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(NASA-CR-192732) THE M68HC11 GRIPPER CONTROLLER ELECTRONICS (Rensselaer Polytechnic Inst.) 71 p

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M68HC11 GRIPPER CONTROLLER ELECTRONICS

by

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ABSTRACT

This document describes the instrumentation, operational theory, circuit implementation, calibration procedures, and general notes for the CIRSSE general purpose pneumatic hand. The mechanical design was done by John Peiffer (Figure 1 and Appendix A) and the control software was written by Jody Tsai (see CIRSSE report #90). The circuit design, PCB layout, hand instrumentation, and controller construction described in detail in this document are the result of a senior project completed by Jeff Bethel under the guidance of Dr. Robert B. Kelley.

PROJECT OVERVIEW

The RPI pneumatic hand is an adaptable general purpose gripper designed and constructed at Rensselaer Polytechnic Institute. The hand and control system is designed for use on a dual arm testbed where coordinated control is dependent on reliable grasping capabilities and accurate grip force data.

As of the onset of this project, the hand had been completely constructed, but no attempts to instrument the device had taken place. It was therefore necessary to design the entire control system from the ground up. Sensor types and locations, along with decisions regarding implementation of control algorithms, interface protocol and physical layout had all to be determined to create a functioning system.

This report describes the system developed by Jeff Bethel in suitable detail to be used as an operations/diagnostics manual. After a brief description of the overall hardware layout, each section of the gripper control system is discussed, including theory, implementation, calibration, and general design notes.

CONTROL SYSTEM ARCHITECTURE

The overall control system architecture can be seen in Figure 1. A processor interfaces to electronics that are interconnected to the individual sensor groups on the hand assembly. The power supply, processor board, and the custom electronics are all contained in a standard $3^1/_2$-inch electronics cabinet that can be integrated into the existing racks in the laboratory.

A single board processor was selected as the low level gripper controller because of its variety of input-output (I/O) capabilities, ease of programming, and low cost.

The hand is actuated by high pressure air with control algorithms running on the Motorola MC68HC11 8-bit micro-controller. Several different algorithms including position and force control are available, along with an interface protocol that allows for simple operation from any high level control system.

The gripper has three basic sensor groups: strain gage force sensors measuring grasping force; infrared crossfire sensor; and a linear position sensor. The gripper base is designed to interface with a force-torque sensor allowing full force data to be available to the control systems. The force-torque system remains unchanged and is operated independently from the gripper sub-system.

The interface from the MC68HC11 to the hand sensors is done with a custom designed Hand Interface Board. The board was developed specifically for this hand and is constructed with a double sided printed circuit board (PCB) similar to the PCB used for the MC68HC11.

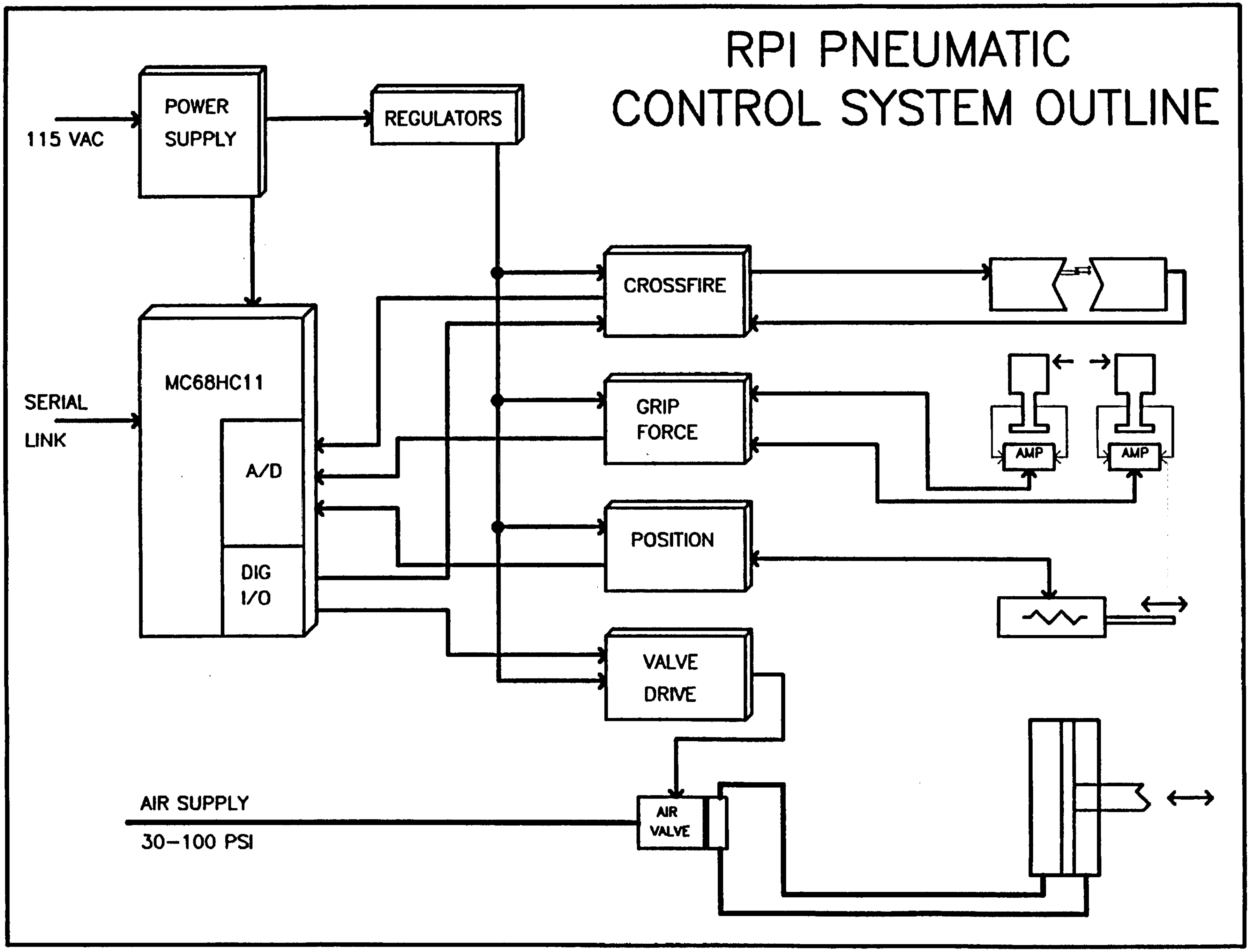


Figure 1: Overall Control System Architecture

A silk screen printed on the PCB surface indicates the placement and purpose of the components, allowing for easier understanding of the circuit operation.

All low level computations and data conversions are done directly on the MC68HC11 micro-controller utilizing an on-chip analog to digital (A/D) conversion system for the majority of the hand signals. Control of the gripper modes and set points is via a serial link to a host processor, which sends high level commands that are implemented by the MC68HC11 and associated hardware. Hand status and feedback information are passed back through this same serial interface for interpretation by high level software. Details of the software structure and interface specifications are included in CIRSSE Report #90. Both the processor and the development board have substantial documentation available from the Motorola Corporation (Document numbers MC68HC11RM/AD; M68HC11EVB/D1; MC68HC11A8/D). Details of the board's operation will not be discussed in this report.

The air flow that drives the gripper is controlled by a high performance air valve (manufactured by Atchley Controls). This same valve was used on previous pneumatic gripper systems at RPI and has proved to be a durable and reliable device. The valve is unique in that it maintains a pressure on the outlets that is linearly proportional to the input voltage. Input voltages that are negative supply air to one output port, while positive voltages supply air to the other port. Given this design, the two output ports can be connected directly to opposing sides of the cylinder-piston assembly to provide a simple and reliable force mode actuator. A special digital to analog (D/A) conversion circuit on the gripper interface board converts the MC68HC11's 8-bit digital signal into a ± 10 V analog control signal capable of driving the air valve. Although not inexpensive, this valve greatly simplifies the overall design, while greatly increasing the reliability and performance of the gripper system.

HARDWARE OVERVIEW

Hand Mechanics

The hand mechanism, shown in Figure 2, is equipped with a pneumatic cylinder of approximately 2-inch diameter with $^1/_2$ inch travel. Dual ports allow an air source to drive the piston both directions with travel limits imposed by the piston mechanism itself. Connected to this piston is a shaft which extends to a cross bar Adapter that drives the two finger Toggles or bases. The fingertip structure that connects to these finger bases is removable in two sections; a Finger section, and a grasping V-Fixture section. The V-Fixture actually contacts the object being grasped, and can easily be machined to conform to any required shape. Full mechanical illustrations and specifications of the V-Fixture, Fingertip, Toggle and the other mechanical components associated with the hand itself, can be found in Appendix A. (Note that these drawings are the work of John Peiffer and do not reflect the modifications required for sensor mounting.)

Air Valve

The pneumatic valve which controls the air flow to the piston is located in the shoulder of the PUMA robot arm. This is done to minimize the distance from the valve to the hand, thereby reducing the tubing length between the control valve and the air cylinder. This is important from a performance point of view where the computer's air-drive commands should reflect a change in cylinder pressure as quickly as possible to reduce the chances of control

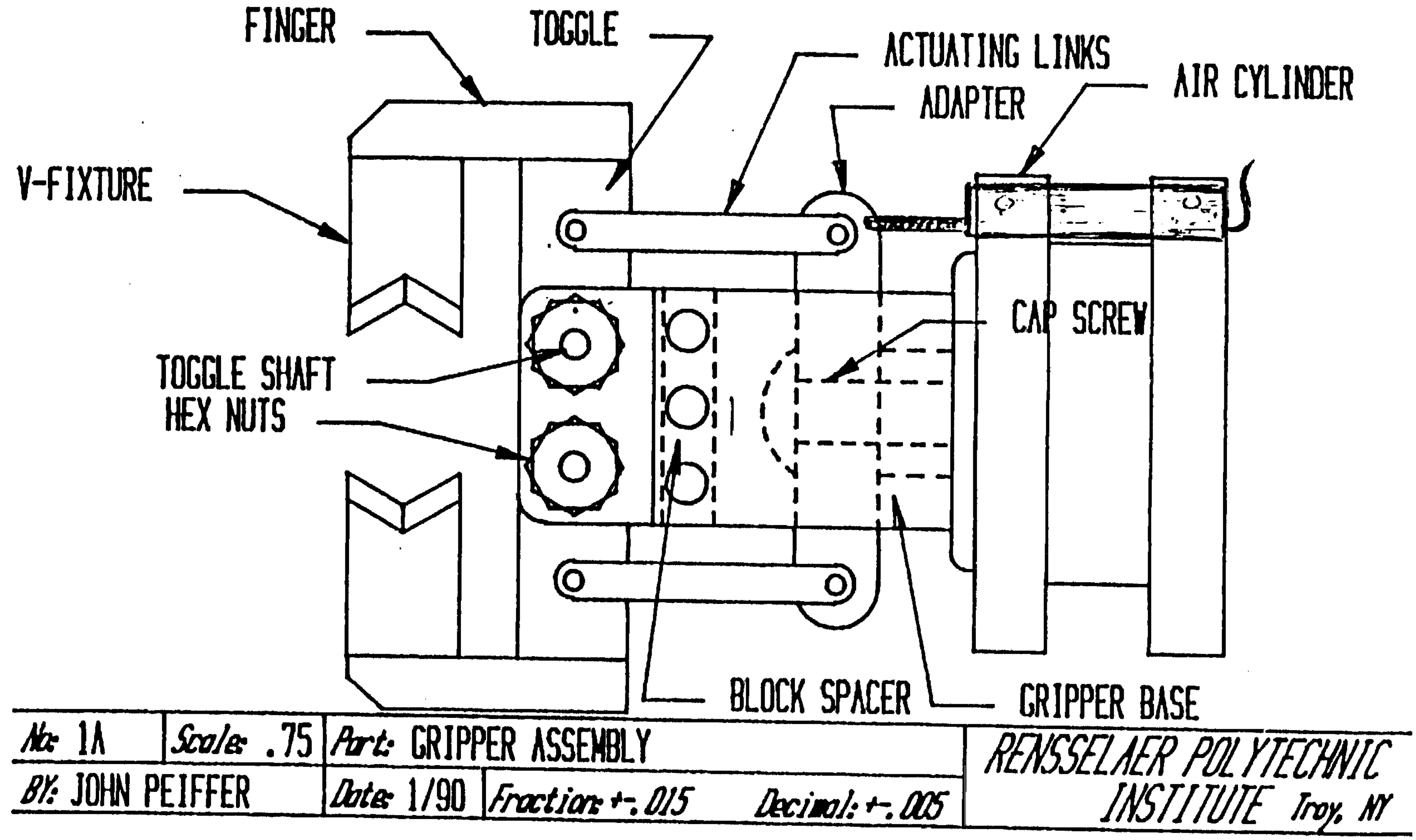


Figure 2: Gripper Assembly

oscillations. The two control wires required for the Atchley valve are routed through the Puma on the existing air valve wires: J8 pins 8 and 9. These two pins are accessible at either the Puma base, or the jack at the Unimation controller.

These two wires should not be allowed to run into the existing Unimation controller, as damage may occur if the valve is driven as the stock air valve.

The Atchley valve is used as a direct replacement for the stock valve, and no reconfiguration of the air lines is required. The air supply line from the base of the Puma should be connected to the air supply port of the Atchley valve, while cylinder ports 1 and 2 should be connected to the two existing tubes that go to the arm end-effector. While not entirely necessary, the return port of the Atchley valve can be connected to the existing vent tube.

The existing air connections to laboratory air supply can be used with no modification. It should be noted that the Atchley valve operates in the range of 80 to 160 psi and the air supply pressure should not be allowed to fall outside this range. A standard operating pressure should be established and maintained as different supply pressures will affect servo parameters that are required for stable operation.

Hand Cabling

All sensor lines coming from the hand are contained in a single 15-pin, D-type connector that extends approximately 8" from the base of the hand (see Appendix B for pin-outs and connector part numbers). This allows the hand to be removed or interchanged easily. Only 11 of the 15 pins are utilized by the hand sensor groups.

As mentioned above, the air valve control wires run from inside the Puma to the base connector. At this point, sensor lines from the hand and the control signals for the valve are combined at another 15-pin D-type connector located at the robot base. Here, the 11 signal lines from the hand and the two from the valve are combined into a single cable that extends to the controller box. The remaining two conductors are designated as auxiliary ground and shield lines.

Controller Box

The controller box is a standard $3^1/_2$ inch rack mount chassis that contains the following components: DC POWER SUPPLY, AC INLET, FUSE, POWER SWITCH, ENABLE SWITCH, ENABLE INDICATOR LAMP, MC68HC11 SINGLE BOARD PROCESSOR, HAND INTERFACE BOARD, AND 15-PIN D-TYPE CONNECTOR.

Controller wiring and schematics are given in Appendix C.

Power is supplied to the controller box from a standard three pronged AC power connector located on the rear of the chassis and is fused through a 2A fuse located on the power supply.

An illuminated rocker switch on the front panel provides control over the DC power supply. This power supply provides +12 V, -12 V, and +5 V for the computer board and the interface board. The LED on the switch is powered by the +5 V output of the power supply through a dropping resistor located at the switch.

The processor board connects to the hand interface board through a 60-pin ribbon cable connector designated P1. Both the processor printed circuit board and the hand interface PCB are similar in size. However, pin 1 on the 60-pin connectors are located on opposite sides.

This was done to prevent a twist in the interconnecting 60-pin ribbon cable. *This must be remembered when identifying pins for testing or diagnostic work.* Note that pin 1 is labeled on the silk screen for the hand interface board. This ribbon cable carries the analog and digital signals to and from the processor to the hand interface board.

The interface board has one 13-pin connector for the sensor signals, and one 4-pin connector for the air valve. Internal chassis wiring connects these two connectors to a single 15-pin, D-type connector on the rear of the chassis. Given this arrangement, it is possible to plug the hand directly into the rear of the module for testing the sensor groups with no need for the entire robot cable assembly. (Note that this arrangement does not allow the air valve to be tested.)

Enable Circuit

A DPDT switch on the front panel is used to enable the air valve output. This is used for two reasons. First, when the controller is first powered up, the D/A chip driving the valve does not get valid data and will open or close the gripper if the air supply is on. Second, because of the high gripping forces involved, it may be necessary to disable the gripping air supply.

Note that in the ON position, the enable switch allows the analog signal to be applied to the air valve. In the OFF position, the analog signal path is interrupted and causes the air valve to apply equal air pressure to both sides of the gripper piston and release any objects being held.

The second set of poles on the enable switch controls a red lamp on the front panel that indicates whether the gripper is enabled or not. When illuminated, the gripper control signal is enabled and, when connected to the air supply, the gripper has the ability to close.

ELECTRONICS OVERVIEW

Custom electronics are utilized in two places in the gripper system: the fingertip strain amplification system, and the Hand Electronics Interface printed circuit board.

Hand Electronics Interface Board

The purpose of the hand electronics interface is to buffer and condition the signal lines that interconnect the processor to the hand. The electronics are mostly analog based circuitry, utilizing op-amps to shift signal levels and various offsets. Each of the sensor groups that are utilized on the hand have unique output signals that vary in form and magnitude. These output signals must be processed into uniform voltage signals that can be read by the A/D converters on the MC68HC11.

A secondary function of the electronics is to supply the hand sensor groups with several fixed voltage sources. The nature of these sensors mandate a non-time varying reference voltage to insure a stable and accurate output. The interface electronics supply these reference voltages, and isolate the sensors from variations in the AC and DC power sources.

Four connectors exist on the printed circuit board: POWER INPUT, P1-COMPUTER INTERFACE, P2-HAND SENSOR INTERFACE, AND P3-AIR VALVE INTERFACE.

Through these four connectors the computer is connected to the hand, regulated supply voltages are supplied to the hand, and the air valve is driven.

It is important to note that no signal line going to the MC68HC11 is allowed to go to a negative value. The MC68HC11 is a CMOS device and latch-up will occur if **ANY** input drops below 0 V. It is entirely possible to adjust the analog sections of the interface board to output negative voltages to the A/D portion of the MC68HC11. While current is limited by the op-amp outputs and no damage may occur, it will prevent the A/D from working properly on all channels used. Attention must also be paid when calibrating the force sensors to ensure that negative voltages will not be encountered under maximum load conditions, (see force calibration; Section 4).

Each of the sensor groups on the hand require a unique circuit to interface to the processor board. For clarity reasons, each of these circuits has been isolated on the PCB with component values labeled and test points indicated. The hand interface board has the following sections:

V1:REGULATED VOLTAGE #1

V2:REGULATED VOLTAGE #2

V3:REGULATED VOLTAGE #3

POSITION FEEDBACK

FORCE FEEDBACK

CROSSFIRE FEEDBACK

AIR VALVE DRIVE

Reference Voltages

The various sensor groups require stable voltage sources to insure accurate readings under various operating conditions. This is implemented by several regulator chips and potentiometer adjustments. It was decided to use variable reference voltages as it allowed for a more flexible system and may provide useful in implementing future circuits. Three regulator circuits exist and are designated V1, V2, and V3 and schematics are given in Appendix C sheet #6.

V1 (Voltage Source 1)

Theory. V1 is used for most of the operational amplifier (op-amp) circuits as the positive supply voltage. The outputs of the op-amps can therefore swing to near +V1. V1 is also used as V_{high} for the A/D converter on the processor board. If the analog input voltage is equal to V1, the resulting digital value will be FF_{16} for the conversion. Note that V_{low} for the A/D converter is set to ground. Therefore, an input to the chip of O V will result in a digital value of 00_{16}.

Implementation. V1 is a positive adjustable voltage source that ranges from about 0.2 to 11.5 VDC. A 350T Positive Voltage Regulator in a TO-220 style case is bolted directly to the printed circuit board. Relatively large pads of isolated copper etched into the PCB are used to dissipate the heat generated from this device.

Calibration. A single turn potentiometer is used to set the voltage level of V1. This potentiometer is designated V1 TRIM 50K on the PCB silk screen. A test point designated TP1 can be used as a convenient contact point for calibration. For all laboratory work done at CIRSSE, this voltage cource was set to a value of about +10 V.

V2 (Voltage Source 2)

V2 is a negative adjustable voltage source and is the bipolar counter part for V1. V2 is used for most of the op-amp circuits as the negative supply voltage. The outputs of the op-amps can therefore swing to the corresponding near V2 value.

It is important to note that the A/D converter on the MC68HC11 is set to read from the 0 to V1 voltage range. This implies that even though the op-amp outputs can swing to negative values, the A/D converter will only function if positive voltages are present on ALL the input lines.

Implementation. V2 ranges from about -0.2 to -11.5 VDC and is created by a 377T Negative Voltage Regulator (TO-220 case). Mounting is the same as the 350T used for V1.

Calibration. A similar trim pot is provided for adjustment of V2 with the test point labeled TP2. V2 should be set to -10 V.

V3 (Voltage Source 3)

Theory. V3 is a positive adjustable voltage source with a similar range to that of V1. V3 is used as a reference voltage source for the strain gages that measure the grasping force. A separate voltage source insures a stable voltage for both the strain gages and associated electronics.

Implementation. The circuit for V3 is an exact duplicate of the circuit used for V1.

Calibration. A trim pot and test point for this voltage source are designated V3 TRIM and TP4.

V3 was set to +8 V for all work being done at CIRSSE. The value of this voltage changes the power dissipated in the resistive elements of the strain gages, along with slightly modifying some of the operating points of the force feedback circuit. (See Force Feedback section below.)

General Adjustment Note

The values that V1, V2, and V3 are set to are not exceedingly critical. However, all adjustments made to other parts of the circuits are based on these reference voltages. It is therefore recommended that they be set to known values before the rest of the circuit is calibrated. These values should be recorded so that if a voltage does drift over time or the settings are disturbed, they can be reset without having to re-calibrate the entire circuit for the new set of reference voltages. The values given above have been tested and deemed suitable for general purpose operation of the gripper system. If, however, special operating circumstances arise where different voltage levels provide more suitable performance, these new values should be noted for future calibration procedures.

Position Feedback

Theory. Accurate position data is required for both position control modes and to recognize mechanical travel limitations in force mode control. Because the original gripper design did not include provisions for any sensor elements, device selection and mounting proved to be slightly more difficult than would be expected. Both rotational and linear potentiometers were investigated with the final decision to go with the latter. The specifications for the linear potentiometer are given in Appendix E.

Implementation. Modifications had to be made to the gripper assembly to mount his potentiometer on the air cylinder. It was necessary to remove one of the four mounting bolts to permit the linear potentiometer to follow the motion of the Adapter attached to the air cylinder piston shaft. Thus, fingertip position is obtained from the spring loaded potentiometer shaft resting against the Adapter piece that drives the two fingers. The potentiometer is rated at 3.4k for the entire travel range of about 1 inch. However, because the cross air cylinder has a motion range of $^1/_2$ inch, only half of the stroke of the potentiometer is actually utilized. Thus, when the gripper moves between fully open and closed, the potentiometer always has a non-zero resistance.

The CIRSSE gripper uses a special V-Fixture to grasp cylindrical strut elements that are approximately 0.75 inch diameter. This removes the requirement that the gripper be able to close completely. In this configuration, there was no absolute zero position to use as a reference point. The mechanical limits of the air piston do not serve as a valid zero point because this changes if V-Fixtures that contact each other when closed are used. The computer reads the entire position range of the air piston's travel. The zero position issue is handled in software.

The ends of the resistor element are connected to V1 and V2. If V1 and V2 are set to $\pm$10 V, this gives a total potential variation of 20 V over the entire travel range. Such a large voltage range is desirable because of the relatively short travel distance of the Adapter piece. Even with a maximum of $^1/_2$-inch travel, the position voltage will still vary by approximately 10 V. This helps to reduce the effects of noise in the potentiometer and signal lines. Power dissipation of the potentiometer at this voltage level is approximately 100 mW and falls below the rated value of 500 mW.

The interface circuit from this position sensor to the MC68HC11 performs two functions. First, it amplifies the reading from the linear potentiometer by a (variable) gain factor. And second, it allows the output to be offset in a positive or negative direction. The variable gain is used to allow the full A/D range, to be used even if a very small travel range is imposed by the air cylinder piston. The offset is used to shift the signal to the correct voltage range for the A/D and while insuring that the signal goes to a negative value.

Both of these functions are implemented by a simple op-amp circuit shown in Appendix C sheet #1. Pin P2-5 is the return signal line from the center tap of the position potentiometer. The fixed portion of the potentiometer is connected between Pins P2-2 and P2-3. Adjustment A1 is an offset voltage that can be summed with the output of the position signal, while A2 controls the gain of the op-amp. The output of this op-amp circuit is applied to analog channel E0 of the MC68HC11 and is converted to an 8-bit digital valve.

Calibration. Both the gain of the interface circuit and the offset value must be set to give optimum performance. A meter connected to test point TP3 will reflect the output voltage being applied to the A/D. By removing the air supply from the gripper, it can easily be moved over the entire travel range. The simplest method of calibrating the position feedback circuit is to first set the gain so that a voltage swing of about 8 V occurs from the fully open to fully closed positions. The offset may have to be adjusted here to prevent the output of the op-amp from saturating at either of the two extreme positions. With the gain set, the offset can then be adjusted so that the lower voltage limit is set to about 0.5 V. This will produce a voltage output from 0.5 V to about 8.5 V over the entire mechanical travel of the gripper. A small amount of guard area should be left at both ends of travel since the air cylinder will move slightly more under higher pressure conditions than were accounted for in the above calibration. In addition, if V1 is set to +10 V, the output op-amp can only swing its output to about +9 V. Again, it is important that the output level is never allowed to drop below 0 V under normal operating conditions.

Assume for example, the linear position potentiometer has an output of -2 to +4 V over the entire mechanical range of motion allowed by the air cylinder. Two adjustments would have to be made. First, a gain greater than one would have to be set to amplify the variation from 6 V to 8 V. Second, the signal would have to be shifted up so that it would vary from 0.5 to +8.5 V. (V1 is assumed to be set to 10 V.)

The output stage of the op-amp contains a low pass filter. This is done to help filter out any high frequency noise and limit the bandwidth that the A/D converter attempts to process.

Force Feedback

Theory. Gripping force feedback is provided to ensure that ample force is being applied to the object to prevent slippage, and to provide a mechanism for limiting this force if damage might result to the object from a too high gripping pressure. With this feedback, software is capable of performing a force servo where constant pressure is applied to the object being held, even if the object shifts or changes orientation.

Several different approaches to obtaining force data were investigated. Initially, efforts were made to purchase two small air pressure sensors that would be located near the air cylinder. These would monitor the air pressure on each side of the piston, and determine a differential pressure that would be proportional to the force being applied at the V-Fixtures.

Although it appeared to be a promising idea, there were two implementation problems. First, it proved to be very difficult to locate the required pressure sensors. The lack of available small sensors that operated in the required pressure range, along with the exceedingly high price of these sensors made device selection impossible. The second problem was with the air piston and mechanical arrangement. A relatively large amount of stiction was present in the piston/cylinder assembly which, when amplified to the fingertips through the mechanical linkages, results in a very limited force sensing resolution. Substantial force was required on the Adapter assembly before the gripper would actually move. When the gripper was moving, this stiction force is substantially less and would have required substantially more complex control routines to take this into account. Because of these two problems, it was decided to use a different method to sense grasping force.

The alternate method investigated is to utilize strain gages mounted closer to the V-Fixtures. Two possible locations were selected for the strain gages; the first was on the Actuating Links where the Adapter assembly drives the Toggle assembly. These actuating links have a relatively small cross sectional area and application of the strain gages would have been simplified. The second area was on the Finger assemblies. If the cross-section between the V-Fixture and the Toggles is modified to obtain a lower structural strength than the surrounding material, the Finger could bend slightly when a force is applied to an object. Strain gages mounted on both sides of this cross-section provide a means to measure this bending, as one surface goes into compression the other goes into tension.

The second of the two above alternatives was chosen for several reasons. If the gages were mounted on the Actuating Links, the lines of force would have been parallel to the surface of the strain gages. Although this would have worked, the strain to the gages in the second alternative are substantially greater because a specific bending point exists under the gage itself. In addition, the second design causes the resistance of one gage to go up, while the resistance of the gage on the other side drops. This effectively doubles the output from each fingertip.

Another reason why the second alternative was chosen was because there exists no sliding surfaces between the measurement point and the point of contact with the object. This eliminates the problem of stiction and also substantially reduces any hysteresis that may occur from bearing and pivot points.

The only disadvantage of this configuration is the weakening of the Finger assembly that imposes a trade off condition between sensitivity and maximum grasping force. Actual test plots of applied force versus measured strain will show where the metal begins to permanently deform, as the slope of the line will change.

The choice was made to use foil strain gages as opposed to silicon strain gages because they could easily be mounted without professional services. However, this choice meant that smaller variations in gage resistance would occur for a given force. Although a higher gain amplifier on the Hand Interface Board could provide enough amplification to bring the foil gage output to the 0 to +10 V level, it was feared that substantial amounts of noise would also be amplified by this same gain factor. Because of the high power PWM systems operating in the laboratory, it would be reasonable to assume that some of this noise would couple into the hand cables no matter how well shielded they were.

To reduce this problem, a small operational amplifier circuit was placed on the Finger assembly in close physical proximity to the foil gage to provide a gain of 150. This would increase the signal level going over the cables thereby increasing the signal to noise ratio by a factor of 150. The amplifier is a surface mount LM741 located in a small cavity machined in the base of the Finger where it bolts onto the Toggle assembly. Epoxy is used to seal and protect the device within the cavity, resulting in a rugged and reliable structure. Small holes are drilled in the Finger to allow the wires from the two strain gages to enter the cavity directly, eliminating the need for external wiring that could be damaged if the hand were to contact a solid object.

The Hand Interface Board performs several functions in processing the analog data from the strain gages to data for the A/D. First, the signal from each fingertip is amplified by a variable gain factor. Second, an offset is added to each to move the zero force operating points to their optimal values. Lastly, the signals are summed to provide a single analog voltage reflecting the absolute force being applied to the object.

Implementation. Because of the non-symmetric cross-section of the original Finger pieces, modifications are made to form a rectangular cross-section to obtain a more uniform stress pattern when bending occurred. The two support ridges on the back of each Finger are milled off and provide a suitable surface to attach the foil gages. Drawings of the modified Finger assembly are shown in Appendix C sheet #2, along with locations of the foil strain gages.

The operation of the foil gages associated fingertip amplifiers is that of a standard half bridge configuration. The embedded LM741 amplifies the voltage potential presented at its two inputs by a factor of 150. One of these inputs is obtained from a fixed voltage divider from V3 to ground. The other input is obtained from a voltage divider created with the two strain gages on either side of the Finger. As strain is applied to the Finger, the gage that goes into compression drops in resistance. This causes the potential at the midpoint of the strain gage voltage divider to move up or down depending on the direction of force applied. This value is compared to the fixed value present at the other input of the op-amp, and amplified. Schematics and physical layout of the fingertip amplifiers are given in Appendix C, sheet #2.

The output of the fingertip amplifier when no force is applied is one half V3. This corresponds to a level of 4 V when V3 is set to 8 V. The output will swing up or down depending on the direction of force applied. Note that at this point in the circuit, the fingertip is equally sensitive to forces in either direction.

Each fingertip is constructed as an exact copy of the other, resulting in output changes of the same polarity when an object is grasped. To obtain the total force being applied to the object, the signals from each fingertip are summed. The fingertips are wired to produce a positive voltage increase when a "positive" force is applied by the gripper, that is, when closing on an object.

There are three lines associated with each fingertip force system: V3, GND and SIGNAL OUT. V3 and GND are the supply voltages for the LM741 and the voltage dividers. SIGNAL OUT is the 150X amplified output. A small pin connector is mounted on the back side of each Finger to allow easy access to these three lines.

The fixed voltage divider and the negative feedback resistors associated with the LM741 are all constructed of $^1/_8$ W carbon resistors embedded within the fingertip.

A hand cable assembly combines the three lines from each fingertip, and other sensor lines to the 15-pin, D-type connector. Force sensor lines on this 15-pin connector and the Hand Interface Board are as follows:

1:GND

4:V3

7:Fingertip 1 Output

9:Fingertip 2 Output

The Hand Interface Board must further condition the fingertip outputs to provide the analog input to the MC68HC11.

Each fingertip output is amplified by a variable gain, summed with variable offset, then summed with the opposing fingertip's value. Summing of the two force signals is performed after the gains and offsets are applied to allow the balancing of the two fingertips. Schematics of this circuit are in Appendix C, sheet #3.

Calibration. Each fingertip must be calibrated to compensate for the small variations that occur in the force versus output relationship between different pieces.

Note, the fingertip structure and associated embedded amplifiers are completely symmetric up to the point of the Hand Interface Board. Equal sensitivity and equal range are available for forces applied in both directions. However, the amplifiers located on the Hand Interface Board can be offset to allow greater range in one direction than the other. Theoretically, if the hand is used for normal gripping functions, a significant force opposite of that which is applied during closing on an object will never exist. This would imply that the zero force voltage could be set at 0 V, at the exact lower limit of the A/D range, allowing the full range for positive gripping force. This is essentially true, with two exceptions. First, if the gripper is opened quickly enough, the mass of the V-Fixtures will apply a certain amount of negative force, and the analog voltage will drop below 0 V. Second, if any force is applied directly the V-Fixtures or Fingers from an external object (i.e., contacting an object with the gripper where a moment is created around the strain gage that appears to be a negative gripping force), the output will again attempt to swing negative.

Because of these two reasons, the zero force output must be offset above 0 V. A trade-off must be made between protecting against the above problem and maintaining a useful positive force range. The gain and offsets for each fingertip need to be adjusted in accordance to the application at hand. If relatively small forces are to be applied and measured, the gain can be adjusted reasonably high and the zero force output point can be moved to about half the operating range. If, on the other hand, large forces are to be dealt with, the gain must be set lower and the zero force output point can be lowered also.

The output of each fingertip adjustment op-amp can be measured on test points TP6 and TP7. Note that, at this point, the voltage values are inverted and are negative.

If required, the force to output voltage relationship of the different fingertips can be matched at this stage in the circuit by adjusting nonequal gains for each signal. In most cases, however, the gains can be adjusted so that they simply have the same approximate force ranges and saturate at the same general force levels.

The final op-amp stage on the Hand Interface Board produces an output that is the inverted summation of the two force values. This amplifier stage has a near unity gain and no offset. The output of this stage goes directly to the A/D and can be sampled at test point

TP8 on the printed circuit board. Again, the voltage level at this point must not be allowed to drop below 0 V, or the A/D will not function properly.

General Notes. Maximum Force Limits: The maximum force that can be gripped is limited by several factors. The most obvious are the available air pressure, mechanical advantage of the gripper assembly, structural failure points at the strain gage locations, and the instrumentation saturation points. The only limitation investigated here is the last of these, instrument saturation points.

Calibration data from laboratory tests indicated that the output of the embedded fingertip amplifiers increased by 50 mV for every pound of force that the gripper applied in the closing direction. This output to force relationship only holds for the specific fingertip tested, as tolerances in fabrication procedures and material variations will cause other fingertips to differ slightly.

Given data from this one test piece, the maximum load that can be measured before the fingertip amplifier saturates can be calculated. Because the supply for the LM347 is V3 and ground, the output cannot fully swing between these two points. With a non-usable range of about 0.5 V on each extreme end, the fingertip has the ability to measure forces up to about 80 pounds before the LM347 output saturates.

Accepting this as the maximum force to be measured, the gain and offset amplifier on the Hand Interface Board is adjusted to give an output of 9.5 V under full force conditions. Zero force voltage is adjusted to the +2 V level, allowing a negative force of slightly more than 20 pounds before the A/D input swings negative.

Note that resistors R6 and R8 are not used. These are provided for on the circuit board if the need arises for a voltage divider circuit if other types of force sensors are to be used.

Note that an error exists on the printed circuit board in the last op-amp stage. The circuit must be changed from a subtracting configuration to the required summing configuration. This is done by placing R11 to Pin 6 of the LF353.

Crossfire Sensor

Theory. The gripper system utilizes an infrared crossfire system that can detect the presence of an object between the V-Fixtures. An infrared LED and photo transistor are located on opposing sides of the gripping area. The IR transmitter is operated as a two-state device, either fully on or fully off. The IR detector feeds into one of the A/D circuits of the MC68HC11 after being processing by the Hand Interface Board.

Two basic modes of operation are available. The first, called the pulse mode, allows the IR transmitter to emit short but strong pulses of light. The maximum power dissipation for the device is exceeded for the time it is on, but because of the small duty cycle, the average power dissipation for the device is kept below the specified limit. The MC68HC11 causes a pulse to be emitted when a low to high transition takes place on one of its software controlled output lines.

The second method of operation is the non-pulsed mode. Here, the MC68HC11 has direct control over the IR transmitter via the same digital output line as above. However, because it is possible to turn the IR transmitter on for extended periods of time in this mode, current flow must be restricted so that it does not exceed the normal device limits.

The two modes are available to allow for flexibility in device selection of the IR devices and fingertip arrangements. If size limitations require a low power IR transmitter, the pulsed mode will probably have to be utilized to get sufficient light to the detector.

To determine if an object is between the gripper V-Fixtures, it is necessary to take into account the ambient light that the IR detector is receiving. If this amount of light were stable, it could simply be subtracted out of the sample value from the A/D. However, because the hand constantly changes orientation relative to laboratory work lights, this value cannot be predicted. In both modes of operation, two received IR samples are taken to determine the presence of an object. The first is taken with the IR transmitter off, giving an indication of the ambient light being received by the detector for the current hand orientation and laboratory lighting. The second reading is taken shortly after, but with the IR transmitter on. Subtracting the first reading from the second reading results in a value directly corresponding to the IR light that is passing between the two V-Fixtures. A threshold is then applied to this value to determine if an object is indeed within grasping range.

This method of operation was chosen over various others, such as modulating the emitter device, and placing a band pass filter on the receiver. Such methods work, but require additional circuitry and more critical calibrations to deal with 120 Hz fluorescent flicker than the above approach.

Implementation. The transmitter and receiver devices are located within machined recesses on opposing V-Fixtures. They are positioned so that when gripping takes place, the infrared devices do not come in contact with the object, thereby reducing the risk of damage to the sensors. Wiring is run through small holes drilled in the V-Fixtures that exit near its base, protecting the leads as much as possible from external damage.

Both devices are of the standard T1-3/4 case styles, allowing a high power IR transmitter to be used. Because of the available power, the non-pulsed mode was selected.

The IR transmitter is a SEP8703-001 and obtains its power from the Hand Interface Board. Pin P2-11 carries +5 V directly to the cathode, while pin P2-10 sinks current from the anode to ground through a 2N3904 transistor and a current limiting resistor. The value of this resistor, R16, determines the amount of current that is allowed to dissipate in the ON state of operation. For the device used, a value of 100 ohms was selected, causing an ON current of 10 mA. This device is rated for 20 mA maximum.

Current flow through the transmitter is controlled by the MC68HC11 port C bit 0. This line is buffered through the Hand Interface Board, and tied to the base of the 2N3904 transistor (see Appendix C sheet #4). This circuit also determines the mode of operation. If non-pulsed mode is used, C2 must be replaced with a wire and R16 adjusted according to device specifications.

The IR receiver is a SDP8403-301 infrared transistor. The circuit on the Hand Interface Board converts the IR light level detected to a signal compatible with the MC68HC11 A/D. A 0.01 \muF capacitor is located in parallel with the receiver device to minimize the effects of the 120 Hz flicker and provide more consistent readings of ambient light. Adjustments for the offset and gain of the active amplifier are available for minor calibrations. Test point TP5 reflects the final output of this circuit before the A/D.

Calibration. Calibration adjustments must be set to compensate for the laboratory lighting conditions and the relative strength and sensitivity of the IR transmitter and receivers used. In most cases, it is acceptable for the output of the interface op-amps to saturate high when the crossfire beam is unobstructed and the V-Fixtures are directly opposing each other. Correspondingly, it is acceptable if a zero output is obtained when the IR transmitter is off and no ambient light is being detected by the receiver.

With the IR transmitter off, the gain and offset should be adjusted so that when the hand is oriented toward the brightest ambient light source, the output will not saturate high. If this were to happen, no change in the output level could occur when the software switched the IR transmitter on. The offset level should be adjusted to insure that the output does not swing below 0 V under zero light conditions.

General Notes. Two general notes regarding software techniques need to be mentioned. The first is regarding the pulsed mode. Here, it is important that the second sample be taken as closely as possible to the IR transmitter turn on as possible. This is required because the pulse circuit will only turn on the device for a short period of time after the digital output line makes the transition. A sample must be initiated and completed while the detector is receiving this pulse. If required, the pulse length can be extended be replacing R14 with a higher value resistor.

The second note is for both modes of operation. The two samples, transmitter off, and transmitter on, should be taken as closely as possible to each other. This is simply to insure that the hand does not change orientation, and to minimize the possibility of other extraneous events changing the ambient light level detected.

Air Valve Drive

Theory. A ± 10 V signal is required to drive the air valve for air switching purposes. The valve has two 250 ohm internal coils that are externally connected in series, to obtain a single 500 ohm coil for control. This coil is actually an armature of sorts that provides a reference force for the pressure servo performed inside the valve itself. For details on the theory and operation of the valve, refer to the General Catalog by Atchley Controls.

A D/A converter on the Hand Interface Electronics utilizes 8 data lines from the MC68HC11 to create this ± 10 V signal. Schematics of the circuit used are shown in Appendix C, sheet #5. The low power signal from the D/A converter is then buffered through a high power op-amp configured as a voltage follower that drives the output pins that go to the air valve.

Implementation. The D/A chip used is a MC1408 in a 16-pin DIP package. Component selection that determines the range and offset of the output is made from the application notes included in Appendix D of this document. A MC1741 is part of the circuit described in the application notes, and is implemented with the direct replacement piece SK3514.

A LM0041 is used as the high power driver and has a maximum output current of 200 mA. This is more than sufficient to drive the valve with any associated inductance that is present on the hand cabling.

The output is provided on a separate 4-pin connector designated P3. Two copies of the output are available at this connector, alternately labeled "G" for the ground and "O" for the output pins. The second set of output pins is provided as a convenient point to attach a more permanent scope or meter to monitor the output of software control algorithms as they are being tested.

Calibration. No calibrations are available for this circuit.

General Notes. Three construction notes are applicable to this portion of the Hand Interface Board.

Note that the LH0041 does not solder directly to the printed circuit board. Pins 5-8 are soldered into the existing holes, while pins 1-4 must be connected with short pieces of wire on the under side of the LH0041. This was a mistake in the layout of the pad spacing for this chip.

The second note is that one of the traces from the MC1741 must be cut to allow proper circuit operation. This trace was added as a loop back from the output of the D/A to the input of the A/D on the MC68HC11. This was provided as an added capability for software to verify that the D/A was functioning properly. However, the output of the D/A circuit has the ability to swing negative, and therefore cannot be allowed as an input to the A/D. This trace should be cut at pin E4 on connector P1.

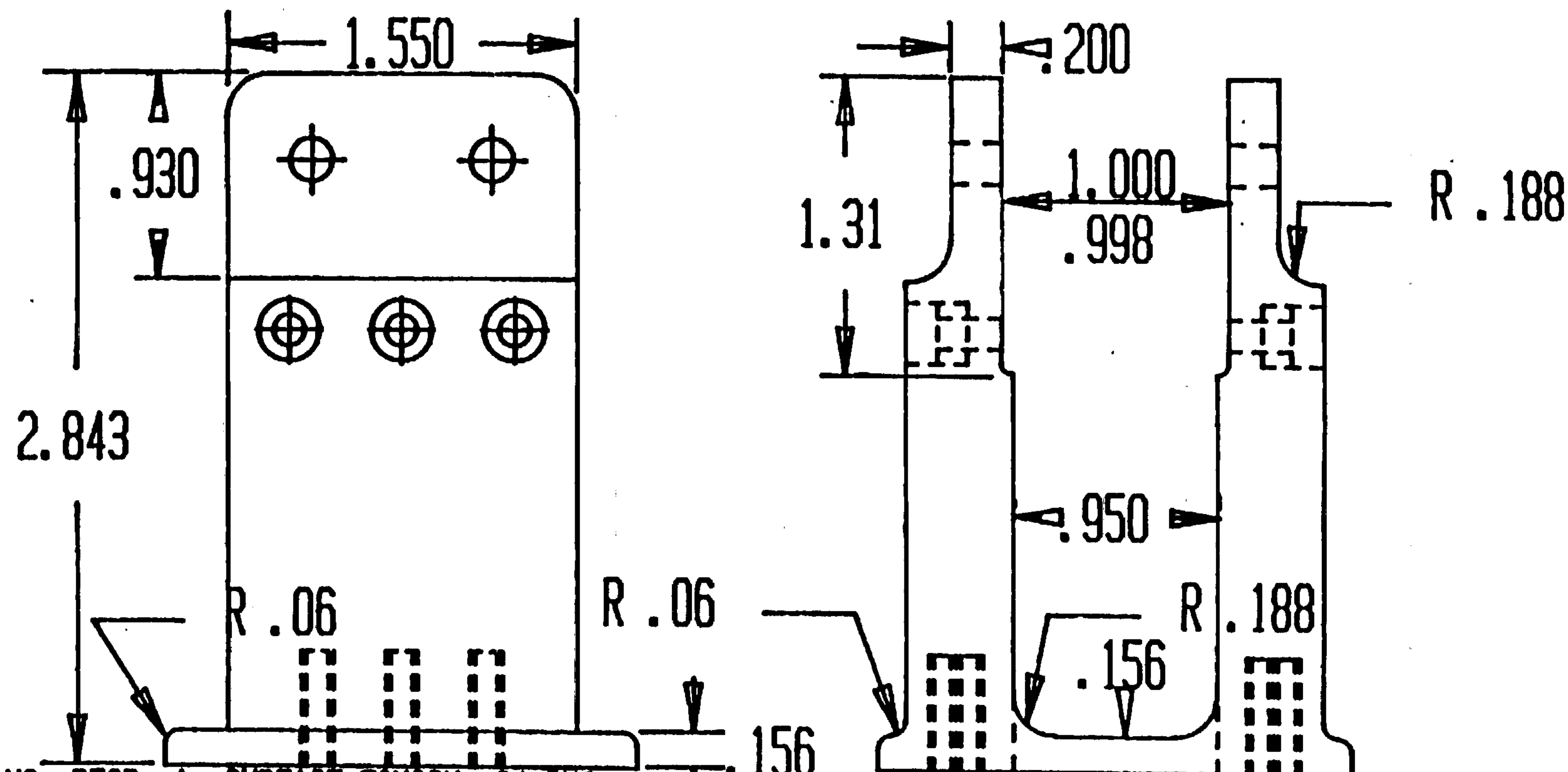
Lastly, it may be possible to operate the air valve without the use of the LH0041. This chip was used to ensure enough power to drive the valve coils, however, the output of the MC1741G may be sufficient.

APPENDICES

APPENDIX A

Mechanical Drawings (J. Peiffer)

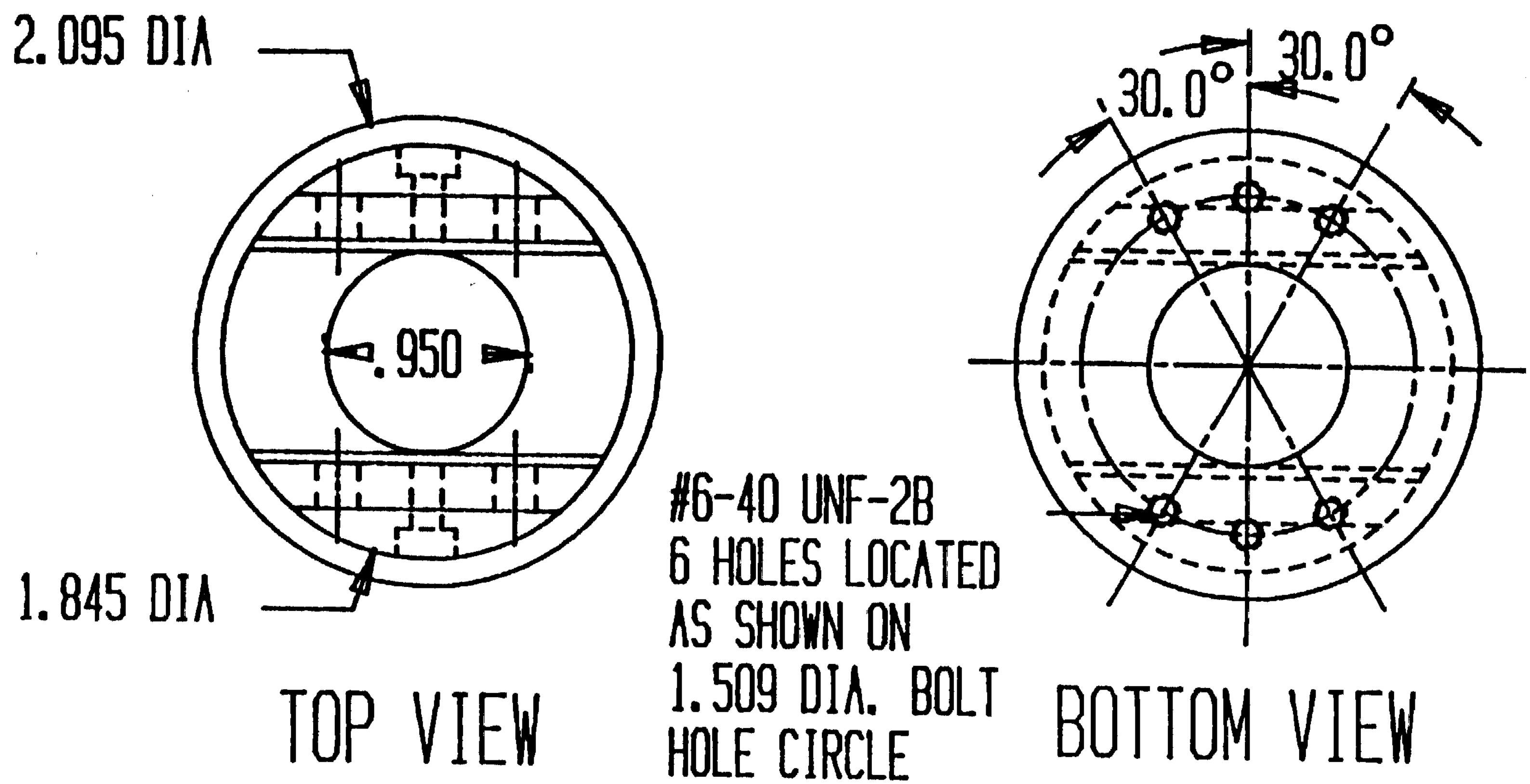
1. Toggle-base assembly
2. Gripper base
3. Adapter
4. Block spacer
5. Toggle
6. Actuating links
7. Toggle shaft
8. Finger
9. V-Fixtures
10. Spacers
11. Air cylinder
12. F/T sensor mounting plate
13. Adapting plate



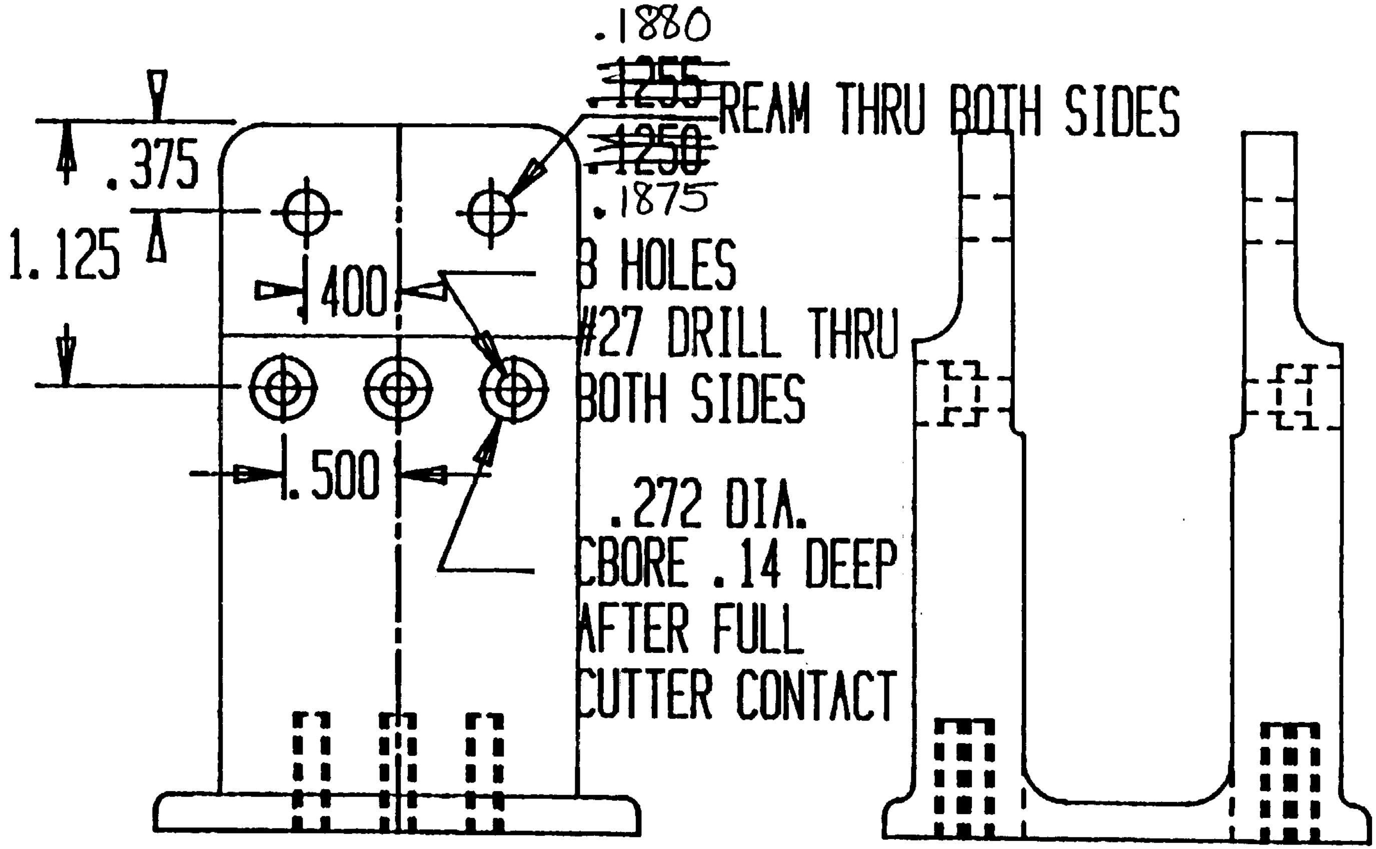
NO. REQD: 1 SURFACE FINISH: 64 RMS

No: 2A	Scale: 1:1	Part: GRIPPER BASE	Mat'l: 6061-T6 ALUM.
BY: JOHN PEIFFER	Date: 1/90	Fraction: +-.015	Decimal: +-.005

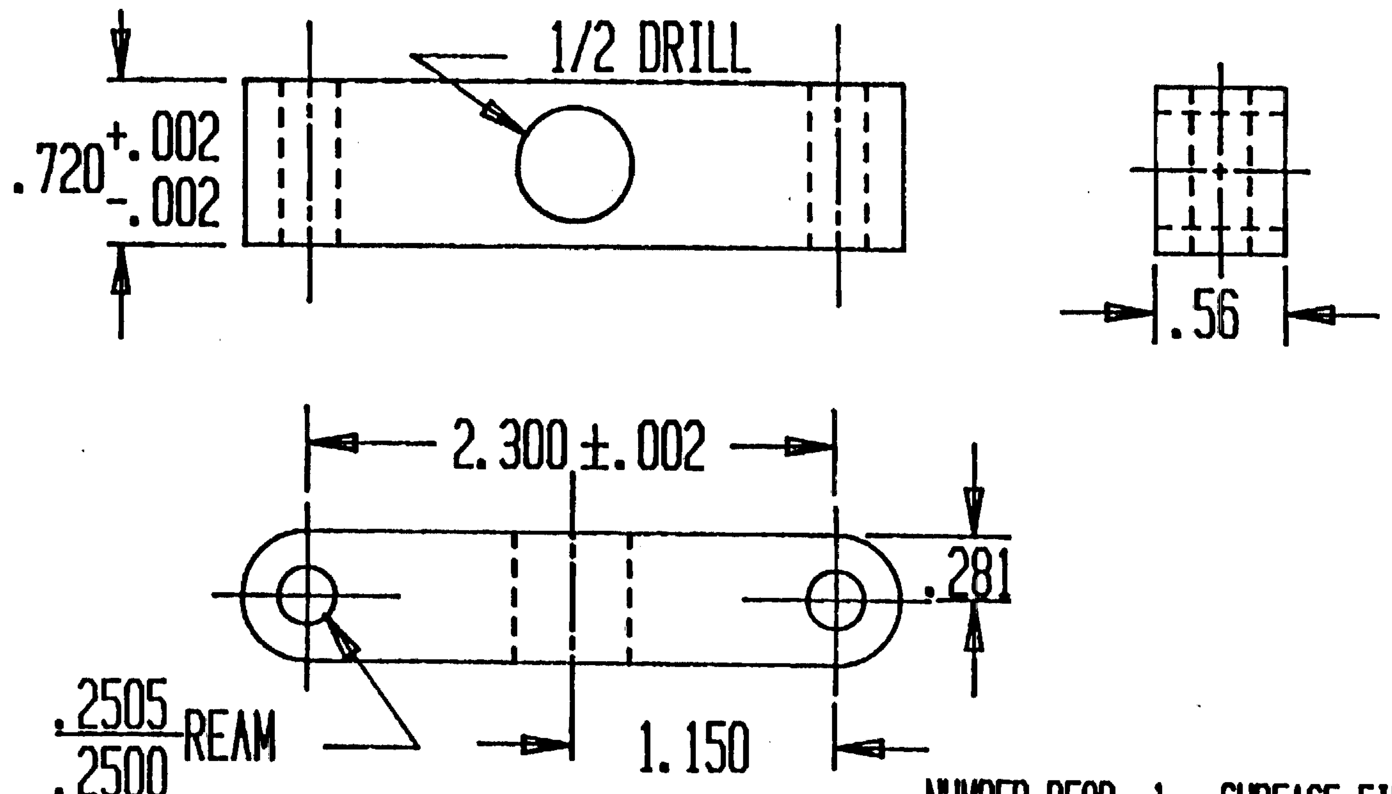
RENSSELAER POLYTECHNIC INSTITUTE Troy, NY



No: 2B	Scale: 1:1	Part: GRIPPER BASE	Mat'l: 6061-T6 ALUM.	RENSSELAER POLYTECHNIC INSTITUTE Troy, NY
BY: JOHN PEIFFER		Date: 1/90	Fraction: +-.015 Decimal: +-.005	

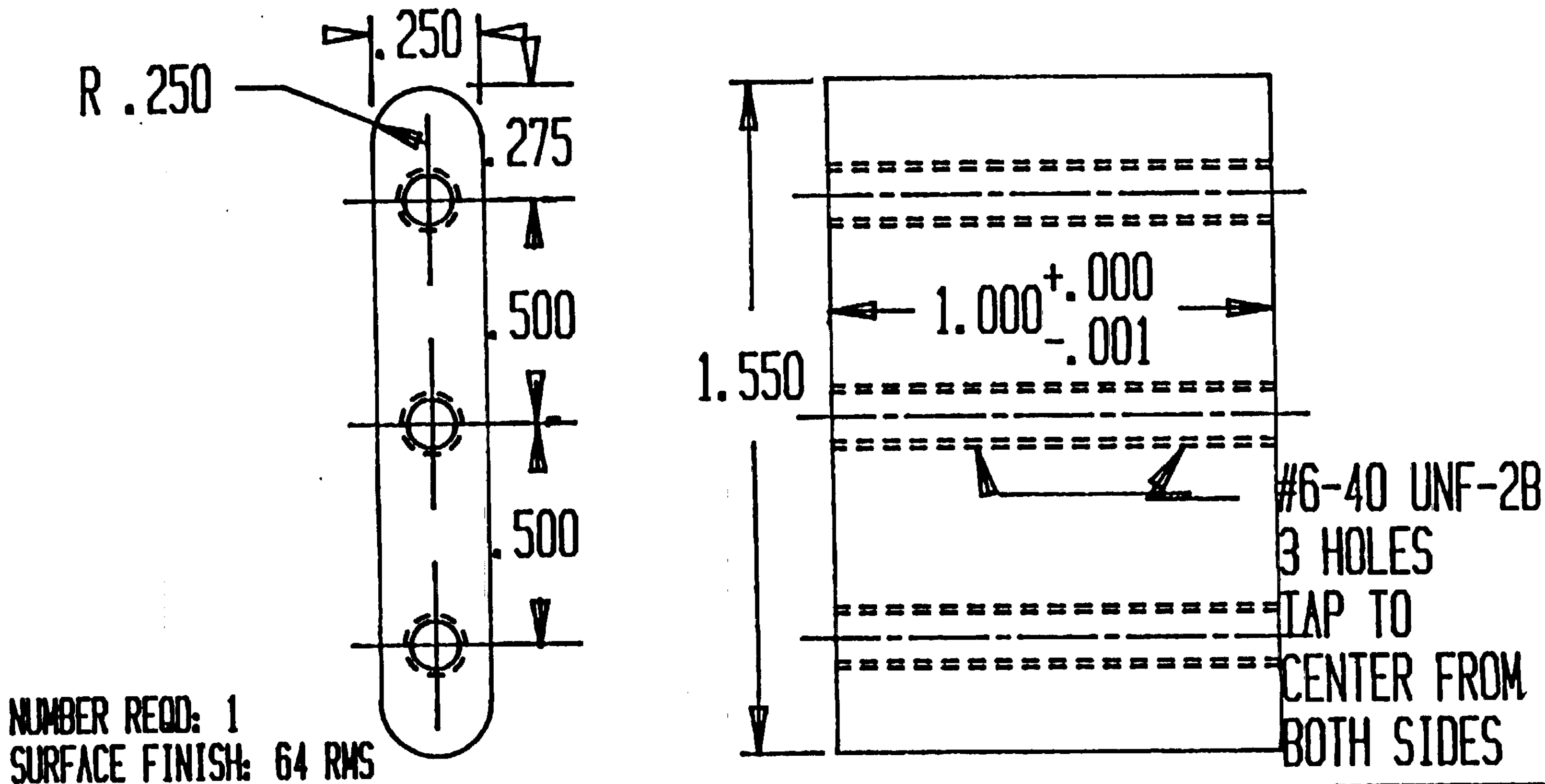


No: 2C	Scale: 1:1	Part: GRIPPER BASE	Mat'l: 6061-T6 ALUM.	RENSSELAER POLYTECHNIC INSTITUTE Troy, NY
By: JOHN PEIFFER		Date: 1/90	Fraction: +-.015 Decimal: +-.005	



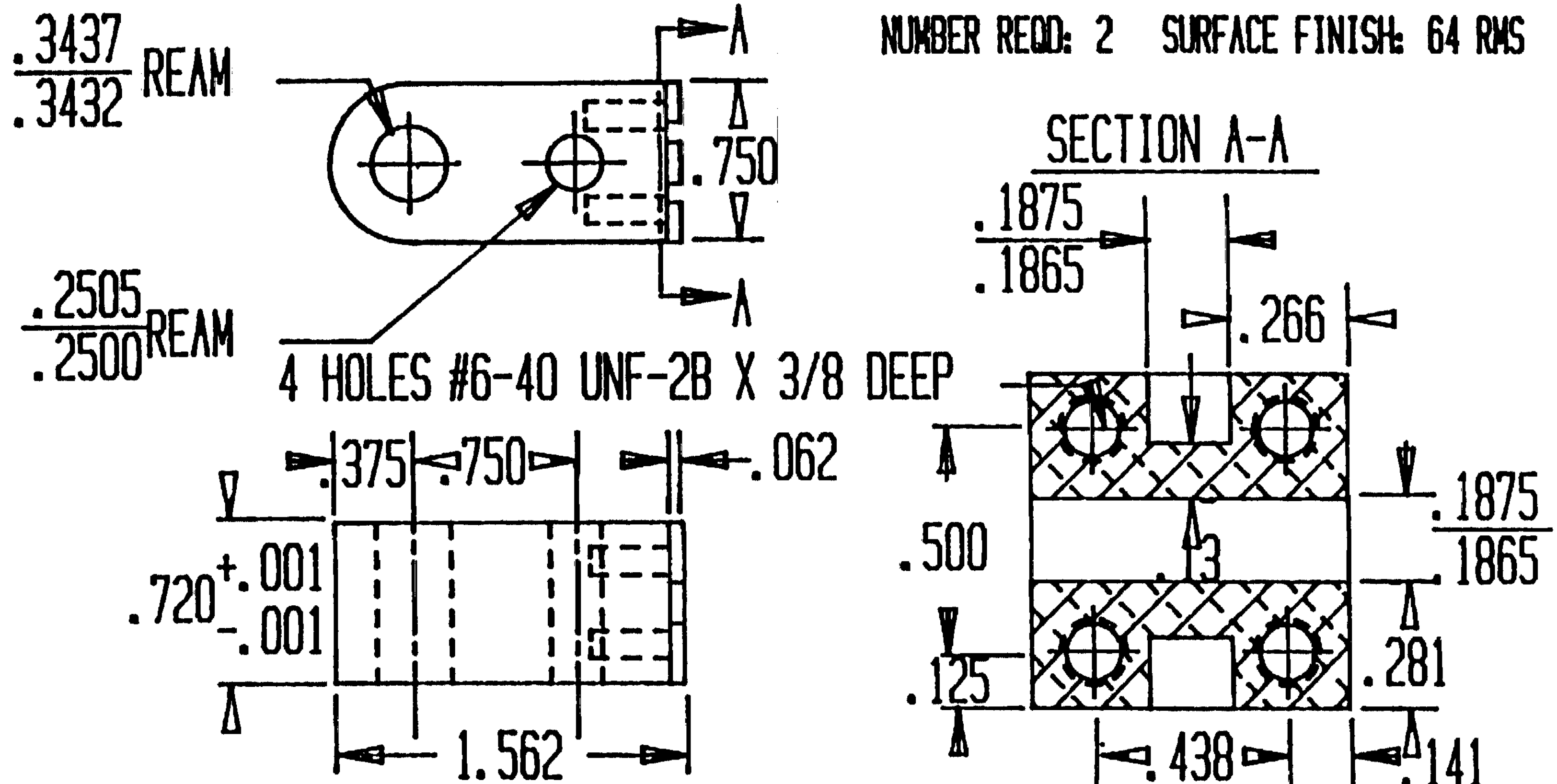
NUMBER REQD: 1 SURFACE FINISH: 64 RMS

No: 3	Scale: 1:1	Part: ADAPTER	Mat'l: 6061-T6 ALUM.	RENSSELAER POLYTECHNIC INSTITUTE Troy, NY
BY: JOHN PEIFFER		Date: 1/90	Fraction: +-.015 Decimal: +-.005	



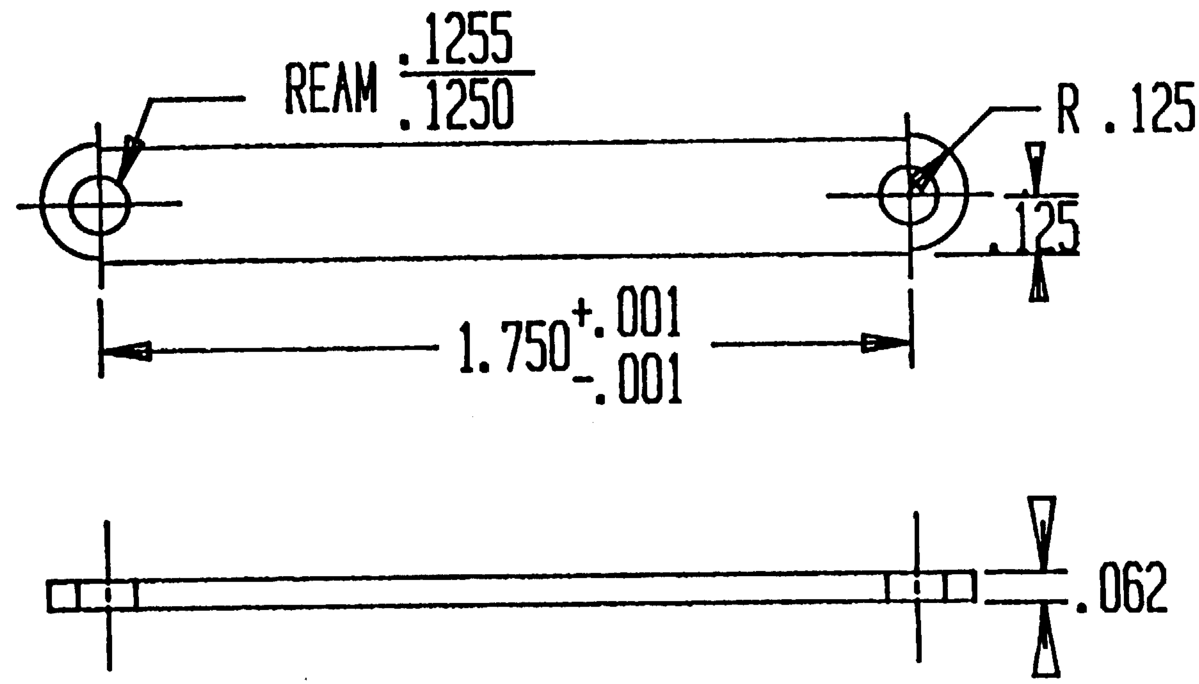
No: 4	Scale: 2:1	Part: BLOCK SPACER	Mat'l: 6061-T6 Alum.	RENSSELAER POLYTECHNIC INSTITUTE Troy, NY
BY: JOHN PEIFFER		Date: 1/90	Fraction: +-.015 Decimal: +-.005	

NUMBER REQD: 2   SURFACE FINISH: 64 RMS



No: 5	Scale: 1:1	Part: TOGGLE	Mat'l: 4340 STEEL
BY: JOHN PEIFFER	Date: 1/90	Fraction: +-.015	Decimal: +-.005

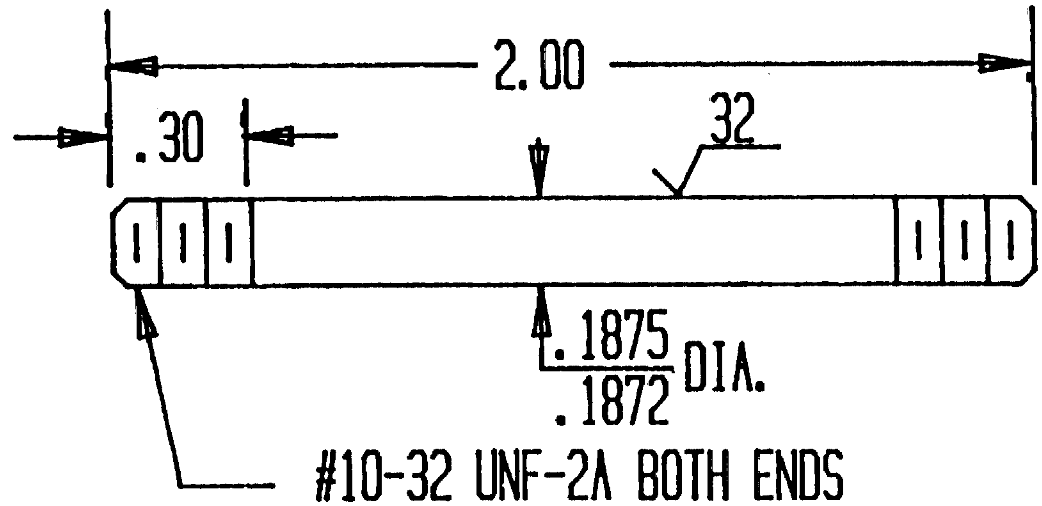
RENSSELAER POLYTECHNIC INSTITUTE Troy, NY



NUMBER REQD: 4   SURFACE FINISH: 64 RMS

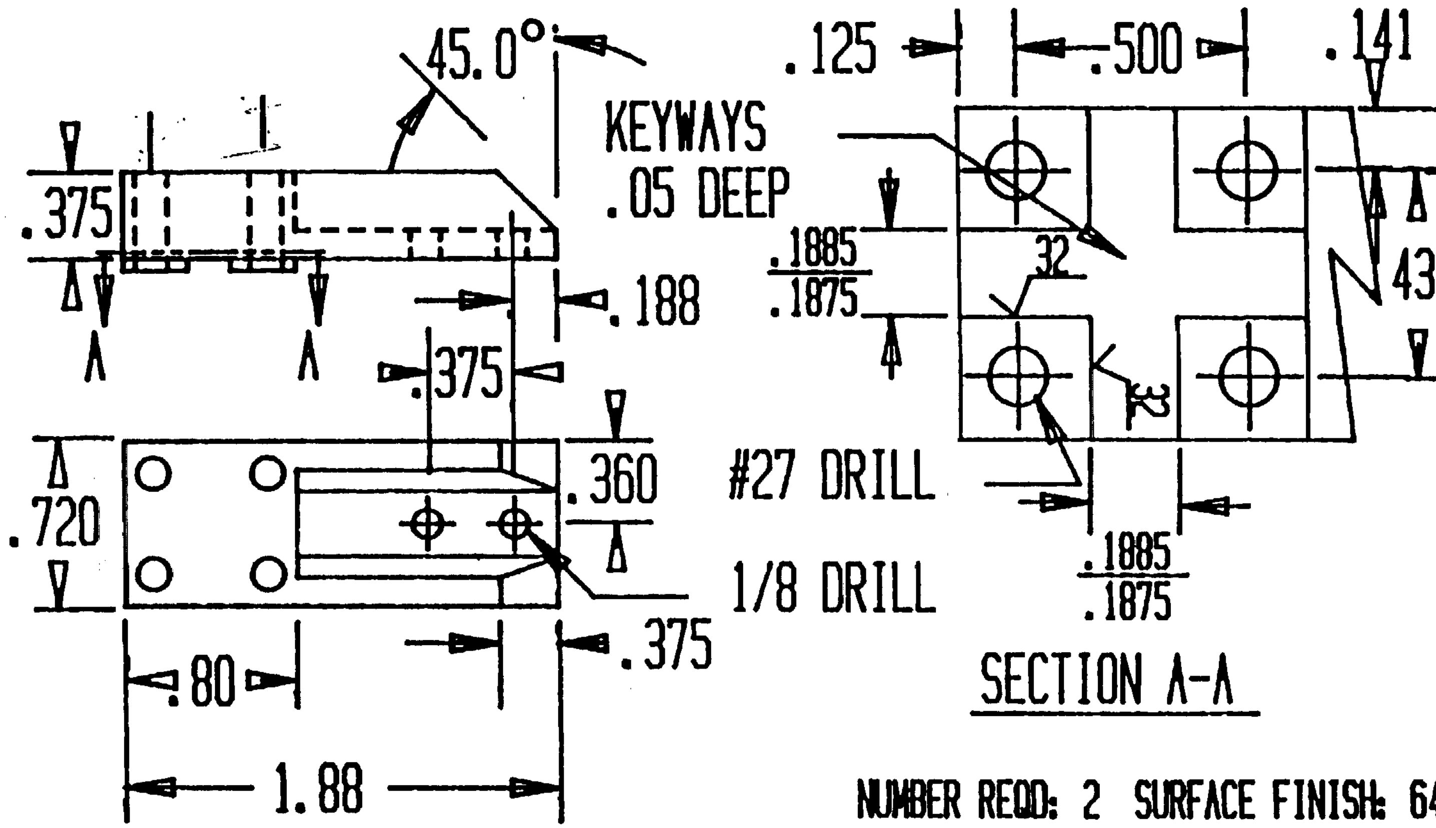
No: 6	Scale: 2:1	Part: ACTUATING LINKS	Mat'l: 6061-T6 ALUM.	RENSSELAER POLYTECHNIC INSTITUTE Troy, NY
BY: JOHN PEIFFER		Date: 1/90	Fraction: +-.015 Decimal: +-.005	

THRU HARDEN AND TEMPER TO 58 ROCKWELL C



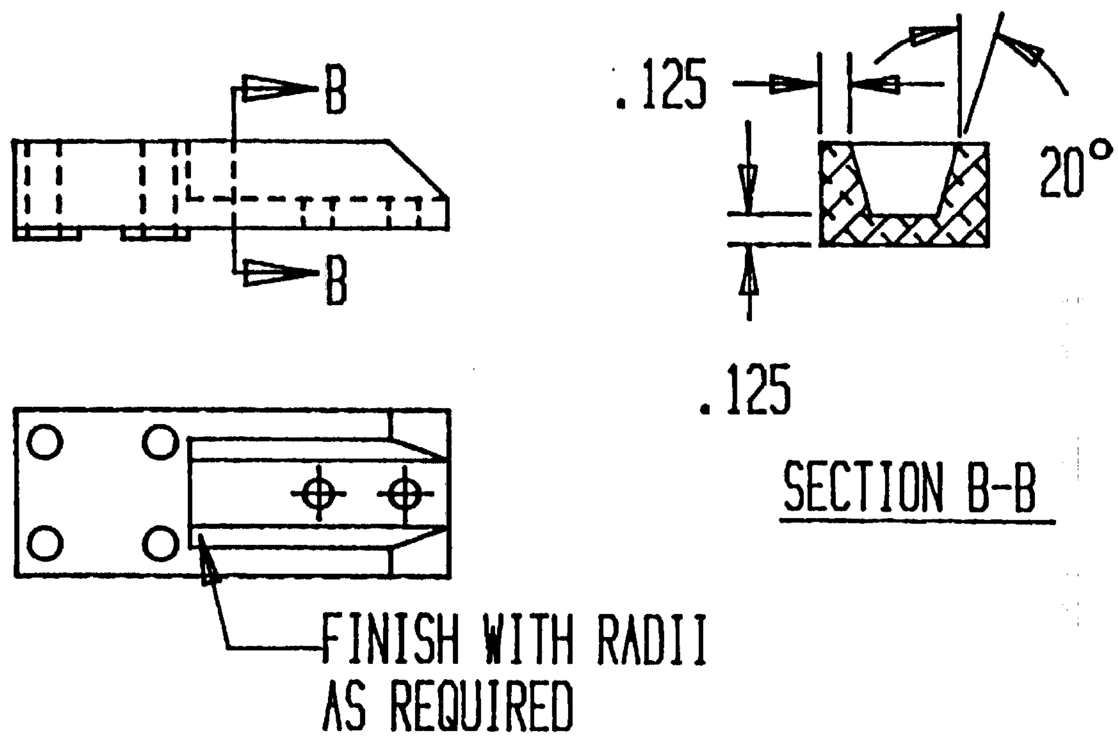
NUMBER REQD: 2 SURFACE FINISH: 32 RMS MATL: 4150 STEEL OR TYPE T1 DRILL ROD

No: 7	Scale: 2:1	Part: TOGGLE SHAFT	Mat'l: 4150 STEEL	RENSSELAER POLYTECHNIC INSTITUTE Troy, NY
BY: JOHN PEIFFER		Date: 1/90	Fraction: +-.015 Decimal: +-.005	

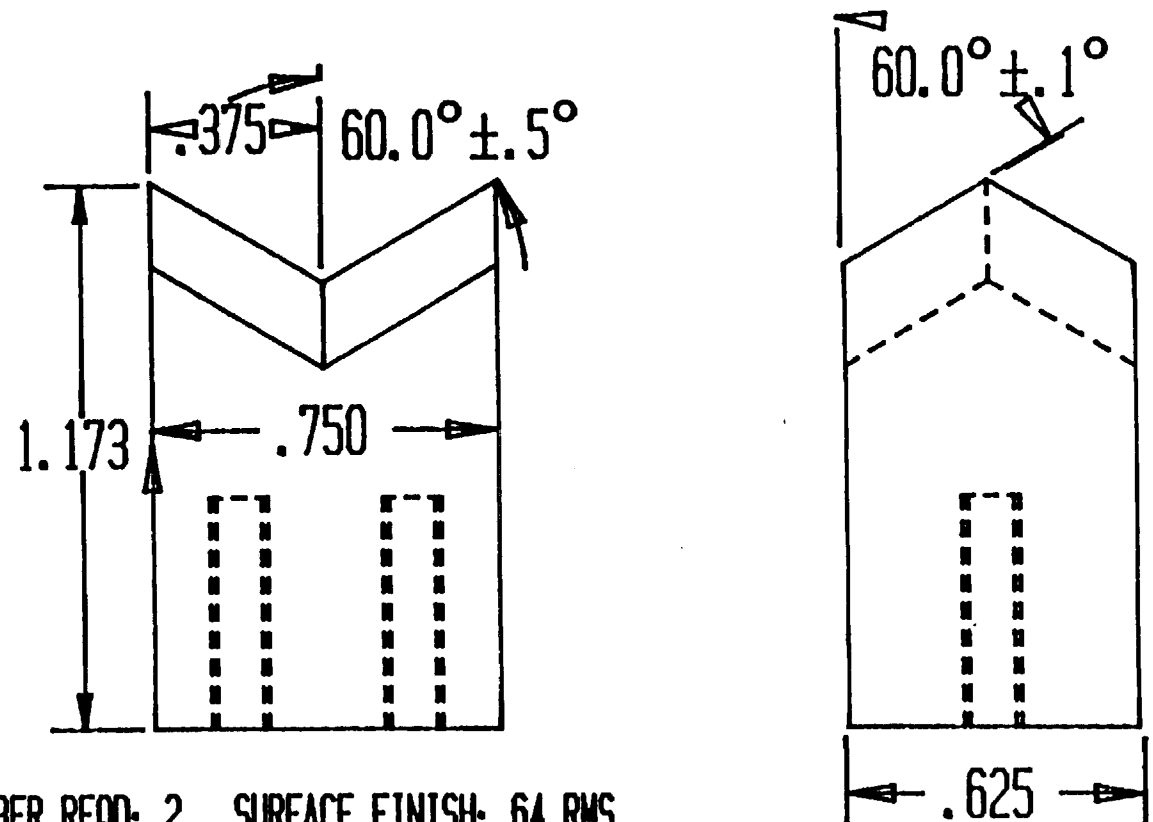


NUMBER REQD: 2 SURFACE FINISH: 64 RMS

No: 8A	Scale: 1:1	Part: STRUT FINGER	Mat'l: 6061-T6 ALUM.	RENSSELAER POLYTECHNIC INSTITUTE Troy, NY
BY: JOHN PEIFFER		Date: 1/90	Fraction: +-.015 Decimal: +-.005	

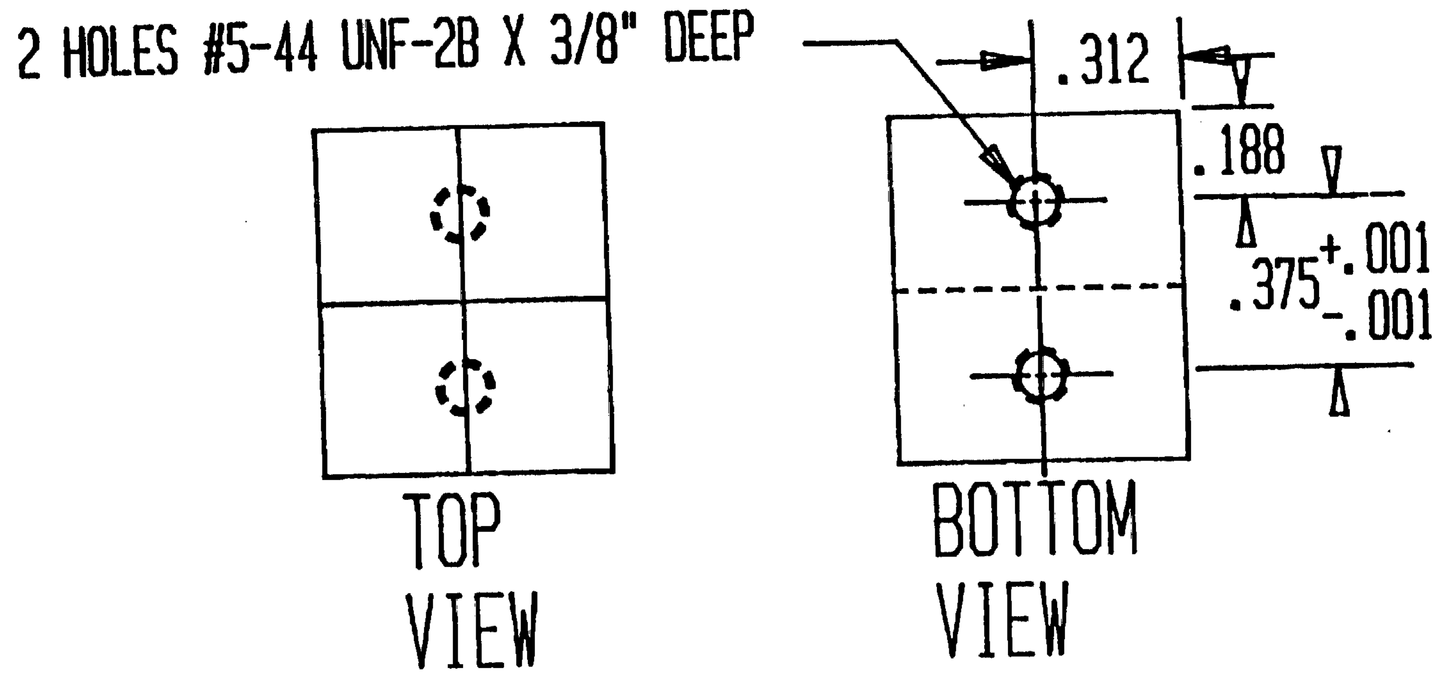


No: 8B	Scale: 1:1	Part: STRUT FINGER	Mat'l: 6061-T6 ALUM.	RENSSELAER POLYTECHNIC INSTITUTE Troy, NY
BY: JOHN PEIFFER		Date: 1/90	Fraction: +-.015 Decimal: +-.005	

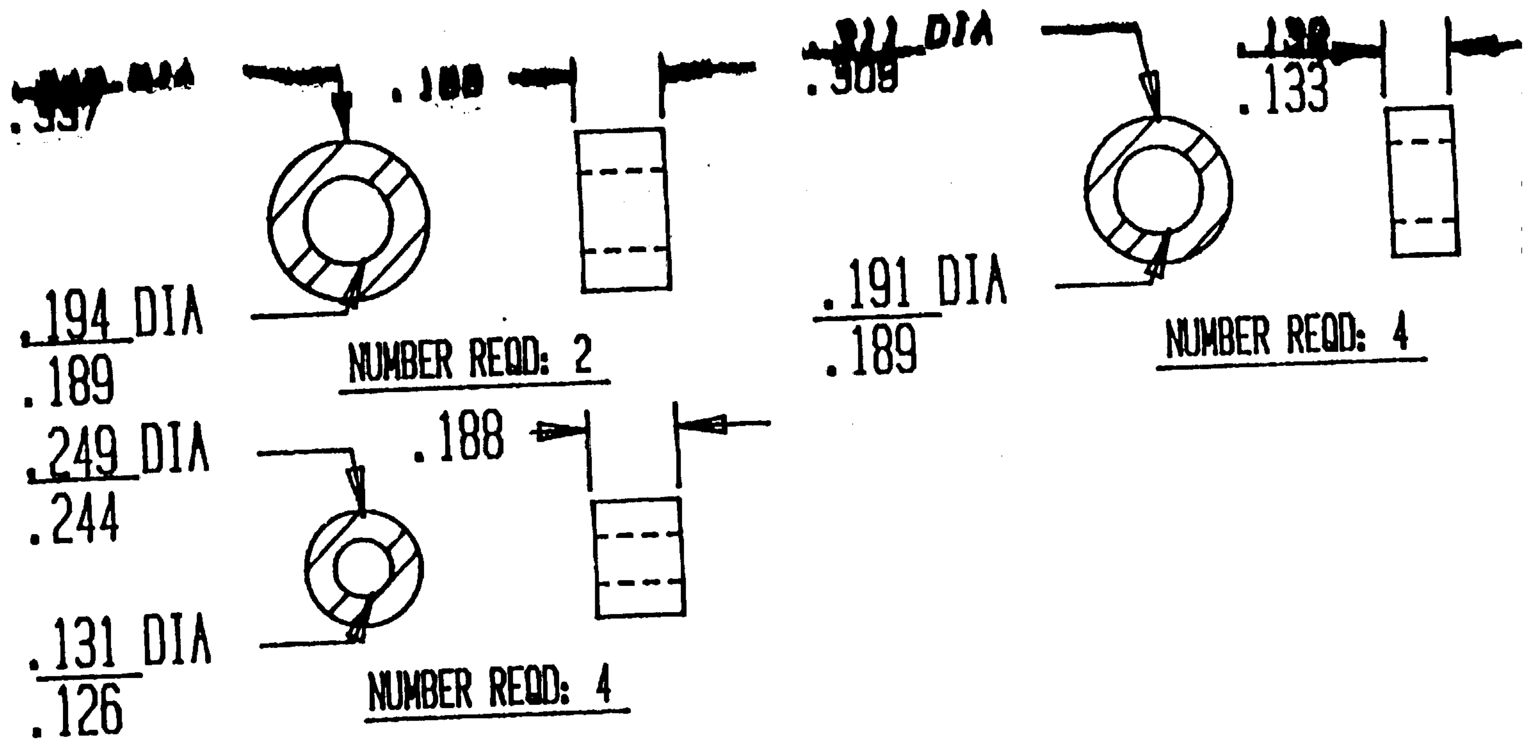


NUMBER REQD: 2   SURFACE FINISH: 64 RMS

No: 9A	Scale: 2:1	Part: STRUT V-FIXTURES	Mat'l: 6061-T6 ALUM.	RENSSELAER POLYTECHNIC INSTITUTE Troy, NY
BY: JOHN PEIFFER		Date: 1/90	Fraction: +-.015 Decimal: +-.005	

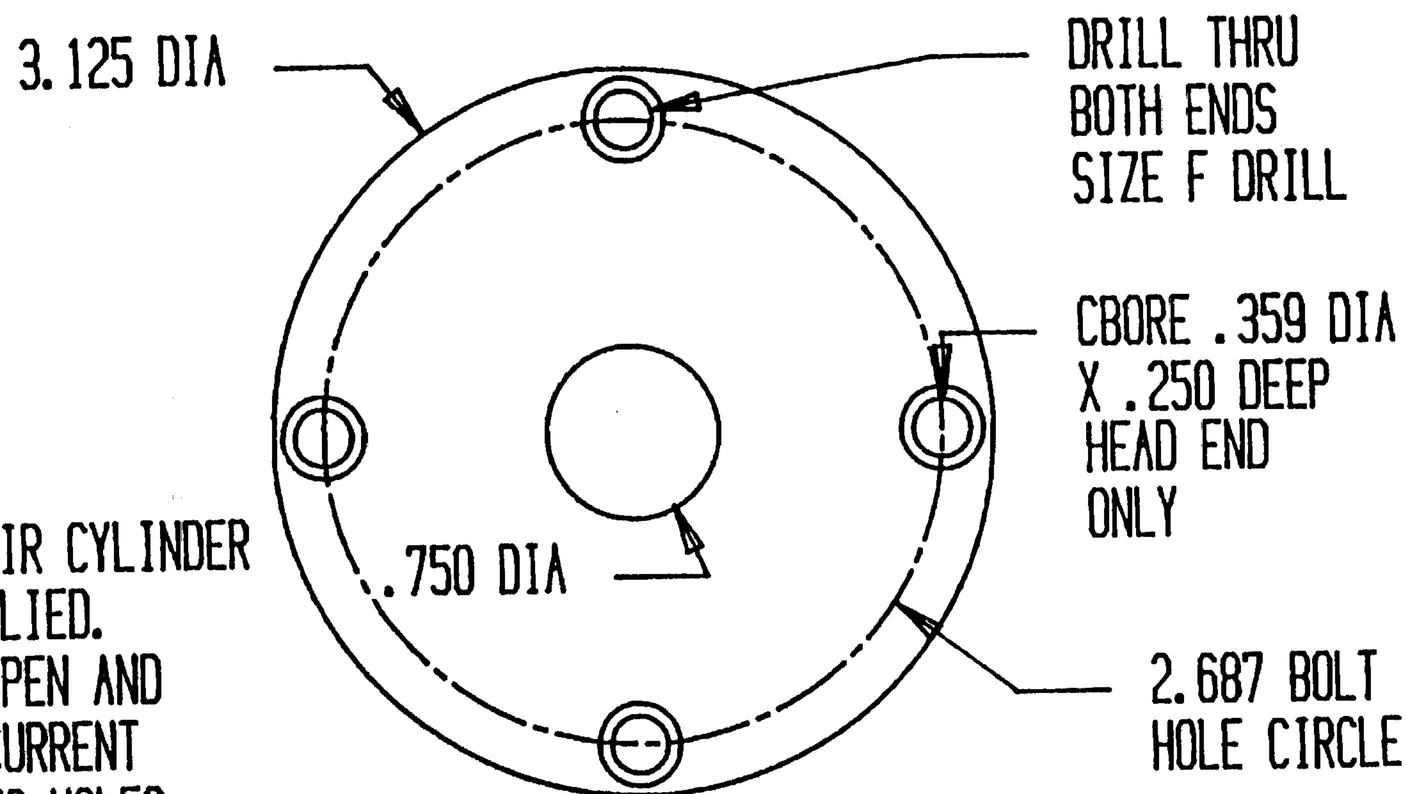


No: 9B	Scale: 2:1	Part: STRUT V-FIXTURES	Mat'l: 6061-T6 ALUM.	RENSSELAER POLYTECHNIC INSTITUTE Troy, NY
BY: JOHN PEIFFER		Date: 1/90	Fraction: +-.015 Decimal: +-.005	



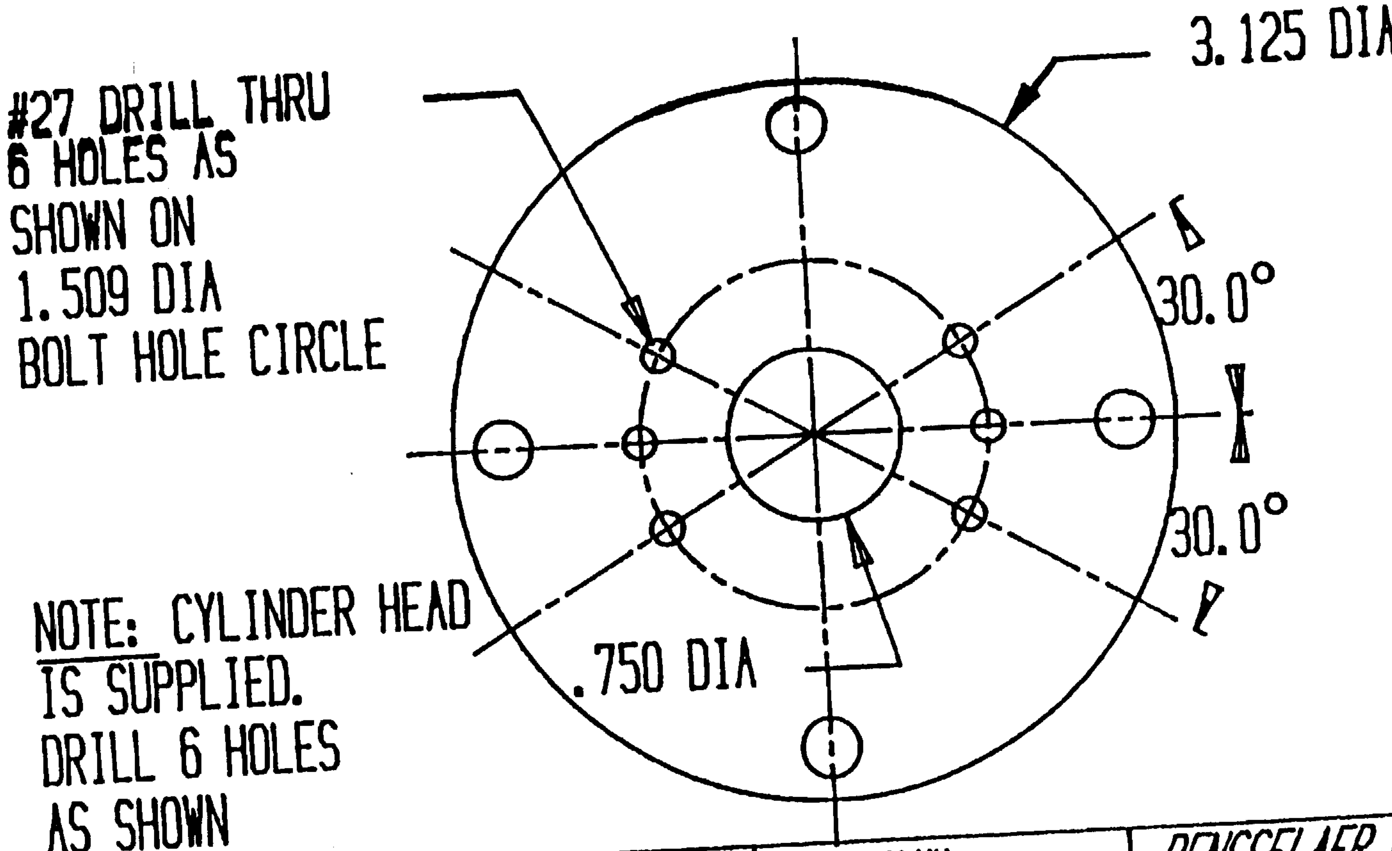
SURFACE FINISH: 64 RMS

No: 10	Scale: 2:1	Part: SPACERS	Mat'l: ALUM.	RENSSELAER POLYTECHNIC INSTITUTE Troy, NY
BY: JOHN PEIFFER		Date: 1/90	Fraction: +-.015 Decimal: +-.005	

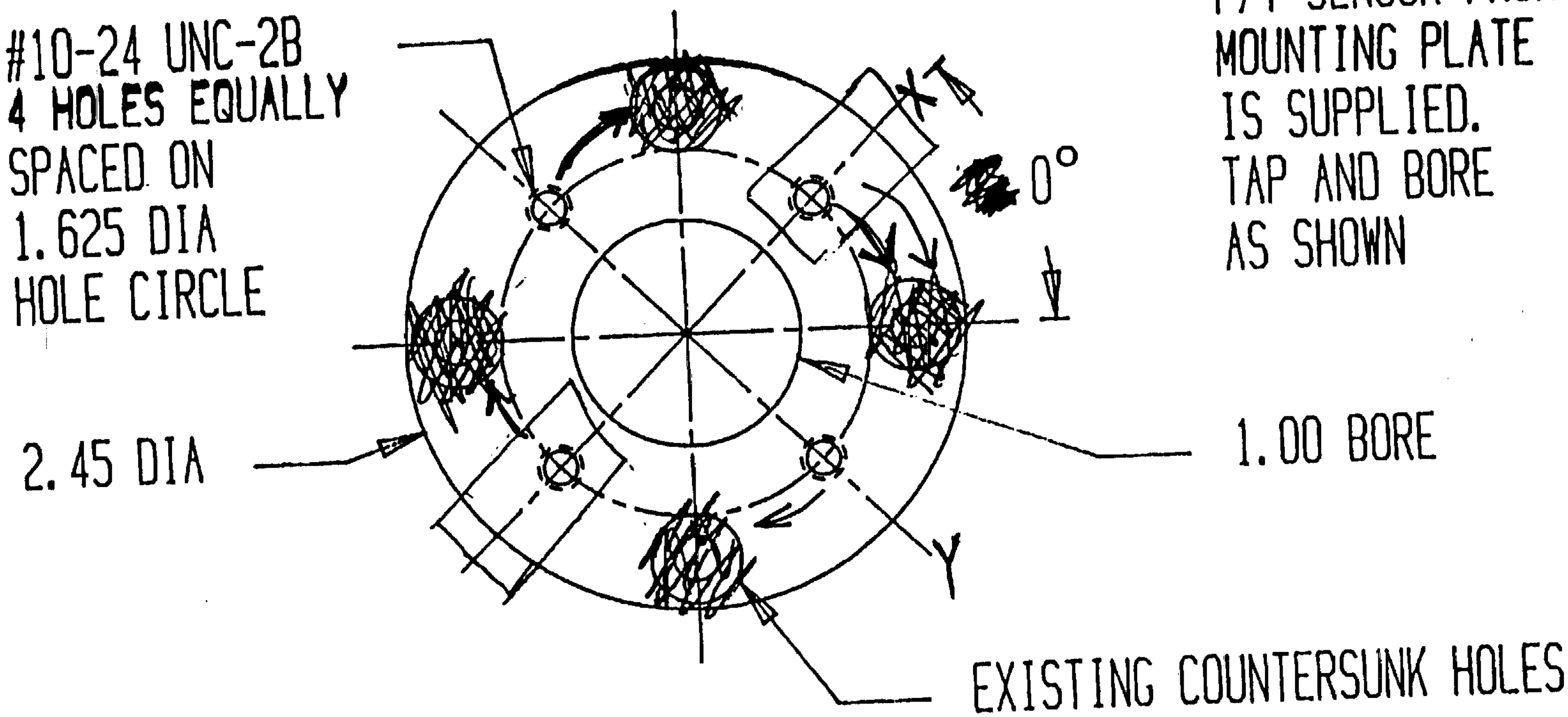


<u>NOTE:</u> AIR CYLINDER
IS SUPPLIED.
DRILL OPEN AND
CBORE CURRENT
MOUNTING HOLES

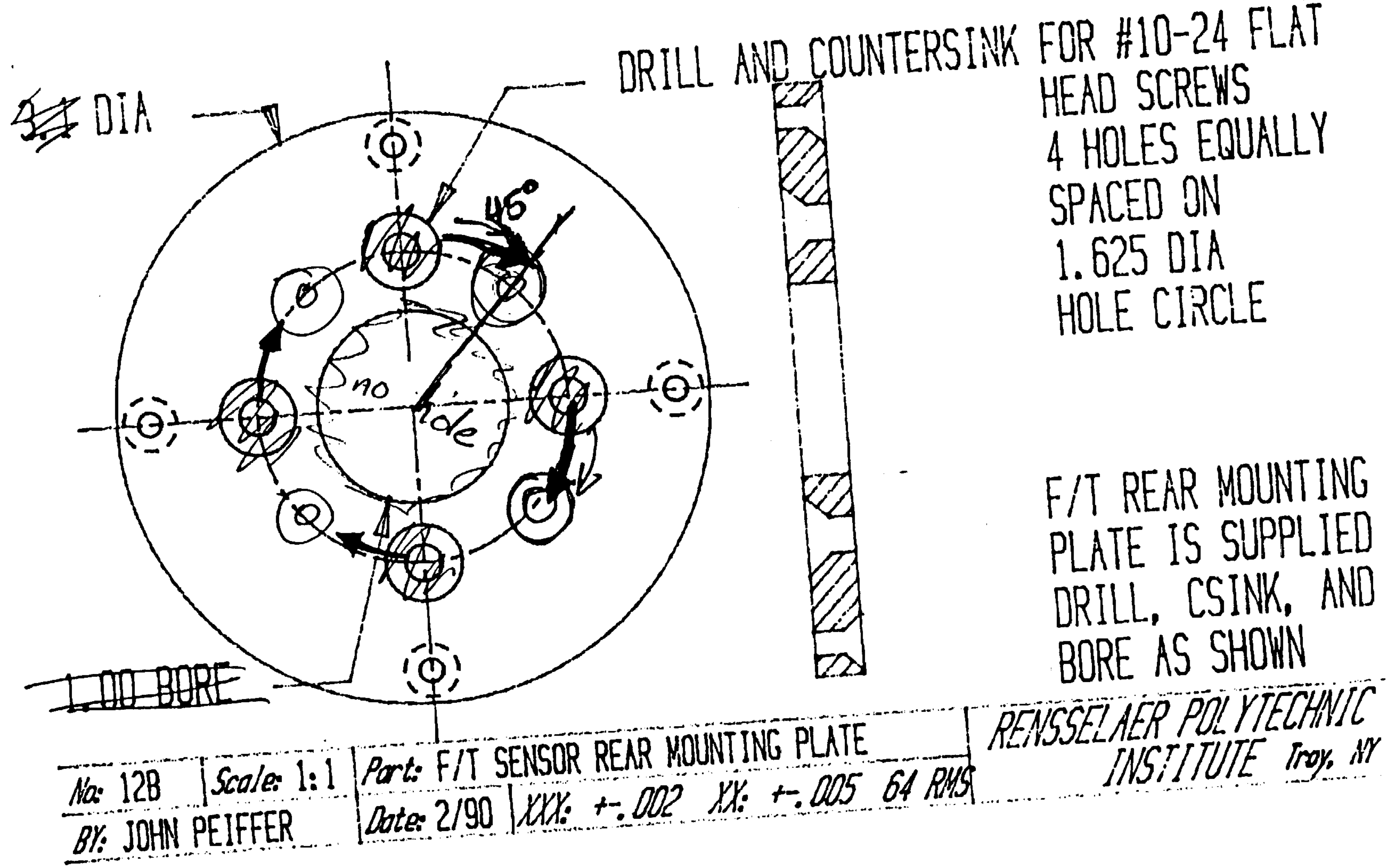
No: 11A	Scale: 1:1	Part: AIR CYLINDER	Mat'l: ALUM.	RENSSELAER POLYTECHNIC INSTITUTE Troy, NY
BY: JOHN PEIFFER		Date: 1/90	Fraction: +-.015 Decimal: +-.005	

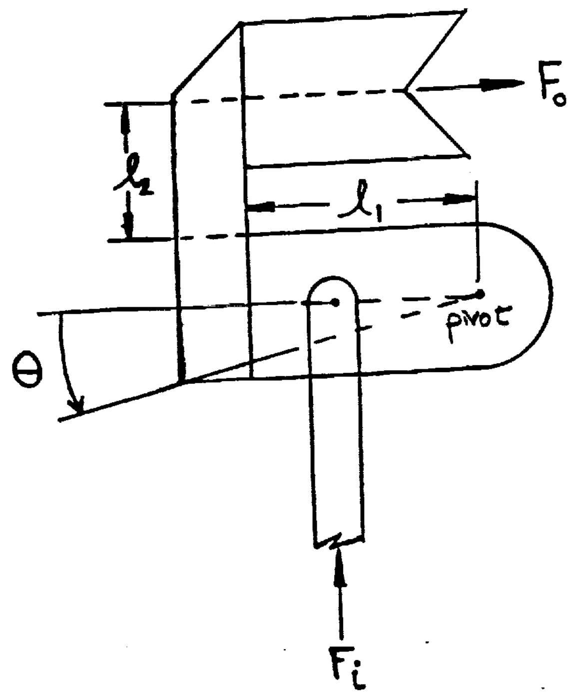


No: 11B	Scale: 1:1	Part: CYLINDER HEAD	Mat'l: ALUM.	RENSSELAER POLYTECHNIC INSTITUTE Troy, NY
BY: JOHN PEIFFER		Date: 1/90	Fraction: +-.015 Decimal: +-.005	



No: 12A-M	Scale: 1:1	Part: F/T SENSOR FRONT MOUNTING PLATE	RENSSELAER POLYTECHNIC INSTITUTE Troy, NY
BY: JOHN PEIFFER		Date: 1/90 | Fraction: +-.015 Decimal: +-.005	


3.1 DIA
DRILL AND COUNTERSINK FOR #10-24 FLAT HEAD SCREWS 4 HOLES EQUALLY SPACED ON 1.625 DIA HOLE CIRCLE
45°
no
hole
~~1.00 BORE~~
F/T REAR MOUNTING PLATE IS SUPPLIED DRILL, CSINK, AND BORE AS SHOWN
No: 12B
Scale: 1:1
BY: JOHN PEIFFER
Part: F/T SENSOR REAR MOUNTING PLATE
Date: 2/90
XXX: +-.002 XX: +-.005 64 RMS
RENSSELAER POLYTECHNIC INSTITUTE Troy, NY



$$\frac{F_o}{F_i} = \frac{.75\cos\Theta}{(l_2+.375)\cos\Theta - l_1\sin\Theta}$$

$$F_i = 1.571\,P$$

$$F_o = \frac{1.178\cos\Theta}{(l_2+.375)\cos\Theta - l_1\sin\Theta}.$$

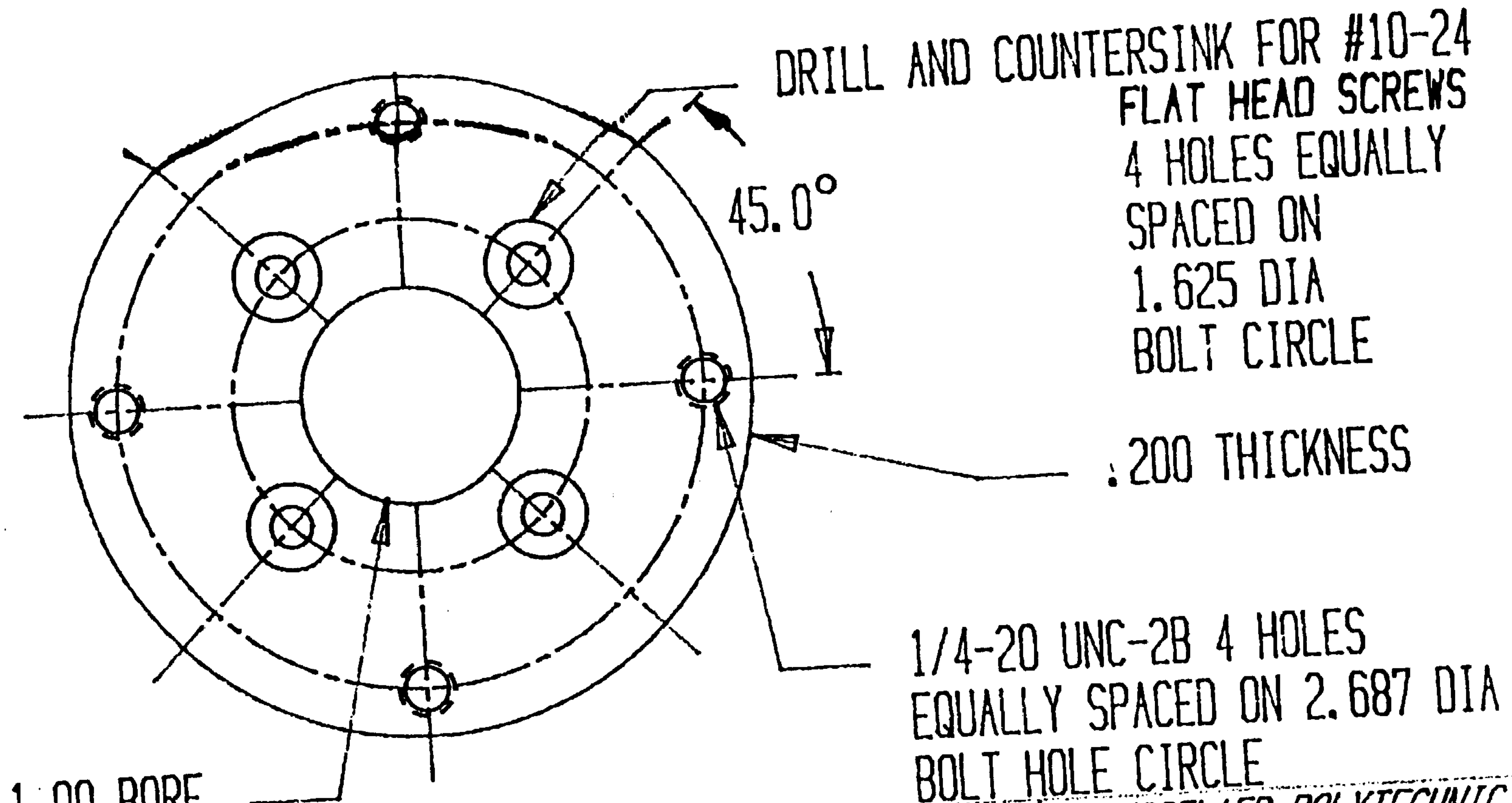
<u>for strut gripper</u>

$l_1 = 1.187$ $\quad \frac{F_o}{F_i} = .66$

$l_2 = .755$

$$F_o = \frac{1.178\cos\Theta}{1.13\cos\Theta - 1.187\sin\Theta}.$$

where P= effective cylinder pressure



No: 13	Scale: 1:1	Part: ADAPTING PLATE	Mat'l: 6061-T6 ALUM.	RENSSELAER POLYTECHNIC INSTITUTE Troy, NY
BY: JOHN PEIFFER		Date: 2/90	XXX: +-.002 XX: +-.005 64 RMS	

APPENDIX B

Hand Interface Connections

P2 CONNECTOR – HAND INTERFACE

GND	V2 –	V1 +	V3 +SEN	POS AN IN	SHLD	FORCE 1 AN IN	GND	FORCE 2 AN IN	IR LED SINK	+5	IR SENS +	IR SENS –
1	2	3	4	5	6	7	8	9	10	11	12	13

HC11 P1 CONNECTOR – COMPUTER INTERFACE

FUNCTION	REQUIREMENTS	HC11 PORTS USED
POSITION	1 ANALOG IN CHANNEL	E0
GRIP FORCE	* 2 ANALOG IN CHANNELS	E1 AND E2
CROSSFIRE	1 DIGITAL OUT BIT	C BIT 0
	1 ANALOG IN CHANNEL	E3
AIR VALVE	8 DIGITAL OUT BITS	B BITS 0–7

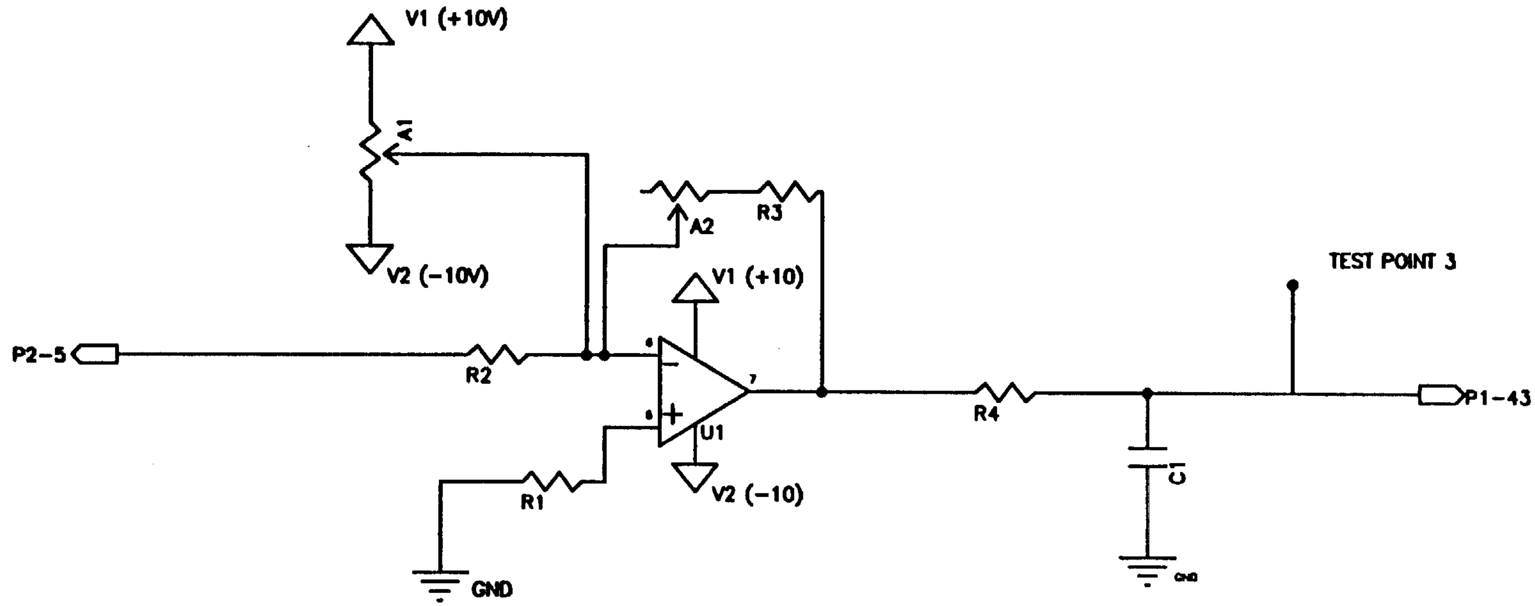
* E2 Currently not implemented

Title	RPI HAND – CONNECTIONS	
Size A	Number 1	Revision A
Date 4/28/01	Drawn By JEFF BETHEL	
File D:\SCH\PRHCON.PCB	Sheet 1 of 1	

APPENDIX C

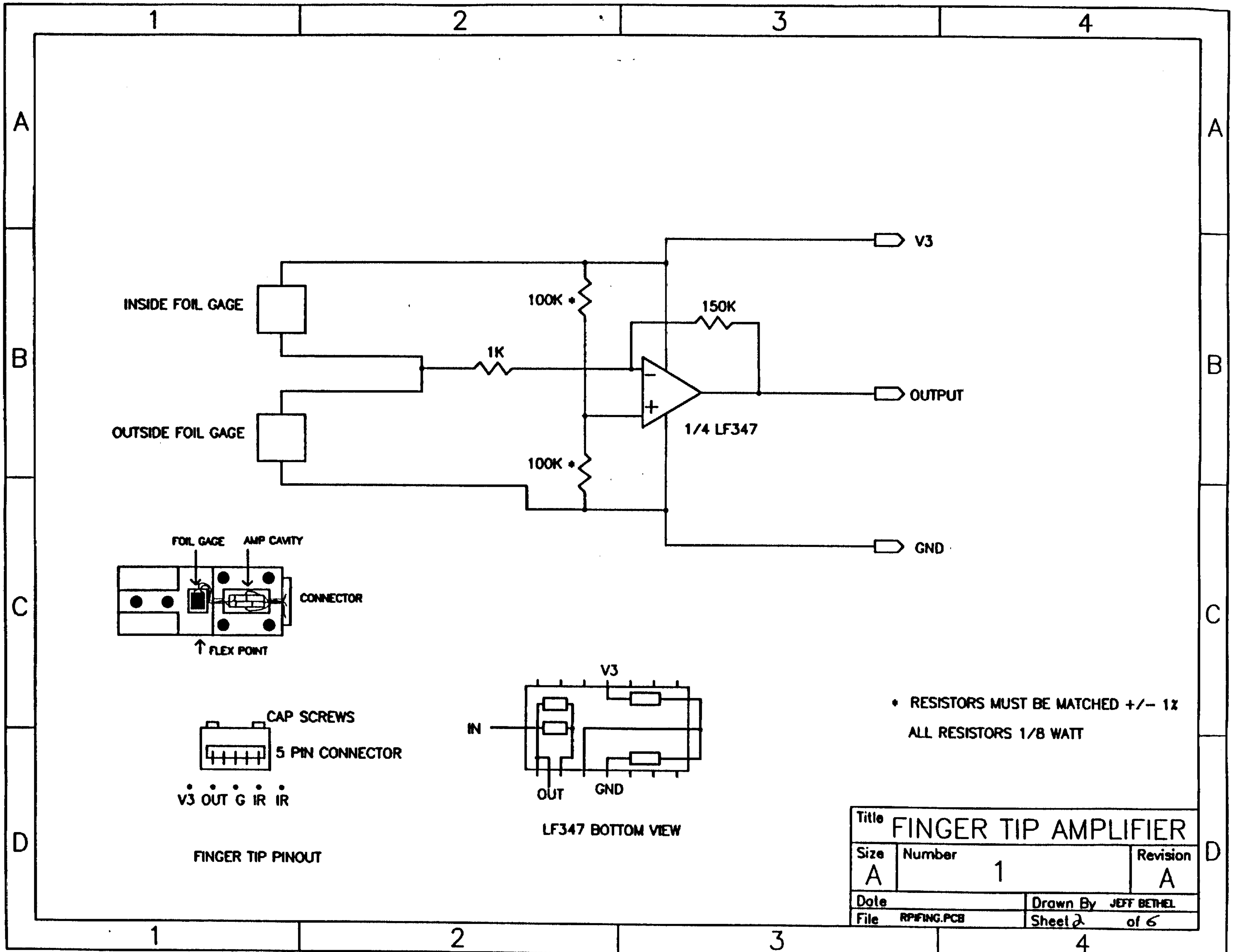
Circuits

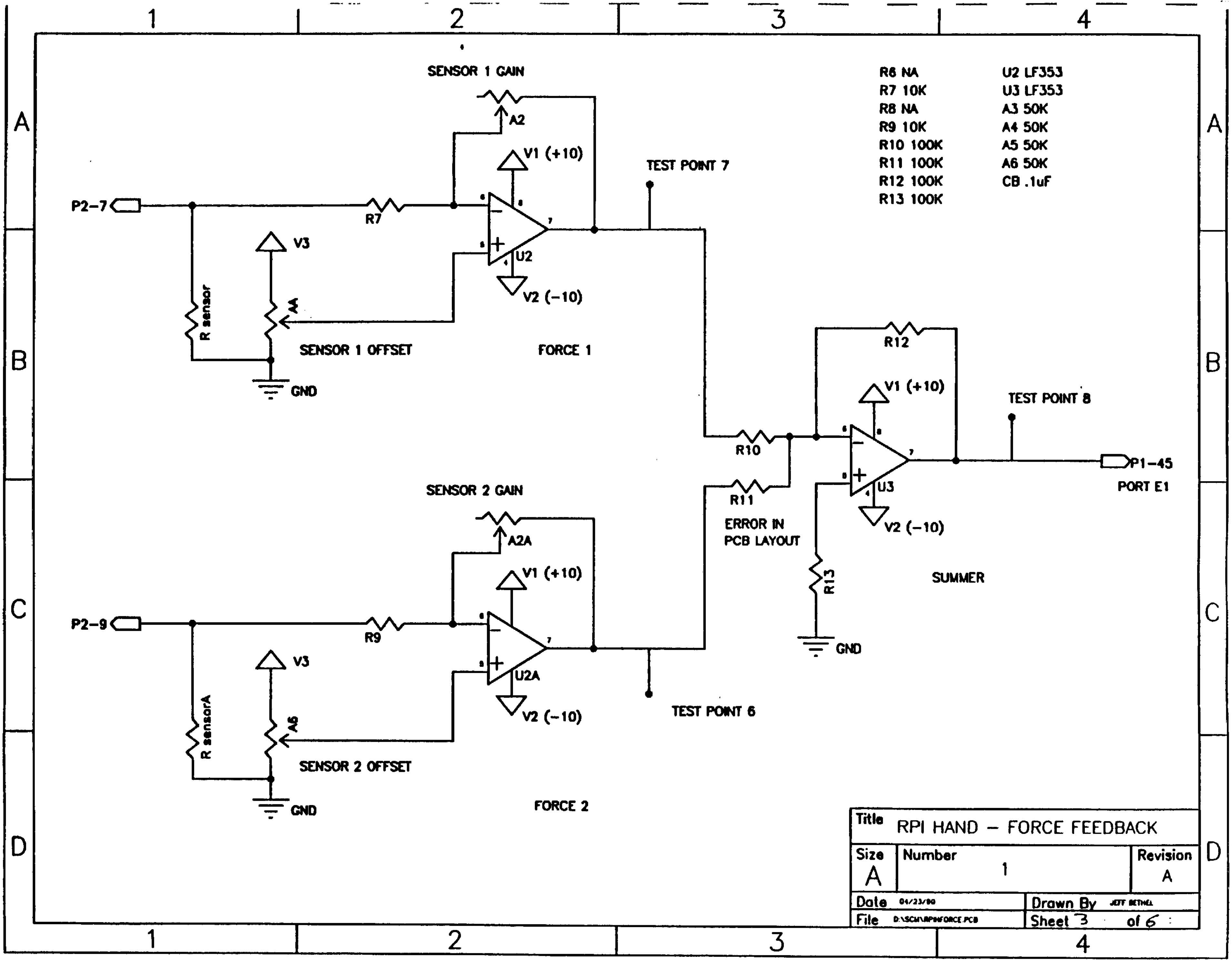
1. Position feedback
2. Fingertip amplifier
3. Force feedback
4. Crossfire
5. Air valve drive
6. Regulator circuits



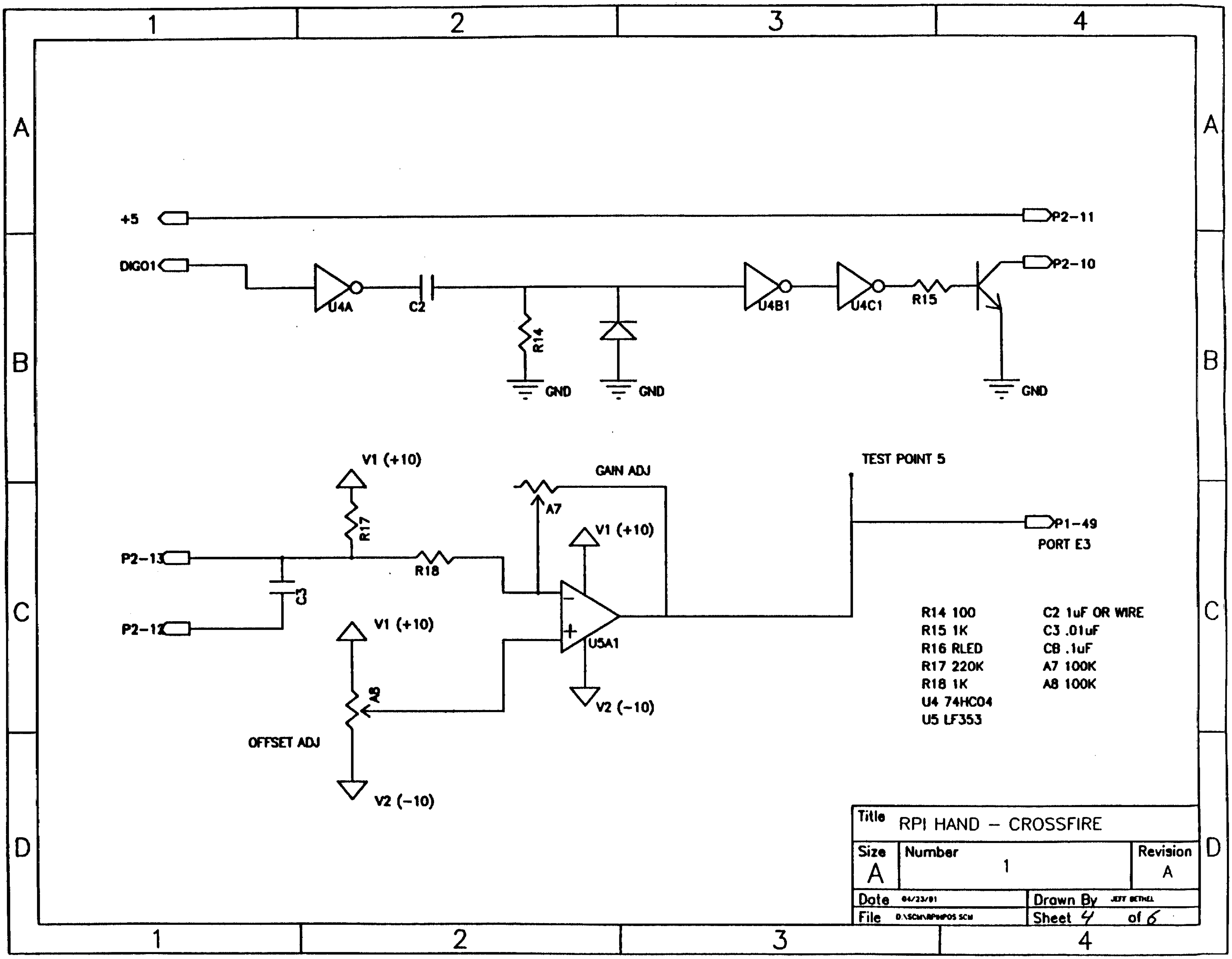
R1 33K	U1 LF353
R2 50K	C1 .1uF
R3 50K	CB .1uF
R4 510	A1 50K
	A2 50K

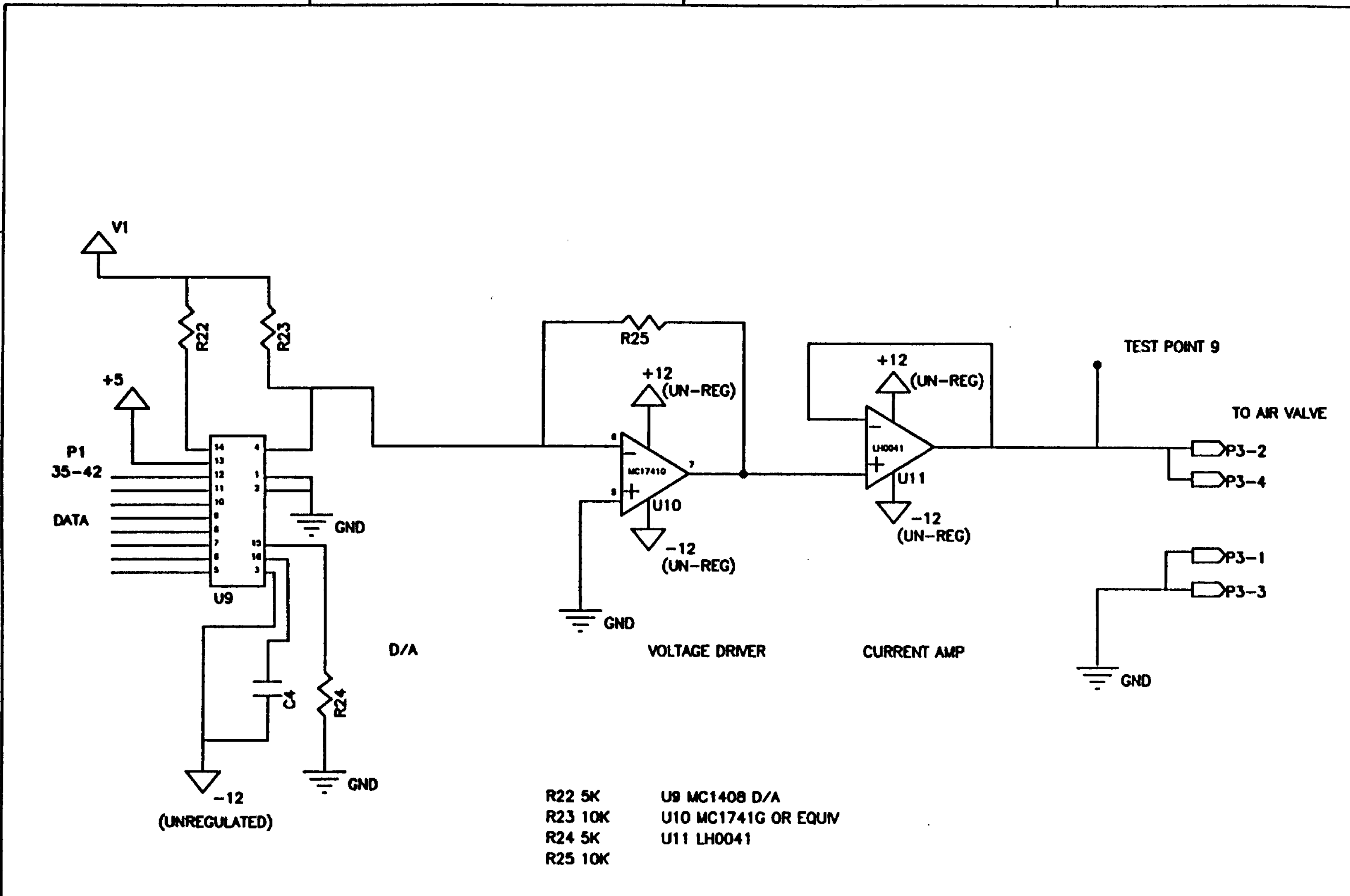
Title	RPI HAND – POSITION FEEDBACK	
Size A	Number 1	Revision A
Date 04/23/01	Drawn By JEFF BETHEL	
File D:\SCM\RPHPOS.SCM	Sheet 1 of 6	


V3
INSIDE FOIL GAGE
100K *
150K
1K
OUTPUT
OUTSIDE FOIL GAGE
1/4 LF347
100K *
GND
FOIL GAGE
AMP CAVITY
CONNECTOR
FLEX POINT
V3
IN
CAP SCREWS
5 PIN CONNECTOR
V3 OUT G IR IR
OUT
GND
* RESISTORS MUST BE MATCHED +/- 1%
ALL RESISTORS 1/8 WATT
LF347 BOTTOM VIEW
FINGER TIP PINOUT
Title FINGER TIP AMPLIFIER
Size A
Number 1
Revision A
Date
Drawn By JEFF BETHEL
File RPIFING.PCB
Sheet 2 of 6

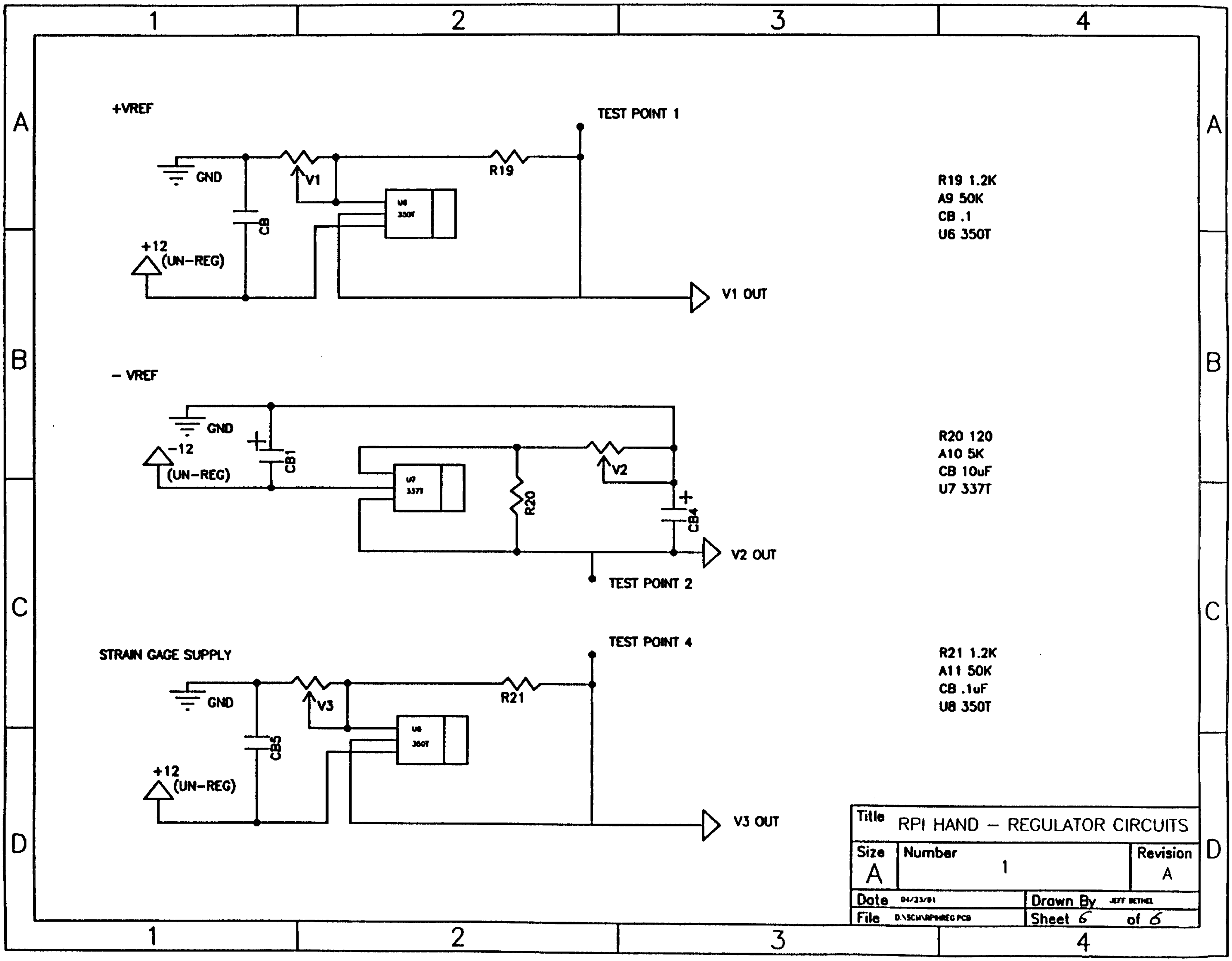


SENSOR 1 GAIN
A2
V1 (+10)
TEST POINT 7
P2-7
R7
U2
V3
V2 (-10)
R sensor
A4
SENSOR 1 OFFSET
FORCE 1
GND
R6 NA
R7 10K
R8 NA
R9 10K
R10 100K
R11 100K
R12 100K
R13 100K
U2 LF353
U3 LF353
A3 50K
A4 50K
A5 50K
A6 50K
CB .1uF
R12
V1 (+10)
TEST POINT 8
R10
U3
P1-45
PORT E1
R11
ERROR IN
PCB LAYOUT
V2 (-10)
SENSOR 2 GAIN
A2A
V1 (+10)
R13
SUMMER
P2-9
R9
GND
V3
U2A
V2 (-10)
TEST POINT 6
R sensorA
A6
SENSOR 2 OFFSET
GND
FORCE 2
Title RPI HAND - FORCE FEEDBACK
Size A
Number 1
Revision A
Date
Drawn By
File
Sheet 3 of 6
A
B
C
D
1
2
3
4


+5
P2-11
DIGO1
U4A
C2
R14
GND
GND
U4B1
U4C1
R15
P2-10
GND
V1 (+10)
R17
GAIN ADJ
A7
TEST POINT 5
P1-49
PORT E3
V1 (+10)
P2-13
R18
C3
P2-12
V1 (+10)
A8
U5A1
V2 (-10)
OFFSET ADJ
V2 (-10)
R14 100
R15 1K
R16 RLED
R17 220K
R18 1K
U4 74HC04
U5 LF353
C2 1uF OR WIRE
C3 .01uF
C8 .1uF
A7 100K
A8 100K
Title RPI HAND - CROSSFIRE
Size A
Number 1
Revision A
Date 04/23/01
Drawn By JEFF BETHEL
File D:\SCH\RPIHPOS.SCH
Sheet 4 of 6



Title RPI HAND – AIR VALVE DRIVE		
Size A	Number 1	Revision A
Date 04/23/91	Drawn By JEFF BETHEL	
File D:\SCM\RPIVALV.PCB	Sheet 5 of 6	



+VREF
TEST POINT 1
GND
V1
R19
U6
350T
CB
+12
(UN-REG)
V1 OUT
R19 1.2K
A9 50K
CB .1
U6 350T
– VREF
GND
-12
(UN-REG)
CB1
U7
337T
R20
V2
CB4
V2 OUT
TEST POINT 2
R20 120
A10 5K
CB 10uF
U7 337T
STRAIN GAGE SUPPLY
TEST POINT 4
GND
V3
R21
U8
350T
CB5
+12
(UN-REG)
V3 OUT
R21 1.2K
A11 50K
CB .1uF
U8 350T
Title RPI HAND – REGULATOR CIRCUITS
Size A
Number 1
Revision A
Date 04/23/01
Drawn By JEFF BETHEL
File D:\SCH\RPIHREG.PCB
Sheet 6 of 6

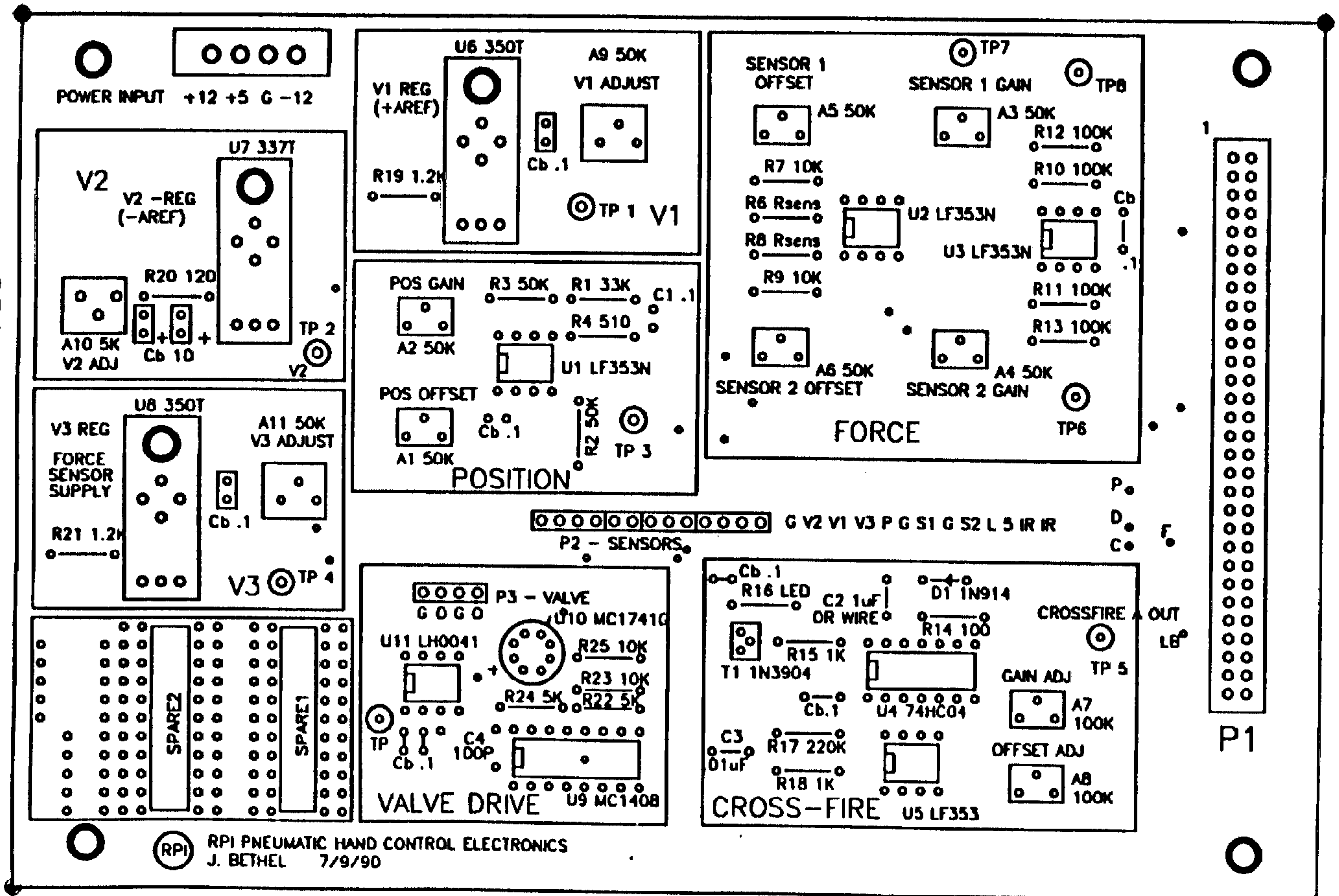
APPENDIX D

Printed Circuit Board Details

1. Labels
2. Drill pattern
3. Top layer
4. Bottom layer

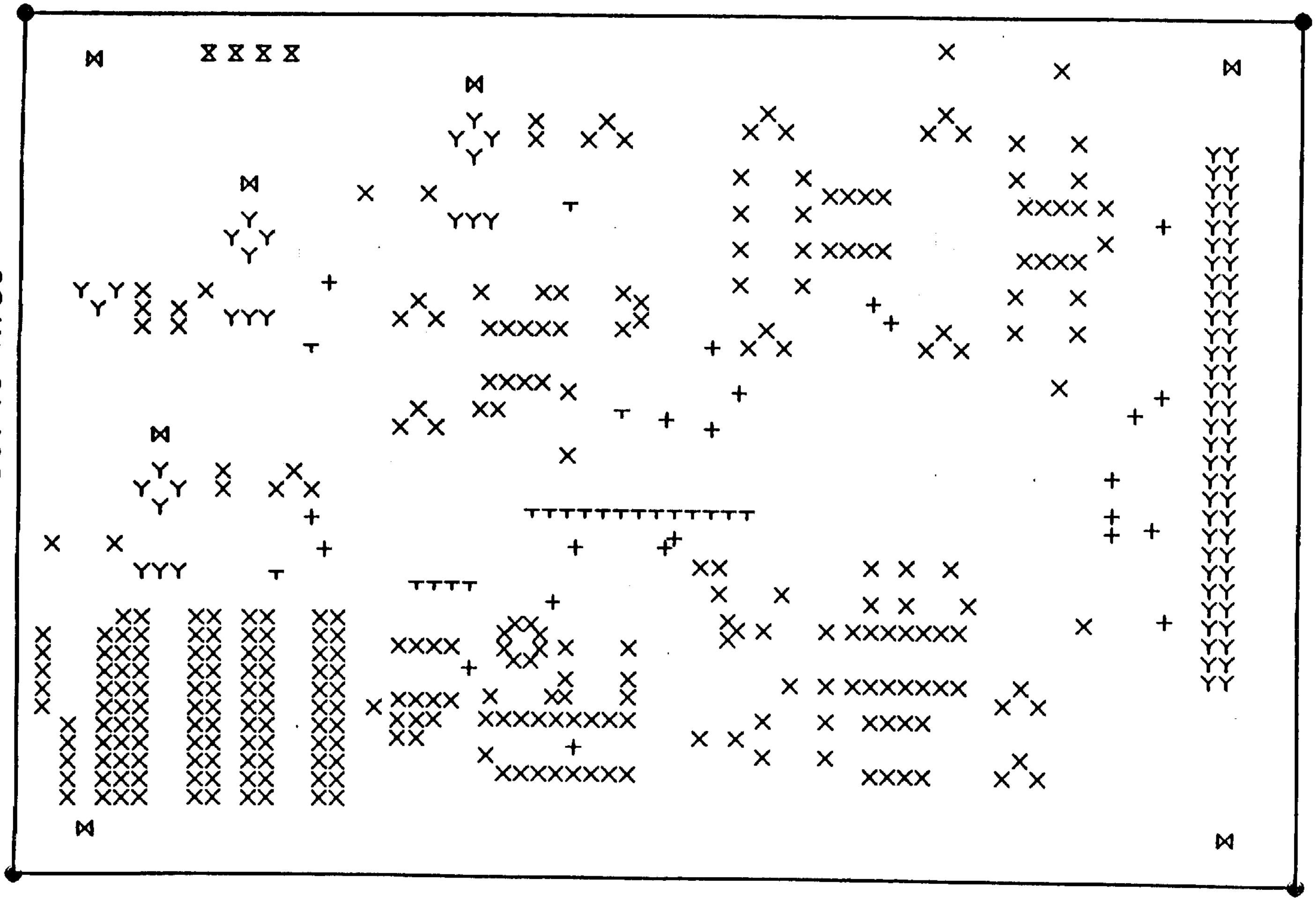
PLOT AND CUT TO 7.2"

PLOT AND CUT TO 4.750

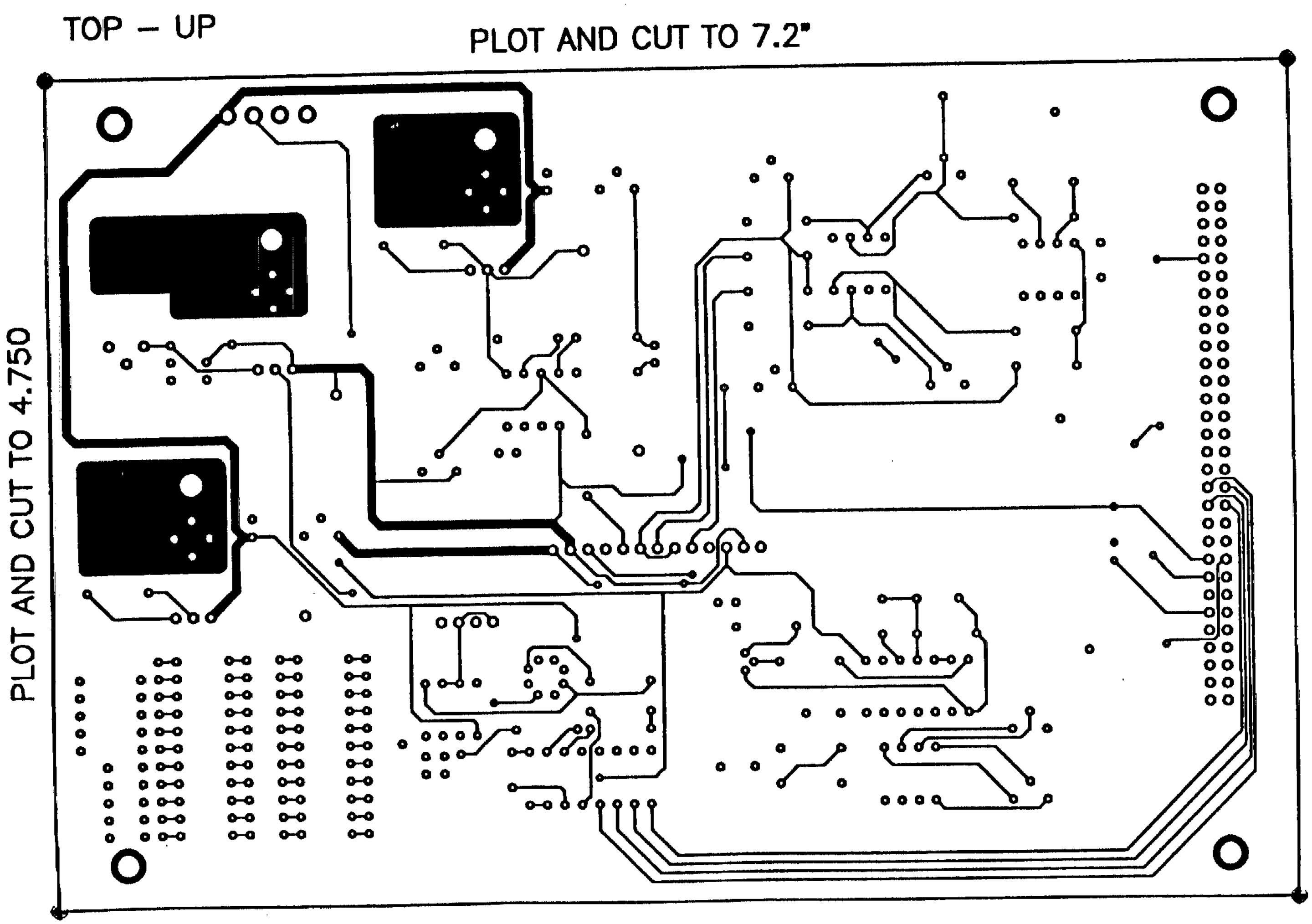


DRILL — UP

PLOT AND CUT TO 7.2"

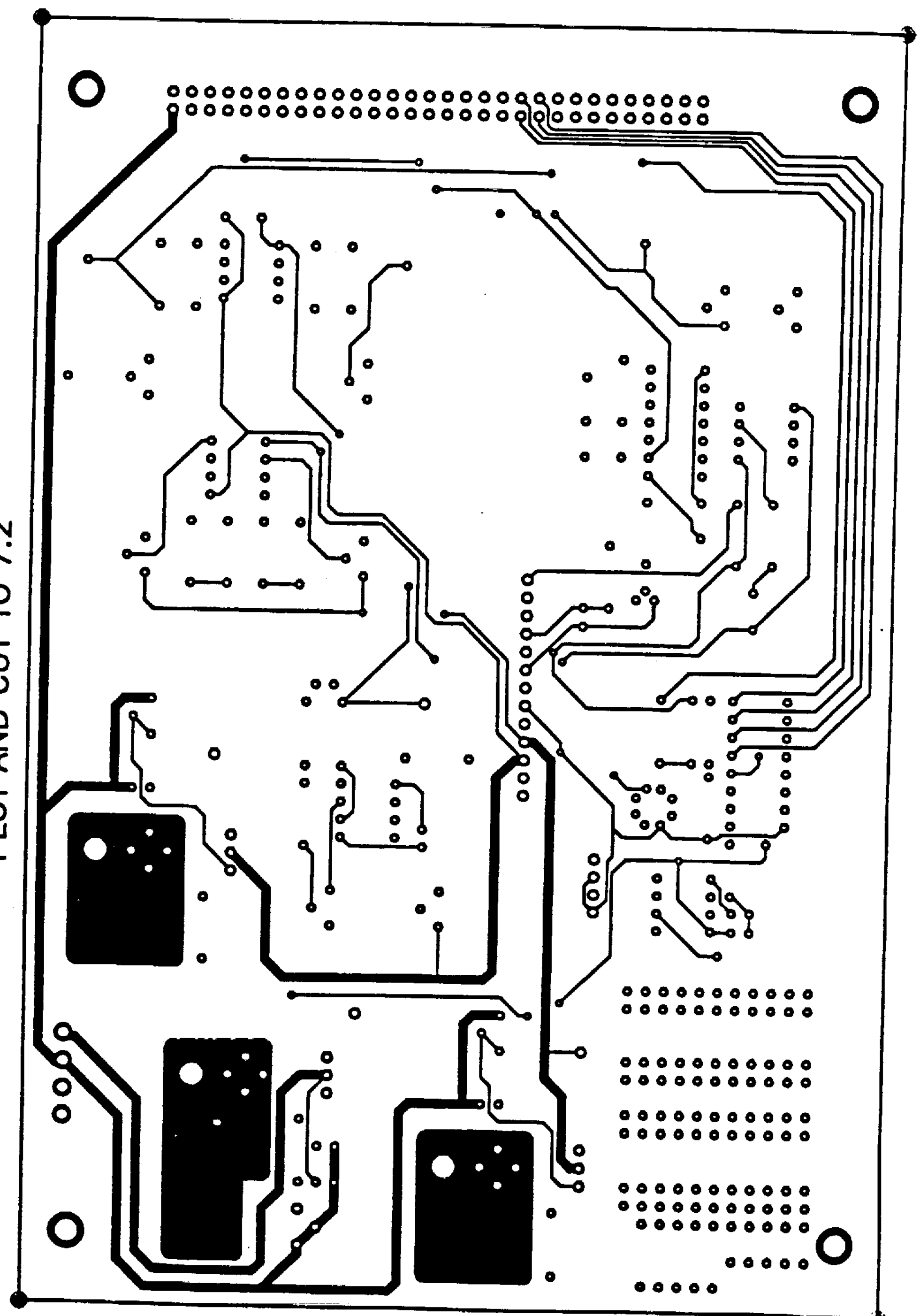


PLOT AND CUT TO 4.750


TOP — UP
PLOT AND CUT TO 7.2"
PLOT AND CUT TO 4.750

BOTTOM – UP

PLOT AND CUT TO 7.2"

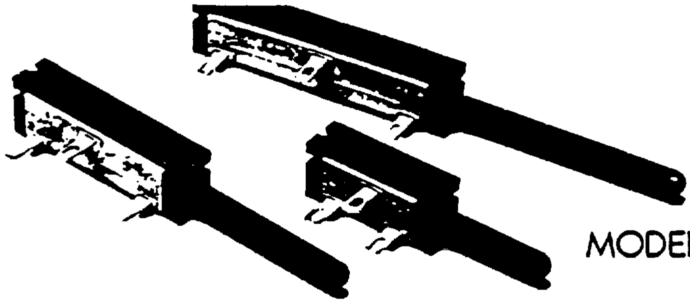


PLOT AND CUT TO 4.750

APPENDIX E

Linear Potentiometer Specifications

Manufacturer: System Donner/Duncan Electronics Division



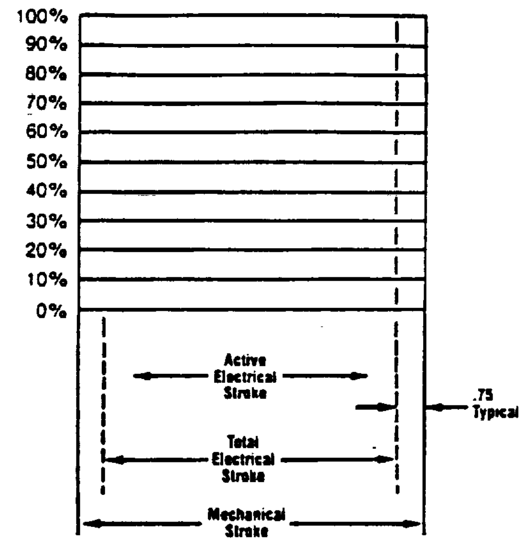
MODELS 9605, 9610, 9615

SPRING RETURN LINEAR/POSITION SENSOR MODULE

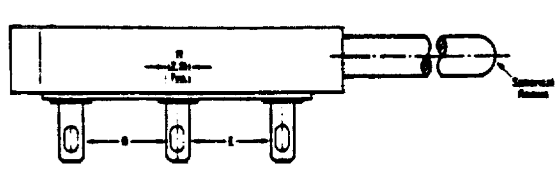
Designed for a variety of miniature-sized, accurate position feedback applications, the Duncan 9600 Series Linear Position Sensor Module is ideally suited for use where reliability in a harsh operating environment is a primary consideration.

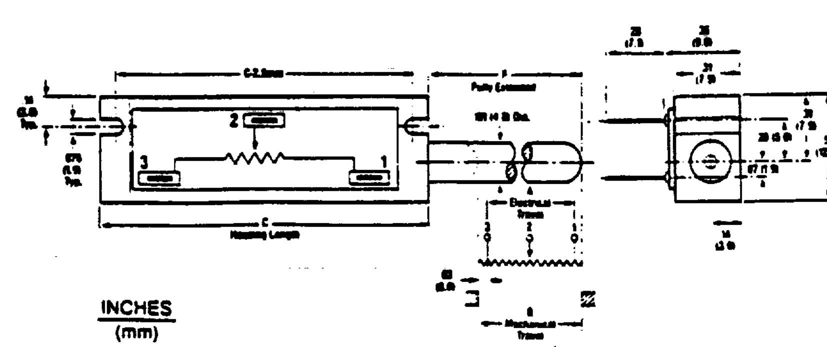
Use in industrial, vehicular, appliance, machine tool, and robotic applications is benefited by the unit's features which include high temperature-stable materials, solderable terminal tabs, suitable for use with .110" (2.8mm) PDQ styled crimped wiring lugs, and a durable spring-loaded function (extended in normal position).

The 9600 Series is available in three standard sizes and provides excellent long-life at 1,000,000 full cycles (5 million dither cycles); resistance, voltage and linearity characteristics.



MODEL	9605	9610	9615
Total Electrical Travel (A) inches (mm)	0.50 (12.7)	1.00 (25.4)	1.50 (38.1)
Total DC Resistance ±25%	1.7K	3.4K	5.1K
Linearity Over Active Electrical Travel	±2%	±2%	±2%
Best Practical Linearity	±1.0%	±0.5%	±0.35%
Power Rating At 70°C, Watts	.25	.50	.75
Mechanical Travel ±.015(±0.4) (B) inches (mm)	0.56 (14.2)	1.06 (26.9)	1.56 (39.6)
Housing Length ±.015(±0.4) (C) inches (mm)	1.06 (26.9)	1.56 (39.6)	2.06 (52.3)
Terminal Spacing: (D) inches (mm)	0.30 (7.6)	0.50 (12.7)	0.80 (20.3)
Terminal Spacing: (E) inches (mm)	0.20 (5.1)	0.50 (12.7)	0.70 (17.8)
Fully Extended Length ±.015(±0.4) (F) inches (mm)	.810 (20.6)	1.310 (33.3)	1.810 (46.0)
Mechanical Life	1,000,000 Full Cycles, 5,000,000 Dither Cycles		
Stop Strength oz. (Newtons)	360 (100)		
Actuation Force oz. (Newtons)	14.4 (4.0) Maximum, supplied with internal spring to return actuator to extended position.		
Humidity	95% @ 38°C		
Vibration	15G's, 50 to 1,000Hz, 2 hrs. each plane		
Shock	Up to 50G's		
Temperature Limits	−40°C to +135°C		





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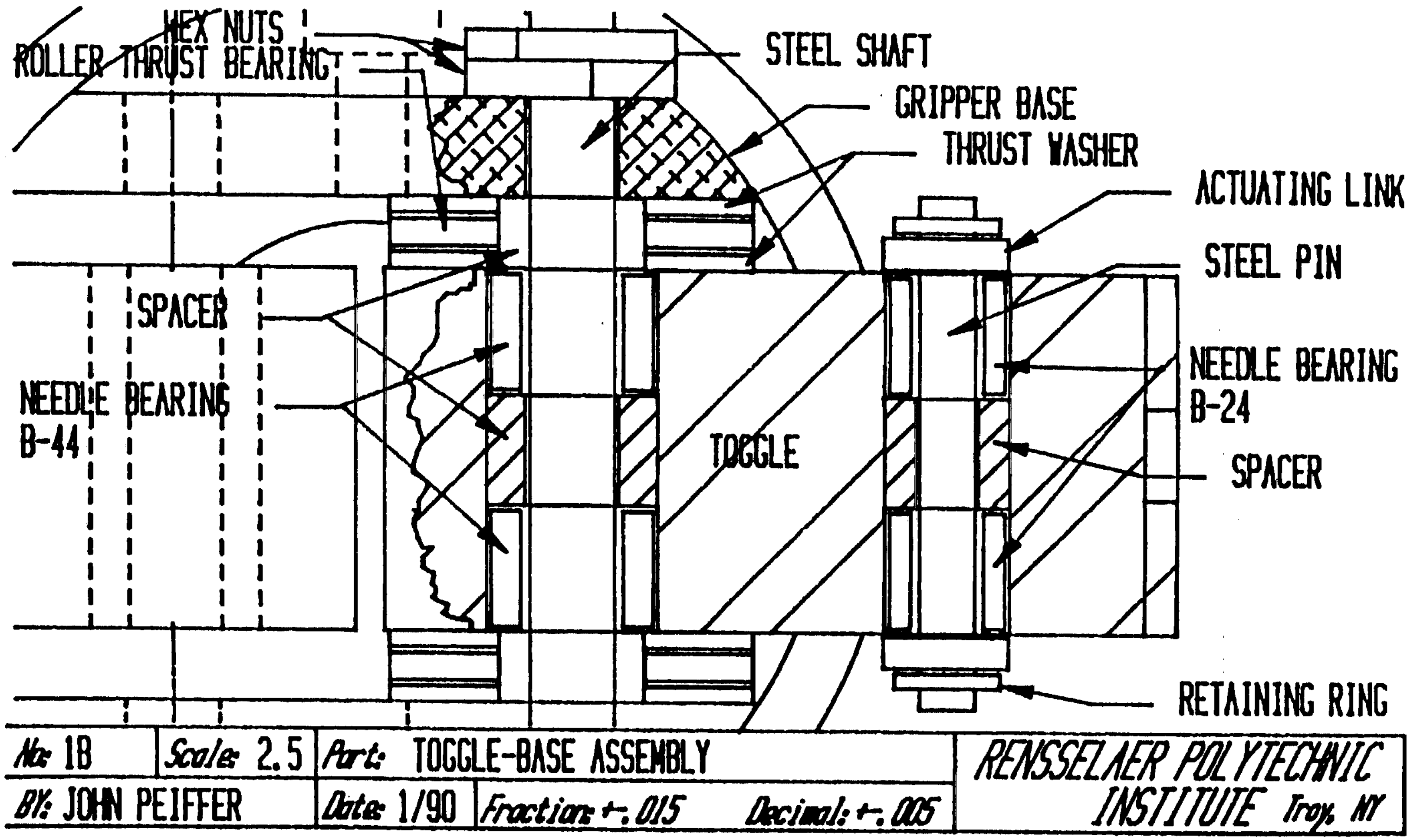
HEX NUTS
ROLLER THRUST BEARING
STEEL SHAFT
GRIPPER BASE
THRUST WASHER
ACTUATING LINK
STEEL PIN
SPACER
NEEDLE BEARING
B-44
NEEDLE BEARING
B-24
TOGGLE
SPACER
RETAINING RING
No: 1B
Scale: 2.5
Part: TOGGLE-BASE ASSEMBLY
BY: JOHN PEIFFER
Date: 1/90
Fraction: +-.015
Decimal: +-.005
RENSSELAER POLYTECHNIC
INSTITUTE Troy, NY