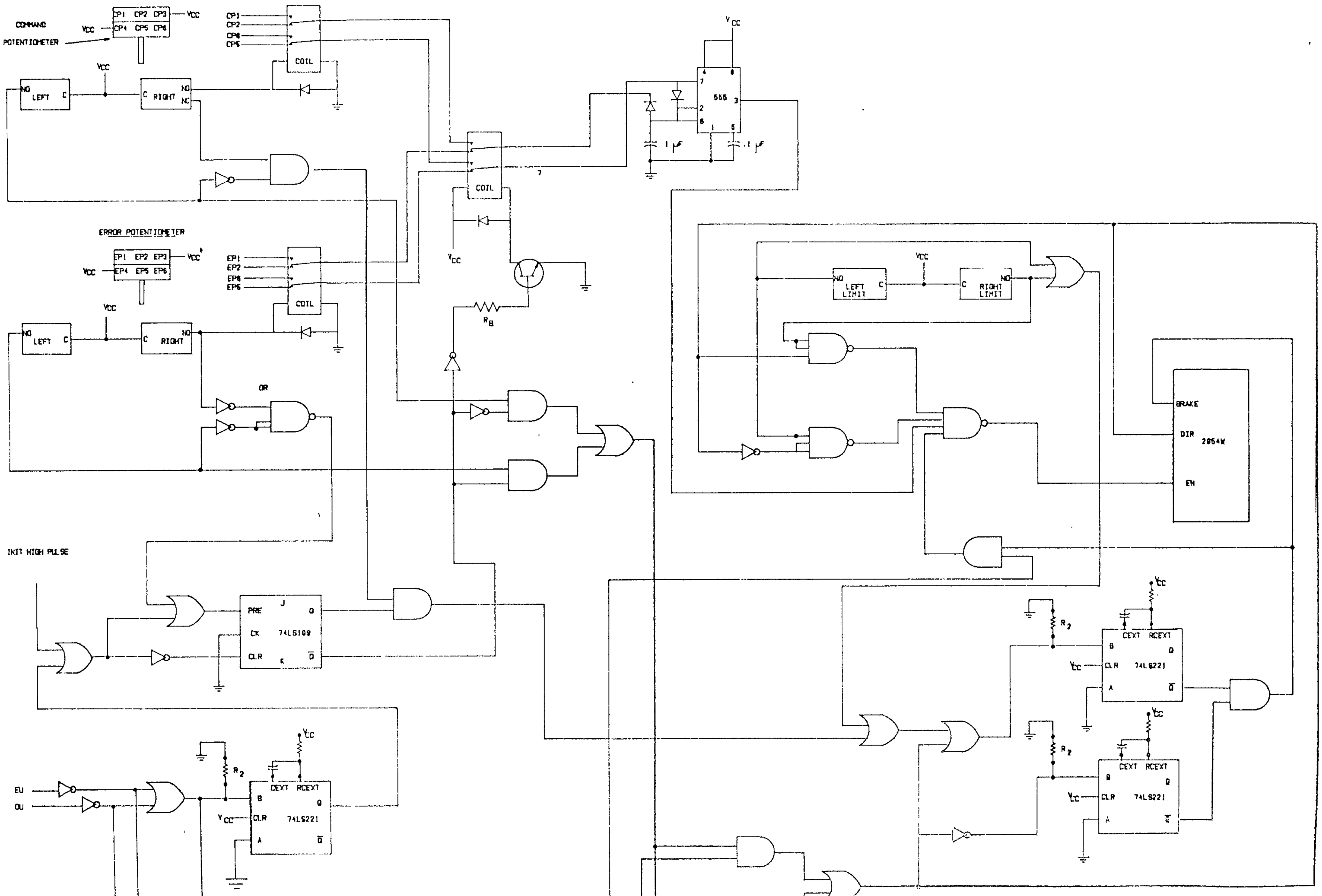

Back Enable D-2
PWM D-1
Initialize D-2
Clock #2 D-1
Leg Forward D-2
Front
Back
Up
Down
5V
1kΩ
10µf
B
Clr
A
J
Pre
Q
Clk
K
Ground
Out B
K
12V
VBB
Vref/Brake
RC
5V
Vcc
Phase
OE
Out A
A
Sense
5kΩ
2.5Ω
Out B D-4
Out A D-4
14.5kΩ
100kΩ
18V
12V
Down Enable D-2
Up Enable D-2
Leg Circuit D-3
Drawn By: George Dunning

Figure 9.

Figure 10.





TURNING LOGIC

DRAWN BY: DOUGLAS HAAK 4/7/87