University of California at Davis
California Department of Transportation

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THE BIG ARTICULATED STENCILING ROBOT (BASR)*

Volume I

Phillip W. Wong, P.E.
Professor Bahram Ravani
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AHMCT

Advanced Highway Maintenance and Construction Technology

Department of Mechanical, Aeronautical & Materials Engineering
Division of New Technology and Materials Research

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16. Abstract

This report provides a description of the Big Articulated Stenciling Robot (BASR) that was developed at the University of California at Davis under contract to the California Department of Transportation (Caltrans). This system is designed to paint markings on the roadway pavement with a primary emphasis on increasing highway worker safety by keeping personnel out of unprotected roadway areas. The system is completely integrated, with all normal operations controlled from a single control panel. Overall system descriptions are given in this report. Furthermore, detail design and operational descriptions are given. The report is contained in four (4) volumes, with each volume providing complete details of specific aspects about BASR. Volume I contains introductory material, theory of operation, system schematics, and source code listings. Volume II is a copy of Robert Olshausen's 1996 U.C. Davis Master's Thesis, "Development of an Articulating Robotic Arm for Spray Painting on Roadways". Volume III is a copy of Richard A. McGrew's 1996 U.C. Davis Master's Thesis, "A Robotic End-Effector for Roadway Stenciling". Volume IV is a copy of Richard Blank's 1996 U.C. Davis Master's Thesis, "Algorithms and Robotic Hardware Improvements for Painting of Roadway Markings".

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ABSTRACT

This report provides a description of the Big Articulated Stenciling Robot (BASR) that was developed at the University of California at Davis under contract to the California Department of Transportation (Caltrans). This system is designed to paint markings on the roadway pavement with a primary emphasis on increasing highway worker safety by keeping personnel out of unprotected roadway areas. The system is completely integrated, with all normal operations controlled from a single control panel. Overall system descriptions are given in this report. Furthermore, detail design and operational descriptions are given. The report is contained in four (4) volumes, with each volume providing complete details of specific aspects about BASR. Volume I contains introductory material, theory of operation, system schematics, and source code listings. Volume II is a copy of Robert H. Olshausen's 1996 U.C. Davis Master's Thesis, " Development of an Articulating Robotic Arm for Spray Painting on Roadways" (report number UCD-ARR-96-09-30-01). Volume III is a copy of Richard A. McGrew's 1996 U.C. Davis Master's Thesis, " A Robotic End-Effector for Roadway Stenciling" (report number UCD-ARR-96-06-30-01). Volume IV is a copy of Richard Blank's 1996 U.C. Davis Master's Thesis, " Algorithms and Robotic Hardware Improvements for Painting of Roadway Markings" (report number UCD-ARR-97-06-15-01).

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DISCLAIMER STATEMENT

1. Introduction

Painting roadway markings on the road surface is a tedious and hazardous maintenance procedure. To create the markings, a work crew first must section off a lane area and then layout a set of stencils corresponding to the desired message. Once everything is in place, the crew uses a paint sprayer and coats the road surface and stencils with paint. Where there are open spots in the stencil is where the paint is deposited on the surface. After a suitable drying period, the stencils are removed and the lane reopened. Each time this process is repeated, the crew is exposed to traffic hazards since the crew must leave the safety of their vehicles and work on the open roadway.

At the University of California, Davis Advanced Highway Maintenance and Construction Technology (AHMCT) Center, we have developed a very long reach pantograph-type robot manipulator to accomplish the painting operations without the use of stencils. When the unit is fully extended, it has a reach of almost 4.575 meters [15 feet]. The base can rotate approximately 270 degrees. One of the unique features of this design is that all of the joint actuators are located at the base of the manipulator. This co-location leads to extremely high stiffness to weight ratios since the manipulator structure does not need to support the weight of the actuators.

As shown in Figure 1, the robot manipulator has two degrees of freedom: ***R*** and θ. The movement in the ***R*** direction is controlled by a linear hydraulic actuator, operating on the pivot of the pantograph. Motion is amplified by the pantograph mechanism according to an 8.3:1 ratio. Thus, for each 2.54 centimeters [1 inch] the hydraulic actuator moves, the tool center point moves linearly 21.082 centimeters [8.3 inches]. Rotation of the manipulator is controlled by a hydraulic motor mounted in the base. Position of the manipulator is determined by two optical encoders. One optical encoder is mounted on the output shaft of the hydraulic motor that rotates the manipulator and the other encoder is mounted on the pivot of one of the manipulator's link. Note that the extension length of the manipulator is indirectly sensed through the rotation angle of the upper manipulator link.

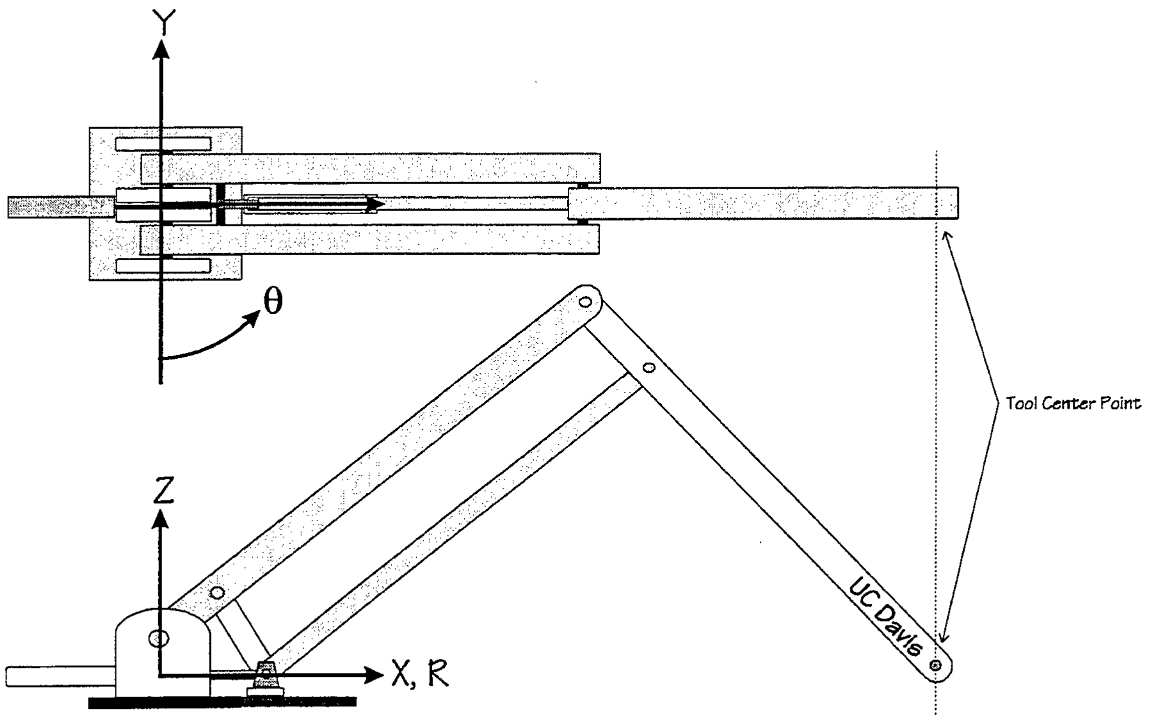


Figure 1: Manipulator Layout

In order to paint the roadway markings in a consistent fashion, the manipulator must move the tool center point (to which is mounted the painting end-effector) from point-to-point locations in an accurate way, as well as follow accurately a prescribed trajectory motion. The manipulator must follow a prescribed trajectory in order to create acceptable letter profiles with an evenly coated painted surface. The following sections describe the major components and subsystems necessary to accomplish the desired painting operations.

2. System Description

The BASR is composed of six (6) major components operated in conjunction with five (5) supporting subsystems. The six major components are:

1) the truck with its stabilizer feet,
2) the paint subsystem,
3) the reflective bead subsystem,
4) the main power unit,
5) the robot arm manipulator,
and 6) the manipulator end-effector

The five supporting subsystems are:

1) the hydraulic supply subsystem,
2) the electrical subsystem,
3) the pneumatic system,
4) the computer control system,
and 5) the embedded software.

Each component and subsystem are described in subsequent sections below.

2.1 Truck

The BASR support vehicle is a 1989 Ford F-350 9 ton flat bed truck modified by Lakeview Metal (Nice, CA). The location of major components on the truck are identified in Figure 2. For added vehicle stability, a set of stabilizer feet (Appendix A) at the front of the truck bed and a set of stabilizer feet (Appendix A) at the back of the bed have been installed. These feet are under computer control during automatic operations, but can be controlled manually (valves 2 through 4) from the hydraulic hand-valve stack located in the utility box on the side of the truck. Major utilities, such are hydraulic, pneumatic and electrical service, are distributed from the main power unit to the rest of the system through a trough located in the middle of the truck bed.

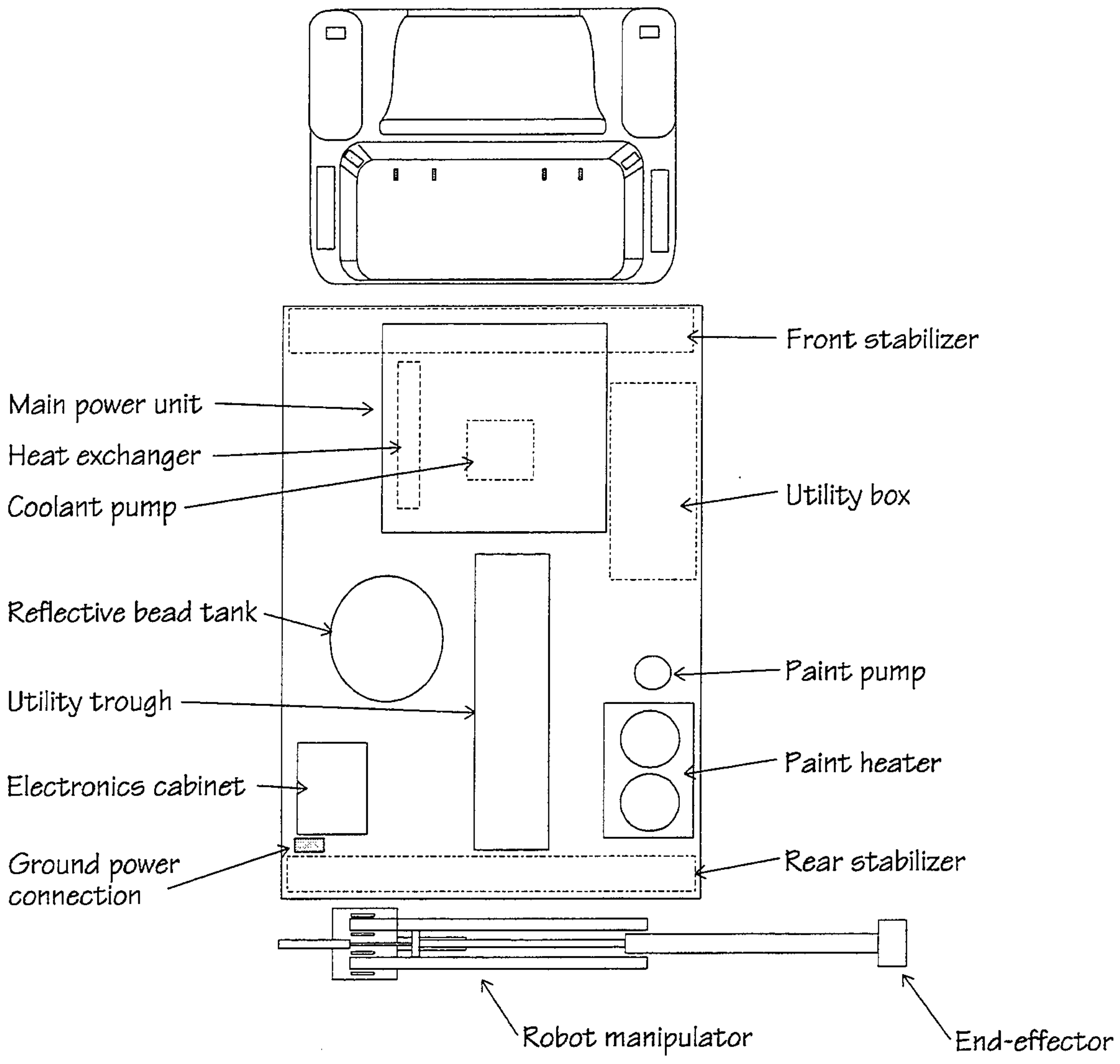


Figure 2: Truck Layout

2.2 Paint Subsystem

The paint subsystem is composed of a paint pump and associated plumbing to transport the paint from the paint supply bucket to the spray tip located at the end of the robot. The paint pump is a Graco Viscount I, operating on a 103.35 bar [1500 psi] hydraulic supply with a 2:1 compression ratio, thus producing an output pressure of 206.7 bar [3000 psi]. The paint system schematic is shown in Figure 3. The operation of the paint pump is under automatic control of the computer. The controlling hydraulic solenoid valve is located in the utility box. During cleaning and maintenance operations of the pump, the pump operation can be controlled by hand-valve number 1 on the hand-valve stack located in the utility box.

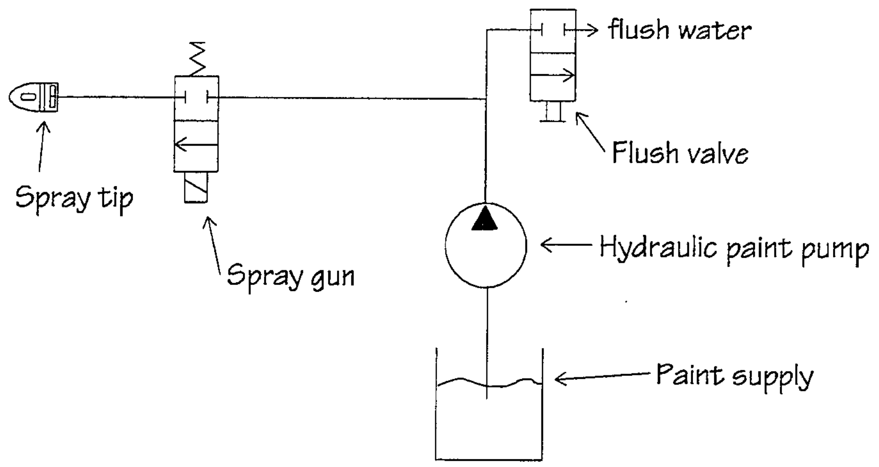


Figure 3: Paint System Schematic

In order to maintain optimal paint viscosity, the paint temperature is regulated by a paint heating system. The heating system schematic is shown in Figure 4. This heating system obtains its heat from an engine exhaust gas heat exchanger located in the main power unit. This heat exchanger operates by passing diesel engine exhaust around a tube containing coolant from the paint bucket reservoir. The coolant is circulated by an electrically driven water pump. A thermostat, which senses the coolant temperature, controls whether the pump recirculates the coolant or redirects the coolant to the heat exchanger. The temperature control schematic is shown in Figure 5. The coolant loop is sealed against outside contamination. The heated paint bucket receptacle has enough capacity for two (2) 18.9 liter [five gallon] containers.

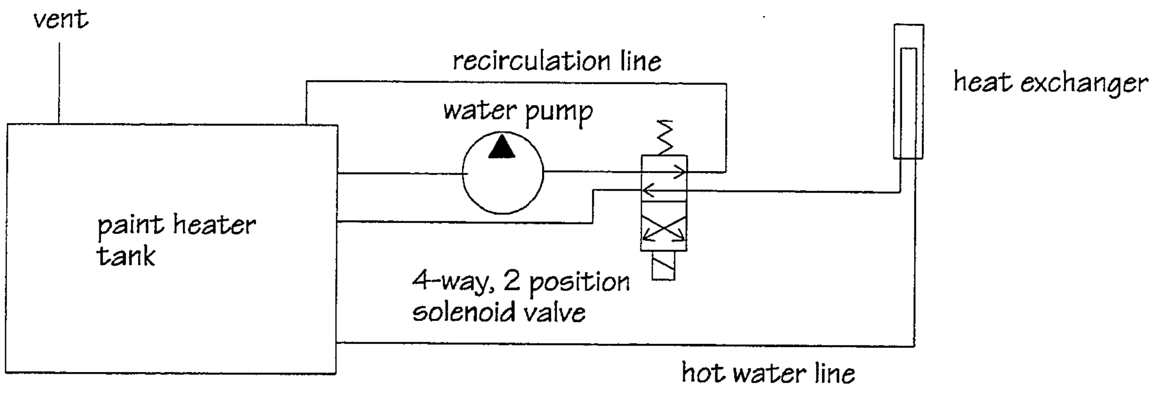


Figure 4: Paint Heating System

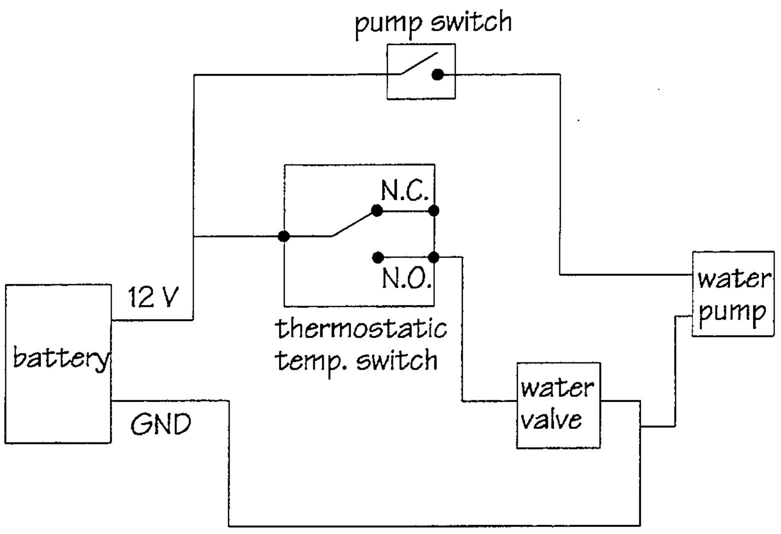


Figure 5: Temperature Control Schematic

After the paint has passed through the paint pump, it is transported to the paint gun by a 7.625 meter [25 feet] high pressure flexible hose. The paint flow then enters a Binks electrically controlled paint gun. This gun opens and closes under authority of an electrical signal from the computer. A Binks carbide spray tip (P/N 1380) converts the paint flow into a rectangular spray pattern on the ground.

2.3 Reflective Bead System

In order to increase reflectivity of the painted pavement markings, reflective glass spheres are placed in the pavement markings while it is still wet. These glass spheres are sprayed on using a pneumatically controlled applicator. This applicator contains a valve and a spreader nozzle. The spheres are supplied from a pressurized supply tank operating at 4.134 bar [60 PSI]. The operation of the applicator, as well as the pressurization of the supply tank, are computer controlled. A schematic of the system is shown in Figure 6.

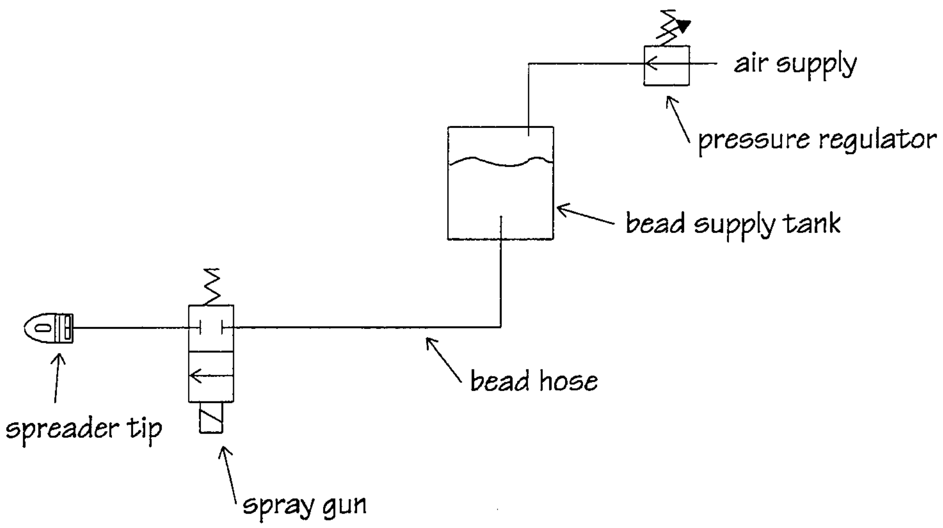


Figure 6: Reflective Bead System Schematic

2.4 Main Power Unit

The main power unit (MPU) provides electrical, pneumatic, and hydraulic power to the entire machine. The MPU layout is shown in Figure 7. The primary motive power for the MPU is a Deutcsh 4 cylinder air-cooled diesel engine. A maximum of 8000 watts, 220/120 volts is provided by a belt-driven alternator. A single-cylinder belt-driven air compressor produces 6.89 bar [100 PSI]. Finally, attached to the crankshaft of the engine are two (2) hydraulic pumps, both drawing hydraulic fluid from a common fluid reservoir. The hydraulic pump nearest to the engine is a pressure-compensated variable-displacement pump producing 37.9 liters [10 gallons] per minute (LPM) [(GPM)] at 206.7 bar [3000 PSI]. Pressure variations are suppressed by a gas-charged fluid accumulator. This pump provide primary motive power to the robotic manipulator and end-effector. The pump at the far-end is a constant displacement pump producing 37.9 LPM [10 GPM] at 103.35 bar [1500 PSI]. This pump provides motive power for the stabilizer feet and paint pump. Fluid output from both pumps is controlled by a toggle switch located under the main control panel for the MPU. Hydraulic fluid is filtered before it is returned to the reservoir.

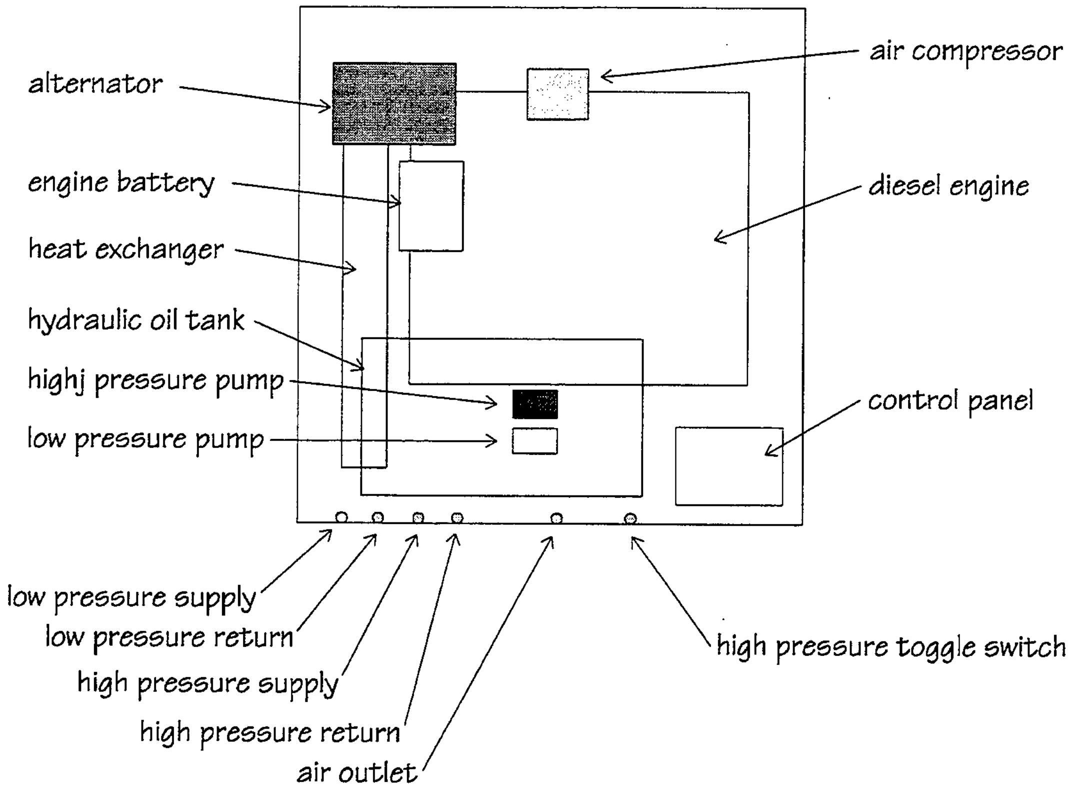


Figure 7: Main Power Unit Layout

Located on the main control panel (Figure 8) are electrical service outlets. Two outlets of 20 amps service and one outlet of 40 amps service are provided. Gauges to monitor MPU performance are located below the electrical outlets. At the bottom of the control panel is located the engine starter key switch and the engine pre-heat button. Both of these controls are used in starting the diesel engine.

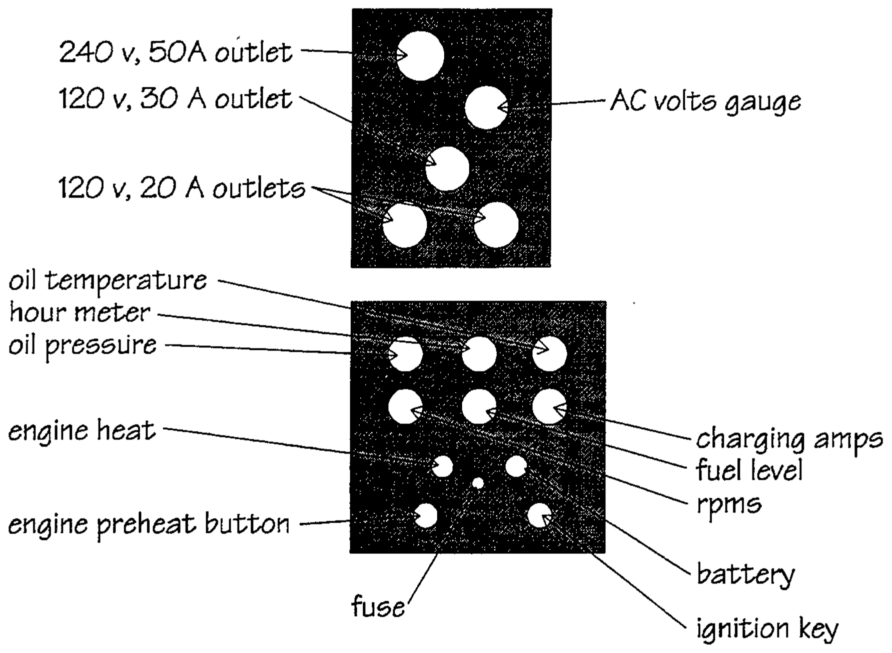


Figure 8: MPU Control Panel

2.5 The Manipulator

The manipulator is of a pantograph-style linkage type, custom built and designed at the University of California at Davis. Further descriptions and design information can be found in Robert H. Olshausen's 1996 U.C. Davis Master's Thesis, "Development of an Articulating Robotic Arm for Spray Painting on Roadways" (report number UCD-ARR-96-09-30-01). For convenience, a copy has been included as Volume II of this report.

2.6 The End-Effector

The manipulator end-effector was custom built and designed at the University of California at Davis. Further descriptions and design information can be found in Richard A. McGrew's 1996 U.C. Davis Master's Thesis, "A Robotic End-Effector for Roadway Stenciling" (report number UCD-ARR-96-06-30-01). For convenience, a copy has been included as Volume III of this report.

2.7 Supporting Subsystems

Five major subsystems are required to operate BASR. The five supporting subsystems are the hydraulic supply subsystem, the electrical subsystem, the pneumatic subsystem, the computer control subsystem, and the embedded software contained on each controller.

2.7.1 The Computer Control Subsystem

BASR is controlled by five (5) single board computers (SBC). Each SBC is manufactured by Z-World, Inc. (Davis, CA). The embedded software on the SBCs is described in Section 2.7.5. Four of the SBCs are Tiny Giants interfaced to a specially designed and manufactured encoder/servo valve control card (ESVCC). These four SBCs are directly associated with a hydraulic actuator. A schematic of the ESVCC is provided in Appendix B. The ESVCC is composed of a HP2020 quadrature decoder chip, a AD667 digital-to-analog converter (D/A), and associated logic control circuitry. The SBC receives position information from the quadrature decoder chip, computes the necessary servo valve position using a predetermined control law, and then outputs the necessary signal to the D/A chip. The output from the D/A chip then is conditioned by the voltage-to-current converter, which directly positions the servo valve, controlling the output of hydraulic flow to the actuator. Figure 9 is a schematic of the control architecture of one of the hydraulic actuator circuits.

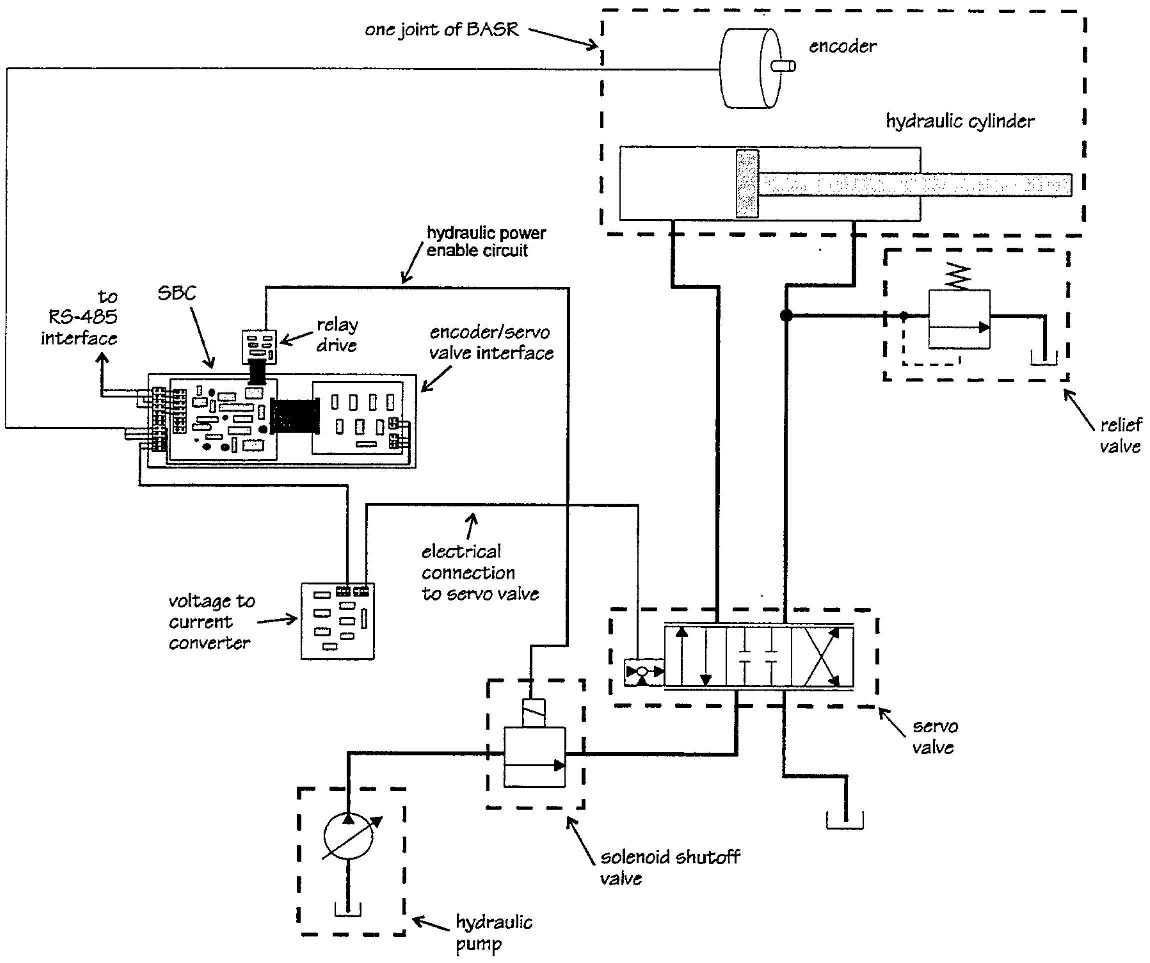


Figure 9: A Hydraulic Actuator Circuit

The fifth SBC is contained in the hand-held pendant. This pendant has a keypad interface, as well as a joystick and three (3) control knobs for positioning BASR. The keypad is used for entering textual information, such as the desired lettering to create on the pavement. A LCD screen displays status and informational messages to the operator.

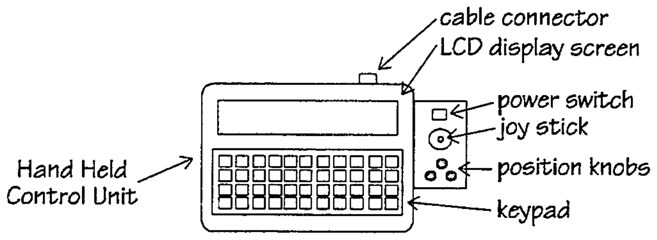
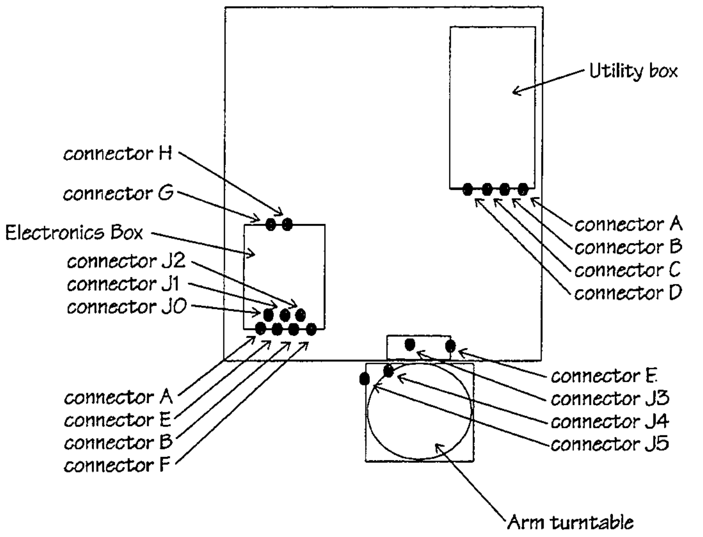


Figure 10: Control Pendant

All SBCs are linked together using RS-485 local area networking. Commands are passed through the network interface and are composed of text strings. Each command string is composed of five parts: a start character, an address, a command, the command option modifiers, and the end character. Appendix C has a list of acceptable commands.

In order to route the electrical signals from the SBCs to different parts of BASR, various cable interconnects are used. The cable connectors are keyed and different sizes and gender are used to prevent accidental connections to the wrong cable plug. Figure 11 shows the location of all connectors. A wiring diagram and pinout table is provided in Appendix D.



name	function
connector A	stabilizer control
connector B	transducer/communications
connector C	transducer/solenoid control
connector D	stabilizer limit switches
connector E	end effector accessories
connector F	accessory control
connector G	pendant
connector H	main power
connector J0	translation control/sensor
connector J1	rotation control/sensor
connector J2	extension control/sensor
connector J3	extension servo control
connector J4	extension sensor
connector J5	trans./rot/ control/sensor

Figure 11: Cable and Connector Routing

2.7.2 Hydraulic Supply Subsystem

Hydraulic power is supplied to BASR via two (2) engine driven hydraulic pumps routed through two separate hydraulic systems. One pump provides 103.35 bar [1500 PSI] and the other provides 206.7 bar [3000 PSI]. The 206.7 bar [3000 PSI] system operates the actuators related to the manipulator and end-effector. The 103.35 bar [1500 PSI] system operates the vehicle's stabilizer feet and the paint pump. Manual operation is provided for the operation of all accessories on the 103.35 bar [1500 PSI] system. The operating hand-valves are located in the utility box on the right side of the truck. Additionally, should it be desirable to use external hydraulic power, ground-service quick-disconnect return and supply ports are provided. The ports are located on the truck near the electronics cabinet. A pressure reducing valve is connected to the ground service port to automatically provide 103.35 bar [1500 PSI] from the 206.7 bar [3000 PSI] ground supply port. Various valves are provided through out the system in order to isolate different hydraulic circuits. The hydraulic system schematic is provided in Appendix K.

2.7.3 Electrical Subsystem

An 8000 watt belt-driven alternator provides the main AC power to BASR. AC power is used to power the paint heater coolant pump and the 12 volt power transformer for the SBCs.

2.7.4 Pneumatic Subsystem

Pneumatic power is supplied by a single-cylinder engine driven compressor. Maximum supply pressure is 6.89 bar [100 psi]. Air pressure is supplied via a manifold to four (4) valves operating the reflective bead pressurization system, the electronics vortex air conditioner, the end-effector stowage system, and the end-effector stowage system lock-out. Figure 13 is a schematic of the pneumatic system.

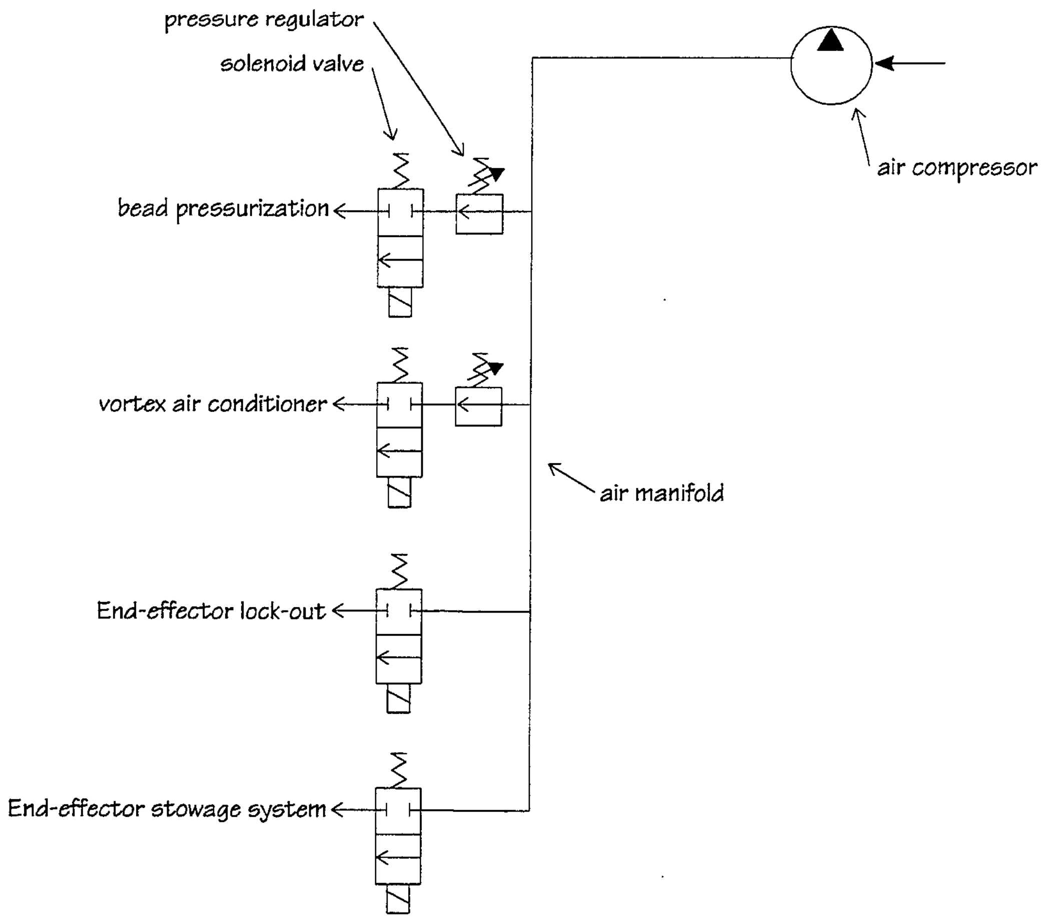


Figure 13: Pneumatic Subsystem

2.7.5 Embedded Software

Each of the SBCs contains embedded compiled program code written in the "C" programming language. Although each of the four manipulator joint SBCs respond to the same commands, the programming varies slightly to account for the kinematics of the mainpulator joint it is controlling. Complete source code listings are provided in Appendices I through L. As of this writing, a complete source code listing of the software for the pendant controller is not available. Operation of the trajectory planner and control module is described in the research paper provided in Appendix E.

Letter profiles for BASR are generated by the techniques discussed in the Master's Thesis of Richard Blank "Algorithms and Robotic Hardware Improvements for Painting of Roadway Markings" (report number UCD-ARR-97-06-15-01). A copy of the thesis has been included as Volume IV of this report. Once the letter profiles have been generated off-line, the data is encoded and programmed into the hand-held pendant control software. When the operator has selected a certain letter, its coordinates are retrieved from the pendant's memory and downloaded to the joint SBCs. These coordinates are then executed by the SBCs and move BASR accordingly.

3. System Operation

As of this writing, field testing has not been completed. As such, a complete description of field operational procedures cannot be provided. However, a description of laboratory operational procedures can be provided.

3.1 System Startup

BASR system startup consists of clearing the workspace of all obstacles and personnel. Then, all restraining chains and harnesses are removed. Finally, the main power unit can be started. MPU starting is accomplished by first depressing the engine preheat button, then turning the ignition key until the engine cranks. Once the engine has started, the engine preheat button and key is released. While the engine operation stabilizes and warms up, striping paint can be mixed and loaded into the paint bucket receptacle. The high pressure enable toggle switch on the MPU is then moved to the "enable" position, thus allowing the main hydraulic system to reach operating pressure. After allowing a few seconds for pressure to build, the paint pump can then be primed. This is accomplished by inserting the pump siphon hose into the paint bucket. The pump outlet valve is opened and the outlet hose placed in a suitable waste receptacle. Hand valve #1 is then operated to allow the paint pump to prime. Once air-bubble-free paint begins to flow from the outlet hose, the outlet valve can be shut off and the hydraulic hand-valve released to stop pump operations. The spray gun is then opened, and the paint pump is cycled once again to fill the paint hose. Once the paint hose is free of air, the spray gun and paint pump are deactivated. A spray tip is then installed on the spray gun. "Calibration mode" is then selected on the control pendant. The manipulator and end-effector then begin automatic check-up and calibration procedures. Once complete, BASR is ready to be used.

3.2 Normal Operations

Once the truck is located at the proper work site, from the control pendant, the operator selects the menu item to lower the stabilizer feet. By using the video screen to target the end-effector, the operator can position BASR by using the manual control joystick and knobs. Properly positioned, the operator types in the message on the control pendant to be painted on the ground. After presenting a confirmation message, the controller then pressurizes the paint system, moves BASR, thus marking the pavement. The operator then selects the "Stow" item from the control pendant. After BASR is stowed, the operator can then drive away from the work site.

3.3 Clean Up

After all operations are complete for the day, BASR cleanup merely involves removing the spray tip and cleaning off the paint deposits. The paint is replaced with water, and water is pumped through the system to remove the paint. The high pressure hydraulic system enable switch is then moved to the "disable" position. The controller power switch is then turned off, and all restraints and harnesses replaced. Finally, the MPU is turned off.

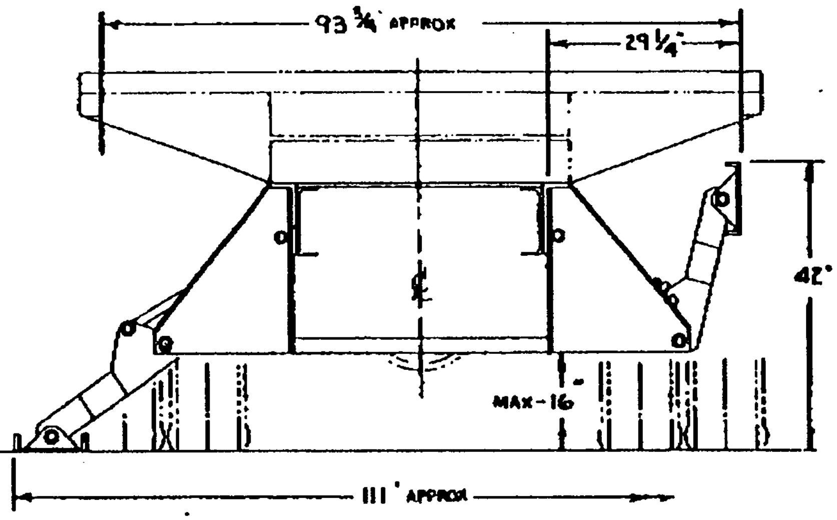
4. Conclusions

Although field testing of BASR is not yet complete, from the results of laboratory testing, a reliable and easy to use pavement marking system has been created. This system maximizes personnel safety, increases efficiency, and improves quality.

Appendix A

Stabilizer Feet Data

STANDARD ON HILIFTS



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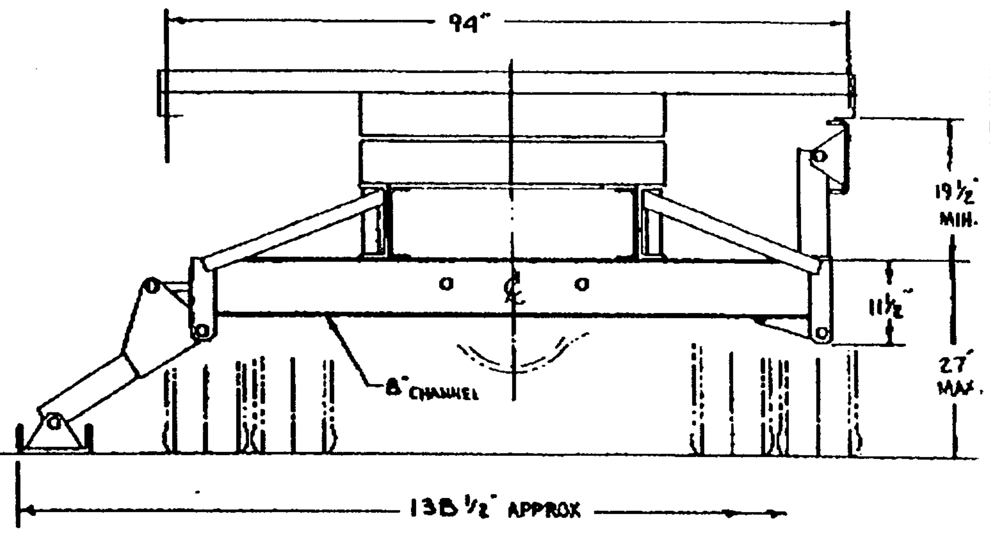
WIDER REACH FOR MORE STABILITY



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4. Other models available upon request
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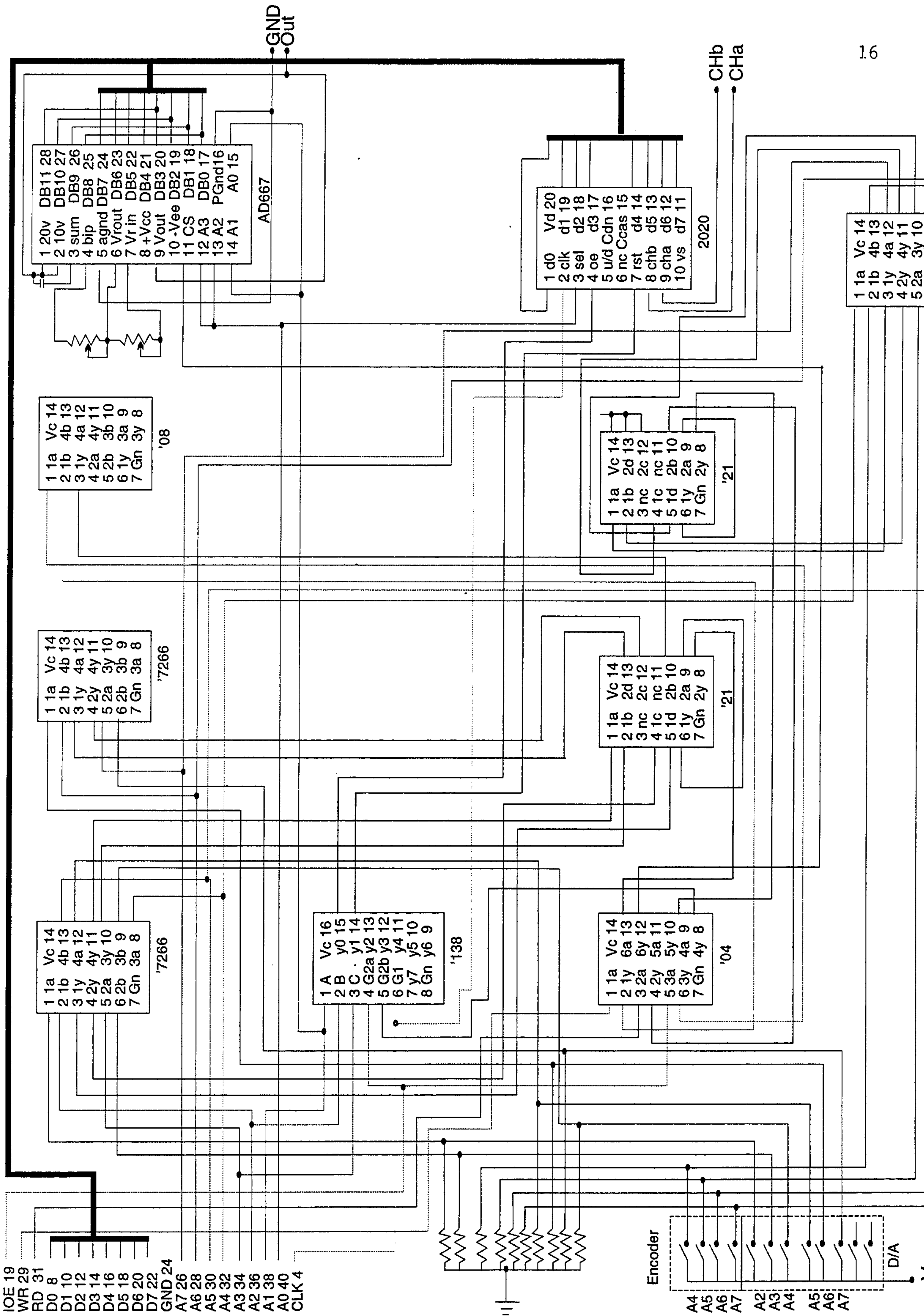
Appendix B

Schematic of ESVCC Board



GND
Out
CHb
CHa
AD667
1 20v
2 10v
3 sum
4 bip
5 agnd
6 Vrout
7 Vr in
8 +Vcc
9 Vout
10 -Vee
11 CS
12 A3
13 A2
14 A1
DB11 28
DB10 27
DB9 26
DB8 25
DB7 24
DB6 23
DB5 22
DB4 21
DB3 20
DB2 19
DB1 18
DB0 17
PGnd16
A0 15
2020
1 d0
2 clk
3 sel
4 oe
5 u/d Cdn 16
6 nc Ccas 15
7 rst
8 chb
9 cha
10 vs
Vd 20
d1 19
d2 18
d3 17
d4 14
d5 13
d6 12
d7 11
'7266
1 1a
2 1b
3 1y
4 2y
5 2a
6 2b
7 Gn
Vc 14
4b 13
4a 12
4y 11
3y 10
3b 9
3a 8
'08
1 1a
2 1b
3 1y
4 2a
5 2b
6 1y
7 Gn
Vc 14
4b 13
4a 12
4y 11
3b 10
3a 9
3y 8
'21
1 1a
2 1b
3 nc
4 1c
5 1d
6 1y
7 Gn
Vc 14
2d 13
2c 12
nc 11
2b 10
2a 9
2y 8
'138
1 A
2 B
3 C
4 G2a
5 G2b
6 G1
7 y7
8 Gn
Vc 16
y0 15
y1 14
y2 13
y3 12
y4 11
y5 10
y6 9
'04
1 1a
2 1y
3 2a
4 2y
5 3a
6 3y
7 Gn
Vc 14
6a 13
6y 12
5a 11
5y 10
4a 9
4y 8
IOE 19
WR 29
RD 31
D0 8
D1 10
D2 12
D3 14
D4 16
D5 18
D6 20
D7 22
GND 24
A7 26
A6 28
A5 30
A4 32
A3 34
A2 36
A1 38
A0 40
CLK 4
Encoder
D/A
+V
A4
A5
A6
A7
A2
A3
A4
A5
A6
A7

Appendix C

Joint SBC Commands

```
Outgoing message format
          |>|x|Command Data|.|

     > indicates command to follow
     . indicates end of message

Inbound message format
          |>|return data|.|
     -or-
          OK

     > indicates response to follow
     . indicates end of message

(x is unit number)
```

Outgoing	**Reponse**	**Comment**
>xLy.	>Lnnnn.	Request analog input on channel *y*. Value *nnnn* is returned.
>xH1.	OK	High voltage enable.
>xH0.	OK	High voltage disable.
>xVyyy.	OK	High voltage pattern *yyy*.
>xPAxxyy.	OK	Initialize PIO port A, mode *xx*, control word *yy*
>xPBxxyy.	OK	Initialize PIO port B, mode *xx*, control word *yy*
>xDOAyyy.	OK	output value *yyy* on PIO port A
>xDOByyy.	OK	output value *yyy* on PIO port B
>xDIA.	>DIAyyy.	return value *yyy* from PIO port A
>xDIB.	>DIByyy.	return value *yyy* from PIO port B
>xGPPyyyy.	OK >GPPyyyy.	Change positional proportional gain setting to *yyyy*. If *yyyy* = __-1, report current gain.
>xGPIyyyy.	OK >GPIyyyy.	Change positional integral gain setting to *yyyy*. If *yyyy* = __-1, report current gain.

>xGPD*yyyy*.	OK >GPD*yyyy*.	Change positional derivative gain setting to *yyyy*. If *yyyy* = __-1, report current gain.
>xGVP*yyyy*.	OK >GVP*yyyy*.	Change velocity proportional gain setting to *yyyy*. If *yyyy* = __-1, report current gain.
>xGVI*yyyy*.	OK >GVI*yyyy*.	Change velocity integral gain setting to *yYyy*. If *yYyy* = __-1, report current gain.
>xGVD*yyyy*.	OK >GVD*yyyy*.	Change velocity derivative gain setting to *yyyy*. If *yyyy* = __-1, report current gain.
>xEL*yyyyyyy*zzzzzzzppp.	OK	Load encoder position *yyyyyyy*, velocity *zzzzzzz*, pio mode *ppp* and autoincrement point list. Move will our on X command.
>xES*yyyyyyy*.	>ES*xxxxxxx*zzzzzzz. >ES*wwwwww*.	If *yyyyyyy* =______-1, report current position *xxxxxxx* and velocity *zzzzzzz*. If *yyyyyyy* = ______-2, report control law actuation *wwwwww*.
>xER*xxxxyyyyyyy*zzzzzzzppp.	OK	Modify data point at *xxxx* with new encoder position *yyyyyyy*, velocity *zzzzzzz*, pio mode *ppp*.
>X.		Execute loaded moves.
>xS.	OK	Emergency shutdown.
>xI*yyy*.	OK	Change timing interval. if *yyy* = 0-1, report timing interval.
>xR.	>R*yyy*.	Report software revision level.
>xMV*yyyyy*.	OK	Max velocity before auto shutdown.
>xML*yyyyy*.	OK	Max extension limit before shutdown.
>xMS*y*.	OK	Gain scaling.

>xESxxxx.	>ESyyyyyyyzzzzzzzppp.	Show position *(yyyyyyy)*, velocity *(zzzzzzz)* and pio mode *(ppp)* for point xxxx.
>xERxxxxyyyyyyyzzzzzzzppp.	OK	Replace position *xxxx* with position *yyyyyyy*, velocity *zzzzzzz* and pio mode *ppp*.
>xELyyyyyyyzzzzzzzppp.	OK	Load position *yyyyyyy*, velocity *zzzzzzz*, pio mode *ppp* and auto-increment point list.
>xEC.	OK	Clear point counter.

Appendix D

Connector Pinout Table

Location	pin	color	function	Connects to:	pin	color	function
Moving carriage connector	A	orange	cable 0 servo +current	Servo valve	B, D	orange	+current
	B	blue	cable 0 servo -current		A, C	blue	-current
	C	gray	cable 0 encoder A channel	Encoder			
	D	purple	cable 0 encoder B channel	(1200 pulses/rev)			
	H	yellow	cable 0 encoder Z channel				
	F	green	N/C				
	J	red	cable 0 encoder +power				
	G	black	cable 0 encoder -power				
	E	white	N/C				
	Q	brown	N/C				
	Z	orange	cable 1 servo +current	Servo valve	B, D	orange	+current
	Y	blue	cable 1 servo -current		A, C	blue	-current
	X	gray	cable 1 encoder A channel	Encoder			
	W	purple	cable 1 encoder B channel	(88000 pulses/rev)			
	R	yellow	cable 1 encoder Z channel				
	S	green	cable 1 encoder case gnd				
	T	red	cable 1 encoder +power				
	U	black	cable 1 encoder -power				
	V	white	N/C				
	K	brown	N/C				
Cable 0 board end	L	orange	servo +current				
	M	blue	servo -current				
	P	gray	encoder A channel				
	N	purple	encoder B channel				
	D	yellow	encoder Z channel				
	E	green	N/C				
	F	red	encoder +power				
	G	black	encoder -power				
	H	white	N/C				
	J	brown	N/C				
Cable 1 board end	L	orange	servo +current				
	M	blue	servo -current				
	P	gray	encoder A channel				
	N	purple	encoder B channel				
	D	yellow	encoder Z channel				
	E	green	N/C				
	F	red	encoder +power				
	G	black	encoder -power				
	H	white	N/C				
	J	brown	N/C				
Cable 2 board end	L	orange	servo +current	Servo valve	B, D	red	+current
	M	blue	servo -current		A, C	black	-current
	P	gray	encoder A channel	Encoder			

	N	purple	encoder B channel	(88000 pulses/rev)
	D	yellow	encoder Z channel	
	E	green	N/C	
	F	red	encoder +power	
	G	black	encoder -power	
	H	white	N/C	
	J	brown	N/C	

Pendant connector	A	CT014
	B	CT114
	C	CT214
	D	CT314
	E	CT +pwr 1
	F	CT414
	G	CT514
	H	CT614
	J	CT714
	K	CT +pwr 2
	L	GND
	M	K
	N	CT relay power
	P	spare
	R	spare
	S	spare
	T	+RS485 Chan. 0
	U	-RS485 Chan. 0
	V	+RS485 Chan. 1 (spare)
	W	-RS485 Chan. 1 (spare)
	X	+pwr
	Z	GND (shield)
	a	piob 1 (note: no piob 0!)
	b	piob 2
	c	piob 3
	d	piob 4
	e	piob 5
	f	piob 6
	g	piob 7
	h	high voltage out 1
	j	high voltage out 2
	k	high voltage out 3
	m	high voltage out 4
	n	high voltage out 5
	p	high voltage out 6
	r	high voltage out 7
	s	high voltage out 8

End effector connector	A	+ 485	end effector	A	+ 485
(board end)	B	- 485		B	- 485
	C	spare		C	spare

	D	intr		D	intr
	E	- pwr		E	- pwr
	F	+ pwr		F	+ pwr
	G	spare		G	spare
	H	spare		H	spare
	J	spare		J	spare
	K	spare		K	spare

Connector A	A	ground
(utility box end)	B	spare
	C	front right foot up
	D	front right foot down
	E	front left foot up
	F	front left foot down
	G	rear right foot up
	H	rear right foot down
	J	rear left foot up
	K	rear left foot down
	L	paint pump +
	M	high pressure +
	N	spare
	P	spare

Connector A	A	ground		
(computer box end)	B	spare		
	C	front right foot up	relay #5 NC terminal	614
	D	front right foot down	relay #5 NO terminal	
	E	front left foot up	relay #2 NC terminal	314
	F	front left foot down	relay #2 NO terminal	
	G	rear right foot up	relay #3 NC terminal	414
	H	rear right foot down	relay #3 NO terminal	
	J	rear left foot up	relay #4 NC terminal	514
	K	rear left foot down	relay #4 NO terminal	
	L	paint pump +	relay #5 NO terminal	
	M	high pressure +	relay #4 NO terminal	
	N	spare		
	P	spare		

Connector B	A	low pressure transducer +
(utility box end)	B	low pressure transducer -
	C	high pressure transducer +
	D	high pressure transducer -
	E	rs-485 +
	F	rs-485 -
	G	spare
	H	shield

Connector C	A	high pressure transducer +
(utility box end)	B	high pressure transducer -

	C	high pressure solenoid +	
	D	high pressure solenoid -	
	E		
	F		
	G		
	H	shield	
Connector D	A	front right foot in	connector A #c
(utility box end)	B	front right foot out	f.r. limit switch
	C	front left foot in	connector A #E
	D	front left foot out	f.l. limit switch
	E	rear right foot in	connector A #g
	F	rear right foot out	r.r. limit switch
	G	rear left foot in	connector A #J
	H	rear left foot out	r.l. limit switch
Connector B	A	low pressure transducer +	
(computer box end)	B	low pressure transducer -	
	C	high pressure transducer +	
	D	high pressure transducer -	
	E	rs-485 +	
	F	rs-485 -	
	G	spare	
	H	shield	
Connector E	A	e/e retract power +	
(computer box end)	B	e/e retract power -	
	C	e/e brake power +	
	D	e/e brake power -	
	E	hyd extend valve power +	
	F	hyd extend valve power -	
	G	e/e gun power +	
	H	e/e gun power -	
	J	bead gun +	
	K	bead gun -	
	L	spare	
	M	spare	
	N	shield	
	P	no connection	
Connector F	A	refrigeration power +	
(computer box end)	B	bead pressure power +	
	C	strobe power +	
	D	spare	
	E	spare	
	F	spare	
	G	spare	
	H	ground	

Appendix E

Source Code Listing for Transverse Joint SBC

```
#use rtk.lib

/*
This program would run on the Little Giant, the Tiny Giant and the CPLC.
If port 0 is also used as the Dynamic C programming port, you have to
load the serial interrupt routine during run time by doing the following:

  (1) comment out:
#INT_VEC SER0_VEC Dz0_circ_int in z0232.lib
  (2) in the code, declare:
            extern void Dz0_circ_int();
  (3) load the routine with:
            reload_vec(14,Dz0_circ_int);

*/
/* #include <stdio.h> */
#define ON 1
#define OFF 0
#define FWD 1
#define REV 0
#define FALSE 0
#define TRUE 1

#define VERSION 4
#define SUBVERSION 01

#define CSAMPLE 900      /* clock periods: 512HZ */
#define CTIME 0.001953   /* clock time */

#define D2AOFFSET 2047
#define ACTSCALE 1

/* int task0(), task1(), task2(), backgnd();
int (*Ftask[])()={task0, task1, task2, backgnd}; */

int task1(), task2(), backgnd();
int (*Ftask[])() = {task1, task2, backgnd};

/*
#define NTASKS 4
#define TASK0 0
#define TASK1 1
#define TASK2 2 */

#define NTASKS 3
#define TASK1 0
#define TASK2 1

#define TASKSTORE_SIZE 500

void (*TaskDispatchTable[30])();

typedef union bytemode
 {
  int word;
  struct ByteStruct
    {
            char lsb;
            char msb;
    } byte;
 } BYTEMODE;

struct PointListPoint
{
  long ListPosition;
  long ListVelocity;
  int TimeSlices;
  char PIOmode;
};
```

```
struct PIOstruct
 {
  char PIOAmode;
  char PIOBmode;
 };

struct PointListPoint PointList[1001];
shared struct PIOstruct PIOstatus;

struct PositionData
 {
  int time[3];
  long position;   /* variables for data logging */
  long velocity;
  int point;
 };

struct PositionData data[410];

float VeloCorrFact[] =
{0.960719, 0.958142, 0.955486, 0.952749, 0.949934,
0.947038, 0.944064, 0.941011, 0.937879, 0.934669,
0.931381, 0.928015, 0.924572, 0.921051, 0.917453,
0.913779, 0.910029, 0.906202, 0.9023  , 0.898322,
0.89427 , 0.890142, 0.885941, 0.881665, 0.877316,
0.872893, 0.868397, 0.863829, 0.859189, 0.854477,
0.849694, 0.84484 , 0.839915, 0.83492 , 0.829855,
0.824721, 0.819518, 0.814247, 0.808907, 0.8035  ,
0.798026, 0.792486, 0.786879, 0.781206, 0.775468,
0.769665, 0.763798, 0.757868, 0.751874, 0.745817,
0.739698, 0.733517, 0.727275, 0.720972, 0.714609,
0.708186, 0.701704, 0.695163, 0.688564, 0.681908,
0.675195, 0.668426, 0.6616  , 0.65472 , 0.647784,
0.640795, 0.633752, 0.626656, 0.619508, 0.612308,
0.605057, 0.597755, 0.590404, 0.583003, 0.575553,
0.568056, 0.560511, 0.552919, 0.545281, 0.537597,
0.529869, 0.522096, 0.51428 , 0.50642 , 0.498519,
0.490575, 0.482591, 0.474566, 0.466502, 0.458399,
0.450258, 0.442079, 0.433863, 0.42561 , 0.417323,
0.409   , 0.400643, 0.392253, 0.38383 , 0.375375,
0.366889, 0.358372, 0.349825, 0.341248, 0.332644,
0.324011, 0.315352, 0.306666, 0.297954, 0.289218,
0.280457, 0.271673, 0.262867, 0.254038, 0.245188,
0.236318, 0.227428, 0.218519, 0.209591, 0.200646};

int datapointer, takedata;

int PointNumber, ExePointNumber;      /* place in point list */
shared long gActPosition, gActVelocity;  /* actual position and velocity */
shared long PseudoVelo;              /* IPC variable b/w pos and velo loop */
shared BYTEMODE Actuation;           /* system actuation */
float kpp, kpi, kpd;       /* system position gains 1 unit, I in .01 units */
int kvp, kvi, kvd;         /* system velocity gains 0.0001 units */
float kff;                 /* system feed forward gain 0.01 units */
int BeginMove;             /* change to TRUE to begin motion */
int NewMove;
int UseVelocityControl;     /* bypasses position controller */
int Acceleration;

BYTEMODE ServoNull;
shared long MaxVelo, MaxLimits, AbsLimits;
shared int ActScale;
int Control, Shutdown, Reset1, Reset2;
int UnitNumber, DumpSerial;
char InString[255], OutString[255];
char PowerFail[] = "!Power fail\0";
char SoftReset[] = "!Soft reset\0";
char tbuf[384], rbuf[384];
```

```
int AnalogInput (char *, char *);
int HighVoltage (char *, char *);
int ChangeHighVoltage (char *, char *);
int InitPIO (char *, char *);
int OutInPIO (char *, char *);
int SetGetGain (char *, char*);
int ControlLaw (char *, char *);
int DtoAOut (char *, char *);
int PosLoad (char *, char *);
int ExecuteMove (char *, char *);
int Diagnostic (char *, char *);
int ShutDown (char *, char *);
int RevisionLevel (char *, char *);
int MaxLimit (char *, char *);
void FatalErrorHandler (unsigned, unsigned);
float p2sin(float);
float p2cos(float);
void NotUsed(void);

/* extern void Dz0_circ_int(); */

/* 0x10 stores network node number, 0x12 stores null.lsb, 0x13 stores
  null.msb */

root main ()
{
 int index;

 if (wderror())
   {
     Shutdown = TRUE;
     Control = OFF;
     outport (0x81, ServoNull.byte.lsb);
     outport (0x82, ServoNull.byte.msb);
     op_kill_z1();
     op_init_z1 (19200/1200, InString, UnitNumber);
     while (1)
             {
              hitwd();
              if (check_opto_command() == 1)
                replyOpto22 (SoftReset, strlen (SoftReset), 0);
             }
   }

 _GLOBAL_INIT();

 ERROR_EXIT = FatalErrorHandler;
 BeginMove = FALSE;
 UseVelocityControl = OFF;
 Control = DumpSerial = OFF;
 Shutdown = takedata = OFF;
 NewMove = FALSE;
 Reset1 = Reset2 = ON;
 ExePointNumber = PointNumber = 0;
 datapointer = 0;
 gActVelocity = gActPosition = 0L;
 kpp = kpi = kpd = kff = 0;
 kvp = kvi = kvd = 0;
 MaxLimits = AbsLimits = 88000L;
 Acceleration = 5000;
 MaxVelo = 0L;
 ActScale = ACTSCALE;
 Actuation.word = 0;    /* zero! */
 PIOstatus.PIOAmode = 0x1;
 PIOstatus.PIOBmode = (char) 0;
 UnitNumber = ee_rd(0x10);
 ServoNull.byte.lsb = ee_rd(0x12);
 ServoNull.byte.msb = ee_rd(0x13);
```

```
  inport (0x82);                    /* clear the encoder */

  outport (0x81, ServoNull.byte.lsb);  /* zero the d-to-a board */
  outport (0x82, ServoNull.byte.msb);
  outport (PIOCA, 0xff);             /* pioa command */
  outport (PIOCA, 0x00);             /* set all bits for output */
  outport (0x41, (char)0x7);         /* disable interrupts */
  outport (PIODA, PIOstatus.PIOAmode);  /* pioa data */

  outport (PIOCB, 0xcf);             /* piob command */
  outport (PIOCB, 0x00);             /* set all bits for input */
  outport (PIOCB, PIOB_VEC);
  outport (PIOCB, 0x17);
  outport (PIOCB, 0xfe);
  outport (0x43, 0x7);               /* disable interrupts */
  /* outport (PIODB, PIOstatus.PIOBmode); */ /* piob data */
  outport (PIOCB, 0x7);

/*
 reload_vec (14, Dz0_circ_int);
 Dinit_z0(rbuf, tbuf, 384, 384, 4, 9600/1200, 0, 0);
*/

  op_init_z1 (19200/1200, InString, UnitNumber);

  for (index = 0; index < 26; index++)
    (TaskDispatchTable[index]) = NotUsed;

  TaskDispatchTable['L'-'A'] = AnalogInput;
  TaskDispatchTable['H'-'A'] = HighVoltage;
  TaskDispatchTable['V'-'A'] = ChangeHighVoltage;
  TaskDispatchTable['P'-'A'] = InitPIO;
  TaskDispatchTable['D'-'A'] = OutInPIO;
  TaskDispatchTable['G'-'A'] = SetGetGain;
  TaskDispatchTable['C'-'A'] = ControlLaw;
  TaskDispatchTable['A'-'A'] = DtoAOut;
  TaskDispatchTable['E'-'A'] = PosLoad;
  TaskDispatchTable['X'-'A'] = ExecuteMove;
  TaskDispatchTable['I'-'A'] = Diagnostic;
  TaskDispatchTable['M'-'A'] = MaxLimit;
  TaskDispatchTable['S'-'A'] = ShutDown;
  TaskDispatchTable['R'-'A'] = RevisionLevel;

  DI ();
  init_kernel ();
  run_every (TASK2, 100);
  run_every (TASK1, 8);   /* was 23  44.92 */ /* was 45 -or- 87.9 ms */
  /* run_every (TASK0, 5); */  /* 11.72 */ /* was 12 -or- 23.4 ms */
  init_timer0 (900);      /* 512 hz clock, 0.001953 seconds */
  EI ();
  backgnd ();
}

void NotUsed(void)
{
 return;
}

nodebug backgnd ()
{
 while (1)
  {
   if (Shutdown)
    {
        op_kill_z1();
        op_init_z1 (19200/1200, InString, UnitNumber);
        outport (0x81, ServoNull.byte.lsb);
        outport (0x82, ServoNull.byte.msb);
```

```
            while (1)
             {
              if (check_opto_command() == 1)
               replyOpto22 (PowerFail, strlen (PowerFail), 0);
              hitwd();
             }
      }

     if (check_opto_command() == 1)
      {
            strcpy (OutString, "!OK\0");

            InString[InString[1]] = '\0';

            if (isalpha (InString[4]))
             {
              (*TaskDispatchTable[toupper(InString[4]) - 'A'])
               (InString+2, OutString);
             }
            /*
             if (DumpSerial)
             {
             Dwrite_z0(InString+1, InString[0] - 2);
             Dwrite_z0(OutString, strlen (OutString));
             }
       */

            replyOpto22 (OutString, strlen (OutString), 0);
      }
   }
 while (1);
}


MaxLimit (char *In, char *Out)
{
 char chvalue[8];
 long value;

 switch (toupper(*(In+3)))
  {
   case 'V':  /* >1MV98765. */ /* velocity limits */
    strncpy (chvalue, (In+4), 5);
    chvalue[5] = '\0';
    MaxVelo = atol (chvalue);
    sprintf (Out, "OK");
    break;
   case 'L':  /* >1ML12345. */ /* Extension limits */
    strncpy (chvalue, (In+4), 5);
    chvalue[5] = '\0';
    MaxLimits = atol (chvalue);
    AbsLimits = MaxLimits + 200L;
    sprintf (Out, "OK");
    break;
   case 'S':  /* >1MS2. */  /* Actuator scaling */
    strncpy (chvalue, (In+4), 1);
    chvalue[1] = '\0';
    ActScale = atoi (chvalue);
    sprintf (Out, "OK");
    break;
   case 'N':  /* >1MN2047. */ /* set null point to 2047 */
    strncpy (chvalue, (In+4), 4);
    chvalue[4] = '\0';
    ServoNull.word = atoi(chvalue);
    if (ServoNull.word == -1)
          {
           ServoNull.byte.lsb = ee_rd (0x12);
           ServoNull.byte.msb = ee_rd (0x13);
```

```
            sprintf (Out, ">MN%4d.\0", ServoNull.word);
           }
      else
           {
            ee_wr (0x12, ServoNull.byte.lsb);
            ee_wr (0x13, ServoNull.byte.msb);
            sprintf (Out, "Servo null: %x %x", ee_rd (0x12), ee_rd(0x13));
            outport (0x81, ServoNull.byte.lsb);
            outport (0x82, ServoNull.byte.msb);
           }
      break;
    case 'U':   /* >1MU2. */  /* set unit number to 2 */
      strncpy (chvalue, (In+4), 1);
      chvalue[1] = '\0';
      ee_wr (0x10, atoi (chvalue));
      sprintf (Out, ">1MU%1d.\0", ee_rd (0x10));
      break;
  }
}

nodebug PosLoad (char *In, char *Out)
{
 char chvalue[8];
 char **pchvalue;
 long value;
 int value1;

 if (*(In+3) == 'S')
  {
   strncpy (chvalue, (In+4), 4);
   chvalue[4] = '\0';
   value1 = atoi (chvalue);

   if (value1 == -1)  /* >1ES__-1. */
         {
          sprintf (Out, ">ES%5ld%5ld.", gActPosition, gActVelocity);
          return;
         }
   else
         if (value1 == -2)  /* >1ES__-2. */
          {
           sprintf (Out, ">ES%5ld%5d.", gActPosition, Actuation.word);
           return;
          }
         else
          if ((value1 >= 0) && (value1 < PointNumber))
           {
            sprintf (Out, ">ES%5ld%5ld%3d.",
                          PointList[value1].ListPosition,
                          PointList[value1].ListVelocity,
                          PointList[value1].PIOmode);
            return;
           }
   sprintf (Out, "!ES ERROR");
   return;
  }

 if (*(In+3) == 'R')
  {                                    /* replace pt 0000 */
   /* >1ER0000123456987654000. pos=123456,velo=987654,pio=000 */
   strncpy (chvalue, (In+4), 4);
   chvalue[4] = '\0';
   value1 = atoi (chvalue);

   strncpy (chvalue, (In+8), 6);
   chvalue[6] = '\0';
   value = atol (chvalue);

   if ((value > MaxLimits))
```

```
        PointList[value1].ListPosition = MaxLimits;
  else
        PointList[value1].ListPosition = value;

  strncpy (chvalue, (In+14), 6);
  chvalue[6] = '\0';
  value = atol(chvalue);

  if ((value > MaxVelo) && (MaxVelo != 0L))
        PointList[value1].ListVelocity = MaxVelo;
  else
        if (value == 0)
         PointList[value1].ListVelocity = 200;
        else
         PointList[value1].ListVelocity = value;

  strncpy (chvalue, (In+20), 3);
  chvalue[3] = 0;
  PointList[value1].PIOmode = atoi (chvalue);
  sprintf (Out, "OK");
  return;
 }

if (*(In+3) == 'L')
 {        /* >1EL12345987600. pos=12345,velo=9876,pio=00, in hex */
  strncpy (chvalue, (In+4), 5);
  chvalue[5]= '\0';
  value = atol (chvalue);

  if ((value > MaxLimits))
        PointList[PointNumber].ListPosition = MaxLimits;
  else
        PointList[PointNumber].ListPosition = value;

  strncpy (chvalue, (In+9), 4);
  chvalue[4] = '\0';
  value = atol(chvalue);

  if ((value == 0) && (UseVelocityControl == OFF))
        PointList[PointNumber].ListVelocity = 200;
  else
        PointList[PointNumber].ListVelocity = value;

  strncpy (chvalue, (In+13), 2);
  chvalue[2] = 0;
  PointList[PointNumber].PIOmode = (int)strtol (chvalue, pchvalue, 16);

  if (PointList[PointNumber].ListVelocity != 0)
        {
         if (PointNumber == 0)
          {
           PointList[PointNumber].TimeSlices =
                 (PointList[PointNumber].ListPosition - gActPosition) * 64.0
                 / PointList[PointNumber].ListVelocity;
          }
         else
          {
           PointList[PointNumber].TimeSlices =
                 (PointList[PointNumber].ListPosition-
                  PointList[PointNumber-1].ListPosition) * 64.0
                 / PointList[PointNumber].ListVelocity;
          }
        }
  else
        {
         PointList[PointNumber].TimeSlices = 0;
        }

  PointNumber++;
```

```
    sprintf (Out, "OK");
    return;
   }

  if (*(In+3) == 'C')
   {
    PointNumber = 0;
    ExePointNumber = 0;
    datapointer = 0;
    takedata = OFF;
    sprintf (Out, "OK");
    return;
   }

  if (*(In+3) == 'V')                    /* >1EV1. */
   {
    sprintf (Out, "OK");
    if (*(In+4) == '1')
           {
            UseVelocityControl = ON;
            /* outport (PIOCB, 0x87); */ /* enable interrupt driven */
           }
    else
           {
            UseVelocityControl = OFF;
            Reset1 = TRUE;
            /* outport (PIOCB, 0x7);  */ /* disable interrupt driven */
           }
    return;
   }
}

ExecuteMove (char *In, char *Out)
{
 datapointer = 0;
 takedata = ON;

 /*
   PIOstatus.PIOAmode =
   (PointList[ExePointNumber].PIOmode & 0xfe);  *//* lower status flag */
 /*  outport (PIODA, PIOstatus.PIOAmode);  */

/*
 if (PointList[0].ListVelocity != 0)
   PointList[0].TimeSlices =
    ((long)((float)(PointList[0].ListPosition - gActPos) /
            ((float)PointList[0].ListVelocity * 0.044919)));
NOTE: This is what i wanted, but a compiler error forced me into the below.
*/

 if (PointList[0].ListVelocity != 0)
   {
    PointList[0].TimeSlices =
           (PointList[0].ListPosition - gActPosition) * 64.0
           / PointList[0].ListVelocity;
   }

 ExePointNumber = 0;
 BeginMove = TRUE;
 NewMove = TRUE;
}

/* #INT_VEC PIOB_VEC intrExecuteMove */

/* interrupt reti int intrExecuteMove () */
/* { */
/*   takedata = ON; */
/*   datapointer = 0; */
/*  PIOstatus.PIOAmode =  */
/*    (PointList[ExePointNumber].PIOmode & 0xfe);  */
/*  outport (PIODA, PIOstatus.PIOAmode);  */

/*  ExePointNumber = 0; */
/*  BeginMove = TRUE; */
/*  UseVelocityControl = OFF; */
/* } */

 Diagnostic (char *In, char *Out)
 {
  static int indexer;

 #GLOBAL_INIT
  {
   indexer = 0;
  }

  switch (*(In+3))
   {
    case '0':
              indexer = 0;
              if (BeginMove == FALSE)
                sprintf (Out, ">%4d.\0", datapointer);
              else
                sprintf (Out, "  -1\0");
              break;
    case '1':
              if (BeginMove == FALSE)
                {
                 sprintf (Out, ">%u,%d,%ld,%ld.\0",
                          data[indexer].time[0], data[indexer].point,
                          data[indexer].position, data[indexer].velocity);
                 indexer++;
                }
              break;
    case '2':
              if (DumpSerial == TRUE)
                DumpSerial = FALSE;
              else
                DumpSerial = TRUE;
              break;
    case '3':
              sprintf (Out, ">%d\0", PointNumber);
              break;
   }
 }

ShutDown (char *In, char *Out)
{
 BYTEMODE index;

 DI();
 inport (0x82);             /* clear the encoder */
 outport (0x81, ServoNull.byte.lsb);       /* zero the d-to-a board */
 outport (0x82, ServoNull.byte.msb);
 outport (0x41, (char)0xf);  /* pioa command */
 outport (0x41, (char)0x0);  /* set all bits for output */
 outport (0x41, (char)0x7);  /* disable interrupts */
 outport (0x40, (char)0x0);  /* pioa data */
 outport (0x43, (char)0xf);  /* piob command */
 outport (0x43, (char)0x0);  /* set all bits for output */;
 outport (0x43, (char)0x7);  /* disable interrupts */
 outport (0x42, (char)0x0);  /* piob data */
 Shutdown = ON;
 UseVelocityControl = OFF;
 sprintf (Out, "OK");
}
```

```
RevisionLevel (char *In, char *Out)
{
 BYTEMODE index;

 Control = OFF;
 Shutdown = OFF;
 BeginMove = FALSE;
 NewMove = FALSE;
 UseVelocityControl = OFF;
 Reset1 = Reset2 = ON;
 gActVelocity = 0L;
 gActPosition = 0L;
 kpp = kpi = kpd = kff = 0;
 kvp = kvi = kvd = 0;
 PointNumber = ExePointNumber = 0;
 Actuation.word = 0;
 outport (0x81, ServoNull.byte.lsb);
 outport (0x82, ServoNull.byte.msb);
 inport (0x82);
 sprintf (Out, ">unit:%d Rev beta %d.%d.", UnitNumber, VERSION, SUBVERSION);
}

AnalogInput (char *In, char *Out)  /* >1L0. channel 0 */
{
 sprintf (Out, ">L%4d.", ad_rd8(atoi(In+3)));
}

HighVoltage (char *In, char *Out)   /* >1H1. on, >1H0. off */
{
 if (*(In+3) == '1')
   {
    hv_enb();
    sprintf (Out, "OK");
   }
 else
   {
    hv_dis();
    sprintf (Out, "OK");
   }
}

ChangeHighVoltage (char *In, char *Out)  /* >1V123.  port pattern 123 */
{
 char chvalue[4];

 strncpy (chvalue, (In+3), 3);
 chvalue[3] = 0;

 hv_wr(atoi(chvalue));
 sprintf (Out, "OK");
}

InitPIO (char *In, char *Out)  /* >1PA0103. mode 01, control 03, on PIO A */
{
 char InChar[3];
 char mode, control;

 strncpy (InChar, (In+4), 2);
 InChar[2] = 0;
 mode = atoi (InChar);

 strncpy (InChar, (In+6), 2);
 control = atoi (InChar);

 switch (*(In+3))
   {
    case 'A':
           outport (PIOCA, ((mode << 6) & 0xf0) | 0x0f);
           outport (PIOCA, (char)control);
```

```
            sprintf (Out, "OK");
            break;
    case 'B':
            outport (PIOCB, ((mode << 6) & 0xf0) | 0x0f);
            outport (PIOCB, (char)control);
            sprintf (Out, "OK");
            break;
   }
}

OutInPIO (char *In, char *Out)  /* >1DOB000. Output on PIO B value 000,
                                         >1DIA.  Input on PIO A returns 145 */
{
 char chvalue[4];
 int value;

 chvalue[3] = 0;
 switch (*(In+3))
  {
    case 'O':
            if (*(In+4) == 'A')
              {
                strncpy (chvalue, (In+5), 3);
                value = atoi(chvalue);
                PIOstatus.PIOAmode = (char)value | (PIOstatus.PIOAmode & 0x3);
                outport (PIODA, PIOstatus.PIOAmode);
                sprintf (Out, "OK");
              }
            else
              if (*(In+4) == 'B')
                {
                  strncpy (chvalue, (In+5), 3);
                  value = atoi (chvalue);
                  PIOstatus.PIOBmode = (char)value;
                  outport (PIODB, (char)value);
                  sprintf (Out, "OK");
                }
            break;
    case 'I':
            if (*(In+4) == 'A')
              {
                value = inport (PIODA);
                sprintf (Out, ">DIA%3d.", value);
              }
            else
              if (*(In+4) == 'B')
                {
                  value = inport (PIODB);
                  sprintf (Out, ">DIB%3d.", value);
                }
              break;
   }
}

SetGetGain (char *In, char *out)  /* >1GPP1234., Pos. Proportional to 1234
                                          " -1" to report */
{
 int value;
 char chvalue[5];

 strncpy (chvalue, (In+5), 4);
 chvalue[4] = '\0';

 value = atoi (chvalue);

 switch (*(In+3))
  {
    case 'V':
            switch (*(In+4))
```

```
                {
                 case 'F':
                  if (value == -1)
                         {
                          sprintf (out, ">GVF%4d.", (int)kff*100);
                          return;
                         }
                  else
                         {
                          Reset1 = Reset2 = ON;
                          kff = (float)value/100.0;
                          sprintf (out, "OK");
                         }
                  break;
                 case 'P':
                  if (value == -1)
                         {
                          sprintf (out, ">GVP%4d.", kvp);
                          return;
                         }
                  else
                         {
                          Reset1 = Reset2 = ON;
                          kvp = value;
                          sprintf (out, "OK");
                         }
                  break;
                 case 'I':
                  if (value == -1)
                         {
                          sprintf (out, ">GVI%4d.", kvi);
                          return;
                         }
                  else
                         {
                          Reset1 = Reset2 = ON;
                          kvi = value;
                          sprintf (out, "OK");
                         }
                 break;
                case 'D':
                 if (value == -1)
                  {
                         sprintf (out, ">GVD%4d.", kvd);
                         return;
                  }
                 else
                  {
                         Reset1 = Reset2 = ON;
                         kvd = value;
                         sprintf (out, "OK");
                  }
                 break;
                }
               break;
case 'P':
          switch (*(In+4))
           {
            case 'P':
             if (value == -1)
                    {
                     sprintf (out, ">GPP%4d.", (int)kpp);
                     return;
                    }
             else
                    {
                     Reset1 = Reset2 = ON;
                     kpp = (float)value;
                     sprintf (out, "OK");
                    }
               break;
              case 'I':
               if (value == -1)
                    {
                     sprintf (out, ">GPI%4d.", (int)kpi);
                     return;
                    }
               else
                    {
                     Reset1 = Reset2 = ON;
                     kpi = (float)value;  /* WAS 10000 */
                     sprintf (out, "OK");
                    }
               break;
              case 'D':
               if (value == -1)
                    {
                     sprintf (out, ">GPD%4d.", (int)kpd);
                     return;
                    }
               else
                    {
                     Reset1 = Reset2 = ON;
                     kpd = (float)value;
                     sprintf (out, "OK");
                    }
               break;
             }
   }
}

ControlLaw (char *In, char *out)  /* >1C1. on, >1C0. off */
{
 if (*(In+3) == '0')
  {
   BeginMove = OFF;
   NewMove = FALSE;
   Control = OFF;
   takedata = OFF;
   UseVelocityControl = OFF;
   outport (0x81, ServoNull.byte.lsb);
   outport (0x82, ServoNull.byte.msb);
   sprintf (out, "OK");
  }
 else
  if (*(In+3) == '1')
   {
        Control = ON;
        Reset1 = Reset2 = ON;
        sprintf (out, "OK");
   }
}

DtoAOut (char *In, char *out)  /* >1A4321. 4321 on DtoA */
{
 char chvalue[5];
 BYTEMODE value;

 Control = OFF;

 strncpy (chvalue, (In+3), 4);
 chvalue[4] = '\0';

 value.word = atoi (chvalue);
 outport (0x81, value.byte.lsb);
 outport (0x82, value.byte.msb);
 sprintf (out, "OK");
}
```

```
/*=================================================================

Position loop!

This task generates the actuation using PID.

communicates with the velocity loop thru the shared variable PseudoVelo

=================================================================*/
nodebug task1()
{
 static long ActPos, ActVelocity;
 static float DeltaPErr0, DeltaPErr1, DeltaPErr2;
 static float ipActuation;
 static long DesVelo;
 static int TimePeriods;
 static float DesPos;
 static float DesPosIncrement;
 static int LastPoint;
 static long dResult, NewPos;
 static BYTEMODE RealActuation;
 static unsigned result, result0;
 static float dAbsPos[5];
 static long OldgActPosition;
 static int index, RollOver;
 static unsigned int lo0, lo1, hi0, hi1;

#GLOBAL_INIT
 {
  ActPos = DesPos = ActVelocity = 0L;
  DeltaPErr0 = DeltaPErr1 = DeltaPErr2 = 0;
  DesVelo = 0L;
  ipActuation = 0;
  TimePeriods = 0;
  DesPosIncrement = 0;
  LastPoint = FALSE;
  RollOver = 0;
  result = 0;
  gActPosition = 0;
  dAbsPos[0] = dAbsPos[1] = dAbsPos[2] = dAbsPos[3] = 0L;
  index = 0;
 }

 OldgActPosition = gActPosition;
/* result = ((inport (0x80) << 8) & 0xff00) | inport (0x81); */

 do
  {
   DI();
   lo0 = inport (0x81);
   hi0 = inport (0x80);  /* stabilize results */
   lo1 = inport (0x81);
   hi1 = inport (0x80);
   EI();
  }
 while ((lo0 != lo1) || (hi0 != hi1));
 result = ((hi1 << 8) & 0xff00) | lo1;

 dResult= (long)((long)result - (long)result0);

 if (dResult > 32000)
  RollOver--;
 else
  if (-32000 > dResult)
   RollOver++;

 result0 = result;
 gActPosition = (long)result + (long)(RollOver * (long)65536);
```

```
dAbsPos[1] = dAbsPos[0];
dAbsPos[0] = gActPosition - OldgActPosition;
gActVelocity = (long)((dAbsPos[0] + dAbsPos[1]) * 32.0 );

if (gActPosition > AbsLimits)
 {
  outport (0x81, ServoNull.byte.lsb);
  outport (0x82, ServoNull.byte.msb);
  Control = OFF;
 }

if (Control == OFF)
 {
  PseudoVelo = 0;
  ipActuation = 0;
  return;
 }

ActPos = gActPosition;  /* transfer to local variables */
ActVelocity = gActVelocity;

if (Reset1)
 {
  DeltaPErr2 = DeltaPErr1 = DeltaPErr0 = 0;
  ipActuation = 0;
  DesPos = ActPos;
  NewPos = ActPos;
  DesVelo = 0;
  DesPosIncrement = 0;
  TimePeriods = 0;
  BeginMove = NewMove = FALSE;
  UseVelocityControl = OFF;
  Reset1 = OFF;
 }

if (BeginMove == TRUE)
 {
  LastPoint = FALSE;
  if (NewMove == TRUE)  /* allows for interrupted move */
        {
         NewMove = FALSE;
         TimePeriods = 0;
         if (UseVelocityControl == ON)
           DesVelo = PointList[0].ListVelocity;
        }
  if (((TimePeriods--) <= 1) && (UseVelocityControl == OFF))
        {
         if (ExePointNumber >= PointNumber)
           {
            ExePointNumber = PointNumber;
            NewPos = PointList[ExePointNumber-1].ListPosition;
            DesVelo = 0;
            DesPosIncrement = 0;
            BeginMove = FALSE;
           }
         else
           {
            if (PointList[ExePointNumber].TimeSlices != 0)
                  {
        NewPos = PointList[ExePointNumber].ListPosition;
                   DesPos = ActPos;
                   DesVelo = PointList[ExePointNumber].ListVelocity;
                   TimePeriods = (int)PointList[ExePointNumber].TimeSlices;

                   if (TimePeriods < 0)
                     {
                      TimePeriods = -TimePeriods;
                      DesVelo = -DesVelo;
```

```
                              }
                             DesPos = ActPos;
                            }
                else
                            {
                             DesPosIncrement = 0;
                             DesPos = PointList[ExePointNumber].ListPosition;
                             DesVelo = 0;
                            }
                 }
                ExePointNumber++;
                if (ExePointNumber == PointNumber) LastPoint = TRUE;
               }
    if (TimePeriods > 0)
               {
                DesPos += (float)(NewPos - ActPos) / (TimePeriods);
               }
    if ((LastPoint == TRUE) && (TimePeriods < 5)) DesVelo = 0;
   }
  else
   {
    DesPosIncrement = 0;
    DesPos = NewPos;
   }

  DeltaPErr2 = DeltaPErr1;  /* generate time history - 2 steps back */
  DeltaPErr1 = DeltaPErr0;
  DeltaPErr0 = DesPos - ActPos;

  ipActuation +=
   (((float)kpp * (DeltaPErr0 - DeltaPErr1)) +
    ((float)kpi * (DeltaPErr0)) +
    ((float)kpd * (DeltaPErr0 - (DeltaPErr1+DeltaPErr1) + DeltaPErr2)) +
    (kff * (DesVelo - ActVelocity)));

  if (UseVelocityControl == ON)
   PseudoVelo = DesVelo;
  else
   {
    PseudoVelo = ipActuation;

    if (PseudoVelo > (long)65504)
           PseudoVelo = 65504;
    else
           if (PseudoVelo < -65504)
             PseudoVelo = -65504;

    RealActuation.word = (int)(PseudoVelo >> 5);

    Actuation.word = RealActuation.word;

    RealActuation.word += D2AOFFSET;
    DI();
    k_lock();
    outport (0x81, (char)(RealActuation.byte.lsb));
    outport (0x82, (char)(RealActuation.byte.msb));
    k_unlock();
    EI();
   }
}

/*==============================================================
This task takes sensor data.
==============================================================*/

nodebug task2()
{
 static int index;
```

```
#GLOBAL_INIT
 {
  index = 0;
 }

 if (Shutdown == TRUE) return;
 hitwd();

 if (takedata == ON)
  {
   if (datapointer == 0) index = 0;

   gettimer (data[datapointer].time);
   data[datapointer].position = gActPosition;
   data[datapointer].velocity = gActVelocity;
   data[datapointer].point = ExePointNumber;

   if (BeginMove == FALSE)
         {
          if (index > 5)
           takedata = OFF;
          else
           index++;
         }

   if (datapointer++ > 395) takedata = OFF;
  }

 if ((PIOstatus.PIOAmode & 0x2) == 0x0)
  PIOstatus.PIOAmode |= 0x2;
 else
  PIOstatus.PIOAmode &= 0xfd;

 outport (PIODA, PIOstatus.PIOAmode);
}

/*=================================================================

Velocity loop!

This task generates the velocity actuation and also takes the sensor
data from the encoder.

uses the shared variables PseudoVelo for input,
and gActPosition, gActVelocity for output.

=================================================================*/

nodebug task0()
{
 static long pVelo, dResult;
 static long DeltaVErr0, DeltaVErr1, DeltaVErr2;
 static BYTEMODE RealActuation;
 static long vActuation;
 static unsigned int result0;
 static int result;
 static float dAbsPos[5];
 static long OldgActPosition;
 static int index, RollOver;
 static unsigned int lo0, lo1, hi0, hi1;

#GLOBAL_INIT
 {
  RollOver = 0;
  result = result0 = 0;
  gActPosition = 0;
  dAbsPos[0] = dAbsPos[1] = dAbsPos[2] = dAbsPos[3] = 0L;
  DeltaVErr0 = DeltaVErr1 = DeltaVErr2 = 0L;
  index = 0;
```

```
    }

    OldgActPosition = gActPosition;
    /*  result = ((inport (0x80) << 8) & 0xff00) | inport (0x81); */

    do
     {
       DI();
       lo0 = inport (0x81);
       hi0 = inport (0x80);   /* stabilize results */
       lo1 = inport (0x81);
       hi1 = inport (0x80);
       EI();
     }
    while ((lo0 != lo1) || (hi0 != hi1));
    result = ((hi1 << 8) & 0xff00) | lo1;

    gActPosition = 5588.0 *  p2sin (16.1125 + (0.00409091 * (float)result));

    dAbsPos[1] = dAbsPos[0];
    dAbsPos[0] = gActPosition - OldgActPosition;
    gActVelocity = (long)((dAbsPos[0] + dAbsPos[1]) * 42.6667);

    pVelo = PseudoVelo;  /* transfer variables to local storage */

    if (Reset2)
     {
       DeltaVErr2 = DeltaVErr1 = DeltaVErr0 = 0L;
       vActuation = 0L;
       Reset2 = OFF;
     }

    if (gActPosition > AbsLimits)
     {
       outport (0x81, ServoNull.byte.lsb);
       outport (0x82, ServoNull.byte.msb);
       Control = OFF;
     }

    if (Control == OFF)
     {
       vActuation = 0;
       return;
     }

  /*  DeltaVErr2 = DeltaVErr1; */
  /*  DeltaVErr1 = DeltaVErr0; */
  /*  DeltaVErr0 = pVelo - gActVelocity; */

  /*  vActuation += (long) */
  /*    ((((long)kvp*(long)(DeltaVErr0-DeltaVErr1)) + */
  /*      ((long)kvi*(long)(DeltaVErr0)) + */
  /*      ((long)kvd*(long)(DeltaVErr0 - (DeltaVErr1 + DeltaVErr1) + */
  /*                                      DeltaVErr2)))); */

  /*  if (vActuation > (long)268304384) */
  /*    vActuation = 268304384; */
  /*  else */
  /*    if (vActuation < -268304384) */
  /*      vActuation = -268304384; */

  /*  RealActuation.word = ((int)(vActuation >> 17)); */

    if (pVelo > (long)2096128)
      pVelo = 2096128;
    else
      if (pVelo < -2096128)
        pVelo = -2096128;
  RealActuation.word = (int)(pVelo >> 10);

  Actuation.word = RealActuation.word;

  RealActuation.word += D2AOFFSET;
  DI();
  k_lock();
  outport (0x81, (char)(RealActuation.byte.lsb));
  outport (0x82, (char)(RealActuation.byte.msb));
  k_unlock();
  EI();
}

#JUMP_VEC NMI_VEC NMI_int

interrupt retn NMI_int()
{
 Shutdown = TRUE;
 Control = OFF;
 outport (0x81, ServoNull.byte.lsb);
 outport (0x82, ServoNull.byte.msb);
 while (1)
   {
    hitwd();
    if (!powerlo()) return;
   }
}

void FatalErrorHandler (unsigned code, unsigned address)
{
 outport (0x81, ServoNull.byte.lsb);
 outport (0x82, ServoNull.byte.msb);
 Shutdown = TRUE;
 Control = OFF;
 while (1);  /* stall until reset by watch dog */
}

float p2cos (float x)
{
 return (p2sin (90.0 - x));
}

/*============================================================
PROCEDURE: p2sin

PARAMETERS: float Y

RETURNS: float

METHOD: computes sin(Y) by:
     sin (y + dy) = (sin y)(cos dy) + ([(cos x)/57.2958])(dy)
     where Y = y + dy, y = int(Y), dy = frac(Y), and
     the parameters are found from a lookup table. result is good
     to about 5 places.

VARIABLES:
     sinx are the values of sin(y) where y varies between 0->90
     cosdx are the values of cos(dy) where dy varies between
             0->1 in 0.01 increments
     cosxd are the values of [(cos y)/57.2958] where y varies
             between 0->90
     ALL fractional values have been shifted by multiplying by
             65535 to obtain integers.
==============================================================*/

nodebug float p2sin (float y)

{
 static unsigned int sinx[] =
                {0x0000,0x0478,0x08EF,0x0D66,0x11DB,
                 0x1650,0x1AC2,0x1F33,0x23A1,0x280C,
                 0x2C74,0x30D9,0x3539,0x3996,0x3DEE,
                 0x4242,0x4690,0x4AD9,0x4F1B,0x5358,
                 0x578E,0x5BBE,0x5FE6,0x6407,0x681F,
                 0x6C30,0x7039,0x7438,0x782F,0x7C1C,
                 0x8000,0x83D9,0x87A8,0x8B6D,0x8F27,
                 0x92D5,0x9679,0x9A10,0x9D9B,0xA11B,
                 0xA48D,0xA7F3,0xAB4B,0xAE97,0xB1D4,
                 0xB504,0xB826,0xBB39,0xBE3E,0xC134,
                 0xC41B,0xC6F2,0xC9BA,0xCC73,0xCF1B,
                 0xD1B3,0xD43B,0xD6B2,0xD919,0xDB6E,
                 0xDDB3,0xDFE6,0xE208,0xE418,0xE616,
                 0xE803,0xE9DD,0xEBA5,0xED5B,0xEEFE,
                 0xF08F,0xF20D,0xF377,0xF4CF,0xF614,
                 0xF746,0xF864,0xF96F,0xFA67,0xFB4B,
                 0xFC1B,0xFCD8,0xFD81,0xFE17,0xFE98,
                 0xFF06,0xFF5F,0xFFA5,0xFFD7,0xFFF5,
                 0xFFFF};

static unsigned int cosdx[] =
                {0xFFFF,0xFFFF,0xFFFF,0xFFFF,0xFFFF,
                 0xFFFF,0xFFFF,0xFFFF,0xFFFF,0xFFFF,
                 0xFFFF,0xFFFF,0xFFFF,0xFFFF,0xFFFF,
                 0xFFFF,0xFFFF,0xFFFF,0xFFFF,0xFFFF,
                 0xFFFF,0xFFFF,0xFFFF,0xFFFE,0xFFFE,
                 0xFFFE,0xFFFE,0xFFFE,0xFFFE,0xFFFE,
                 0xFFFE,0xFFFE,0xFFFE,0xFFFE,0xFFFE,
                 0xFFFE,0xFFFE,0xFFFE,0xFFFE,0xFFFD,
                 0xFFFD,0xFFFD,0xFFFD,0xFFFD,0xFFFD,
                 0xFFFD,0xFFFD,0xFFFD,0xFFFD,0xFFFD,
                 0xFFFD,0xFFFC,0xFFFC,0xFFFC,0xFFFC,
                 0xFFFC,0xFFFC,0xFFFC,0xFFFC,0xFFFC,
                 0xFFFB,0xFFFB,0xFFFB,0xFFFB,0xFFFB,
                 0xFFFB,0xFFFB,0xFFFB,0xFFFA,0xFFFA,
                 0xFFFA,0xFFFA,0xFFFA,0xFFFA,0xFFFA,
                 0xFFF9,0xFFF9,0xFFF9,0xFFF9,0xFFF9,
                 0xFFF9,0xFFF8,0xFFF8,0xFFF8,0xFFF8,
                 0xFFF8,0xFFF8,0xFFF7,0xFFF7,0xFFF7,
                 0xFFF7,0xFFF7,0xFFF7,0xFFF6,0xFFF6,
                 0xFFF6,0xFFF6,0xFFF6,0xFFF5,0xFFF5,
                 0xFFF5};

static unsigned int cosxd[] =
                {0x478,0x478,0x477,0x476,0x475,0x473,0x472,
                 0x46F,0x46D,0x46A,0x466,0x463,0x45F,0x45A,
                 0x456,0x451,0x44B,0x446,0x440,0x439,0x433,
                 0x42C,0x425,0x41D,0x415,0x40D,0x404,0x3FB,
                 0x3F2,0x3E8,0x3DF,0x3D4,0x3CA,0x3BF,0x3B4,
                 0x3A9,0x39D,0x391,0x385,0x379,0x36C,0x35F,
                 0x352,0x345,0x337,0x329,0x31B,0x30C,0x2FD,
                 0x2EE,0x2DF,0x2D0,0x2C0,0x2B0,0x2A0,0x290,
                 0x280,0x26F,0x25E,0x24D,0x23C,0x22B,0x219,
                 0x207,0x1F5,0x1E3,0x1D1,0x1BF,0x1AC,0x19A,
                 0x187,0x174,0x161,0x14E,0x13B,0x128,0x115,
                 0x101,0x0EE,0x0DA,0x0C7,0x0B3,0x09F,0x08B,
                 0x078,0x064,0x050,0x03C,0x028,0x014,0x000};

static float fremainder, x;
static unsigned int whole;

x = y;
if (x < 0)
 {
  do
   {
        x = x + 360;
   }
  while (x < 0);
  }

 if (x <= 90.0)
  {
   whole = (int)x;
   fremainder = (x - whole);

   return ((float)((((unsigned long)sinx[whole]  *
                              (unsigned)cosdx[(int)(fremainder * 100.0)]) +
                             ((unsigned long)cosxd[whole] *
                              (unsigned)(fremainder * 65535)))
                            * 2.328377E-10));
  }
 else
  if (x <= 180)
   {
    x = 180.0 - x;
    whole = (int)x;
    fremainder = (x - whole);

    return ((float)((((unsigned long)sinx[whole]  *
                                   (unsigned long)cosdx[(int)(fremainder * 100.0)]) +
                                  ((unsigned long)cosxd[whole] *
                                   (unsigned long)(fremainder * 65535)))
                             * 2.328377E-10));
   }
 else
  if (x <= 270)
   {
    x = x - 180.0;
    whole = (int)x;
    fremainder = (x - whole);

    return ((float)((((unsigned long)sinx[whole]  *
                                   (unsigned long)cosdx[(int)(fremainder * 100.0)]) +
                                  ((unsigned long)cosxd[whole] *
                                   (unsigned long)(fremainder * 65535)))
                             * (-2.328377E-10)));
   }
 else
  if (x <= 360)
   {
    x = 360.0 - x ;
    whole = (int)x;
    fremainder = (x - whole);

    return ((float)((((unsigned long)sinx[whole]  *
                                   (unsigned long)cosdx[(int)(fremainder * 100.0)]) +
                                  ((unsigned long)cosxd[whole] *
                                   (unsigned long)(fremainder * 65535)))
                             * (-2.328377E-10)));
   }
 return (-2);
}
```

Appendix F

Source Code Listing for Rotation Joint SBC

```
#use rtk.lib

/*
This program would run on the Little Giant, the Tiny Giant and the CPLC.
If port 0 is also used as the Dynamic C programming port, you have to
load the serial interrupt routine during run time by doing the following:

  (1) comment out:
#INT_VEC SER0_VEC Dz0_circ_int in z0232.lib
  (2) in the code, declare:
          extern void Dz0_circ_int();
  (3) load the routine with:
          reload_vec(14,Dz0_circ_int);

*/

/*=====
For use on unit 3, rotation joint

Changes:
5/15/97 v5.01 Changed PIOmode to single char only.
7/15/97 v6.00 changed to burst serial reception. 8 at a time!
=====*/

#define SIMULATION 0

#define ON 1
#define OFF 0
#define FWD 1
#define REV 0
#define FALSE 0
#define TRUE 1

#define VERSION 6
#define SUBVERSION 00

#define CSAMPLE 900      /* clock periods: 512HZ */
#define CTIME 0.001953   /* clock time */

#define D2AOFFSET 2047
#define ACTSCALE 1

/* int task0(), task1(), task2(), backgnd();
int (*Ftask[])()={task0, task1, task2, backgnd}; */

int task1(), task2(), backgnd();
int (*Ftask[])() = {task1, task2, backgnd};

/*
#define NTASKS 4
#define TASK0 0
#define TASK1 1
#define TASK2 2 */

#define NTASKS 3
#define TASK1 0
#define TASK2 1

#define TASKSTORE_SIZE 500

void (*TaskDispatchTable[30])();

typedef union bytemode
 {
  int word;
  struct ByteStruct
   {
          char lsb;
          char msb;
```

```
     } byte;
   } BYTEMODE;

 struct PointListPoint
  {
   int toY, toX;
   int Velocity;
   int TimeSlices;
   char PIOmode;
  };

 struct PIOstruct
  {
   char PIOAmode;
   char PIOBmode;
  };

 struct PointListPoint PointList[1001];
 shared struct PIOstruct PIOstatus;

 struct PositionData
  {
   int time[3];
   long position;    /* variables for data logging */
   long velocity;
   int point;
  };

 struct PositionData data[410];

 int datapointer, takedata;

 int PointNumber, ExePointNumber;       /* place in point list */
 shared long gActPosition, gActVelocity;  /* actual position and velocity */
 shared long PseudoVelo;               /* IPC variable b/w pos and velo loop */
 shared BYTEMODE Actuation;          /* system actuation */
 float kpp, kpi, kpd;         /* system position gains 1 unit, I in .01 units */
 int kvp, kvi, kvd;          /* system velocity gains 0.0001 units */
 float kff;               /* system feed forward gain 0.01 units */
 int BeginMove;               /* change to TRUE to begin motion */
 int NewMove;
 int UseVelocityControl;     /* bypasses position controller */
 int Acceleration;
 int BegTime[3], EndTime[3];

 BYTEMODE ServoNull;
 shared long MaxVelo, MaxLimits, AbsLimits;
 shared int ActScale;
 int Control, Shutdown, Reset1, Reset2;
 int UnitNumber, DumpSerial;
 char InString[255], OutString[255];
 char PowerFail[] = "!Power fail\0";
 char SoftReset[] = "!Soft reset\0";
 char tbuf[384], rbuf[384];

 int AnalogInput (char *, char *);
 int HighVoltage (char *, char *);
 int ChangeHighVoltage (char *, char *);
 int InitPIO (char *, char *);
 int OutInPIO (char *, char *);
 int SetGetGain (char *, char*);
 int ControlLaw (char *, char *);
 int DtoAOut (char *, char *);
 int PosLoad (char *, char *);
 int ExecuteMove (char *, char *);
 int Diagnostic (char *, char *);
 int ShutDown (char *, char *);
 int RevisionLevel (char *, char *);
 int MaxLimit (char *, char *);
```

```
void FatalErrorHandler (unsigned, unsigned);
float p2sin(float);
float p2cos(float);
void NotUsed(void);
long plant (int, int);

/* extern void Dz0_circ_int(); */

/* 0x10 stores network node number, 0x12 stores null.lsb, 0x13 stores
  null.msb */

root main ()
{
  int index;

  if (wderror())
   {
    Shutdown = TRUE;
    Control = OFF;
    outport (0x81, ServoNull.byte.lsb);
    outport (0x82, ServoNull.byte.msb);
    op_kill_z1();
    op_init_z1 (19200/1200, InString, UnitNumber);
    while (1)
          {
           hitwd();
           if (check_opto_command() == 1)
             replyOpto22 (SoftReset, strlen (SoftReset), 0);
          }
   }

  _GLOBAL_INIT();

  ERROR_EXIT = FatalErrorHandler;
  BeginMove = FALSE;
  UseVelocityControl = OFF;
  Control = DumpSerial = OFF;
  Shutdown = takedata = OFF;
  NewMove = FALSE;
  Reset1 = Reset2 = ON;
  ExePointNumber = PointNumber = 0;
  datapointer = 0;
  gActVelocity = gActPosition = 0L;
  kpp = kpi = kpd = kff = 0;
  kvp = kvi = kvd = 0;
  MaxLimits = AbsLimits = 88000L;
  Acceleration = 5000;
  MaxVelo = 0L;
  ActScale = ACTSCALE;
  Actuation.word = 0;    /* zero! */
  PIOstatus.PIOAmode = 0x1;
  PIOstatus.PIOBmode = (char) 0;
  UnitNumber = ee_rd(0x10);
  ServoNull.byte.lsb = ee_rd(0x12);
  ServoNull.byte.msb = ee_rd(0x13);

#if (SIMULATION == 0)
  inport (0x82);                    /* clear the encoder */
#else
  plant (2,0);
#endif

  outport (0x81, ServoNull.byte.lsb);  /* zero the d-to-a board */
  outport (0x82, ServoNull.byte.msb);
  outport (PIOCA, 0xff);             /* pioa command */
  outport (PIOCA, 0x00);             /* set all bits for output */
  outport (0x41, (char)0x7);         /* disable interrupts */
  outport (PIODA, PIOstatus.PIOAmode);  /* pioa data */
  outport (PIOCB, 0xcf);              /* piob command */
  outport (PIOCB, 0x00);              /* set all bits for input */
  outport (PIOCB, PIOB_VEC);
  outport (PIOCB, 0x17);
  outport (PIOCB, 0xfe);
  outport (0x43, 0x7);                /* disable interrupts */
  /* outport (PIODB, PIOstatus.PIOBmode); */ /* piob data */
  outport (PIOCB, 0x7);

/*
 reload_vec (14, Dz0_circ_int);
 Dinit_z0(rbuf, tbuf, 384, 384, 4, 9600/1200, 0, 0);
*/

  op_init_z1 (19200/1200, InString, UnitNumber);

  for (index = 0; index < 26; index++)
    (TaskDispatchTable[index]) = NotUsed;

  TaskDispatchTable['L'-'A'] = AnalogInput;
  TaskDispatchTable['H'-'A'] = HighVoltage;
  TaskDispatchTable['V'-'A'] = ChangeHighVoltage;
  TaskDispatchTable['P'-'A'] = InitPIO;
  TaskDispatchTable['D'-'A'] = OutInPIO;
  TaskDispatchTable['G'-'A'] = SetGetGain;
  TaskDispatchTable['C'-'A'] = ControlLaw;
  TaskDispatchTable['A'-'A'] = DtoAOut;
  TaskDispatchTable['E'-'A'] = PosLoad;
  TaskDispatchTable['X'-'A'] = ExecuteMove;
  TaskDispatchTable['I'-'A'] = Diagnostic;
  TaskDispatchTable['M'-'A'] = MaxLimit;
  TaskDispatchTable['S'-'A'] = ShutDown;
  TaskDispatchTable['R'-'A'] = RevisionLevel;

  DI ();
  init_kernel ();
  run_every (TASK2, 100);
#if (SIMULATION == 0)
  run_every (TASK1, 8);
#endif
  init_timer0 (900);
  EI ();

  backgnd ();
}

void NotUsed(void)
{
  return;
}

nodebug backgnd ()
{
 while (1)
  {
#if (SIMULATION == 1)
  task1();
#endif

    if (Shutdown)
     {
          op_kill_z1();
          op_init_z1 (19200/1200, InString, UnitNumber);
          outport (0x81, ServoNull.byte.lsb);
          outport (0x82, ServoNull.byte.msb);

          while (1)
           {
            if (check_opto_command() == 1)
```

```
                replyOpto22 (PowerFail, strlen (PowerFail), 0);
              hitwd();
              }
      }

    if (check_opto_command() == 1)
      {
            strcpy (OutString, "!OK\0");

            InString[InString[1]] = '\0';

            if (isalpha (InString[4]))
              {
                (*TaskDispatchTable[toupper(InString[4]) - 'A'])
                  (InString+2, OutString);
              }
            /*
              if (DumpSerial)
              {
              Dwrite_z0(InString+1, InString[0] - 2);
              Dwrite_z0(OutString, strlen (OutString));
              }
       */

            replyOpto22 (OutString, strlen (OutString), 0);
      }
   }
 while (1);
}


MaxLimit (char *In, char *Out)
{
 char chvalue[8];
 long value;

 switch (toupper(*(In+3)))
  {
   case 'V':  /* >1MV98765. */ /* velocity limits */
     strncpy (chvalue, (In+4), 5);
     chvalue[5] = '\0';
     MaxVelo = atol (chvalue);
     sprintf (Out, "OK");
     break;
   case 'L':  /* >1ML12345. */ /* Extension limits */
     strncpy (chvalue, (In+4), 5);
     chvalue[5] = '\0';
     MaxLimits = atol (chvalue);
     AbsLimits = MaxLimits + 200L;
     sprintf (Out, "OK");
     break;
   case 'S':  /* >1MS2. */ /* Actuator scaling */
     strncpy (chvalue, (In+4), 1);
     chvalue[1] = '\0';
     ActScale = atoi (chvalue);
     sprintf (Out, "OK");
     break;
   case 'N':  /* >1MN2047. */ /* set null point to 2047 */
     strncpy (chvalue, (In+4), 4);
     chvalue[4] = '\0';
     ServoNull.word = atoi(chvalue);
     if (ServoNull.word == -1)
            {
             ServoNull.byte.lsb = ee_rd (0x12);
             ServoNull.byte.msb = ee_rd (0x13);
             sprintf (Out, ">MN%4d.\0", ServoNull.word);
            }
     else
            {
```

```
            ee_wr (0x12, ServoNull.byte.lsb);
            ee_wr (0x13, ServoNull.byte.msb);
            sprintf (Out, "Servo null: %x %x", ee_rd (0x12), ee_rd(0x13));
            outport (0x81, ServoNull.byte.lsb);
            outport (0x82, ServoNull.byte.msb);
           }
    break;
   case 'U':   /* >1MU2. */ /* set unit number to 2 */
    strncpy (chvalue, (In+4), 1);
    chvalue[1] = '\0';
    ee_wr (0x10, atoi (chvalue));
    sprintf (Out, ">1MU%1d.\0", ee_rd (0x10));
    break;
 }
}

PosLoad (char *In, char *Out)
{
 char chvalue[8];
 char **pchvalue;
 long value;
 int value1, index, index2, offset;
 float CycTime;
 float TempFloat1, TempFloat2;

 if (*(In+3) == 'S')
  {
   strncpy (chvalue, (In+4), 4);
   chvalue[4] = '\0';
   value1 = atoi (chvalue);

   if (value1 == -1)  /* >1ES__-1. */
         {
          sprintf (Out, ">ES%5ld%5ld.", gActPosition, gActVelocity);
          return;
         }
   else
         if (value1 == -2)  /* >1ES__-2. */
          {
           sprintf (Out, ">ES%5ld%5d.", gActPosition, Actuation.word);
           return;
          }
         else
          if ((value1 >= 0) && (value1 < PointNumber))
           {
            sprintf (Out, ">ES%5d%5d%4d%4d%1d.",
                       PointList[value1].toX,
                       PointList[value1].toY,
                       PointList[value1].Velocity,
                       PointList[value1].TimeSlices,
                       PointList[value1].PIOmode);
            return;
           }
   sprintf (Out, "!ES ERROR");
   return;
  }

 if (*(In+3) == 'R')
  {                               /* replace pt 0000 */
   /* >1ER0000123456987654000. pos=123456,velo=987654,pio=000 */
   sprintf (Out, "OK");
   return;
  }

 if (*(In+3) == 'L')
  {       /* >1EL1234512345987600. pos=12345,velo=9876,pio=00, in hex */
   strncpy (chvalue, (In+4), 1);
   chvalue[1]= '\0';
   index = atoi (chvalue);
```

```
    for (index2 = 0; index2 < index;)
            {
             offset = index2 * 15;
             strncpy (chvalue, In+(offset+5), 5);
             chvalue[5] = '\0';
             value = atoi (chvalue);

             if ((value > MaxLimits))
               PointList[PointNumber+index2].toX = MaxLimits;
             else
               PointList[PointNumber+index2].toX = (int)value;

             strncpy (chvalue, In + (offset+10), 5);
             chvalue[5] = '\0';
             value = atoi (chvalue);
             if (value > MaxLimits)
               PointList[PointNumber+index2].toY = MaxLimits;
             else
               PointList[PointNumber+index2].toY = (int)value;

             strncpy (chvalue, In + (offset + 15), 4);
             chvalue[4] = '\0';
             value = atoi(chvalue);

             if ((value == 0) && (UseVelocityControl == OFF))
               PointList[PointNumber+index2].Velocity = 200;
             else
               PointList[PointNumber+index2].Velocity = (int)value;

             PointList[PointNumber+index2].PIOmode = atoi (In+(offset+18));

             if (PointList[PointNumber+index2].Velocity != 0)
               {
          if (PointNumber == 0)
            {
             PointList[PointNumber].TimeSlices = 0;
            }
          else
            {
#if (SIMULATION == 1)
                          printf ("PosLoad Velocity: %d\n",
                                      PointList[PointNumber].Velocity);
#endif
                          TempFloat1 = (float)(PointList[PointNumber+index2].toY -
                                                   PointList[PointNumber-1+index2].toY);
                          TempFloat2 = (float)(PointList[PointNumber+index2].toX -
                                                   PointList[PointNumber-1+index2].toX);
                   CycTime =
                           sqrt((TempFloat1 * TempFloat1)+(TempFloat2 * TempFloat2))
                          / (float)PointList[PointNumber+index2].Velocity;
                          PointList[PointNumber+index2].TimeSlices = CycTime * 64;

#if (SIMULATION == 1)
            printf ("TimeSlices %d\n", PointList[PointNumber].TimeSlices);
#endif

                          }
              }
             else
              {
                PointList[PointNumber+index2].TimeSlices = 0;
              }
             index2++;
            }
    PointNumber += index2;
    sprintf (Out, "OK");
    return;
    }

  if (*(In+3) == 'C')
    {
     PointNumber = 0;
     ExePointNumber = 0;
     datapointer = 0;
     takedata = OFF;
     sprintf (Out, "OK");
     return;
    }

  if (*(In+3) == 'V')                /* >1EV1. */
    {
     sprintf (Out, "OK");
     if (*(In+4) == '1')
            {
             UseVelocityControl = ON;
             /* outport (PIOCB, 0x87); */ /* enable interrupt driven */
            }
     else
            {
             UseVelocityControl = OFF;
             Reset1 = TRUE;
             /* outport (PIOCB, 0x7);  */ /* disable interrupt driven */
            }
     return;
    }
}

ExecuteMove (char *In, char *Out)
{
 datapointer = 0;
 takedata = ON;
 ExePointNumber = 1;
 BeginMove = TRUE;
 NewMove = TRUE;
}

/* #INT_VEC PIOB_VEC intrExecuteMove */

/* interrupt reti int intrExecuteMove () */
/* { */
/*  takedata = ON; */
/*  datapointer = 0; */

/*  PIOstatus.PIOAmode =  */
/*    (PointList[ExePointNumber].PIOmode & 0xfe); */
/*  outport (PIODA, PIOstatus.PIOAmode);  */

/*  ExePointNumber = 0; */
/*  BeginMove = TRUE; */
/*  UseVelocityControl = OFF; */
/* } */

Diagnostic (char *In, char *Out)
{
 static int indexer;

#GLOBAL_INIT
 {
  indexer = 0;
 }

 switch (*(In+3))
  {
   case '0':
          indexer = 0;
          if (BeginMove == FALSE)
```

```
              sprintf (Out, ">%4d.\0", datapointer);
             else
              sprintf (Out, "  -1\0");
             break;
      case '1':
             if (BeginMove == FALSE)
              {
                sprintf (Out, ">%u,%d,%ld,%ld.\0",
                            data[indexer].time[0], data[indexer].point,
                            data[indexer].position, data[indexer].velocity);
                indexer++;
              }
             break;
      case '2':
             if (DumpSerial == TRUE)
              DumpSerial = FALSE;
             else
              DumpSerial = TRUE;
             break;
      case '3':
             sprintf (Out, ">%d\0", PointNumber);
             break;
   }
}

ShutDown (char *In, char *Out)
{
 BYTEMODE index;

#if (SIMULATION == 1)
 plant (2,0);
#endif

 DI();
 inport (0x82);             /* clear the encoder */
 outport (0x81, ServoNull.byte.lsb);        /* zero the d-to-a board */
 outport (0x82, ServoNull.byte.msb);
 outport (0x41, (char)0xf);  /* pioa command */
 outport (0x41, (char)0x0);  /* set all bits for output */
 outport (0x41, (char)0x7);  /* disable interrupts */
 outport (0x40, (char)0x0);  /* pioa data */
 outport (0x43, (char)0xf);  /* piob command */
 outport (0x43, (char)0x0);  /* set all bits for output */;
 outport (0x43, (char)0x7);  /* disable interrupts */
 outport (0x42, (char)0x0);  /* piob data */
 Shutdown = ON;
 UseVelocityControl = OFF;
 sprintf (Out, "OK");
}

RevisionLevel (char *In, char *Out)
{
 BYTEMODE index;

 Control = OFF;
 Shutdown = OFF;
 BeginMove = FALSE;
 NewMove = FALSE;
 UseVelocityControl = OFF;
 Reset1 = Reset2 = ON;
 gActVelocity = 0L;
 gActPosition = 0L;
 kpp = kpi = kpd = kff = 0;
 kvp = kvi = kvd = 0;
 PointNumber = ExePointNumber = 0;
 Actuation.word = 0;
 outport (0x81, ServoNull.byte.lsb);
 outport (0x82, ServoNull.byte.msb);
 inport (0x82);
 sprintf (Out, ">unit:%d Rev beta %d.%d.", UnitNumber, VERSION, SUBVERSION);
#if (SIMULATION == 1)
 plant (2,0);
#endif
}

AnalogInput (char *In, char *Out)  /* >1L0. channel 0 */
{
 sprintf (Out, ">L%4d.", ad_rd8(atoi(In+3)));
}

HighVoltage (char *In, char *Out)    /* >1H1. on, >1H0. off */
{
 if (*(In+3) == '1')
  {
   hv_enb();
   sprintf (Out, "OK");
  }
 else
  {
   hv_dis();
   sprintf (Out, "OK");
  }
}

ChangeHighVoltage (char *In, char *Out)   /* >1V123.  port pattern 123 */
{
 char chvalue[4];

 strncpy (chvalue, (In+3), 3);
 chvalue[3] = 0;

 hv_wr(atoi(chvalue));
 sprintf (Out, "OK");
}

InitPIO (char *In, char *Out)  /* >1PA0103. mode 01, control 03, on PIO A */
{
 char InChar[3];
 char mode, control;

 strncpy (InChar, (In+4), 2);
 InChar[2] = 0;
 mode = atoi (InChar);

 strncpy (InChar, (In+6), 2);
 control = atoi (InChar);

 switch (*(In+3))
  {
   case 'A':
          outport (PIOCA, ((mode << 6) & 0xf0) | 0x0f);
          outport (PIOCA, (char)control);
          sprintf (Out, "OK");
          break;
   case 'B':
          outport (PIOCB, ((mode << 6) & 0xf0) | 0x0f);
          outport (PIOCB, (char)control);
          sprintf (Out, "OK");
          break;
  }
}

OutInPIO (char *In, char *Out)  /* >1DOB000. Output on PIO B value 000,
                                    >1DIA.  Input on PIO A returns 145 */
{
 char chvalue[4];
 int value;
```

```
  chvalue[3] = 0;
  switch (*(In+3))
   {
    case 'O':
            if (*(In+4) == 'A')
             {
              stmcpy (chvalue, (In+5), 3);
              value = atoi(chvalue);
              PIOstatus.PIOAmode = (char)value I (PIOstatus.PIOAmode & 0x3);
              outport (PIODA, PIOstatus.PIOAmode);
              sprintf (Out, "OK");
             }
            else
             if (*(In+4) == 'B')
              {
               stmcpy (chvalue, (In+5), 3);
               value = atoi (chvalue);
               PIOstatus.PIOBmode = (char)value;
               outport (PIODB, (char)value);
               sprintf (Out, "OK");
              }
            break;
    case 'I':
            if (*(In+4) == 'A')
             {
              value = inport (PIODA);
              sprintf (Out, ">DIA%3d.", value);
             }
            else
             if (*(In+4) == 'B')
              {
               value = inport (PIODB);
               sprintf (Out, ">DIB%3d.", value);
              }
             break;
   }
}

SetGetGain (char *In, char *out)  /* >1GPP1234., Pos. Proportional to 1234
                                                 "  -1" to report */
{
 int value;
 char chvalue[5];

 stmcpy (chvalue, (In+5), 4);
 chvalue[4] = '\0';

 value = atoi (chvalue);

 switch (*(In+3))
  {
   case 'V':
           switch (*(In+4))
            {
             case 'F':
              if (value == -1)
                    {
                     sprintf (out, ">GVF%4d.", (int)kff*100);
                     retum;
                    }
              else
                    {
                     Reset1 = Reset2 = ON;
                     kff = (float)value/100.0;
                     sprintf (out, "OK");
                    }
              break;
             case 'P':
              if (value == -1)
```

```
                {
                 sprintf (out, ">GVP%4d.", kvp);
                 return;
                }
          else
                {
                 Reset1 = Reset2 = ON;
                 kvp = value;
                 sprintf (out, "OK");
                }
          break;
         case 'I':
          if (value == -1)
                {
                 sprintf (out, ">GVI%4d.", kvi);
                 return;
                }
          else
                {
                 Reset1 = Reset2 = ON;
                 kvi = value;
                 sprintf (out, "OK");
                }
         break;
        case 'D':
         if (value == -1)
          {
                sprintf (out, ">GVD%4d.", kvd);
                return;
          }
         else
          {
                Reset1 = Reset2 = ON;
                kvd = value;
                sprintf (out, "OK");
          }
         break;
        }
       break;
case 'P':
        switch (*(In+4))
         {
          case 'P':
           if (value == -1)
                {
                 sprintf (out, ">GPP%4d.", (int)kpp);
                 return;
                }
           else
                {
                 Reset1 = Reset2 = ON;
                 kpp = (float)value/10.0;
                 sprintf (out, "OK");
                }
           break;
          case 'I':
           if (value == -1)
                {
                 sprintf (out, ">GPI%4d.", (int)kpi);
                 return;
                }
           else
                {
                 Reset1 = Reset2 = ON;
                 kpi = (float)value/10.0;  /* WAS 10000 */
                 sprintf (out, "OK");
                }
           break;
          case 'D':
              if (value == -1)
                   {
                    sprintf (out, ">GPD%4d.", (int)kpd);
                    return;
                   }
              else
                   {
                    Reset1 = Reset2 = ON;
                    kpd = (float)value/10.0;
                    sprintf (out, "OK");
                   }
              break;
            }
     }
}

ControlLaw (char *In, char *out)  /* >1C1. on, >1C0. off */
{
 if (*(In+3) == '0')
   {
    BeginMove = OFF;
    NewMove = FALSE;
    Control = OFF;
    takedata = OFF;
    UseVelocityControl = OFF;
    outport (0x81, ServoNull.byte.lsb);
    outport (0x82, ServoNull.byte.msb);
    sprintf (out, "OK");
   }
 else
   if (*(In+3) == '1')
    {
          Control = ON;
          Reset1 = Reset2 = ON;
          sprintf (out, "OK");
    }
}

DtoAOut (char *In, char *out)  /* >1A4321. 4321 on DtoA */
{
 char chvalue[5];
 BYTEMODE value;

 Control = OFF;

 strncpy (chvalue, (In+3), 4);
 chvalue[4] = '\0';

 value.word = atoi (chvalue);
 outport (0x81, value.byte.lsb);
 outport (0x82, value.byte.msb);
 sprintf (out, "OK");
}

/*=================================================================

Position loop!

This task generates the actuation using PID.

communicates with the velocity loop thru the shared variable PseudoVelo

=================================================================*/
nodebug task1 ()
{
 static long ActPos, ActVelocity;
 static float DeltaPErr0, DeltaPErr1, DeltaPErr2;
 static float ipActuation;
 static long DesVelo;
 static int TimePeriods;
 static float DesPos;
 static int LastPoint;
 static long dResult, NewPos, EndPos;
 static BYTEMODE RealActuation;
 static unsigned result, result0;
 static float dAbsPos[5];
 static long OldgActPosition;
 static int index, RollOver;
 static unsigned int lo0, lo1, hi0, hi1;
 static float yPosIncrement, xPosIncrement;
 static float yPosBegin, xPosBegin, PrevNewPos;

#GLOBAL_INIT
 {
  ActPos  = ActVelocity = 0L;
  DesPos = EndPos = 0;
  DeltaPErr0 = DeltaPErr1 = DeltaPErr2 = 0;
  DesVelo = 0L;
  ipActuation = 0;
  TimePeriods = 0;
  LastPoint = FALSE;
  RollOver = 0;
  result = result0 = 0;
  gActPosition = 0;
  dAbsPos[0] = dAbsPos[1] = dAbsPos[2] = dAbsPos[3] = 0L;
  index = 0;
 }

 OldgActPosition = gActPosition;

#if (SIMULATION == 0)
 do
  {
   DI();
   lo0 = inport (0x81);
   hi0 = inport (0x80);   /* stabilize results */
   lo1 = inport (0x81);
   hi1 = inport (0x80);
   EI();
  }
 while ((lo0 != lo1) || (hi0 != hi1));
 result = ((hi1 << 8) & 0xff00) | lo1;
#else
 result = plant (1, 0);
#endif

 dResult = (long)((long)result - (long)result0);

 if (dResult > 32000)
  RollOver--;
 else
  if (-32000 > dResult)
   RollOver++;

 result0 = result;
 gActPosition = (long)result + (long)(RollOver * (long)65536);

 dAbsPos[1] = dAbsPos[0];
 dAbsPos[0] = gActPosition - OldgActPosition;
 gActVelocity = (long)((dAbsPos[0] + dAbsPos[1]) * 32.0 );

 if (gActPosition > AbsLimits)
  {
   outport (0x81, ServoNull.byte.lsb);
   outport (0x82, ServoNull.byte.msb);
   Control = OFF;
  }
 if (Control == OFF)
  {
   PseudoVelo = 0;
   ipActuation = 0;
   return;
  }

 ActPos = gActPosition;  /* transfer to local variables */
 ActVelocity = gActVelocity;

 if (Reset1)
  {
   DeltaPErr2 = DeltaPErr1 = DeltaPErr0 = 0;
   ipActuation = 0;
   DesPos = ActPos;
   NewPos = ActPos;
   EndPos = ActPos;
   DesVelo = 0;
   TimePeriods = 0;
   BeginMove = NewMove = FALSE;
   UseVelocityControl = OFF;
   Reset1 = OFF;
   TimePeriods = 0;
  }

#if (SIMULATION == 1)
 gettimer (BegTime);
#endif

 if (BeginMove == TRUE)
  {
   LastPoint = FALSE;
   if (NewMove == TRUE)  /* allows for interrupted move */
         {
          NewMove = FALSE;
          TimePeriods = 0;
          if (UseVelocityControl == ON)
            DesVelo = PointList[0].Velocity;
         }
   if (((TimePeriods--) <= 1) && (UseVelocityControl == OFF))
         {
          if (ExePointNumber >= PointNumber)
            {
             ExePointNumber = PointNumber;
             yPosBegin = PointList[ExePointNumber-1].toY;
             xPosBegin = PointList[ExePointNumber-1].toX;
             EndPos = atan2 (PointList[ExePointNumber-1].toY,
                             PointList[ExePointNumber-1].toX) * 14005.6;
             DesVelo = 0;
             yPosIncrement = 0;
             xPosIncrement = 0;
             BeginMove = FALSE;
            }
          else
            {
             if (PointList[ExePointNumber].TimeSlices != 0)
                    {
                     TimePeriods = (int)PointList[ExePointNumber].TimeSlices;
                     yPosIncrement = (PointList[ExePointNumber].toY -
                                      PointList[ExePointNumber-1].toY) /
                             (float) TimePeriods;
                     xPosIncrement = (PointList[ExePointNumber].toX -
                                      PointList[ExePointNumber-1].toX)
                             / (float)TimePeriods;
                     yPosBegin = PointList[ExePointNumber-1].toY;
                     xPosBegin = PointList[ExePointNumber-1].toX;
                     DesPos = ActPos;
                    }
             else
```

```
                        {
                         TimePeriods = 0;
                         yPosBegin = PointList[ExePointNumber].toY;
                         xPosBegin = PointList[ExePointNumber].toX;
                         yPosIncrement = xPosIncrement = 0;
                         DesPos = ActPos;
                         DesVelo = 0;
                        }
                  }
                 hv_wr (PointList[ExePointNumber].PIOmode);
                 ExePointNumber++;
                 if (ExePointNumber == PointNumber) LastPoint = TRUE;
                }

     yPosBegin += yPosIncrement;
     xPosBegin += xPosIncrement;
     PrevNewPos = DesPos;
     DesPos = atan2 (yPosBegin, xPosBegin) * 14005.6;
     DesVelo = (DesPos - PrevNewPos) * 64;
     if ((LastPoint == TRUE) && (TimePeriods < 5)) DesVelo = 0;
    }
   else
    {
     yPosIncrement = xPosIncrement = 0;
     DesPos = EndPos;
    }

 #if (SIMULATION == 1)
  /*  printf ("time: %d Despos: %f\n", TimePeriods, DesPos); */
 #endif

  DeltaPErr2 = DeltaPErr1;  /* generate time history - 2 steps back */
  DeltaPErr1 = DeltaPErr0;
  DeltaPErr0 = DesPos - ActPos;

  ipActuation +=
   (((float)kpp * (DeltaPErr0 - DeltaPErr1)) +
    ((float)kpi * (DeltaPErr0)) +
    ((float)kpd * (DeltaPErr0 - (DeltaPErr1+DeltaPErr1) + DeltaPErr2)) +
    (kff * (DesVelo - ActVelocity)));

 #if (SIMULATION == 1)
  gettimer(EndTime);
 #endif

  if (UseVelocityControl == ON)
   PseudoVelo = DesVelo;
  else
   {
    PseudoVelo = ipActuation;

    if (PseudoVelo > (long)65504)
            PseudoVelo = 65504;
    else
            if (PseudoVelo < -65504)
             PseudoVelo = -65504;

    RealActuation.word = (int)(PseudoVelo >> 5);

    Actuation.word = RealActuation.word;

    RealActuation.word += D2AOFFSET;
 #if (SIMULATION == 0)
    DI();
    k_lock();
    outport (0x81, (char)(RealActuation.byte.lsb));
    outport (0x82, (char)(RealActuation.byte.msb));
    k_unlock();
    EI();
```

```
#else
    plant (0, RealActuation.word);
    printf ("D,V,A,A: %f %ld %ld %d %ld\n", DesPos, DesVelo, gActPosition,
                RealActuation.word, PseudoVelo);
#endif
  }
}

/*================================================================
This task takes sensor data.
================================================================*/

nodebug task2()
{
 static int index;

#GLOBAL_INIT
 {
  index = 0;
 }

 if (Shutdown == TRUE) return;
 hitwd();

 if (takedata == ON)
  {
   if (datapointer == 0) index = 0;

   gettimer (data[datapointer].time);
   data[datapointer].position = gActPosition;
   data[datapointer].velocity = gActVelocity;
   data[datapointer].point = ExePointNumber;

   if (BeginMove == FALSE)
          {
           if (index > 5)
            takedata = OFF;
           else
            index++;
          }

   if (datapointer++ > 395) takedata = OFF;
  }

 if ((PIOstatus.PIOAmode & 0x2) == 0x0)
  PIOstatus.PIOAmode |= 0x2;
 else
  PIOstatus.PIOAmode &= 0xfd;

 outport (PIODA, PIOstatus.PIOAmode);
}

/*================================================================

Velocity loop!

This task generates the velocity actuation and also takes the sensor
data from the encoder.

uses the shared variables PseudoVelo for input,
and gActPosition, gActVelocity for output.

================================================================*/

nodebug task0()
{
 static long pVelo, dResult;
 static long DeltaVErr0, DeltaVErr1, DeltaVErr2;
 static BYTEMODE RealActuation;
 static long vActuation;
 static unsigned int result0, result;
 static float dAbsPos[5];
 static long OldgActPosition;
 static int index, RollOver;
 static unsigned int lo0, lo1, hi0, hi1;

#GLOBAL_INIT
 {
  RollOver = 0;
  result = result0 = 0;
  gActPosition = 0;
  dAbsPos[0] = dAbsPos[1] = dAbsPos[2] = dAbsPos[3] = 0L;
  DeltaVErr0 = DeltaVErr1 = DeltaVErr2 = 0L;
  index = 0;
 }

 OldgActPosition = gActPosition;

 do
  {
   DI();
   lo0 = inport (0x81);
   hi0 = inport (0x80);   /* stabilize results */
   lo1 = inport (0x81);
   hi1 = inport (0x80);
   EI();
  }
 while ((lo0 != lo1) || (hi0 != hi1));
 result = ((hi1 << 8) & 0xff00) | lo1;

 dResult = (long)((long)result - (long)result0);

 if (dResult > 32000)
  RollOver--;
 else
  if (-32000 > dResult)
   RollOver++;

 result0 = result;
 gActPosition = (long)result + (long)(RollOver * (long)65536);

 dAbsPos[1] = dAbsPos[0];
 dAbsPos[0] = gActPosition - OldgActPosition;
 gActVelocity = (long)((dAbsPos[0] + dAbsPos[1]) * 42.6667);

 pVelo = PseudoVelo;  /* transfer variables to local storage */

 if (Reset2)
  {
   DeltaVErr2 = DeltaVErr1 = DeltaVErr0 = 0L;
   vActuation = 0L;
   Reset2 = OFF;
  }

 if (gActPosition > AbsLimits)
  {
   outport (0x81, ServoNull.byte.lsb);
   outport (0x82, ServoNull.byte.msb);
   Control = OFF;
  }

 if (Control == OFF)
  {
   vActuation = 0;
   return;
  }

/*  DeltaVErr2 = DeltaVErr1; */
/*  DeltaVErr1 = DeltaVErr0; */
/*  DeltaVErr0 = pVelo - gActVelocity; */

/*  vActuation += (long) */
/*    ((((long)kvp*(long)(DeltaVErr0-DeltaVErr1)) + */
/*      ((long)kvi*(long)(DeltaVErr0)) + */
/*      ((long)kvd*(long)(DeltaVErr0 - (DeltaVErr1 + DeltaVErr1) + */
/*                                        DeltaVErr2)))); */

/*  if (vActuation > (long)268304384) */
/*    vActuation = 268304384; */
/*  else */
/*    if (vActuation < -268304384) */
/*      vActuation = -268304384; */

/*  RealActuation.word = ((int)(vActuation >> 17)); */

  if (pVelo > (long)2096128)
    pVelo = 2096128;
  else
    if (pVelo < -2096128)
      pVelo = -2096128;

  RealActuation.word = (int)(pVelo >> 10);

  Actuation.word = RealActuation.word;

  RealActuation.word += D2AOFFSET;
  DI();
  k_lock();
  outport (0x81, (char)(RealActuation.byte.lsb));
  outport (0x82, (char)(RealActuation.byte.msb));
  k_unlock();
  EI();
}

#JUMP_VEC NMI_VEC NMI_int

interrupt retn NMI_int()
{
  Shutdown = TRUE;
  Control = OFF;
  outport (0x81, ServoNull.byte.lsb);
  outport (0x82, ServoNull.byte.msb);
  while (1)
   {
    hitwd();
    if (!powerlo()) return;
   }
}

void FatalErrorHandler (unsigned code, unsigned address)
{
  outport (0x81, ServoNull.byte.lsb);
  outport (0x82, ServoNull.byte.msb);
  Shutdown = TRUE;
  Control = OFF;
  while (1);  /* stall until reset by watch dog */
}

float p2cos (float x)
{
  return (p2sin (90.0 - x));
}

/*==========================================================
PROCEDURE: p2sin

PARAMETERS: float Y
```

```
RETURNS: float

METHOD: computes sin(Y) by:
    sin (y + dy) = (sin y)(cos dy) + ([(cos x)/57.2958])(dy)
    where Y = y + dy, y = int(Y), dy = frac(Y), and
    the parameters are found from a lookup table. result is good
    to about 5 places.

VARIABLES:
    sinx are the values of sin(y) where y varies between 0->90
    cosdx are the values of cos(dy) where dy varies between
           0->1 in 0.01 increments
    cosxd are the values of [(cos y)/57.2958] where y varies
           between 0->90
    ALL fractional values have been shifted by multiplying by
           65535 to obtain integers.
=================================================================*/

nodebug float p2sin (float y)

{
 static unsigned int sinx[] =
             {0x0000,0x0478,0x08EF,0x0D66,0x11DB,
              0x1650,0x1AC2,0x1F33,0x23A1,0x280C,
              0x2C74,0x30D9,0x3539,0x3996,0x3DEE,
              0x4242,0x4690,0x4AD9,0x4F1B,0x5358,
              0x578E,0x5BBE,0x5FE6,0x6407,0x681F,
              0x6C30,0x7039,0x7438,0x782F,0x7C1C,
              0x8000,0x83D9,0x87A8,0x8B6D,0x8F27,
              0x92D5,0x9679,0x9A10,0x9D9B,0xA11B,
              0xA48D,0xA7F3,0xAB4B,0xAE97,0xB1D4,
              0xB504,0xB826,0xBB39,0xBE3E,0xC134,
              0xC41B,0xC6F2,0xC9BA,0xCC73,0xCF1B,
              0xD1B3,0xD43B,0xD6B2,0xD919,0xDB6E,
              0xDDB3,0xDFE6,0xE208,0xE418,0xE616,
              0xE803,0xE9DD,0xEBA5,0xED5B,0xEEFE,
              0xF08F,0xF20D,0xF377,0xF4CF,0xF614,
              0xF746,0xF864,0xF96F,0xFA67,0xFB4B,
              0xFC1B,0xFCD8,0xFD81,0xFE17,0xFE98,
              0xFF06,0xFF5F,0xFFA5,0xFFD7,0xFFF5,
              0xFFFF};

 static unsigned int cosdx[] =
             {0xFFFF,0xFFFF,0xFFFF,0xFFFF,0xFFFF,
              0xFFFF,0xFFFF,0xFFFF,0xFFFF,0xFFFF,
              0xFFFF,0xFFFF,0xFFFF,0xFFFF,0xFFFF,
              0xFFFF,0xFFFF,0xFFFF,0xFFFF,0xFFFF,
              0xFFFF,0xFFFF,0xFFFF,0xFFFE,0xFFFE,
              0xFFFE,0xFFFE,0xFFFE,0xFFFE,0xFFFE,
              0xFFFE,0xFFFE,0xFFFE,0xFFFE,0xFFFE,
              0xFFFE,0xFFFE,0xFFFE,0xFFFE,0xFFFD,
              0xFFFD,0xFFFD,0xFFFD,0xFFFD,0xFFFD,
              0xFFFD,0xFFFD,0xFFFD,0xFFFD,0xFFFD,
              0xFFFD,0xFFFC,0xFFFC,0xFFFC,0xFFFC,
              0xFFFC,0xFFFC,0xFFFC,0xFFFC,0xFFFC,
              0xFFFB,0xFFFB,0xFFFB,0xFFFB,0xFFFB,
              0xFFFB,0xFFFB,0xFFFB,0xFFFA,0xFFFA,
              0xFFFA,0xFFFA,0xFFFA,0xFFFA,0xFFFA,
              0xFFF9,0xFFF9,0xFFF9,0xFFF9,0xFFF9,
              0xFFF9,0xFFF8,0xFFF8,0xFFF8,0xFFF8,
              0xFFF8,0xFFF8,0xFFF7,0xFFF7,0xFFF7,
              0xFFF7,0xFFF7,0xFFF7,0xFFF6,0xFFF6,
              0xFFF6,0xFFF6,0xFFF6,0xFFF5,0xFFF5,
              0xFFF5};

 static unsigned int cosxd[] =
             {0x478,0x478,0x477,0x476,0x475,0x473,0x472,
              0x46F,0x46D,0x46A,0x466,0x463,0x45F,0x45A,
                0x456,0x451,0x44B,0x446,0x440,0x439,0x433,
                0x42C,0x425,0x41D,0x415,0x40D,0x404,0x3FB,
                0x3F2,0x3E8,0x3DF,0x3D4,0x3CA,0x3BF,0x3B4,
                0x3A9,0x39D,0x391,0x385,0x379,0x36C,0x35F,
                0x352,0x345,0x337,0x329,0x31B,0x30C,0x2FD,
                0x2EE,0x2DF,0x2D0,0x2C0,0x2B0,0x2A0,0x290,
                0x280,0x26F,0x25E,0x24D,0x23C,0x22B,0x219,
                0x207,0x1F5,0x1E3,0x1D1,0x1BF,0x1AC,0x19A,
                0x187,0x174,0x161,0x14E,0x13B,0x128,0x115,
                0x101,0x0EE,0x0DA,0x0C7,0x0B3,0x09F,0x08B,
                0x078,0x064,0x050,0x03C,0x028,0x014,0x000};

static float fremainder, x;
static unsigned int whole;

x = y;
if (x < 0)
 {
  do
   {
        x = x + 360;
   }
  while (x < 0);
 }


if (x <= 90.0)
 {
  whole = (int)x;
  fremainder = (x - whole);

  return ((float)((((unsigned long)sinx[whole]  *
                          (unsigned)cosdx[(int)(fremainder * 100.0)]) +
                         ((unsigned long)cosxd[whole] *
                          (unsigned)(fremainder * 65535)))
                        * 2.328377E-10));
 }
else
 if (x <= 180)
  {
   x = 180.0 - x;
   whole = (int)x;
   fremainder = (x - whole);

   return ((float)((((unsigned long)sinx[whole]  *
                              (unsigned long)cosdx[(int)(fremainder * 100.0)]) +
                             ((unsigned long)cosxd[whole] *
                              (unsigned long)(fremainder * 65535)))
                        * 2.328377E-10));
  }
else
 if (x <= 270)
  {
   x = x - 180.0;
   whole = (int)x;
   fremainder = (x - whole);

   return ((float)((((unsigned long)sinx[whole]  *
                              (unsigned long)cosdx[(int)(fremainder * 100.0)]) +
                             ((unsigned long)cosxd[whole] *
                              (unsigned long)(fremainder * 65535)))
                        * (-2.328377E-10)));
  }
else
 if (x <= 360)
  {
   x = 360.0 - x ;
   whole = (int)x;
   fremainder = (x - whole);
```

```
      return ((float)((((unsigned long)sinx[whole]  *
                                             (unsigned long)cosdx[(int)(fremainder * 100.0)]) +
                                            ((unsigned long)cosxd[whole] *
                                             (unsigned long)(fremainder * 65535)))
                                   * (-2.328377E-10)));
    }
 return (-2);
}

#if (SIMULATION == 1)

#define FLOWGAIN 0.1

long plant (int service, int input)

{
  static float position;

#GLOBAL_INIT
  {
   position = 0.0;
  }

  if (service == 1)
   return ((long)position);
  else
   if (service == 2)
    {
          position = 0.0;
          return ((long)position);
    }

  position += ((float)(input - 2047) * FLOWGAIN);
}

#endif
```

Appendix G

Source Code Listing for Extension Joint SBC

```
#use rtk.lib

/* this program to be used on EXTENSION joint only! */

/*
This program would run on the Little Giant, the Tiny Giant and the CPLC.
If port 0 is also used as the Dynamic C programming port, you have to
load the serial interrupt routine during run time by doing the following:

  (1) comment out:
#INT_VEC SER0_VEC Dz0_circ_int in z0232.lib
  (2) in the code, declare:
          extern void Dz0_circ_int();
  (3) load the routine with:
          reload_vec(14,Dz0_circ_int);

*/

/*======
For unit 4, translation joint only!

CHANGES:
5/15/97 v5.11 changed PIOmode to single char only. 1 turns on gun,
        0 turns it off again
7/15/97 v6.10 changed to burst point loading technique. loads 8 at a time.
======*/

#define SIMULATION 0

#define ON 1
#define OFF 0
#define FWD 1
#define REV 0
#define FALSE 0
#define TRUE 1

#define VERSION 6
#define SUBVERSION 10

#define CSAMPLE 900      /* clock periods: 512HZ */
#define CTIME 0.001953   /* clock time */

#define D2AOFFSET 2047
#define ACTSCALE 1

char HVreg[8];

#define HV0 HVreg[0]
#define HV1 HVreg[1]
#define HV2 HVreg[2]
#define HV3 HVreg[3]
#define HV4 HVreg[4]
#define HV5 HVreg[5]
#define HV6 HVreg[6]    /* hydraulic shutoff solenoid */
#define HV7 HVreg[7]    /* paint gun solenoid */

int task0(), task1(), task2(), backgnd();
int (*Ftask[])()={task0, task1, task2, backgnd};

#define NTASKS 4
#define TASK0 0
#define TASK1 1
#define TASK2 2

#define TASKSTORE_SIZE 500

void (*TaskDispatchTable[30])();

typedef union bytemode
```

```
 {
  int word;
  struct ByteStruct
   {
          char lsb;
          char msb;
   } byte;
 } BYTEMODE;

struct PointListPoint
 {
  int toY, toX;
  int Velocity;
  int TimeSlices;
  char PIOmode;
 };

struct PIOstruct
 {
  char PIOAmode;
  char PIOBmode;
 };

struct PointListPoint PointList[1001];
shared struct PIOstruct PIOstatus;

struct PositionData
 {
  int time[3];
  long position;    /* variables for data logging */
  long velocity;
  int point;
 };

struct PositionData data[410];

int datapointer, takedata;

int PointNumber, ExePointNumber;        /* place in point list */
shared long gActPosition, gActVelocity;  /* actual position and velocity */
shared long PseudoVelo;                 /* IPC variable b/w pos and velo loop */
shared BYTEMODE Actuation;              /* system actuation */
float kpp, kpi, kpd;        /* system position gains 1 unit, I in .01 units */
int kvp, kvi, kvd;          /* system velocity gains 0.0001 units */
float kff;                  /* system feed forward gain 0.01 units */
int BeginMove;              /* change to TRUE to begin motion */
int NewMove;
int UseVelocityControl;     /* bypasses position controller */
int Acceleration;
int BegTime[3], EndTime[3];

BYTEMODE ServoNull;
shared long MaxVelo, MaxLimits, AbsLimits;
shared int ActScale;
int Control, Shutdown, Reset1, Reset2;
int UnitNumber, DumpSerial;
char InString[255], OutString[255];
char PowerFail[] = "!Power fail\0";
char SoftReset[] = "!Soft reset\0";
char tbuf[384], rbuf[384];

int AnalogInput (char *, char *);
int HighVoltage (char *, char *);
int ChangeHighVoltage (char *, char *);
int InitPIO (char *, char *);
int OutInPIO (char *, char *);
int SetGetGain (char *, char*);
int ControlLaw (char *, char *);
int DtoAOut (char *, char *);
int PosLoad (char *, char *);
int ExecuteMove (char *, char *);
int Diagnostic (char *, char *);
int ShutDown (char *, char *);
int RevisionLevel (char *, char *);
int MaxLimit (char *, char *);
void FatalErrorHandler (unsigned, unsigned);
float p2sin(float);
float p2cos(float);
void NotUsed(void);
long plant (int, int);

/* extern void Dz0_circ_int(); */

/* 0x10 stores network node number, 0x12 stores null.lsb, 0x13 stores
  null.msb */

root main ()
{
 int index;

 if (wderror())
  {
    Shutdown = TRUE;
    Control = OFF;
    outport (0x81, ServoNull.byte.lsb);
    outport (0x82, ServoNull.byte.msb);
    op_kill_z1();
    op_init_z1 (19200/1200, InString, UnitNumber);
    while (1)
          {
           hitwd();
           if (check_opto_command() == 1)
             replyOpto22 (SoftReset, strlen (SoftReset), 0);
          }
  }

 _GLOBAL_INIT();

 ERROR_EXIT = FatalErrorHandler;
 BeginMove = FALSE;
 UseVelocityControl = OFF;
 Control = DumpSerial = OFF;
 Shutdown = takedata = OFF;
 HV0 = HV1 = HV2 = HV3 = HV4 = HV5 = HV6 = HV7 = 0;
 NewMove = FALSE;
 Reset1 = Reset2 = ON;
 ExePointNumber = PointNumber = 0;
 datapointer = 0;
 gActVelocity = gActPosition = 0L;
 kpp = kpi = kpd = kff = 0;
 kvp = kvi = kvd = 0;
 MaxLimits = AbsLimits = 88000L;
 Acceleration = 5000;
 MaxVelo = 0L;
 ActScale = ACTSCALE;
 Actuation.word = 0;    /* zero! */
 PIOstatus.PIOAmode = 0x1;
 PIOstatus.PIOBmode = (char) 0;
 UnitNumber = ee_rd(0x10);
 ServoNull.byte.lsb = ee_rd(0x12);
 ServoNull.byte.msb = ee_rd(0x13);

#if (SIMULATION == 0)
 inport (0x82);                 /* clear the encoder */
#else
 plant (2,0);
#endif
```

```
   outport (0x81, ServoNull.byte.lsb);  /* zero the d-to-a board */
   outport (0x82, ServoNull.byte.msb);
   outport (PIOCA, 0xff);              /* pioa command */
   outport (PIOCA, 0x00);               /* set all bits for output */
   outport (0x41, (char)0x7);          /* disable interrupts */
   outport (PIODA, PIOstatus.PIOAmode);  /* pioa data */

   outport (PIOCB, 0xcf);              /* piob command */
   outport (PIOCB, 0x00);               /* set all bits for input */
   outport (PIOCB, PIOB_VEC);
   outport (PIOCB, 0x17);
   outport (PIOCB, 0xfe);
   outport (0x43, 0x7);              /* disable interrupts */
  /* outport (PIODB, PIOstatus.PIOBmode); */ /* piob data */
   outport (PIOCB, 0x7);

 /*
  reload_vec (14, Dz0_circ_int);
  Dinit_z0(rbuf, tbuf, 384, 384, 4, 9600/1200, 0, 0);
 */

  op_init_z1 (19200/1200, InString, UnitNumber);

  for (index = 0; index < 26; index++)
    (TaskDispatchTable[index]) = NotUsed;

  TaskDispatchTable['L'-'A'] = AnalogInput;
  TaskDispatchTable['H'-'A'] = HighVoltage;
  TaskDispatchTable['V'-'A'] = ChangeHighVoltage;
  TaskDispatchTable['P'-'A'] = InitPIO;
  TaskDispatchTable['D'-'A'] = OutInPIO;
  TaskDispatchTable['G'-'A'] = SetGetGain;
  TaskDispatchTable['C'-'A'] = ControlLaw;
  TaskDispatchTable['A'-'A'] = DtoAOut;
  TaskDispatchTable['E'-'A'] = PosLoad;
  TaskDispatchTable['X'-'A'] = ExecuteMove;
  TaskDispatchTable['I'-'A'] = Diagnostic;
  TaskDispatchTable['M'-'A'] = MaxLimit;
  TaskDispatchTable['S'-'A'] = ShutDown;
  TaskDispatchTable['R'-'A'] = RevisionLevel;

  DI ();
  init_kernel ();
  run_every (TASK2, 100);
#if (SIMULATION == 0)
  run_every (TASK1, 8);
  run_every (TASK0, 20);
#endif
  init_timer0 (900);
  EI ();

  backgnd ();
}

void NotUsed(void)
{
  return;
}

backgnd ()
{
 while (1)
   {
#if (SIMULATION == 1)
   task1();
#endif

    if (Shutdown)
      {
            op_kill_z1();
            op_init_z1 (19200/1200, InString, UnitNumber);
            outport (0x81, ServoNull.byte.lsb);
            outport (0x82, ServoNull.byte.msb);
            hv_wr (0);
            hv_dis();

            while (1)
             {
              if (check_opto_command() == 1)
                replyOpto22 (PowerFail, strlen (PowerFail), 0);
              hitwd();
             }
     }

    if (check_opto_command() == 1)
     {
            /* strcpy (OutString, "!OK\0"); */
       OutString[0] = '!';
       OutString[1] = 'O';
       OutString[2] = 'K';
       OutString[3] = 0;

            InString[InString[1]] = '\0';

/*          if (isalpha (InString[4])) */
             {
             /* (*TaskDispatchTable[toupper(InString[4]) - 'A']) */
             (*TaskDispatchTable[InString[4] - 'A'])
               (InString+2, OutString);
             }
            /*
             if (DumpSerial)
             {
             Dwrite_z0(InString+1, InString[0] - 2);
             Dwrite_z0(OutString, strlen (OutString));
             }
       */

            replyOpto22 (OutString, strlen (OutString), 0);
     }
  }
 while (1);
}


MaxLimit (char *In, char *Out)
{
 char chvalue[8];
 long value;

 switch (toupper(*(In+3)))
  {
   case 'V':  /* >1MV98765. */ /* velocity limits */
    strncpy (chvalue, (In+4), 5);
    chvalue[5] = '\0';
    MaxVelo = atol (chvalue);
    sprintf (Out, "OK");
    break;
   case 'L':  /* >1ML12345. */ /* Extension limits */
    strncpy (chvalue, (In+4), 5);
    chvalue[5] = '\0';
    MaxLimits = atol (chvalue);
    AbsLimits = MaxLimits + 200L;
    sprintf (Out, "OK");
    break;
   case 'S':  /* >1MS2. */  /* Actuator scaling */
    strncpy (chvalue, (In+4), 1);
    chvalue[1] = '\0';
    ActScale = atoi (chvalue);
    sprintf (Out, "OK");
    break;
   case 'N':   /* >1MN2047. */ /* set null point to 2047 */
    strncpy (chvalue, (In+4), 4);
    chvalue[4] = '\0';
    ServoNull.word = atoi(chvalue);
    if (ServoNull.word == -1)
          {
           ServoNull.byte.lsb = ee_rd (0x12);
           ServoNull.byte.msb = ee_rd (0x13);
           sprintf (Out, ">MN%4d.\0", ServoNull.word);
          }
    else
          {
           ee_wr (0x12, ServoNull.byte.lsb);
           ee_wr (0x13, ServoNull.byte.msb);
           sprintf (Out, "Servo null: %x %x", ee_rd (0x12), ee_rd(0x13));
           outport (0x81, ServoNull.byte.lsb);
           outport (0x82, ServoNull.byte.msb);
          }
    break;
   case 'U':   /* >1MU2. */ /* set unit number to 2 */
    strncpy (chvalue, (In+4), 1);
    chvalue[1] = '\0';
    ee_wr (0x10, atoi (chvalue));
    sprintf (Out, ">1MU%1d.\0", ee_rd (0x10));
    break;
  }
}

PosLoad (char *In, char *Out)
{
 char chvalue[8];
 char **pchvalue;
 long value;
 int value1, index, index2, offset;
 float CycTime;
 float TempFloat1, TempFloat2;

 if (*(In+3) == 'S')
  {
   strncpy (chvalue, (In+4), 4);
   chvalue[4] = '\0';
   value1 = atoi (chvalue);

   if (value1 == -1)  /* >1ES__-1. */
         {
          sprintf (Out, ">ES%5ld%5ld.", gActPosition, gActVelocity);
          return;
         }
   else
         if (value1 == -2)  /* >1ES__-2. */
          {
           sprintf (Out, ">ES%5ld%5d.", gActPosition, Actuation.word);
           return;
          }
         else
          if ((value1 >= 0) && (value1 < PointNumber))
           {
            sprintf (Out, ">ES%5d%5d%4d%4d%1d.",
                     PointList[value1].toX,
                     PointList[value1].toY,
                     PointList[value1].Velocity,
                     PointList[value1].TimeSlices,
                     PointList[value1].PIOmode);
            return;
           }
   sprintf (Out, "!ES ERROR");
```

```
      return;
    }

  if (*(In+3) == 'R')
    {                                   /* replace pt 0000 */
     /* >1ER0000123456987654000. pos=123456,velo=987654,pio=000 */
     sprintf (Out, "OK");
     return;
    }

  if (*(In+3) == 'L')
    {       /* >1EL123451234598760. pos=12345,velo=9876,pio=0 */
     strncpy (chvalue, (In+4), 1);
     chvalue[1]= '\0';
     index = atoi (chvalue);

     for (index2 = 0; index2 < index;)
            {
             offset = index2 * 15;
             strncpy (chvalue, In + (offset+5), 5);
             chvalue[5] = '\0';
             value = atoi (chvalue);

             if ((value > MaxLimits))
               PointList[PointNumber+index2].toX = MaxLimits;
             else
               PointList[PointNumber+index2].toX = (int)value;

             strncpy (chvalue, In +(offset+10), 5);
             chvalue[5] = '\0';
             value = atoi (chvalue);

             if ((value > MaxLimits))
               PointList[PointNumber+index2].toY = MaxLimits;
             else
               PointList[PointNumber+index2].toY = (int)value;

             strncpy (chvalue, In + (offset+15), 4);
             chvalue[4] = '\0';
             value = atoi(chvalue);

             if ((value == 0) && (UseVelocityControl == OFF))
               PointList[PointNumber+index2].Velocity = 200;
             else
               PointList[PointNumber+index2].Velocity = (int)value;

             PointList[PointNumber+index2].PIOmode = atoi ((In + (offset+19)));

             if (PointList[PointNumber+index2].Velocity != 0)
               {
                if (PointNumber == 0)
                      {
                       PointList[PointNumber].TimeSlices = 0;
                      }
         else
           {
#if (SIMULATION == 1)
                       printf ("PosLoad Velocity: %d\n",
                               PointList[PointNumber].Velocity);
#endif
                       TempFloat1 = (float)(PointList[PointNumber+index2].toY -
                                            PointList[PointNumber-1+index2].toY);
                       TempFloat2 = (float)(PointList[PointNumber+index2].toX -
                                            PointList[PointNumber-1+index2].toX);
                  CycTime =
                        sqrt((TempFloat1*TempFloat1) + (TempFloat2*TempFloat2))
                        / (float)PointList[PointNumber+index2].Velocity;
                       PointList[PointNumber+index2].TimeSlices = CycTime * 64;
#if (SIMULATION == 1)
          printf ("TimeSlices %d\n", PointList[PointNumber].TimeSlices);
#endif
              }
            }
           else
            {
              PointList[PointNumber+index2].TimeSlices = 0;
            }
           index2++;
          }

   PointNumber += index2;
   sprintf (Out, "OK");
   return;
  }

 if (*(In+3) == 'C')
  {
   PointNumber = 0;
   ExePointNumber = 1;
   datapointer = 0;
   takedata = OFF;
   sprintf (Out, "OK");
   return;
  }

 if (*(In+3) == 'V')                    /* >1EV1. */
  {
   sprintf (Out, "OK");
   if (*(In+4) == '1')
          {
           UseVelocityControl = ON;
           /* outport (PIOCB, 0x87); */ /* enable interrupt driven */
          }
   else
          {
           UseVelocityControl = OFF;
           Reset1 = TRUE;
           /* outport (PIOCB, 0x7);  */ /* disable interrupt driven */
          }
   return;
  }
}

ExecuteMove (char *In, char *Out)
{
 datapointer = 0;
 takedata = ON;
 ExePointNumber = 1;
 BeginMove = TRUE;
 NewMove = TRUE;
}

Diagnostic (char *In, char *Out)
{
 static int indexer;

#GLOBAL_INIT
 {
  indexer = 0;
 }

 switch (*(In+3))
  {
   case '0':
          indexer = 0;
          if (BeginMove == FALSE)
```

```
              sprintf (Out, ">%4d.\0", datapointer);
             else
              sprintf (Out, "  -1\0");
             break;
      case '1':
             if (BeginMove == FALSE)
              {
               sprintf (Out, ">%u,%d,%ld,%ld.\0",
                         data[indexer].time[0], data[indexer].point,
                         data[indexer].position, data[indexer].velocity);
               indexer++;
              }
             break;
      case '2':
             if (DumpSerial == TRUE)
              DumpSerial = FALSE;
             else
              DumpSerial = TRUE;
             break;
      case '3':
             sprintf (Out, ">%d\0", PointNumber);
             break;
   }
}

ShutDown (char *In, char *Out)
{
 BYTEMODE index;

#if (SIMULATION == 1)
 plant (2,0);
#endif

 hv_wr (0);
 hv_dis();
 DI();
 inport (0x82);              /* clear the encoder */
 outport (0x81, ServoNull.byte.lsb);        /* zero the d-to-a board */
 outport (0x82, ServoNull.byte.msb);
 outport (0x41, (char)0xf);  /* pioa command */
 outport (0x41, (char)0x0);  /* set all bits for output */
 outport (0x41, (char)0x7);  /* disable interrupts */
 outport (0x40, (char)0x0);  /* pioa data */
 outport (0x43, (char)0xf);  /* piob command */
 outport (0x43, (char)0x0);  /* set all bits for output */;
 outport (0x43, (char)0x7);  /* disable interrupts */
 outport (0x42, (char)0x0);  /* piob data */
 Shutdown = ON;
 UseVelocityControl = OFF;
 sprintf (Out, "OK");
}

RevisionLevel (char *In, char *Out)
{
 BYTEMODE index;


 Control = OFF;
 Shutdown = OFF;
 BeginMove = FALSE;
 NewMove = FALSE;
 UseVelocityControl = OFF;
 Reset1 = Reset2 = ON;
 gActVelocity = 0L;
 gActPosition = 0L;
 kpp = kpi = kpd = kff = 0;
 kvp = kvi = kvd = 0;
 PointNumber = ExePointNumber = 0;
 Actuation.word = 0;
```

```
  outport (0x81, ServoNull.byte.lsb);
  outport (0x82, ServoNull.byte.msb);
  inport (0x82);
  sprintf (Out, ">unit:%d Rev beta %d.%d.", UnitNumber, VERSION, SUBVERSION);
#if (SIMULATION == 1)
  plant (2,0);
#endif
}

AnalogInput (char *In, char *Out)  /* >1L0. channel 0 */
{
  sprintf (Out, ">L%4d.", ad_rd8(atoi(In+3)));
}

nodebug HighVoltage (char *In, char *Out)    /* >1H1. on, >1H0. off */
{
  if (*(In+3) == '1')
    {
     hv_enb();
/*      sprintf (Out, "OK"); */
     /* strcpy (Out, "OK\0"); */
     *Out = 'O';
     *(Out + 1) = 'K';
     *(Out + 2) = 0;
    }
  else
    {
     hv_dis();
/*      sprintf (Out, "OK"); */
/*     strcpy (Out, "OK\0"); */
      *Out = 'O';
      *(Out+1) = 'K';
      *(Out+2) = 0;
    }
}

nodebug ChangeHighVoltage (char *In, char *Out)   /* >1V123.  port pattern 123 */
{
  char chvalue[4];
  char value;

/*  strncpy (chvalue, (In+3), 3);
  chvalue[3] = 0;

  value = atoi(chvalue); */
  value = atoi (In+3);
  HVreg[0] = value & 0x1;
  HVreg[1] = (value >> 1) & 0x1;
  HVreg[2] = (value >> 2) & 0x1;
  HVreg[3] = (value >> 3) & 0x1;
  HVreg[4] = (value >> 4) & 0x1;
  HVreg[5] = (value >> 5) & 0x1;
  HVreg[6] = (value >> 6) & 0x1;
  HVreg[7] = (value >> 7) & 0x1;

/*   sprintf (Out, "OK"); */
/*  strcpy (Out, "OK\0"); */
  *Out = 'O';
  *(Out+1) = 'K';
  *(Out+2) = 0;
}

InitPIO (char *In, char *Out)  /* >1PA0103. mode 01, control 03, on PIO A */
{
  char InChar[3];
  char mode, control;

  strncpy (InChar, (In+4), 2);
  InChar[2] = 0;
  mode = atoi (InChar);

  strncpy (InChar, (In+6), 2);
  control = atoi (InChar);

  switch (*(In+3))
   {
    case 'A':
              outport (PIOCA, ((mode << 6) & 0xf0) | 0x0f);
              outport (PIOCA, (char)control);
              sprintf (Out, "OK");
              break;
    case 'B':
              outport (PIOCB, ((mode << 6) & 0xf0) | 0x0f);
              outport (PIOCB, (char)control);
              sprintf (Out, "OK");
              break;
   }
}

OutInPIO (char *In, char *Out)  /* >1DOB000. Output on PIO B value 000,
                                              >1DIA.  Input on PIO A returns 145 */
{
 char chvalue[4];
 int value;

 chvalue[3] = 0;
 switch (*(In+3))
  {
   case 'O':
             if (*(In+4) == 'A')
              {
               strncpy (chvalue, (In+5), 3);
               value = atoi(chvalue);
               PIOstatus.PIOAmode = (char)value | (PIOstatus.PIOAmode & 0x3);
               outport (PIODA, PIOstatus.PIOAmode);
               sprintf (Out, "OK");
              }
             else
              if (*(In+4) == 'B')
               {
                strncpy (chvalue, (In+5), 3);
                value = atoi (chvalue);
                PIOstatus.PIOBmode = (char)value;
                outport (PIODB, (char)value);
                sprintf (Out, "OK");
               }
             break;
   case 'I':
             if (*(In+4) == 'A')
              {
               value = inport (PIODA);
               sprintf (Out, ">DIA%3d.", value);
              }
             else
              if (*(In+4) == 'B')
               {
                value = inport (PIODB);
                sprintf (Out, ">DIB%3d.", value);
               }
              break;
  }
}

SetGetGain (char *In, char *out)  /* >1GPP1234., Pos. Proportional to 1234
                                              " -1" to report */
{
 int value;
 char chvalue[5];
```

```
strncpy (chvalue, (ln+5), 4);
chvalue[4] = '\0';

value = atoi (chvalue);

switch (*(ln+3))
 {
  case 'V':
        switch (*(ln+4))
         {
          case 'F':
           if (value == -1)
                 {
                  sprintf (out, ">GVF%4d.", (int)kff*100);
                  return;
                 }
           else
                 {
                  Reset1 = Reset2 = ON;
                  kff = (float)value/100.0;
                  sprintf (out, "OK");
                 }
           break;
          case 'P':
           if (value == -1)
                 {
                  sprintf (out, ">GVP%4d.", kvp);
                  return;
                 }
           else
                 {
                  Reset1 = Reset2 = ON;
                  kvp = value;
                  sprintf (out, "OK");
                 }
           break;
          case 'I':
           if (value == -1)
                 {
                  sprintf (out, ">GVI%4d.", kvi);
                  return;
                 }
           else
                 {
                  Reset1 = Reset2 = ON;
                  kvi = value;
                  sprintf (out, "OK");
                 }
          break;
         case 'D':
          if (value == -1)
           {
                 sprintf (out, ">GVD%4d.", kvd);
                 return;
           }
          else
           {
                 Reset1 = Reset2 = ON;
                 kvd = value;
                 sprintf (out, "OK");
           }
          break;
         }
        break;
  case 'P':
        switch (*(ln+4))
         {
          case 'P':
                if (value == -1)
                        {
                         sprintf (out, ">GPP%4d.", (int)kpp);
                         return;
                        }
                else
                        {
                         Reset1 = Reset2 = ON;
                         kpp = (float)value;
                         sprintf (out, "OK");
                        }
                break;
              case 'I':
                if (value == -1)
                        {
                         sprintf (out, ">GPI%4d.", (int)kpi);
                         return;
                        }
                else
                        {
                         Reset1 = Reset2 = ON;
                         kpi = (float)value;  /* WAS 10000 */
                         sprintf (out, "OK");
                        }
                break;
              case 'D':
                if (value == -1)
                        {
                         sprintf (out, ">GPD%4d.", (int)kpd);
                         return;
                        }
                else
                        {
                         Reset1 = Reset2 = ON;
                         kpd = (float)value;
                         sprintf (out, "OK");
                        }
                break;
            }
     }
}

nodebug ControlLaw (char *In, char *out)  /* >1C1. on, >1C0. off */
{
 if (*(In+3) == '0')
   {
    HV6 = 0;
    hv_dis ();
    BeginMove = OFF;
    NewMove = FALSE;
    Control = OFF;
    takedata = OFF;
    UseVelocityControl = OFF;
    outport (0x81, ServoNull.byte.lsb);
    outport (0x82, ServoNull.byte.msb);
/*     sprintf (out, "OK"); */
/*    strcpy (out, "OK\0"); */
    *out = 'O';
    *(out+1) = 'K';
    *(out+2) = 0;
   }
 else
  if (*(In+3) == '1')
    {
            hv_enb ();
            HV6 = 1;
            Control = ON;
            Reset1 = Reset2 = ON;
/*          sprintf (out, "OK"); */
/*    strcpy (out, "OK\0"); */
     *out = 'O';
     *(out+1) = 'K';
     *(out+2) = 0;
     }
}

DtoAOut (char *In, char *out)  /* >1A4321. 4321 on DtoA */
{
  char chvalue[5];
  BYTEMODE value;

  Control = OFF;

  strncpy (chvalue, (In+3), 4);
  chvalue[4] = '\0';

  value.word = atoi (chvalue);
  outport (0x81, value.byte.lsb);
  outport (0x82, value.byte.msb);
  sprintf (out, "OK");
}

/*=====================================================================

Position loop!

This task generates the actuation using PID.

communicates with the velocity loop thru the shared variable PseudoVelo

=====================================================================*/
nodebug task1()
{
  static long ActPos, ActVelocity;
  static float DeltaPErr0, DeltaPErr1, DeltaPErr2;
  static float ipActuation;
  static long DesVelo;
  static int TimePeriods;
  static float DesPos;
  static int LastPoint;
  static long dResult, NewPos, EndPos;
  static BYTEMODE RealActuation;
  static int result;
  static float dAbsPos[5];
  static long OldgActPosition;
  static int index, RollOver;
  static unsigned int lo0, lo1, hi0, hi1;
  static float yPosIncrement, xPosIncrement;
  static float yPosBegin, xPosBegin, PrevNewPos;

#GLOBAL_INIT
 {
   ActPos  = ActVelocity = 0L;
   DesPos = EndPos = 0;
   DeltaPErr0 = DeltaPErr1 = DeltaPErr2 = 0;
   DesVelo = 0L;
   ipActuation = 0;
   TimePeriods = 0;
   LastPoint = FALSE;
   RollOver = 0;
   result = 0;
   gActPosition = 0;
   dAbsPos[0] = dAbsPos[1] = dAbsPos[2] = dAbsPos[3] = 0L;
   index = 0;
 }

 OldgActPosition = gActPosition;
```

```
#if (SIMULATION == 0)
 do
   {
    DI();
    lo0 = inport (0x81);
    hi0 = inport (0x80);   /* stabilize results */
    lo1 = inport (0x81);
    hi1 = inport (0x80);
    EI();
   }
 while ((lo0 != lo1) || (hi0 != hi1));
 result = ((hi1 << 8) & 0xff00) | lo1;
#else
 result = plant (1, 0);
#endif

 gActPosition = 5588.0 * p2sin (16.1125 + (0.00409091 * (float)result));
 dAbsPos[1] = dAbsPos[0];
 dAbsPos[0] = gActPosition - OldgActPosition;
 gActVelocity = (long)((dAbsPos[0] + dAbsPos[1]) * 32.0 );

 if (gActPosition > AbsLimits)
   {
    outport (0x81, ServoNull.byte.lsb);
    outport (0x82, ServoNull.byte.msb);
    Control = OFF;
   }

 if (Control == OFF)
   {
    PseudoVelo = 0;
    ipActuation = 0;
    return;
   }

 ActPos = gActPosition;  /* transfer to local variables */
 ActVelocity = gActVelocity;

 if (Reset1)
   {
    DeltaPErr2 = DeltaPErr1 = DeltaPErr0 = 0;
    ipActuation = 0;
    DesPos = ActPos;
    NewPos = ActPos;
    EndPos = ActPos;
    DesVelo = 0;
    TimePeriods = 0;
    BeginMove = NewMove = FALSE;
    UseVelocityControl = OFF;
    Reset1 = OFF;
    ExePointNumber = PointNumber = 0;
   }

#if (SIMULATION == 1)
 gettimer (BegTime);
#endif

 if (BeginMove == TRUE)
   {
    LastPoint = FALSE;
    if (NewMove == TRUE)  /* allows for interrupted move */
            {
             NewMove = FALSE;
             TimePeriods = 0;
             if (UseVelocityControl == ON)
               DesVelo = PointList[0].Velocity;
            }
    if (((TimePeriods--) <= 1) && (UseVelocityControl == OFF))
            {
              if (ExePointNumber >= PointNumber)
               {
                ExePointNumber = PointNumber;
                yPosBegin = PointList[ExePointNumber-1].toY;
                xPosBegin = PointList[ExePointNumber-1].toX;

                EndPos = sqrt ((yPosBegin * yPosBegin) +
                                  (xPosBegin * xPosBegin));
                DesVelo = 0;
                yPosIncrement = 0;
                xPosIncrement = 0;
                BeginMove = FALSE;
               }
              else
               {
                if (PointList[ExePointNumber].TimeSlices != 0)
                      {
                       TimePeriods = (int)PointList[ExePointNumber].TimeSlices;
                       yPosIncrement = (PointList[ExePointNumber].toY -
                                          PointList[ExePointNumber-1].toY) /
                                 (float) TimePeriods;

                       xPosIncrement = (PointList[ExePointNumber].toX -
                                          PointList[ExePointNumber-1].toX)
                                 / (float)TimePeriods;
                      yPosBegin = PointList[ExePointNumber-1].toY;
                      xPosBegin = PointList[ExePointNumber-1].toX;
                       DesPos = ActPos;
                      }
                else
                      {
                      TimePeriods = 0;
                      yPosBegin = PointList[ExePointNumber].toY;
                      xPosBegin = PointList[ExePointNumber].toX;
                      yPosIncrement = xPosIncrement = 0;
                      DesPos = ActPos;
                      DesVelo = 0;
                      }
               }
              HV7 = (PointList[ExePointNumber].PIOmode);
              ExePointNumber++;
              if (ExePointNumber == PointNumber) LastPoint = TRUE;
             }

      yPosBegin += yPosIncrement;
      xPosBegin += xPosIncrement;
      PrevNewPos = DesPos;
      DesPos = sqrt ((xPosBegin * xPosBegin) + (yPosBegin * yPosBegin));
      DesVelo = (DesPos - PrevNewPos) * 64;
      if ((LastPoint == TRUE) && (TimePeriods < 5)) DesVelo = 0;
     }
    else
     {
      yPosIncrement = xPosIncrement = 0;
      DesPos = EndPos;
     }

#if (SIMULATION == 1)
 /*  printf ("time: %d Despos: %f\n", TimePeriods, DesPos); */
#endif

  DeltaPErr2 = DeltaPErr1; /* generate time history - 2 steps back */
  DeltaPErr1 = DeltaPErr0;
  DeltaPErr0 = DesPos - ActPos;

  ipActuation +=
   (((float)kpp * (DeltaPErr0 - DeltaPErr1)) +
    ((float)kpi * (DeltaPErr0)) +
    ((float)kpd * (DeltaPErr0 - (DeltaPErr1+DeltaPErr1) + DeltaPErr2)) +
    (kff * (DesVelo - ActVelocity)));

 #if (SIMULATION == 1)
  gettimer(EndTime);
 #endif

  if (UseVelocityControl == ON)
   PseudoVelo = DesVelo;
  else
   {
    PseudoVelo = ipActuation;

    if (PseudoVelo > (long)65504)
          PseudoVelo = 65504;
    else
          if (PseudoVelo < -65504)
            PseudoVelo = -65504;

    RealActuation.word = (int)(PseudoVelo >> 5);

    Actuation.word = RealActuation.word;

    RealActuation.word += D2AOFFSET;

#if (SIMULATION == 0)
    DI();
    k_lock();
    outport (0x81, (char)(RealActuation.byte.lsb));
    outport (0x82, (char)(RealActuation.byte.msb));
    k_unlock();
    EI();
#else
    plant (0, RealActuation.word);
    printf ("D,V,A,A: %f %ld %ld %d %d %d\n", DesPos, DesVelo, gActPosition,
                 RealActuation.word, EndTime[0], BegTime[0]);
#endif
   }
}

/*=================================================================
This task takes sensor data.
=================================================================*/

nodebug task2()
{
 static int index;

#GLOBAL_INIT
 {
  index = 0;
 }

 if (Shutdown == TRUE) return;
 hitwd();

 if (takedata == ON)
  {
   if (datapointer == 0) index = 0;

   gettimer (data[datapointer].time);
   data[datapointer].position = gActPosition;
   data[datapointer].velocity = gActVelocity;
   data[datapointer].point = ExePointNumber;

   if (BeginMove == FALSE)
         {
          if (index > 5)
            takedata = OFF;
          else
```

```
            index++;
          }

    if (datapointer++ > 395) takedata = OFF;
   }

  if ((PIOstatus.PIOAmode & 0x2) == 0x0)
   PIOstatus.PIOAmode |= 0x2;
  else
   PIOstatus.PIOAmode &= 0xfd;

  outport (PIODA, PIOstatus.PIOAmode);
}

/*=====================================================================

=====================================================================*/

nodebug task0()
{
  char OldValue, NewValue;
#GLOBAL_INIT
  {
   OldValue = 0;
   NewValue = 0;
  }

  NewValue = HVreg[0] | (HVreg[1] << 1) | (HVreg[2] << 2) |
   (HVreg[3] << 3) | (HVreg[4] << 4) | (HVreg[5] << 5) |
   (HVreg[6] << 6) | (HVreg[7] << 7);

  if (OldValue != NewValue)
   {
    hv_wr (NewValue);
    OldValue = NewValue;
   }
}

#JUMP_VEC NMI_VEC NMI_int

interrupt retn NMI_int()
{
  Shutdown = TRUE;
  Control = OFF;
  outport (0x81, ServoNull.byte.lsb);
  outport (0x82, ServoNull.byte.msb);
  hv_dis();
  while (1)
   {
    hitwd();
    if (!powerlo()) return;
   }
}

void FatalErrorHandler (unsigned code, unsigned address)
{
  outport (0x81, ServoNull.byte.lsb);
  outport (0x82, ServoNull.byte.msb);
  Shutdown = TRUE;
  Control = OFF;
  hv_dis();
  while (1);  /* stall until reset by watch dog */
}

float p2cos (float x)
{
  return (p2sin (90.0 - x));
}
```

```
/*=============================================================
PROCEDURE: p2sin

PARAMETERS: float Y

RETURNS: float

METHOD: computes sin(Y) by:
     sin (y + dy) = (sin y)(cos dy) + ([(cos x)/57.2958])(dy)
     where Y = y + dy, y = int(Y), dy = frac(Y), and
     the parameters are found from a lookup table. result is good
     to about 5 places.

VARIABLES:
     sinx are the values of sin(y) where y varies between 0->90
     cosdx are the values of cos(dy) where dy varies between
              0->1 in 0.01 increments
     cosxd are the values of [(cos y)/57.2958] where y varies
              between 0->90
     ALL fractional values have been shifted by multiplying by
              65535 to obtain integers.
==============================================================*/

nodebug float p2sin (float y)

{
 static unsigned int sinx[] =
               {0x0000,0x0478,0x08EF,0x0D66,0x11DB,
                0x1650,0x1AC2,0x1F33,0x23A1,0x280C,
                0x2C74,0x30D9,0x3539,0x3996,0x3DEE,
                0x4242,0x4690,0x4AD9,0x4F1B,0x5358,
                0x578E,0x5BBE,0x5FE6,0x6407,0x681F,
                0x6C30,0x7039,0x7438,0x782F,0x7C1C,
                0x8000,0x83D9,0x87A8,0x8B6D,0x8F27,
                0x92D5,0x9679,0x9A10,0x9D9B,0xA11B,
                0xA48D,0xA7F3,0xAB4B,0xAE97,0xB1D4,
                0xB504,0xB826,0xBB39,0xBE3E,0xC134,
                0xC41B,0xC6F2,0xC9BA,0xCC73,0xCF1B,
                0xD1B3,0xD43B,0xD6B2,0xD919,0xDB6E,
                0xDDB3,0xDFE6,0xE208,0xE418,0xE616,
                0xE803,0xE9DD,0xEBA5,0xED5B,0xEEFE,
                0xF08F,0xF20D,0xF377,0xF4CF,0xF614,
                0xF746,0xF864,0xF96F,0xFA67,0xFB4B,
                0xFC1B,0xFCD8,0xFD81,0xFE17,0xFE98,
                0xFF06,0xFF5F,0xFFA5,0xFFD7,0xFFF5,
                0xFFFF};

static unsigned int cosdx[] =
               {0xFFFF,0xFFFF,0xFFFF,0xFFFF,0xFFFF,
                0xFFFF,0xFFFF,0xFFFF,0xFFFF,0xFFFF,
                0xFFFF,0xFFFF,0xFFFF,0xFFFF,0xFFFF,
                0xFFFF,0xFFFF,0xFFFF,0xFFFF,0xFFFF,
                0xFFFF,0xFFFF,0xFFFF,0xFFFE,0xFFFE,
                0xFFFE,0xFFFE,0xFFFE,0xFFFE,0xFFFE,
                0xFFFE,0xFFFE,0xFFFE,0xFFFE,0xFFFE,
                0xFFFE,0xFFFE,0xFFFE,0xFFFE,0xFFFD,
                0xFFFD,0xFFFD,0xFFFD,0xFFFD,0xFFFD,
                0xFFFD,0xFFFD,0xFFFD,0xFFFD,0xFFFD,
                0xFFFD,0xFFFC,0xFFFC,0xFFFC,0xFFFC,
                0xFFFC,0xFFFC,0xFFFC,0xFFFC,0xFFFC,
                0xFFFB,0xFFFB,0xFFFB,0xFFFB,0xFFFB,
                0xFFFB,0xFFFB,0xFFFB,0xFFFA,0xFFFA,
                0xFFFA,0xFFFA,0xFFFA,0xFFFA,0xFFFA,
                0xFFF9,0xFFF9,0xFFF9,0xFFF9,0xFFF9,
                0xFFF9,0xFFF8,0xFFF8,0xFFF8,0xFFF8,
                0xFFF8,0xFFF8,0xFFF7,0xFFF7,0xFFF7,
                0xFFF7,0xFFF7,0xFFF7,0xFFF6,0xFFF6,
                0xFFF6,0xFFF6,0xFFF6,0xFFF5,0xFFF5,
                OxFFF5};

static unsigned int cosxd[] =
                {0x478,0x478,0x477,0x476,0x475,0x473,0x472,
                 0x46F,0x46D,0x46A,0x466,0x463,0x45F,0x45A,
                 0x456,0x451,0x44B,0x446,0x440,0x439,0x433,
                 0x42C,0x425,0x41D,0x415,0x40D,0x404,0x3FB,
                 0x3F2,0x3E8,0x3DF,0x3D4,0x3CA,0x3BF,0x3B4,
                 0x3A9,0x39D,0x391,0x385,0x379,0x36C,0x35F,
                 0x352,0x345,0x337,0x329,0x31B,0x30C,0x2FD,
                 0x2EE,0x2DF,0x2D0,0x2C0,0x2B0,0x2A0,0x290,
                 0x280,0x26F,0x25E,0x24D,0x23C,0x22B,0x219,
                 0x207,0x1F5,0x1E3,0x1D1,0x1BF,0x1AC,0x19A,
                 0x187,0x174,0x161,0x14E,0x13B,0x128,0x115,
                 0x101,0x0EE,0x0DA,0x0C7,0x0B3,0x09F,0x08B,
                 0x078,0x064,0x050,0x03C,0x028,0x014,0x000};

static float fremainder, x;
static unsigned int whole;

x = y;
if (x < 0)
 {
  do
   {
        x = x + 360;
   }
  while (x < 0);
 }


if (x <= 90.0)
 {
  whole = (int)x;
  fremainder = (x - whole);

  retum ((float)((((unsigned long)sinx[whole]  *
                       (unsigned)cosdx[(int)(fremainder * 100.0)]) +
                      ((unsigned long)cosxd[whole] *
                       (unsigned)(fremainder * 65535)))
                     * 2.328377E-10));
 }
else
 if (x <= 180)
  {
   x = 180.0 - x;
   whole = (int)x;
   fremainder = (x - whole);

   retum ((float)((((unsigned long)sinx[whole]  *
                          (unsigned long)cosdx[(int)(fremainder * 100.0)]) +
                         ((unsigned long)cosxd[whole] *
                          (unsigned long)(fremainder * 65535)))
                     * 2.328377E-10));
  }
else
 if (x <= 270)
  {
   x = x - 180.0;
   whole = (int)x;
   fremainder = (x - whole);

   retum ((float)((((unsigned long)sinx[whole]  *
                          (unsigned long)cosdx[(int)(fremainder * 100.0)]) +
                         ((unsigned long)cosxd[whole] *
                          (unsigned long)(fremainder * 65535)))
                     * (-2.328377E-10)));
  }
else
```

```
   if (x <= 360)
     {
      x = 360.0 - x ;
      whole = (int)x;
      fremainder = (x - whole);

      return ((float)((((unsigned long)sinx[whole]  *
                                        (unsigned long)cosdx[(int)(fremainder * 100.0)]) +
                                       ((unsigned long)cosxd[whole] *
                                        (unsigned long)(fremainder * 65535)))
                              * (-2.328377E-10)));
     }
 return (-2);
}

#if (SIMULATION == 1)

#define FLOWGAIN 0.1

long plant (int service, int input)

{
 static float position;

 if (service == 1)
   return ((long)position);
 else
   if (service == 2)
     {
          position = 0.0;
          return;
     }

 position += ((float)(input - 2047) * FLOWGAIN);
}

#endif
```

Appendix H

Source Code Listing for End Effector SBC

```
#include <stdio.h>

#define KEYPAD_SIZE 24
#define LK_LINES 4
#define LK_COLS 20
#define LK_BLINK 1
#define ON 1
#define OFF 0
#define FWD 1
#define REV 0
#define FALSE 0
#define TRUE 1

#define VERSION 2
#define SUBVERSION 7

#define CSAMPLE 900      /* clock periods: 512HZ */
#define CTIME 0.001953  /* clock time */

#define D2AOFFSET 2072
#define DEADBAND 300
#define ACTSCALE 1

/*** defines for RS232 communication ***/
#define IBAUD   1200        /* baud rate
                        without modem => 19200,9600, 4800, etc   */
#define TBUFSIZE 384        // size of transmit buffer
#define RBUFSIZE 384        // size of receive buffer
#define CR '\x0d'

int task0(), task1(), task2(), backgnd();
/* int (*Ftask[4])()={task0, task1, task2, backgnd}; */
int (*Ftask[2])()={task2, backgnd};


/*
#define NTASKS 4
#define TASK0 0
#define TASK1 1
#define TASK2 2

*/
#define NTASKS 2
#define TASK2 0

typedef union bytemode
  {
   int word;
   struct ByteStruct
     {
       char lsb;
       char msb;
     } byte;
  } BYTEMODE;

/*** Structures ***/
struct CmmndFormat
{
 char *Cmmnd;    /* command string - pad with 0 for fill-in-the-blanks */
 char ComLength; /* transmission length in bytes */
 char RespLength;/* command response length */
 char VarCommand;/* reserved for future use. Leave 0 */
};

struct CmmndFormat InitCmmnds[] = {

 {"",1,0,0},            /* 0: send two carriage returns to */
 {"",1,0,0},            /* 1: autobaud the SR233 */
 {"W00",4,0,0},          /* 2: send two carriage returns to */
 {"W00",4,0,0},          /* 3: autobaud both motor controllers */
 {"W00O 0A0H",10,0,0},     /* 4: set up handshaking */
 {"W00/B 0",8,0,0},       /* 5: initialize motor drivers */
 {"W00/B 2",7,0,0},       /* 6: set encoder initial value */
 {"W00B 3",8,0,0},        /* 7: HI,LO,HI,LO == 10, where bit 2 is */
 {"W00/B 4",8,0,0},       /* 8: the low bit and bit 5 is the high bit */
 {"W00B 5",8,0,0},        /* 9: possible values are 0 to 15. */
 {"W00/B 1",8,0,0},       /* 10: latch encoder value */
 {"W00B 1",7,0,0},        /* 11: */
 {"W00B 2",7,0,0},        /* 12: reset all user bits high before move */
 {"W00B 3",7,0,0},        /* 13: */
 {"W00B 4",7,0,0},        /* 14: */
 {"W00B 5",7,0,0}};       /* 15: */

struct PointListPoint
 {
  long ListPosition;
  long ListVelocity;
  char PIOmode;
  float ListpGainScale;
  float ListiGainScale;
 };

struct PIOstruct
 {
  char PIOAmode;
  char PIOBmode;
 };

struct PointListPoint PointList[100], MotPointList[100];
shared struct PIOstruct PIOstatus;
struct CmmndFormat MotHomList[100];

long data[500][2];
int datapointer, takedata;
int PointNumber, ExePointNumber;
shared int timeBeg[3], timeEnd[3];
shared long AbsPos;
shared long Velocity, PseudoVelo;
shared int VelocityControl;
int UseVelocityControl;
int kpp, kpi, kpd;
int kvp, kvi, kvd;
shared float pGainScale, iGainScale;
shared BYTEMODE Actuation, dActuation;
shared long MaxVelo, MaxLimits, AbsLimits;
shared int ActScale;
int Control, Shutdown, Reset1, Reset2;
int UnitNumber;
char InString[255], OutString[255];
int BeginMove;

/*** Global Variables for RS232 Communication ***/
char Out232[100], In232[100];
shared int ReadDelay;
char tbuf[TBUFSIZE];    // transmit buffer
char rbuf[RBUFSIZE];    // receive buffer
char buf[RBUFSIZE + 1]; // dummy buffer for receiving a complete command
char HomingCommands[50][15];// storage for homing commands

int AnalogInput (char *, char *);
int HighVoltage (char *, char *);
int ChangeHighVoltage (char *, char *);
int InitPIO (char *, char *);
int OutInPIO (char *, char *);
int SetGetGain (char *, char*);
int ControlLaw (char *, char *);
int DtoAOut (char *, char *);
int PosLoad (char *, char *);
int ExecuteMove (char *, char *);
int TimingChange (char *, char *);
int ShutDown (char *, char *);
int RevisionLevel (char *, char *);
int MaxLimit (char *, char *);
int FlipRelay8 (char *, char *);

/*** Function Prototypes for RS232 Communication ***/
int init_232();
int TurnMotor (char *, char *);
int ClearBuf(char *, int);
int Serial232Service(char *, int, int);
int EncoderService();
unsigned int CombineBits(char *, char *, char *, char *);

root main ()
{
 _GLOBAL_INIT();

  BeginMove = FALSE;
  Control = OFF;
  Shutdown = OFF;
  takedata = OFF;
  VelocityControl = OFF;
  UseVelocityControl = OFF;
  Reset1 = Reset2 = ON;
  ExePointNumber = 0;
  Velocity = AbsPos = 0L;
  kpp = kpi = kpd = 0;
  kvp = kvi = kvd = 0;
  MaxLimits = AbsLimits = MaxVelo = 0L;
  ActScale = ACTSCALE;
  Actuation.word = 0;    /* zero! */
  dActuation.word = 0;
  pGainScale = iGainScale = 1.0;
  PIOstatus.PIOAmode = 0x1;
  PIOstatus.PIOBmode = (char) 0;
  UnitNumber = ee_rd(0x10);

  inport (0x82);                    /* clear the encoder */
  outport (0x81, 0xff);              /* zero the d-to-a board */
  outport (0x82, 0x07);
  outport (PIOCA, 0xff);             /* pioa command */
  outport (PIOCA, 0x00);              /* set all bits for output */
/*  outport (0x41, (char)0x7); */    /* disable interrupts */
  outport (PIODA, PIOstatus.PIOAmode); /* pioa data */

/*  outport (PIOCB, 0xcf);          */  /* piob command */
/*  outport (PIOCB, 0x00);          */  /* set all bits for input */;
/*  outport (PIOCB, PIOB_VEC);       */
/*  outport (PIOCB, 0x17);           */
/*  outport (PIOCB, 0xfe);          */
  /*  outport (0x43, 0x7); */        /* disable interrupts */
  /* outport (PIODB, PIOstatus.PIOBmode); */ /* piob data */
/*  outport (PIOCB, 0x7); */

  op_init_z1 (19200/1200, InString, UnitNumber);

  Reset_PBus();  /* Initialize Relay8 board */
  Stall(5000);  /* 350 ms wait required after reset */
  _GLOBAL_INIT();

  DI ();
  init_kernel ();
  run_every (TASK2, 100);
/*  run_every (TASK1, 23); */ /* 44.92 */ /* was 45 -or- 87.9 ms */
/*  run_every (TASK0, 6); */ /* 11.72 */ /* was 12 -or- 23.4 ms */
  init_timer0 (900);      /* 512 hz clock, 0.001953 seconds */
  EI ();
  backgnd ();
 }


indirect backgnd ()
{
 while (1)
 {
  if (check_opto_command() == 1)
  {
   InString[InString[1]] = '\0';
   switch (toupper(InString[4]))
   {
   case 'L':  /* analog input requested */
    AnalogInput (InString+2, OutString);
    break;
   case 'H':  /* high voltage enable/disable */
    HighVoltage (InString+2, OutString);
    break;
   case 'V':  /* high voltage change */
    ChangeHighVoltage (InString+2, OutString);
    break;
   case 'P':  /* Initialize PIO */
    InitPIO (InString+2, OutString);
    break;
   case 'D':  /* Output/Input on PIO */
    OutInPIO (InString+2, OutString);
    break;
   case 'G':  /* Change gains */
    SetGetGain (InString+2, OutString);
    break;
   case 'C':  /* Control law */
    ControlLaw (InString+2, OutString);
    break;
   case 'A':  /* DtoA output */
    DtoAOut (InString+2, OutString);
    break;
   case 'E':  /* position load */
    PosLoad (InString+2, OutString);
    break;
   case 'X':  /* execute move */
    ExecuteMove (InString+2, OutString);
    break;
   case 'I':  /* change timing interval */
    TimingChange (InString+2, OutString);
   break;
   case 'M':  /* Maximum limits */
    MaxLimit (InString+2, OutString);
    break;
   case 'S':  /* Emergency shutdown */
    ShutDown (InString+2, OutString);
    break;
   case 'R':  /* Software revision level */
    RevisionLevel (InString+2, OutString);
    break;
   case 'F':  /* Flip relay 8 */
    FlipRelay8 (InString+2, OutString);
    break;
   case 'T':  /* Turn motor */
    TurnMotor (InString+2, OutString);
   }
   replyOpto22 (OutString, strlen (OutString), 0);
   if (Shutdown) break;
  }
 }
 while (1);
}
```

```
MaxLimit (char *In, char *Out)
{
 char chvalue[8];
 long value;

 switch (*(In+3))
  {
   case 'V':  /* >1MV98765. */ /* velocity limits */
    strncpy (chvalue, (In+4), 5);
    chvalue[5] = '\0';
    MaxVelo = atol (chvalue);
    sprintf (Out, "OK");
    break;
   case 'L':  /* >1ML12345. */ /* Extension limits */
    strncpy (chvalue, (In+4), 5);
    chvalue[5] = '\0';
    MaxLimits = atol (chvalue);
    AbsLimits = MaxLimits + 200L;
    sprintf (Out, "OK");
    break;
   case 'S':  /* >1MS2. */ /* Actuator scaling */
    strncpy (chvalue, (In+4), 1);
    chvalue[1] = '\0';
    ActScale = atoi (chvalue);
    sprintf (Out, "OK");
    break;
  }
}

PosLoad (char *In, char *Out)
{
 char chvalue[8];
 long value;
 int value1;

 switch (*(In+3))
 {
  case 'S':
   strncpy (chvalue, (In+4), 7);
   chvalue[7] = '\0';
   value1 = atoi (chvalue);

   if (value1 == -1)  /* >1ES     -1. */
   {
    sprintf (Out, ">ES%7ld%7ld.", AbsPos, Velocity);
    return;
   }
   else
   if (value1 == -2)  /* >1ES     -2. */
   {
    /*    sprintf (Out, ">ES%6d.", Actuation.word);  */
    sprintf (Out, ">ES%6d.", timeEnd[0] - timeBeg[0]);
    return;
   }
   else
   if (value1 >= 0)
   {
    sprintf (Out, ">ES%7ld%7ld%3d.",
    PointList[value1].ListPosition,
    PointList[value1].ListVelocity,
    PointList[value1].PIOmode);
    return;
   }
   sprintf (Out, "OK");
   return;
   break;                              /* replace pt 0000 */
  case 'R': /* >1ER00001234567987654300O. pos=1234567,velo=9876543,pio=0 */
   strncpy (chvalue, (In+4), 4);
```

```
chvalue[4] = '\0';
value1 = atoi (chvalue);

strncpy (chvalue, (In+8), 7);
chvalue[7] = '\0';
value = atol (chvalue);

if ((value > MaxLimits) && (MaxLimits != 0L))
  PointList[value1].ListPosition = MaxLimits;
else
  PointList[value1].ListPosition = value;

strncpy (chvalue, (In+15), 7);
chvalue[7] = '\0';
value = atol(chvalue);

if ((value > MaxVelo) && (MaxVelo != 0L))
  PointList[value1].ListVelocity = MaxVelo;
else
  PointList[value1].ListVelocity = value;

if (PointList[value1].ListVelocity != 0L)
{
  if (PointList[value1].ListVelocity < 20000L)
  {
    PointList[value1].ListpGainScale = 1.8;
    PointList[value1].ListiGainScale = 0.2;
  }
  else
  if (PointList[value1].ListVelocity < 80000L)
  {
    PointList[value1].ListpGainScale = 1.4;
    PointList[value1].ListiGainScale = 0.5;
  }
  else
  {
    PointList[value1].ListpGainScale = 1.0;
    PointList[value1].ListiGainScale = 1.0;
  }
}
else
{
  PointList[value1].ListpGainScale = 1.0;
  PointList[value1].ListiGainScale = 1.0;
}

strncpy (chvalue, (In+22), 3);
chvalue[3] = 0;
PointList[value1].PIOmode = atoi (chvalue);
sprintf (Out, "OK");
break;
case 'L':  /* >1EL12345679876543000. pos=1234567,velo=9876543,pio=0 */
strncpy (chvalue, (In+4), 7);
chvalue[7] = '\0';
value = atol (chvalue);

if ((value > MaxLimits) && (MaxLimits != 0L))
  PointList[PointNumber].ListPosition = MaxLimits;
else
  PointList[PointNumber].ListPosition = value;

strncpy (chvalue, (In+11), 7);
chvalue[7] = '\0';
value = atol(chvalue);

if ((value > MaxVelo) && (MaxVelo != 0L))
  PointList[PointNumber].ListVelocity = MaxVelo;
else
  PointList[PointNumber].ListVelocity = value;
```

```
      if (PointList[PointNumber].ListVelocity != 0L)
      {
       if (PointList[PointNumber].ListVelocity < 20000L)
       {
         PointList[PointNumber].ListpGainScale = 1.8;
         PointList[PointNumber].ListiGainScale = 0.2;
       }
       else
       if (PointList[PointNumber].ListVelocity < 80000L)
       {
         PointList[PointNumber].ListpGainScale = 1.4;
         PointList[PointNumber].ListiGainScale = 0.5;
       }
       else
       {
         PointList[PointNumber].ListpGainScale = 1.0;
         PointList[PointNumber].ListiGainScale = 1.0;
       }
      }
      else
      {
       PointList[PointNumber].ListpGainScale = 1.0;
       PointList[PointNumber].ListiGainScale = 1.0;
      }

      stmcpy (chvalue, (In+18), 3);
      chvalue[3] = 0;
      PointList[PointNumber].PIOmode = atoi (chvalue);
      sprintf (Out, "OK");
      PointNumber++;
      break;
    case 'C':
      PointNumber = 0;
      ExePointNumber = 0;
      datapointer = 0;
      sprintf (Out, "OK");
      break;
    case 'V': /* >1EV1. */
      sprintf (Out, "OK");
      if (*(In+4) == '1')
      {
       /*    UseVelocityControl = ON; */
       outport (PIOCB, 0x87); /* enable interrupt driven */
      }
      else
      {
       /*    UseVelocityControl = OFF; */
       outport (PIOCB, 0x7);  /* disable interrupt driven */
      }
      break;
  }
}

ExecuteMove (char *In, char *Out)
{
 takedata = ON;
 PIOstatus.PIOAmode =
   (PointList[ExePointNumber].PIOmode & 0xfe); /* lower status flag */
 outport (PIODA, PIOstatus.PIOAmode);

 ExePointNumber = 0;
 BeginMove = TRUE;
}

#INT_VEC PIOB_VEC intrExecuteMove

interrupt reti int intrExecuteMove ()
{
 takedata = ON;

 PIOstatus.PIOAmode =
   (PointList[ExePointNumber].PIOmode & 0xfe);  /* lower status flag */
 outport (PIODA, PIOstatus.PIOAmode);

 ExePointNumber = 0;
 BeginMove = TRUE;
}


TimingChange (char *In, char *Out)
{
 int index;

 for (index=0; index < datapointer; index++)
   {
/*     printf ("\n%d,%ld,%ld", index, data[index][0], data[index][1]); */
   }
 sprintf (Out, "OK");
}

ShutDown (char *In, char *Out)
{
 BYTEMODE index;

 index.word = D2AOFFSET;
 inport (0x82);              /* clear the encoder */
 outport (0x81, index.byte.lsb);       /* zero the d-to-a board */
 outport (0x82, index.byte.msb);
 outport (0x41, (char)0xf);  /* pioa command */
 outport (0x41, (char)0x0);  /* set all bits for output */
 outport (0x41, (char)0x7);  /* disable interrupts */
 outport (0x40, (char)0x0);  /* pioa data */
 outport (0x43, (char)0xf);  /* piob command */
 outport (0x43, (char)0x0);  /* set all bits for output */;
 outport (0x43, (char)0x7);  /* disable interrupts */
 outport (0x42, (char)0x0);  /* piob data */
 Shutdown = ON;
 sprintf (Out, "OK");
}

RevisionLevel (char *In, char *Out)
{
 BYTEMODE index;

 Control = OFF;
 Shutdown = OFF;
 Reset1 = Reset2 = ON;
 Velocity = AbsPos = 0L;
 kpp = kpi = kpd = 0;
 kvp = kvi = kvd = 0;
 PointNumber = ExePointNumber = 0;
 Actuation.word = 0;
 index.word = D2AOFFSET;
 outport (0x81, index.byte.lsb);
 outport (0x82, index.byte.msb);
 inport (0x82);
 sprintf (Out, ">unit:%d Rev beta %d.%d.", UnitNumber, VERSION, SUBVERSION);
}

AnalogInput (char *In, char *Out)  /* >1L0. channel 0 */
{
 sprintf (Out, ">L%4d.", ad_rd8(atoi(In+3)));
}

HighVoltage (char *In, char *Out)   /* >1H1. on, >1H0. off */
{
 if (*(In+3) == '1')
```

```
    {
     hv_enb();
     sprintf (Out, "OK");
    }
  else
    {
     hv_dis();
     sprintf (Out, "OK");
    }
}

ChangeHighVoltage (char *In, char *Out)   /* >1V123.  port pattern 123 */
{
 char chvalue[4];

 strncpy (chvalue, (In+3), 3);
 chvalue[3] = 0;

 hv_wr(atoi(chvalue));
 sprintf (Out, "OK");
}

InitPIO (char *In, char *Out)  /* >1PA0103. mode 01, control 03, on PIO A */
{
 char InChar[3];
 char mode, control;

 strncpy (InChar, (In+4), 2);
 InChar[2] = 0;
 mode = atoi (InChar);

 strncpy (InChar, (In+6), 2);
 control = atoi (InChar);

 switch (*(In+3))
  {
   case 'A':
     outport (PIOCA, ((mode << 6) & 0xf0) | 0x0f);
     outport (PIOCA, (char)control);
     sprintf (Out, "OK");
     break;
   case 'B':
     outport (PIOCB, ((mode << 6) & 0xf0) | 0x0f);
     outport (PIOCB, (char)control);
     sprintf (Out, "OK");
     break;
  }
}

OutInPIO (char *In, char *Out)  /* >1DOB000. Output on PIO B value 000,
                                   >1DIA.  Input on PIO A returns 145 */
{
 char chvalue[4];
 int value;

 chvalue[3] = 0;
 switch (*(In+3))
  {
   case 'O':
    if (*(In+4) == 'A')
      {
       strncpy (chvalue, (In+5), 3);
       value = atoi(chvalue);
   PIOstatus.PIOAmode = (char)value | (PIOstatus.PIOAmode & 0x3);
       outport (PIODA, PIOstatus.PIOAmode);
       sprintf (Out, "OK");
      }
    else
      if (*(In+4) == 'B')
      {
        strncpy (chvalue, (In+5), 3);
        value = atoi (chvalue);
      PIOstatus.PIOBmode = (char)value;
        outport (PIODB, (char)value);
        sprintf (Out, "OK");
      }
    break;
   case 'I':
    if (*(In+4) == 'A')
     {
      value = inport (PIODA);
      sprintf (Out, ">DIA%3d.", value);
     }
    else
     if (*(In+4) == 'B')
      {
       value = inport (PIODB);
       sprintf (Out, ">DIB%3d.", value);
      }
     break;
  }
}

SetGetGain (char *In, char *out)  /* >1GPP1234., Pos. Proportional to 1234
                                   " -1" to report */
{
 int value;
 char chvalue[5];

 strncpy (chvalue, (In+5), 4);
 chvalue[4] = '\0';

 value = atoi (chvalue);

 switch (*(In+3))
  {
   case 'V':
    switch (*(In+4))
     {
      case 'P':
       if (value == -1)
        {
         sprintf (out, ">GVP%4d.", kvp);
         return;
        }
       else
        {
         Reset1 = Reset2 = ON;
         kvp = value;
         sprintf (out, "OK", kvp);
        }
       break;
      case 'I':
       if (value == -1)
        {
         sprintf (out, ">GVI%4d.", kvi);
         return;
        }
       else
        {
         Reset1 = Reset2 = ON;
         kvi = value;
         sprintf (out, "OK");
        }
      break;
     case 'D':
      if (value == -1)
       {
              sprintf (out, ">GVD%4d.", kvd);
              return;
             }
           else
             {
              Reset1 = Reset2 = ON;
              kvd = value;
              sprintf (out, "OK");
             }
           break;
          }
         break;
       case 'P':
         switch (*(In+4))
          {
           case 'P':
            if (value == -1)
             {
              sprintf (out, ">GPP%4d.", kpp);
              return;
             }
            else
             {
              Reset1 = Reset2 = ON;
              kpp = value;
              sprintf (out, "OK", kpp);
             }
            break;
           case 'I':
            if (value == -1)
             {
              sprintf (out, ">GPI%4d.", kpi);
              return;
             }
            else
             {
              Reset1 = Reset2 = ON;
              kpi = value;
              sprintf (out, "OK", kpi);
             }
            break;
           case 'D':
            if (value == -1)
             {
              sprintf (out, ">GPD%4d.", kpd);
              return;
             }
            else
             {
              Reset1 = Reset2 = ON;
              kpd = value;
              sprintf (out, "OK", kpd);
             }
            break;
          }
       }
}

ControlLaw (char *In, char *out)  /* >1C1. on, >1C0. off */
{
 if (*(In+3) == '0')
  {
   Control = OFF;
   sprintf (out, "OK");
  }
 else
  if (*(In+3) == '1')
   {
    Control = ON;
```

```
      Reset1 = Reset2 = ON;
      sprintf (out, "OK");
     }
}

DtoAOut (char *In, char *out)  /* >1A4321. 4321 on DtoA */
{
 char chvalue[5];
 BYTEMODE value;

 Control = OFF;

 strncpy (chvalue, (In+3), 4);
 chvalue[4] = '\0';

 value.word = atoi (chvalue);
 outport (0x81, value.byte.lsb);
 outport (0x82, value.byte.msb);
 sprintf (out, "OK");
}

FlipRelay8 (char *In, char *Out) /* >1F51., relay 5, status 1*/
{                              /* 1=ON, 0=OFF */
 int board;
 board=7;

 /* check to see if relay board is alive */
 if(Poll_PBus_Node(Relay_Board_Addr(board))) sprintf(Out, "OK");
 else
 {
   sprintf(Out, "Error");
   return;
 }
 /* Set or clear relay */
 Set_PBus_Relay(board,*(In+3),*(In+4));
}

/*===================================================================
This task generates the actuation using PID.
===================================================================*/
indirect task1()
{
 static long ActPos, DesPos, DesVelo;
 static int DeltaPErr0, DeltaPErr1, DeltaPErr2;
 static long dpActuation, pActuation;
 static long ipActuation;
 static long DeltaPos;
 static int TimeIntervals;
 static float initialDesVelo;

#GLOBAL_INIT
 {
   ActPos = DesPos = DesVelo = 0L;
   DeltaPErr0 = DeltaPErr1 = DeltaPErr2 = 0;
   dpActuation = pActuation = 0L;
   ipActuation = DeltaPos = 0L;
 }

 gettimer (timeBeg);

 if (BeginMove == TRUE)
  {
    BeginMove = FALSE;
    DesPos = PointList[ExePointNumber].ListPosition;
    initialDesVelo = PointList[ExePointNumber].ListVelocity;
    pGainScale = PointList[ExePointNumber].ListpGainScale;
    iGainScale = PointList[ExePointNumber].ListiGainScale;

    if (UseVelocityControl)
 {
  if (ExePointNumber == PointNumber)
    VelocityControl = OFF;
  else
    VelocityControl = ON;
 }
   if (ExePointNumber++ >= PointNumber) ExePointNumber = PointNumber;
   DeltaPos = DesPos - ActPos;
   TimeIntervals = (int) ((labs(DeltaPos) * 22.2618) / initialDesVelo);
  }
else
  {
   DeltaPos = DesPos - ActPos;
  }

if (labs(DeltaPos) < 100)
  {
   PIOstatus.PIOAmode |= 0x1;    /* signal that we are done */
   outport (PIODA, PIOstatus.PIOAmode);
   takedata=OFF;
  }

if (Reset1)
  {
   DeltaPErr2 = DeltaPErr1 = DeltaPErr0 = 0;
   ipActuation = 0L;
   dpActuation = 0L;
   Reset1 = OFF;
  }

if (Control)
  {
   DeltaPErr2 = DeltaPErr1;  /* generate time history - 2 steps back */
   DeltaPErr1 = DeltaPErr0;
   DeltaPErr0 = DeltaPos;

   dpActuation = (long)( ( ((float)kpp*pGainScale)*
                          (float)(DeltaPErr0-DeltaPErr1)) +
                    ( ((float)kpi*iGainScale)*
                          (float)(DeltaPErr0)) +
                    ( (float)kpd*(float)(DeltaPErr0 -
                                (DeltaPErr1+DeltaPErr1) +
                                DeltaPErr2)) );
   ipActuation += dpActuation;

   if (VelocityControl)
 {
  if (TimeIntervals == 0)
      {
    PseudoVelo = (long)((float)ipActuation * 0.001);
       BeginMove = TRUE;
      }
  else
   {
    PseudoVelo = (long)((float)DeltaPos * TimeIntervals * 22.2618);
    TimeIntervals--;
   }
 }
  else
 if (DesVelo != 0L)
  {
      pActuation = (long)((float)ipActuation * 0.001);

   if (pActuation > DesVelo)
        pActuation = DesVelo;
   else
     if (pActuation < -(DesVelo))
  pActuation = -DesVelo;
  }
```

```
   else
     PseudoVelo = (long)((float)ipActuation * 0.001);
    }
  else
    {
     pActuation = 0;
     ipActuation = dpActuation = 0;
    }
  gettimer (timeEnd);
}

/*=================================================================
This task takes sensor data.
=================================================================*/

indirect task2()
{
 if (takedata)
   {
    data[datapointer][0] = AbsPos;
    data[datapointer++][1] = Velocity;
    if (datapointer > 1000) datapointer = 1000;
   }

 if ((PIOstatus.PIOAmode & 0x2) == 0x0)
   PIOstatus.PIOAmode |= 0x2;
 else
   PIOstatus.PIOAmode &= 0xfd;

 outport (PIODA, PIOstatus.PIOAmode);
}

indirect task0()
{
 static long DesPos, pVelo;
 static long DeltaVErr0, DeltaVErr1, DeltaVErr2;
 static BYTEMODE RealActuation;
 static long dvActuation, vActuation;
 static unsigned int result0;
 static unsigned int result;
 static long dAbsPos[4], OldAbsPos;
 static int index, RollOver;
 static long dResult;

#GLOBAL_INIT
 {
   RollOver = 0;
   result = 0;
   result0 = 0;
   AbsPos = 0;
   dAbsPos[0] = 0;
   dAbsPos[1] = 0;
   dAbsPos[2] = 0;
   dAbsPos[3] = 0;
   DeltaVErr0 = 0;
   DeltaVErr1 = 0;
   DeltaVErr2 = 0;
   index = 0;
 }
/*  gettimer (timeBeg); */
 OldAbsPos = AbsPos;
 result = ((inport (0x80) << 8) & 0xff00) | inport (0x81);
 dResult = (long) ((long)result - (long)result0);

 if (dResult > 32000)
   RollOver--;
 else
   if (-32000 > dResult)
  RollOver++;
  result0 = result;

  AbsPos = (long)result + (long)(RollOver * 65535);

  dAbsPos[index] = AbsPos - OldAbsPos;
  if ((index++) > 2) index = 0;
  Velocity = (long)((float)(dAbsPos[0] + dAbsPos[1] + dAbsPos[2]) * 42.67);

/*  if (labs(Velocity) > (MaxVelo + 500L)) Control = OFF; */
/*  if (AbsPos > AbsLimits) Control = OFF;  */

  pVelo = PseudoVelo;  /* transfer variables to local storage */

  if (Reset2)
    {
      DeltaVErr2 = DeltaVErr1 = DeltaVErr0 = 0L;
      dvActuation = 0L;
      vActuation = 0L;
      Reset2 = OFF;
    }

  if (Control)
    {
      DeltaVErr2 = DeltaVErr1;
      DeltaVErr1 = DeltaVErr0;

      DeltaVErr0 = pVelo - Velocity;

      dvActuation = (long)(((kvp*(long)(DeltaVErr0-DeltaVErr1)) +
                        (kvi*(long)(DeltaVErr0)) +
                        (kvd*(long)(DeltaVErr0 -
                               (DeltaVErr1 + DeltaVErr1) +
                                DeltaVErr2))));
      vActuation += dvActuation;

      RealActuation.word = ((int)((float)vActuation * 0.0001));

      Actuation.word = RealActuation.word;

      RealActuation.word += D2AOFFSET;

      if (RealActuation.word > 4095)
        RealActuation.word = 4095;
      else
        if (RealActuation.word < 0)
          RealActuation.word = 0;

      outport (0x81, (char)(RealActuation.byte.lsb));
      outport (0x82, (char)(RealActuation.byte.msb));
    }
  else
    {
      dvActuation = vActuation = 0;
      RealActuation.word = D2AOFFSET;
    }
/*  gettimer (timeEnd);     */
}


/*** Initialization Function ***/
int init_232()
{
  int i;
  int mode = 4;          /* 1 stop bit */
                      /* no parity */
                      /* 8 data bits */
                      /* even parity */
                      /* CTS/RTS disabled */
```

```
                        /* set to 4 for CTS off */

 reload_vec(14,Dz0_circ_int); /* installs interrupt vector at runtime */
 Dreset_z0rbuf(); /* reset receive and transmit buffers */
 Dreset_z0tbuf();
 Dinit_z0(rbuf,tbuf,RBUFSIZE,TBUFSIZE,mode,IBAUD/1200,0,0);

 /* initialize the SMC */
 for(i=0;i<=15;i++)
 {
  sprintf(Out232,"%s%c",InitCmmnds[i].Cmmnd,CR);
  Dwrite_z0(Out232,InitCmmnds[i].ComLength);
 }
 ClearBuf(Out232,98);
 ClearBuf(In232,98);
 ReadDelay=IBAUD/2;
 lk_init_keypad();
 lk_setbeep(500);
}

int ClearBuf(char in[100], int cnt)
{
 static int index,count;

 count=atoi(cnt);
 for(index=0;index<count;index++) in[index] = '\0';
}

int Serial232Service(char *In, int ComLen, int RespLen)
{
 int err, cnt1;
 char cnt[5];

 ClearBuf(InString,40);
 if(ComLen) /* if writing */
 {
  if(Dwrite_z0(In,ComLen)); /* check for serial error */
  else return 0; /* write not successful */
  In[ComLen-1]='\0';
  In[ComLen]='\0';
 }
 if(RespLen) /* if reading */
 {
  if(ComLen) lk_tdelay(ReadDelay);
      /* delay if just wrote to smc */
  err=cnt1=0;
  do /* look for string length longer than one.  if looked more
      than 20 times, exit. */
  {
   if(cnt1>=20) /* took too long to get a response */
   {
    /*lk_setbeep(1000);
    lk_printf("Took too long\n");*/
    return 0;
   }
   if(err=Dread_z0(In,CR))
   {
    if(strlen(In)>1) err=1;
    else /* only carriage return in return */
    {
     err=0;
     /*lk_setbeep(300);
     lk_printf("Only CR\n");*/
    }
   }
   cnt1++;
  }
  while(err == 0);
 }
```

```
  return 1;
}

int EncoderService(char *Out, char mot[])
{
  unsigned int value;
  int i;
  char a[40],b[40],c[40],d[40];

  #GLOBAL_INIT
  {
    ClearBuf(a,40);
    ClearBuf(b,40);
    ClearBuf(c,40);
    ClearBuf(d,40);
  }

  sprintf(Out232,"W0%cY 200%c",mot,CR);
  if(Serial232Service(Out232, 9,0));
  else return 0;
  sprintf(Out232,"W0%cX%c",mot,CR);
  if(Serial232Service(Out232, 5,0));
  else return 0;
  lk_tdelay(ReadDelay);
  sprintf(Out232,"");
  if(Serial232Service(Out232, 0,8));
  else return 0;
  lk_printf("after first read\n");
  strncpy(a,(Out232+2),5);
  if(Serial232Service(Out232, 0,8));
  else return 0;
  lk_printf("after second read\n");
  strncpy(b,(Out232+2),5);
  if(Serial232Service(Out232, 0,8));
  else return 0;
  lk_printf("after third read\n");
  strncpy(c,(Out232+2),5);
  if(Serial232Service(Out232, 0,8));
  else return 0;
  lk_printf("after fourth read\n");
  strncpy(d,(Out232+2),5);
  value=CombineBits(a,b,c,d);
  sprintf(Out,"%u",value);
  lk_printf("E=%u\n",value);
  return 1;
}

/*** CombineBits ***************************************************
  This function uses the formula:
  value=(x>>(p+1-n))&~(~0<<n).  It gets n bits from position
  p of x.  For example, if (x,p,n)=(x,5,4), value would return
  the four bits in positions 5,4,3,2. */
/*******************************************************************/
unsigned int CombineBits(char *a, char *b, char *c, char *d)
{
  unsigned int value, value1, value2, value3, value4;

  value1 = (unsigned)atoi(a);
  value2 = (unsigned)atoi(b);
  value3 = (unsigned)atoi(c);
  value4 = (unsigned)atoi(d);

  value1 = (value1 >> 2) & ~(~0 << 4);
  value2 = (value2 >> 2) & ~(~0 << 4);
  value3 = (value3 >> 2) & ~(~0 << 4);
  value4 = (value4 >> 2) & ~(~0 << 4);
  value2<<=4;
  value3<<=8;
  value4<<=12;
```

```
 value=value1|value2|value3|value4;
 return value;
}


TurnMotor (char *In, char *Out)
/*    V - >1T0VF010.
         Sets values F, R, or S on motor0
         >1T0VP10000.
         Sets P, A, or N on motor0, P = 10000
      C - >1T0CG.
         Sends a command to motor0
         G = Go
         I = Initialize
      L - >1T0LP11234987. Load Memory.
         Motor 0, Pos #1 = 1234, Vel #1 = 987
         >1T0LX 200.
         Motor 0, Execute memory at loc 200
         >1T0LH1R 100.
         Motor 0, Homing Routine command #1, R 100
      Q - >1T0QP.
         Queries for F,R,S,E,N */
{
 int i, j, value, ret, PointNum, length;
 static int index;
 long lvalue;
 char chvalue[10], mot, dir;

 #GLOBAL_INIT
 {
  for(i=0;i<50;i++) for(j=0;j<15;j++) HomingCommands[i][j]='\0';
 }
 ClearBuf(Out232,30); /* place null chars in Out232 */
 strncpy (chvalue, In+3, 1);
 chvalue[1]='\0';
 value = atoi(chvalue);
 if(value==0) mot = 'D';
 else if(value==1) mot = 'E';
 else mot = '0';

 switch (In[4])
 {
  case 'V':
   if((In[5]=='F')||(In[5]=='R')||(In[5]=='S'))
   { /* value changes of F,R,S */
    strncpy (chvalue, In+6, 3);
    chvalue[3] = '\0';
    value = atoi (chvalue);
    sprintf (Out232, "W0%c%c %d%c",mot,In[5],value,CR);
    Serial232Service (Out232, 9,0);
   }
   else if((In[5]=='P')||(In[5]=='A')||(In[5]=='N'))
   { /* value changes of P,A,N */
    strncpy (chvalue, In+6, 5);
    chvalue[5] = '\0';
    lvalue = atol (chvalue);
    sprintf (Out232, "W0%c%c %ld%c",mot,In[5],lvalue,CR);
    Serial232Service (Out232, 11,0);
   }
   break;
  case 'C': /* send a command to motor */
   switch (In[5])
   {
    case 'G':
     sprintf(Out232, "W0%cG%c",mot,CR);
     Serial232Service(Out232, 5,0);
     break;
    case 'I':
     init_232(); /* RS232 initialization routine */
```

```
      break;
     case 'R':
                                                          if (dir == '+') dir='-';
      else dir='+';
           sprintf(Out232, "W0%c%c%c",mot,dir,CR);
           Serial232Service(Out232, 5,0);
           break;
   }
  case 'L':
   switch (In[5])
   {
    case 'X':
      sprintf(Out232, "W0%cY 200%c",mot,CR);
      Serial232Service(Out232, 9,0);
      sprintf(Out232, "W0%cX%c",mot,CR);
      Serial232Service(Out232, 5,0);
      break;
    case 'P':
      sprintf(Out232, "W0%c0%c",mot,CR);
      Serial232Service(Out232, 5,0);
      sprintf(Out232, "W0%cQ%c",mot,CR);
      Serial232Service(Out232, 5,0);
      break;
    case 'H':
     strncpy (chvalue, In+6, 1);
     chvalue[1]='\0';
     PointNum = atoi(chvalue);
     if(PointNum==0) /* dump point list to smc */
     {
       sprintf(Out232, "W0%cY 10%c",mot,CR);
       Serial232Service(Out232, 8,0);
       sprintf(Out232, "W0%cE%c",mot,CR);
       Serial232Service(Out232, 5,0);
       for(i=1;i<=index;i++)
       {
        ClearBuf(Out232,30); /* place null chars in Out232 */
        sprintf(Out232, "W0%c%s\0%c",mot,
          HomingCommands[(PointNum-1)*15],CR);
        value=strlen(Out232);
        length=strlen(HomingCommands[(PointNum-1)*15])+4;
        lk_printf("%d,%d,",length,value);
        Serial232Service(Out232, length,0);
       }
       sprintf(Out232, "W0%c0%c",mot,CR);
       Serial232Service(Out232, 5,0);
       sprintf(Out232, "W0%cQ%c",mot,CR);
       Serial232Service(Out232, 5,0);
       return;
     }
     else
     {
      In[In[0]]='\0';
      In[strlen(In)-1]='\0';
      strcpy (HomingCommands[(PointNum-1)*15], In+7);
      lk_printf("%s,",HomingCommands[(PointNum-1)*15]);
      index=PointNum;
     }
     break;
    case 'E':
                                                         sprintf(Out232, "W0%cY 200%c",mot,CR);
     Serial232Service(Out232, 9,0);
     sprintf(Out232, "W0%cE%c",mot,CR);
     Serial232Service(Out232, 5,0);
     break;
  }
  break;
 case 'Q':
  if((In[5]=='F')||(In[5]=='R')||(In[5]=='S'))
  {
      sprintf(Out232, "W0%c? %c%c",mot,In[5],CR);
      Serial232Service(Out232, 7,7);
      lk_printf("%s\n",Out232);
    }
    if((In[5]=='P')||(In[5]=='N'))
    {
      sprintf(Out232, "W0%c? %c%c",mot,In[5],CR);
      Serial232Service(Out232, 7,10);
      lk_printf("%s\n",Out232);
    }
    if(In[5]=='E')
    {
      EncoderService(Out232,mot);
      lk_printf("E=%s\n",Out232);
    }
    break;
  }
  strncpy(Out,Out232,40);
}
```

Appendix I

End Effector SBC Commands

The CY545 motion controller receives commands as a string of ASCII characters, of the form W0xy z, where "x" denotes the motor to receive the commands ("E" sends the command to motor controlling yaw, "D" sends the command to the motor controlling the pitch of the paint gun, and "0" sends the command to both motors), "y" denotes the command to be sent (a list of available commands appears in the CY545 users manual, but the most frequently used commands are listed below), and "z" is a number of either 8 bits or 24 bits, depending on the command (not all commands require a number following them, thus a value for "z" is not always used). For example, to move the paint gun motor to position 300 using previously defined values for speed, acceleration, and initial speed, the full command would be W0DP 300 (here "P" is the command used to send the motor to a specified position).

Commands sent to the motion controller may either be executed one at a time, or queued and written to the controller's EEPROM. The sending of commands to the motion controller is handled by the slave code. Each command issued by the slave code is of the form >1Twxyz, where "w" specifies the motor ("0" denotes motor "E", "1" denotes motor "D", and "2" denotes both motors), "x" specifies the type of command to be sent (the command types are as follows: "V" indicates a value to be sent (such as a change in motor speed, or a command to send the motor to a specific location), "C" indicates a command (such as the initialization routine, or a change in motor direction), "Q" queries the value of a defined parameter (speed, acceleration, position, etc.), and "L" indicates a command involving the loading of points into the EEPROM), "y" denotes the specific command to be sent (the commands are the same as those described above), and "z" is a numerical value of either 8- or 24-bits.

To load points into the EEPROM for subsequent execution, it is first necessary to initialize the motors to be used, with the command string >1TxCI, where "x" defines which motor is to be initialized. The values for "x" are described above. After initialization, the motion controller must be prepared to queue commands, i.e., it must be informed that the commands to followed are to be written to the EEPROM and not to be executed immediately. This is accomplished by the command string >1TxLP. Next, the commands to be queued are entered one at a time as detailed above. The commands may be parameter changes, positions to be moved to, or queries for parameter values, etc. When the commands to be queued have been entered, the controller must be informed that the queuing is complete. This is accomplished with the command string >1TxLX. After this command has been entered, the program will have been successfully written to the system's EEPROM, starting at value 200 in memory by default. In order to change the starting memory location, changes must be made to the slave code. To begin executing the commands thus written, the command string >1TxLX must be sent. The queued commands will then run in sequence until the end of the queue has been reached. At this point, the current memory location will be the location of the final executed command.

Example: To write a program for motor 1 that will set the speed value to 25, the acceleration to 30, the initial speed to 10, and then move the motor to position 1300, the following command strings would be sent:

>1T1CI	(initializes motor 1)
>1T1LP	(begins queuing sequence)
>1T1VR25	(sets speed of motor 1 to 25)
>1T1VS30	(sets acceleration of motor 1 to 30)
>1T1VF10	(sets initial speed of motor 1 to 10)
>1T1VP1300	(sends motor to position 1300)
>1T1LX	(ends queuing sequence)

To execute these commands, the following command string would be sent:

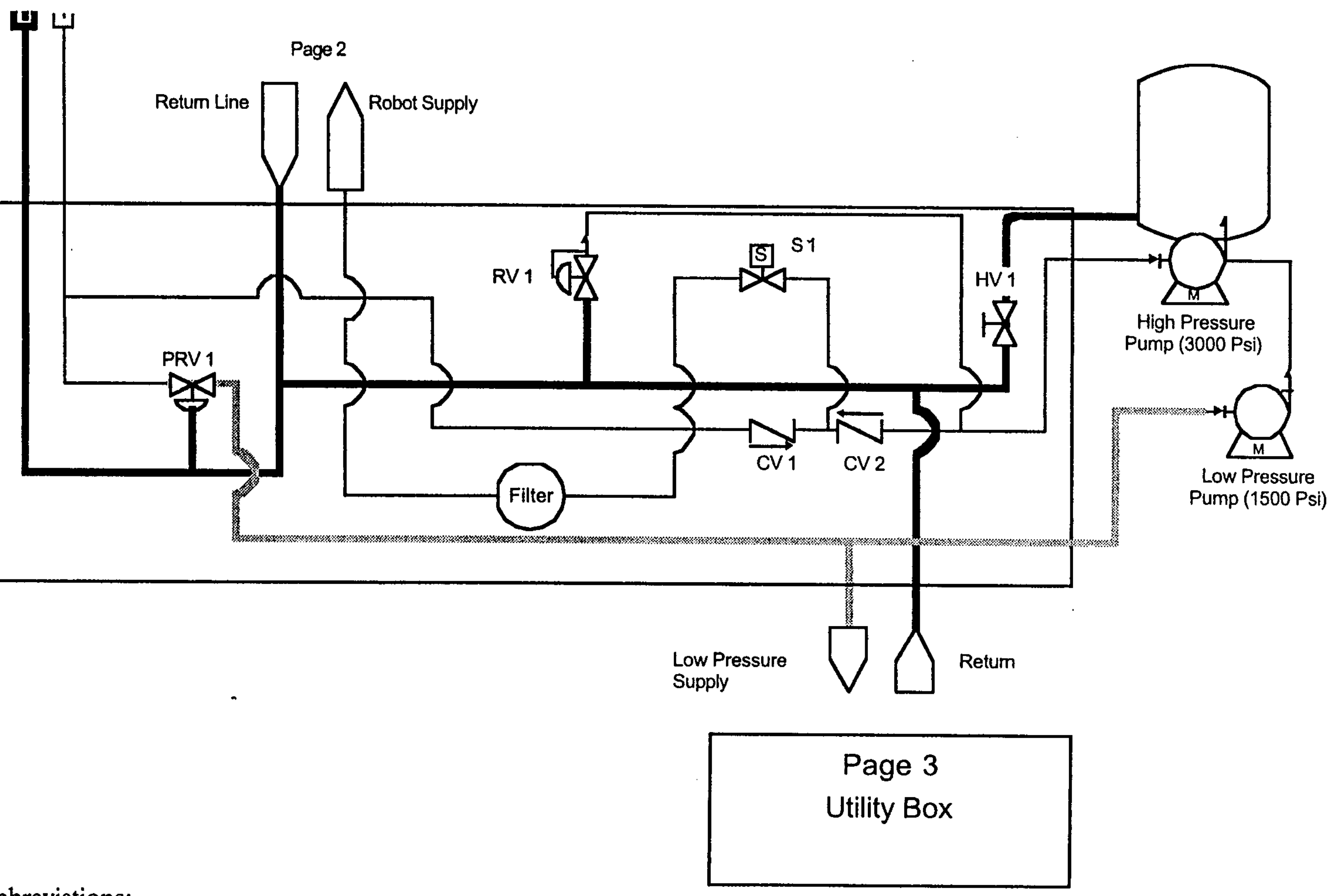
>1T1LX

After the commands had executed, the current memory location would be equal to that of the command >1T1VP1300.

Appendix J

Hydraulic System Schematic

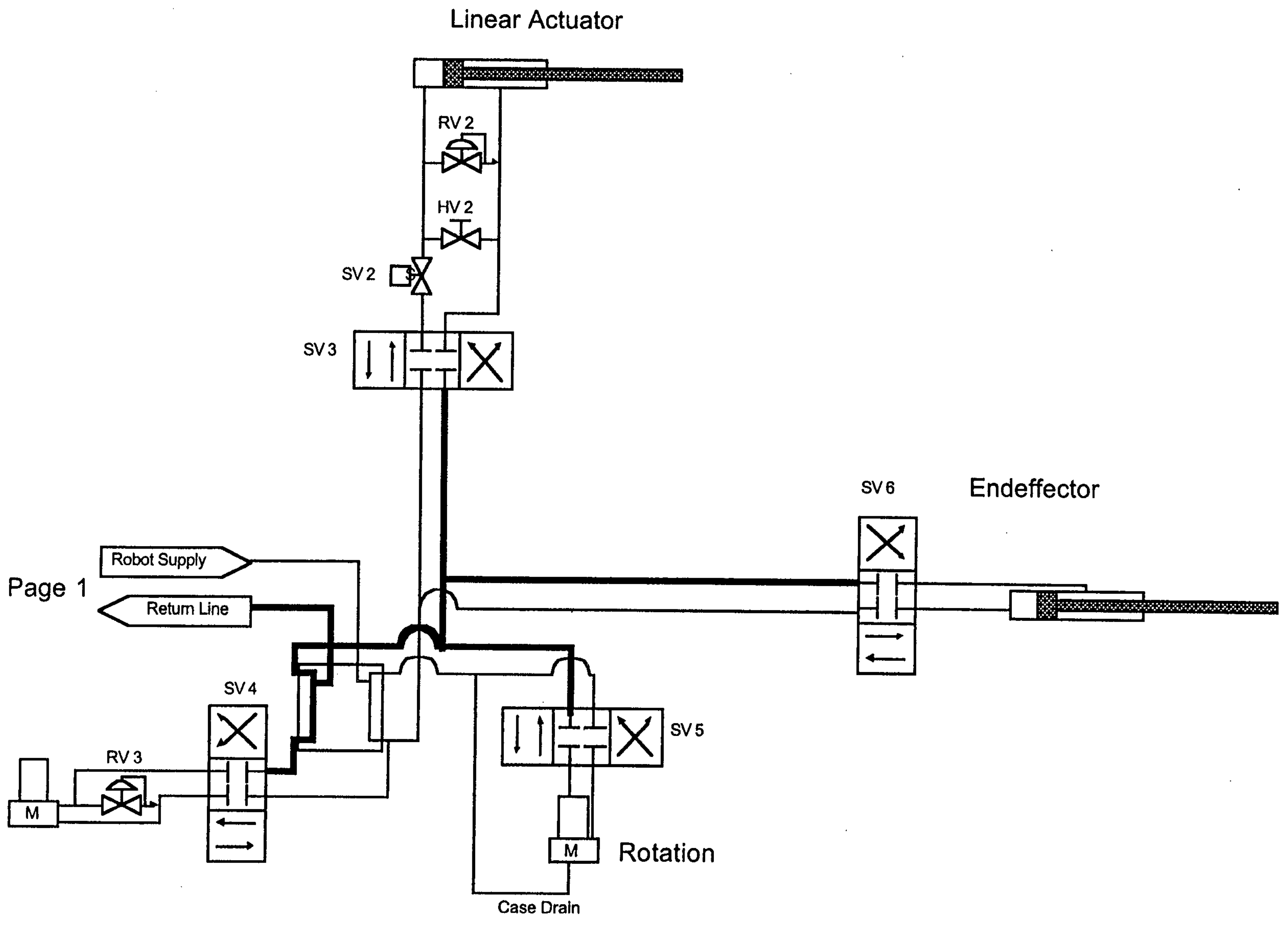
Hydraulic Schematic (Page 1 of 3)



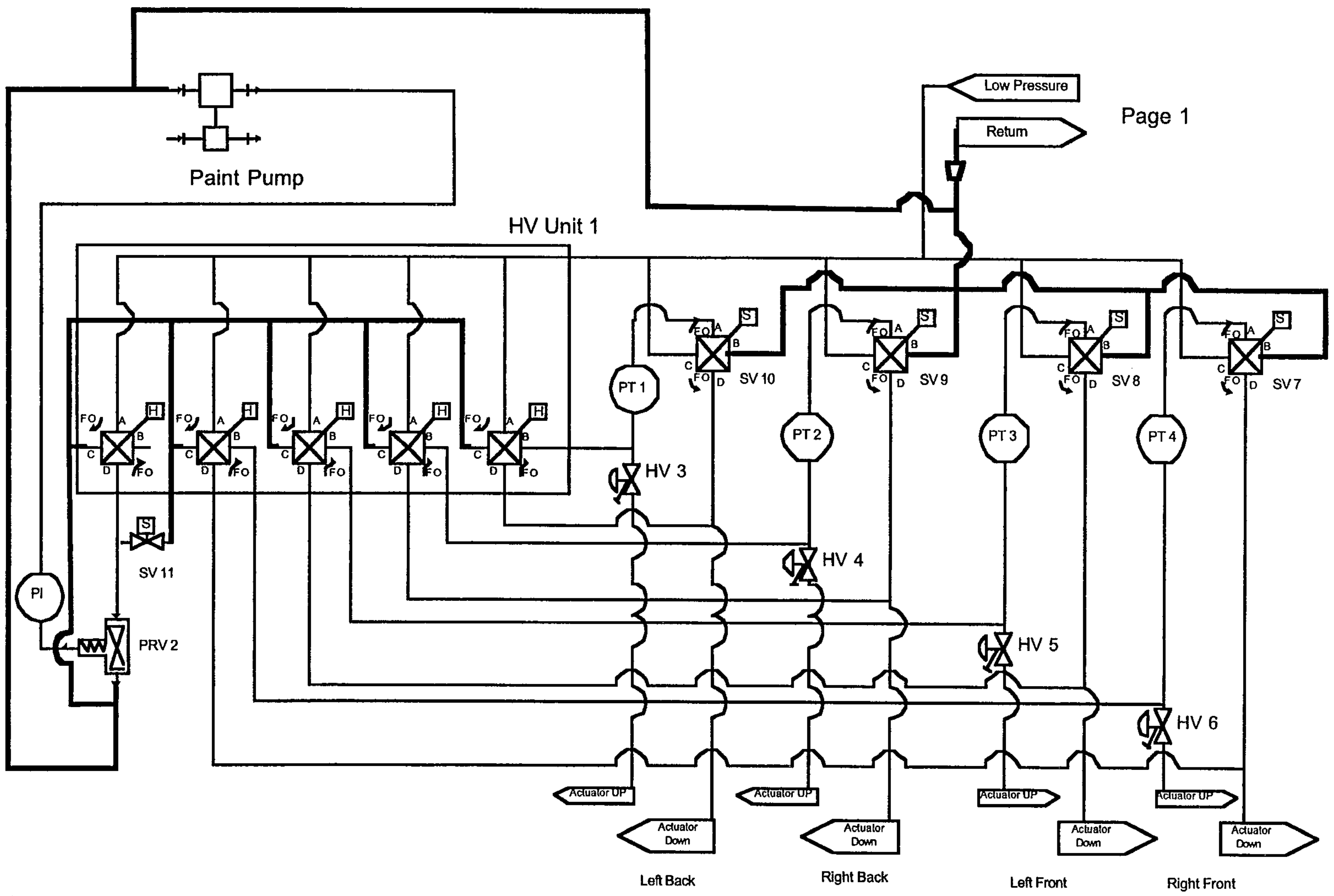
Abbreviations:

ACT	Actuator	RV	Return Valve
CV	Check Valve	SV	Solenoid Valve
HV	Hand Valve	PI	Pressure Indicator
PRV	Pressure Regulator Valve	PT	Pressure Transducer

Hydraulic Schematic (Page 2 of 3)



Hydraulic Schematic (Page 3 of 3)



Appendix K

Research Paper on BASR Motion Planning Software

Control Structure of the U.C. Davis Stenciling Robot

B. Ravani and P.W. Wong
U.C. Davis, Davis, CA 95616

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Abstract

At the University of California, Davis Advance Highway Maintenance and Construction Technology (AHMCT) Center, in conjunction with the California Department of Transportation (Caltrans), we have developed a very large pantograph-type robot. When a painting subsystem is mated to the robot's end-effector mounting plate, the robot system will be used to paint highway and roadway markings on the road surface. Each roadway marking consists of a message of eight (8) foot high alphanumeric characters, generally spanning the width (12 feet) of a traffic lane. This paper discusses the control system structure of the UCD/AHMCT robot, and introduces a unique way to decouple coupled kinematic motion in order to allow for simplied implementation of the robot controller.

1 Introduction

Painting roadway markings on the road surface is a tedious and hazardous maintenance procedure. To create the markings, a work crew first must section off a lane area and then layout a set of stencils corresponding to the desired message. Once everything is in place, the crew uses a paint sprayer and coats the road surface and stencils with paint. Where there are open spots in the stencil is where the paint is deposited on the surface. After a suitable drying period, the stencils are removed and the lane reopened. Each time this process is repeated, the crew is exposed to traffic hazards since the crew must leave the safety of their vehicles and work on the open roadway.

At the University of California, Davis Advanced Highway Maintenance and Construction Technology (AHMCT) Center, we have developed a very long reach pantograph-type robot (Figure 1) to accomplish the painting operations. When the unit is fully extended, it has a reach of almost 15 feet. The base can rotate approximately 270 degrees. One of the unique features of this design is that all the joint actuators are located at the base of the robot. This co-location

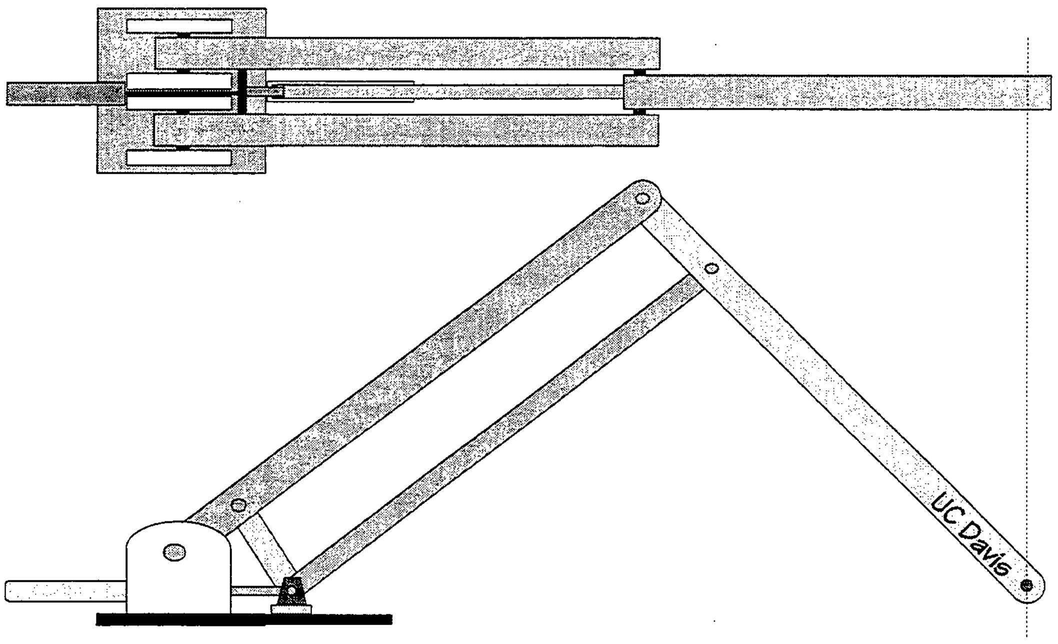


Figure 1: A Large Robot

leads to extremely high stiffness to weight ratios since the robot structure does not need to support the weight of the actuators.

As shown in Figure 2, the robot has two degrees of freedom: R and θ. The movement in the R direction is controlled by a linear hydraulic acutator, operating on the pivot of the pantograph. Motion is amplified by the pantograph mechanism according to an 8.3:1 ratio. Thus, for each inch the hydraulic actuator moves, the tool center point moves linearly 8.3 inches. Rotation of the robot arm is controlled by a hydraulic motor mounted in the base. Position of the arm is determined by two optical encoders mounted as shown in Figure 2. Note that the extension length of the arm is indirectly sensed through the rotation angle of the upper arm link.

In order to paint the roadway markings in a consistent fashion, the robot arm must move the tool center point (to which is mounted the painting mechanism) from point-to-point locations in an accurate way, as well as follow accurately a prescribed trajectory motion. The arm must follow a prescribed trajectory in order to create acceptable letter profiles with an evenly coated painted surface. The trajectory path planning is done in a separate software module that is discussed elsewhere.

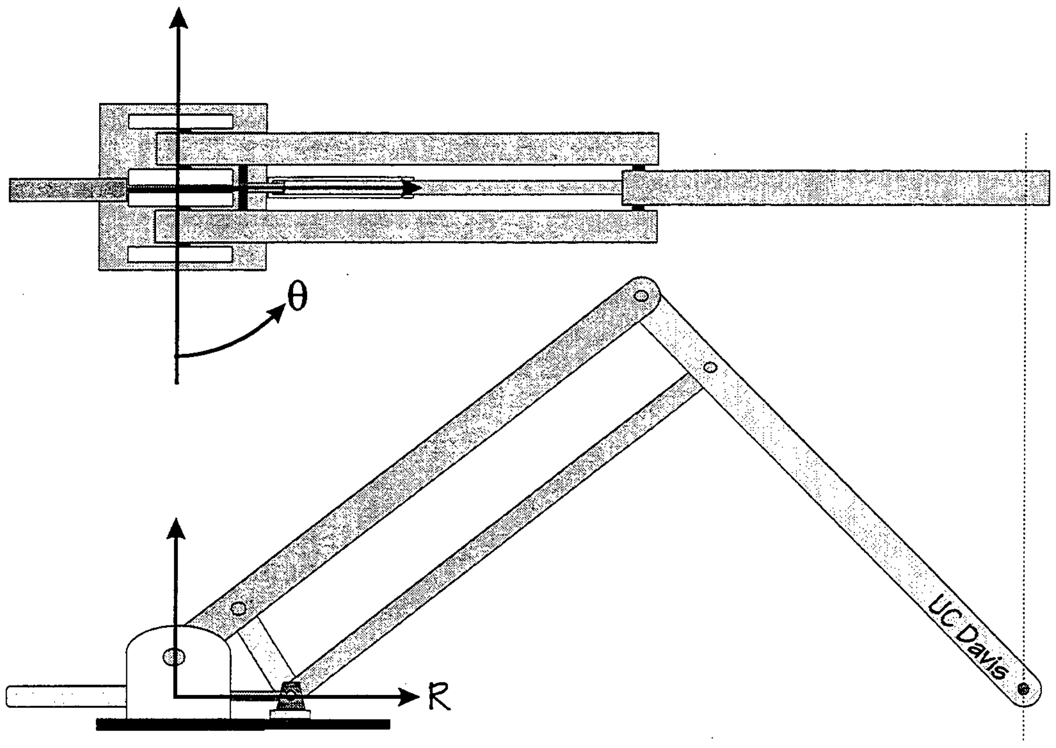


Figure 2: Degrees of Freedom

2 Arm Hardware Description

2.1 Sensor Configuration

The location of the tool center point is determined by two (2) rotary optical encoders. Each encoder is a quadrature type encoder capable of resolving forward and backward motion. The encoder resolution is 88,000 pulses per revolution or approximately 0.0041 degrees. One encoder is mounted on the shaft of the hydraulic motor and senses the rotation of the base of the arm. The other encoder is mounted on one joint to the pantograph parallelogram mechanism and senses the angle of the parallelogram. This angle is converted by software into a linear distance for the arm extension. Joint velocity is also computed by software using a finite difference approximation. Both encoders are interfaced with a custom designed encoder board. On this encoder board is an HP2020 which maintains an absolute encoder pulse count, and thus relieves the need for a computer or microcontroller to constantly monitor the encoders.

2.2 Kinematics

From Figure 3, the x, y coordinates of the tool center point is determined by the following:

$$x = Rcos(\theta)$$
$$y = Rsin(\theta)$$

where R is the length of extension and θ is the angle of rotation of the base of the arm.

Since trajectory control is necessary to create a consistently coated painted surface, accurate velocity control of motion is important. By taking time derivatives of the equations for the location of the tool center point and rearranging, we get the following:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} cos\theta & -Rsin\theta \\ sin\theta & Rcos\theta \end{bmatrix} \begin{bmatrix} \dot{R} \\ \dot{\theta} \end{bmatrix} \tag{1}$$

where the above $2x2$ matrix is known as the Jacobian.

From the above equations, it can be seen that in order to move the tool center point with a desired cartesian velocity ($\dot{x}$ and $\dot{y}$), the configuration of all the joints (θ and R) must be known to compute the necessary joint velocities ($\dot{\theta}$ and $\dot{R}$) to accomplish the desired trajectory. In other words, the joints are kinematically coupled together, since velocity profiles for individual joints cannot be computed independently of the other joint configuration information.

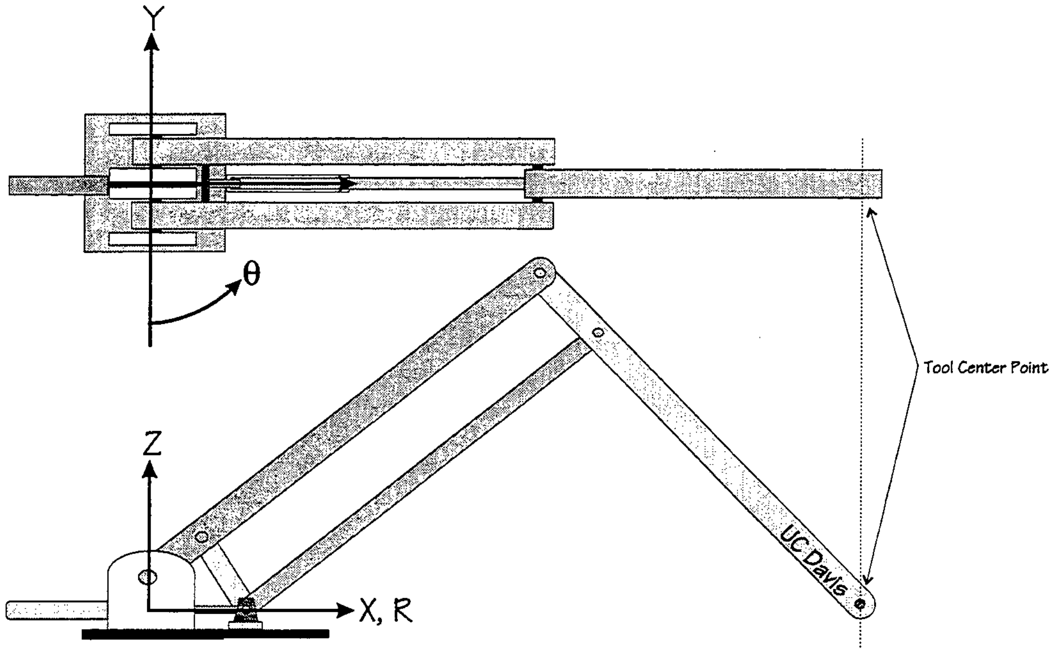


Figure 3: Arm Coordinate System

Figure Not Available.

Figure 4: Hydraulic System Schematic

2.3 Inverse Kinematics

By using the kinematic eqauations presented in Section 2.2, the inverse kinematics for the UC Davis arm mechanism can be derived. Dividing the equation for the y coordinate by the one for the x coordinate gives the following result:

$$\frac{y}{x} = tan(\theta) \tag{2}$$

or

$$\theta = tan^{-1}(\frac{y}{x}). \tag{3}$$

. From Figure 3, it can be seen that

$$R = \sqrt{(x^2 + y^2)}. \tag{4}$$

2.4 Hydraulic Control

Each arm joint motion is accomplished by using hydraulic motive power (Figure 4). For arm rotation, motion is accomplished by a hydraulic motor. For the arm extension, linear motion is created by using a hydraulic cylinder. The cylinder's motion is amplified by the pantograph mechanism. The hydraulic power to both the cylinder and the motor is controlled by a flow rate control hydraulic servo valve. By supplying electrical current to the servo valve, a directly proportional flow rate of hydraulic fluid is supplied from the hydraulic pump to the actuator. Electrical current to the servo valve is supplied from custom designed voltage-to-current (V-to-C) converters. The input to the V-to-C converter is a voltage signal from a computer controlled digital-to-analog (D-to-A) converter.

3 Arm Control System

The UC Davis arm control system is composed of a special microcontroller architecture. Instead of a uniprocessor computer control system, each joint is controlled by its own single-board microcontroller. Communiation and coordination between the joints is accomplished by low-cost and robust RS-485 serial communication local area networking.

3.1 Controller Arrangement

The UC Davis control system is a distributed processor system. However, instead of a dedicated joint processor residing in one main computer, each joint is independently controlled by its own microcontroller and signal conditioning board (Figure 5). Input/Output to the joint controllers is accomplished by a RS-485 Local Area Network (LAN) (see Section 3.2) The microcontrollers are from Z-World Engineering and are software programmable in the C language. The main CPU is from the Zilog Z-80 family and runs at 9.216 Mhz. The control software for each of the joints is contained on the microcontroller. Each of the signal conditioning boards are UC Davis custom designed and contain on-board a 12 bit digital-to-analog converter, an encoder control chip, and associated logic interface chips. Thus, to control the motion of the arm's tool center point, two (2) microcontrollers are required, one for each of the joints. Additional units are used to control the paint gun, as well as monitor the robot's hydraulic and electric subsystems. Furthermore, there is one microcontroller with a keypad that is used for user interaction and information display. Together with the joint controllers, a master/slave arrangement is formed. Commands are transferred from the keypad unit (master) to each of the joints (slave), which then execute the commands.

3.2 Networking

Master/slave controller communication is accomplished through the use of RS-485 serial communications (Figure 5). This protocol uses a two-wire interconnection scheme and has a maximum line length of approximately 5000 feet. Commands are transferred throughout the network at 19,200 bits per second. Full error correction and detection are provided on both the sending and the receiving side.

3.3 Communication Protocols

All joint controllers receive operating parameters through the RS-485 LAN interface. A command string of the form **>2A1090**. is sent through the network. The "2" in the command string is the address of the controller to which the command is directed. The letter "A" is the command to be executed, followed

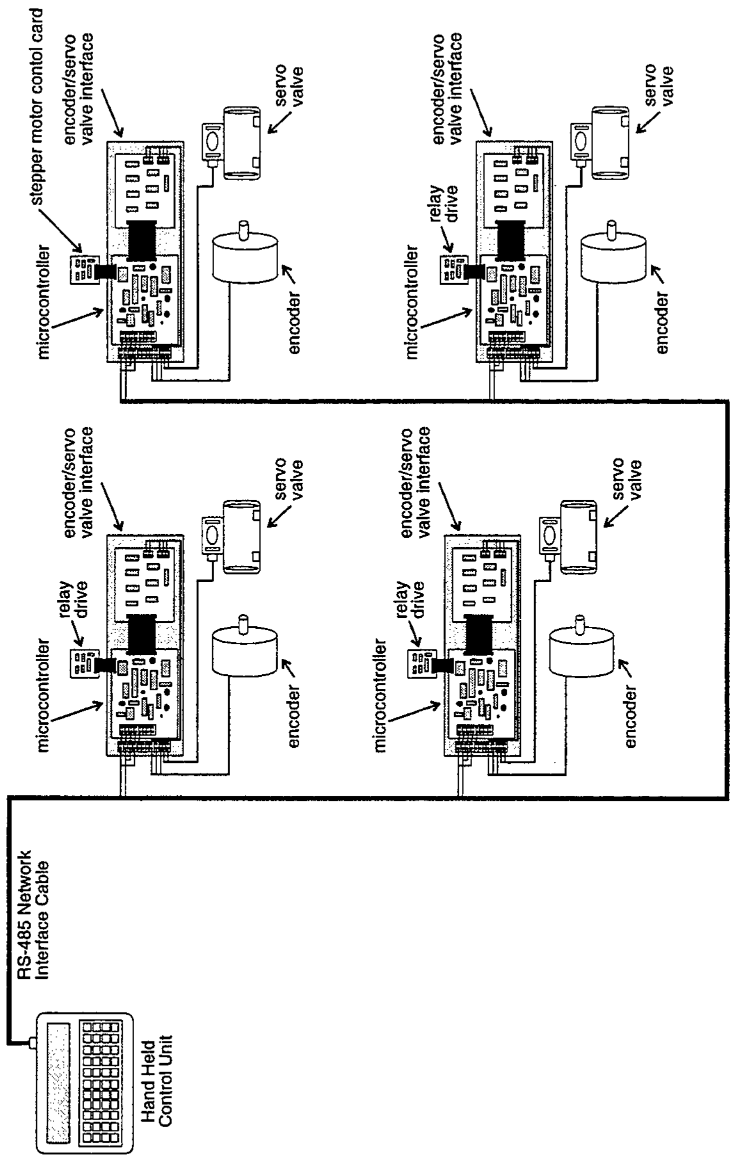


Figure 5: Control System Configuration

by "1090" which is the parameter for the "A" command. The "." marks the end of the command. Also appended automatically to the command string during network transmission is Error Correction Code (ECC) which informs the receiving controller of whether the command was corrupted in transit or not. If the command is corrupt, a retransmission is requested automatically. After the receiving controller has decoded and executed the command, it transmits the appropriate response back to the commanding unit. The response string generally looks like >**OK**. All operating parameters, from gain changes to relay driver status, is changable and obtainable through the network interface.

3.4 Control Software

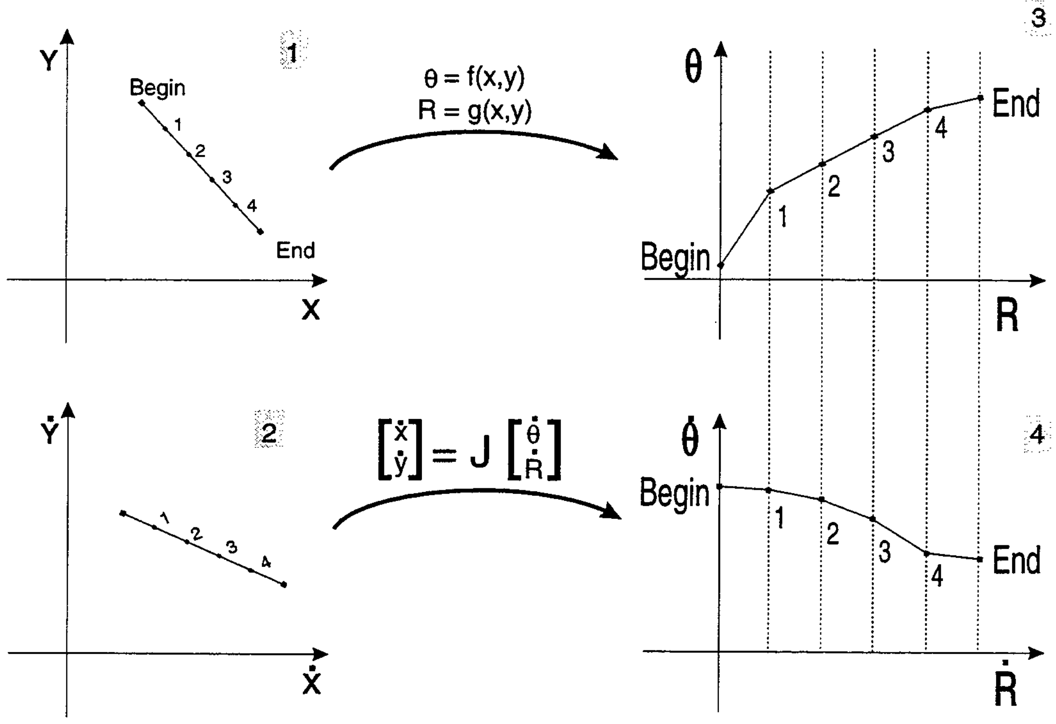
Traditional robot path and trajectory planning generally involves the use of coordinate transformations and the Jacobian to transform Cartesian space coordinates (Figure 6, graph 1) and velocities (Figure 6, graph 2) into joint coordinates (Figure 6, graph 3) and velocities (Figure 6, section 4). The joint coordinates and velocities are then fed into the robot's joint controllers and executed.

However, due to the latencies involved in inter-joint communications over the LAN, the traditional techniques cannot be used on the UC Davis system. The reason is evident when the terms in the Jacobian are examined (Equation 1). In order to compute the output joint velocities, $\dot{\theta}$ and $\dot{R}$, from the input cartesian velocities, $\dot{x}$ and $\dot{y}$, both the θ and R values of the current configuration must be known in order to complete the calculation. The UC Davis *Motion Planner* uses a different approach. Instead of using the inverse kinematics and the Jacobian to compute the joint coordinates and velocities, respectively, the UCD joint software first uses inverse kinematics to compute the joint coordinates, then derives the necessary joint velocities by taking a backwards difference time derivative of the joint coordinates. Schematically, in Figure 6, the UCD software starts at graph 1, proceeds to graph 3 (by using inverse kinematics) and then arrives at graph 4 (by using a backwards difference approximation) (Figure 7).

The control system software necessary to operate the arm consists of three parts (Figure 8): the letter path generator, motion planner, and the control law itself. Due to the distributed computing nature of the UC Davis controller architecture, the different parts operate on different microcontrollers and coordinate their activities through the network. In addition to the software that directly controls the arm movement, fault tolerance and diagnostic software is also present on each joint microcontroller.

3.4.1 Letter Path Generator (LPG)

The Letter Path Generator (LPG) is a software module that runs on the handheld interface unit. This software is responsible for interpreting user inputs and generating the trajectory in cartesian space (x and y locations, as well as $\dot{x}$ and $\dot{y}$) that the arm's tool center point must move through in order to generate the


1
Y
X
Begin
End
1
2
3
4
θ = f(x,y)
R = g(x,y)
3
θ
R
Begin
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2
Ẏ
Ẋ
$\begin{bmatrix}\dot{x}\\ \dot{y}\end{bmatrix} = J \begin{bmatrix}\dot{\theta}\\ \dot{R}\end{bmatrix}$
4
θ̇
Ṙ

Figure 6: Cartesian to Joint Space Transformations

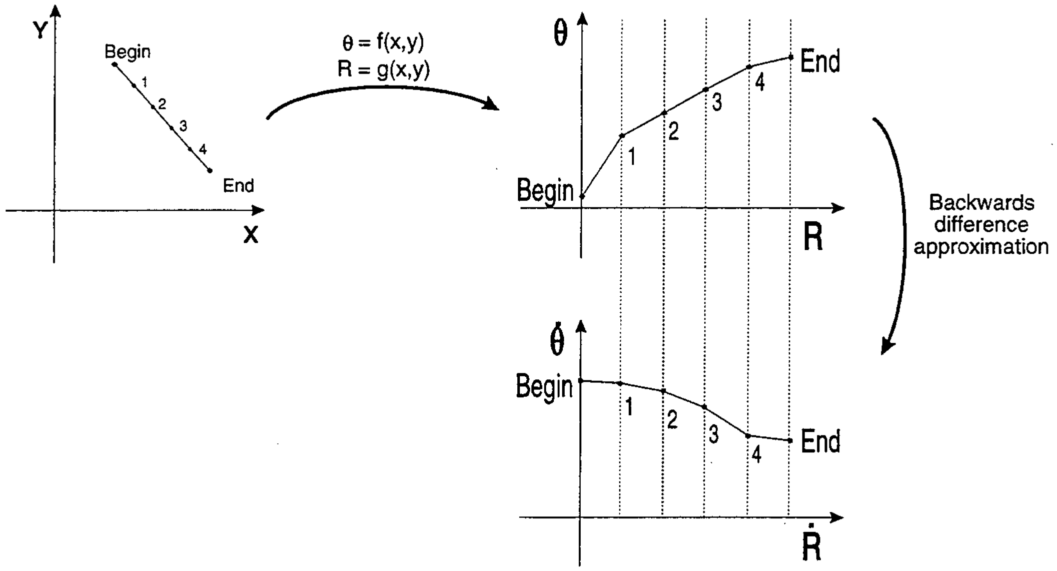

Figure 7: UC Davis Cartesian to Joint Space Transformations

desired letter shape. Once all the trajectory points have been computed, the x, y, $\dot{x}$, and $\dot{y}$ values are uploaded through the network to each of the joint microcontrollers.

3.4.2 Motion Planner

Once the joint microcontroller has received the trajectory points (Figure 9), the *Motion Planner* software on the joint controller comes into use. First, the *trajectory planner* calculates, based on the path length (s) between the trajectory points and the requested velocity (V), the cycle time for the interval. Using the cycle time for the interval, the *motion interpolator* then subdivides the path into straight line segments that correspond to a distance $\Delta s = Vx0.015625$. (Figure 10).

Since the control architecture does not allow inter-controller coummunications, individual joint microcontrollers do not have access to the other joints' configuration information, such as position and velocity. Thus, in order to complete the calculation of the inverse kinematics, the missing kinematic parameters must be estimated. The *kinematic parameter estimator (KPE)* module is used for this purpose. As the system runs, the *KPE* estimates the cartesian coordinates of the tool centerpoint. In effect, the system is generating an idealized trajectory profile for the tool centerpoint to follow. Once the estimated parameters are complete, the inverse kinematic transform (Section 2.3) equations are used to compute the joint coordinates. Depending on the joint microcontroller,

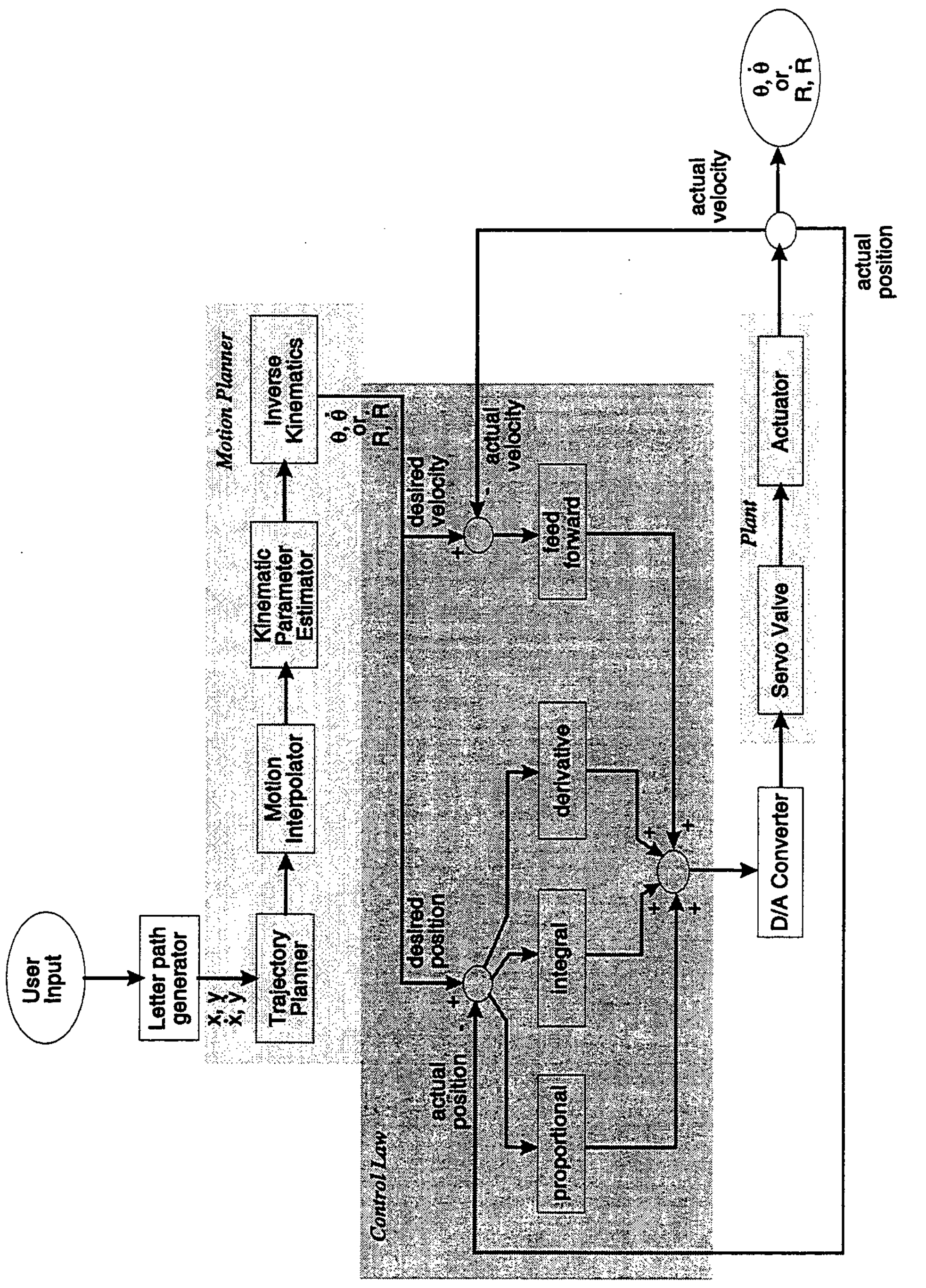

Figure 8: Control System Block Diagram

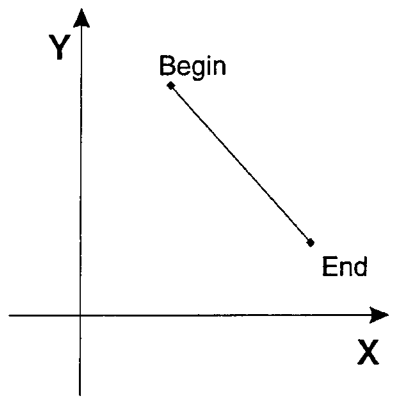

Figure 9: A Simple Two Point Path

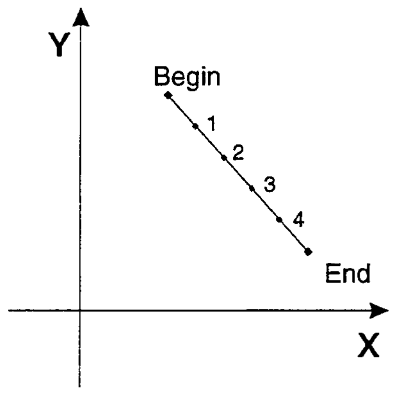

Figure 10: Path Subdivision by Motion Interpolator

either θ or R is utilized for control law input. In addition, $\dot{\theta}$ or $\dot{R}$ is computed as described earlier, and also utilized for control law input.

3.4.3 PID Control Structure

The control law used on all joint microcontrollers is the standard "velocity-form" of the descrete proportional-integral-derivative control law. However, for enhanced transcient startup and shutdown performance, the control law is modified by the addition of a velocity feedforward term. When high startup speed is required by the *motion planner*, this velocity feedforward term gives an additional actuator output boost to overcome the inertial and static friction effects within the arm mechanism. Additionally, the *motion planner* is designed so that near the end of the motion it inputs a large magnitude braking velocity

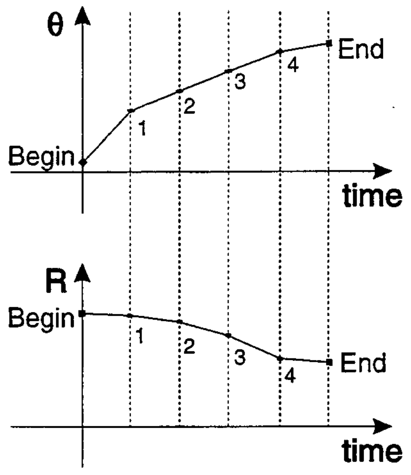

Figure 11: Joint Motion Profile After Using Estimator and Inverse Kinematics

to the control law to aid in deceleration of the arm mechanism.

3.5 Fault tolerance

Safety of the workers is paramount during operation of the robot. In addition to using engineering and design analysis to create a safe and reliable robot system design, system safety during adverse and unanticipated conditions must also be provided for. The UC Davis robot design incorporates four (4) different design features in order to create a safe design. The four design features are: power subsystem health monitoring, mechanical subsystem fault tolerance, electronic subsystem fault tolerance, and software fault tolerance.

3.5.1 Power Subsystem Health Monitoring

The UC Davis robot design incorporates a dedicated microcontroller whose sole purpose is to monitor the status of the power subsystem of the robot (Figure 12). Inputs to the microcontroller include pressure readings of the high pressure hydraulic system, the low pressure hydraulic system, differential hydraulic filter pressure, and system pneumatic pressure. Additionally, temperature readings of the engine coolant, paint heater and hydraulic oil tank are monitored by the microcontroller. Paint fluid levels are also reported to the microcontroller. If any parameter is out of specification, the microcontroller signals the hand-held control pendant that a fault condition exists. Using the RS-485 local area network, the hand controller then queries the power subsystem monitor for the fault that was detected. If the fault is serious, the hand controller then will initiate an auto-shutdown of the robot by broadcasting through the LAN that

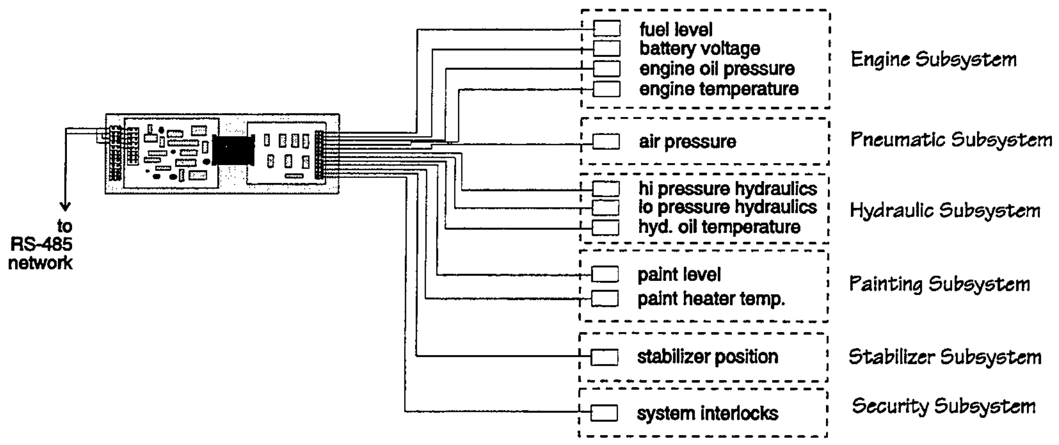

Figure 12: Health Monitoring

all joint controllers begin automatic shutdown procedures. The joint controllers will center the hydraulic servo valves, thereby stopping the flow of hydraulic oil to the robot actuators. Then the hand controller will close the main hydraulic supply valves. An informational message will flash on the display screen as to what the error condition was and what actions were taken. If the fault is not serious, but may indicate a future problem if preventive actions are not taken, a warning message will be displayed on the hand controller as a reminder to the operator that a condition exists that will provide degraded robot performance.

3.5.2 Mechanical Fault Tolerance

The UC Davis robot arm incorporates several mechanical design features to allow for fault tolerance in the event of any unanticipated mechanical failure. One of the major design rules is that all components be inactive or unpowered in the quiescent state and that a constantly supplied actuation signal be necessary to activitate the system. With the removal of the actuation signal, the system would revert back to its quiescent state. For example, although the arm links weigh several hundred pounds, the entire pantograph mechanism is gravity compensated with a counterbalance mechanism (Figure 13). With this counterbalance system, the mechanism cannot extend or retract by itself in the event that actuating force is lost due to a hydraulic hose rupture or other actuator failure. As a further backup to the counterbalance (FIgure 14), the hydraulic input to the actuator ports are closed automatically by a self-closing valve when electric power is lost. Thus, the self-closing valve traps the hydraulic oil within the actuator and locks its last position. Furthermore, the main hydraulic supply line is controlled by a spring loaded normally closed control valve. Thus, with no electric power applied to the valve, no hydraulic power is supplied to the

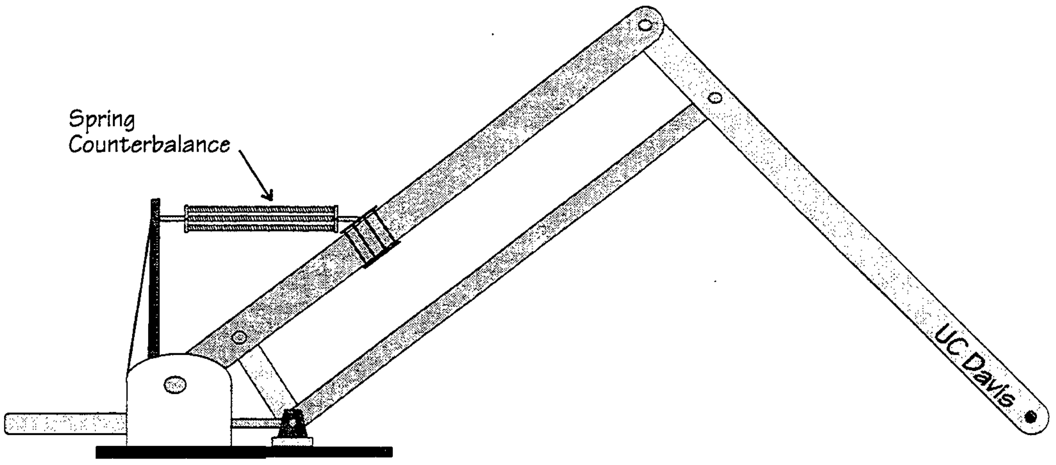

Figure 13: Mechanical Counterbalancing

system. In the event of a power failure for whatever reason to the valve, the hydraulic power will be shutoff automatically. Hydraulic relief valves are also located throughout the system. Should any hydraulic component experience any overpressure, rather than damage the component, the relief valves would open and relieve the pressure.

3.5.3 Electronic Fault Tolerance

All of the microcontrollers of the UC Davis robot are equipped with electronic fault tolerance features. The microcontroller power supplies have built in low power and power fail detection circuitry. If input power reaches a certain threshold, the detection circuitry notifies the microcontroller's main CPU. Once notified, the CPU has approximately 100 microseconds of residual power. During this time, the CPU executes a quick shutdown procedure to safe and secure the robot. This procedure involves closing the main hydraulic supply valve and centering the joint servo valves to stop the flow of hydraulic fluid to the actuators. If enough power remains, the microcontroller CPU attempts to continue to monitor the power supply to see if main power has returned to normal. If main power does return, the network command interface will refuse to execute any commands and return to the hand controller a message that a power failure or transcient had occured. If main power does not return to normal by the time the residual power has run out, when main power does eventually return, the microcontroller will re-initialize itself and become ready to accept commands in a normal fashion.

In addition to power supply monitoring, each microcontroller has independent circuitry to monitor the main CPU performance. On-board each microcon-

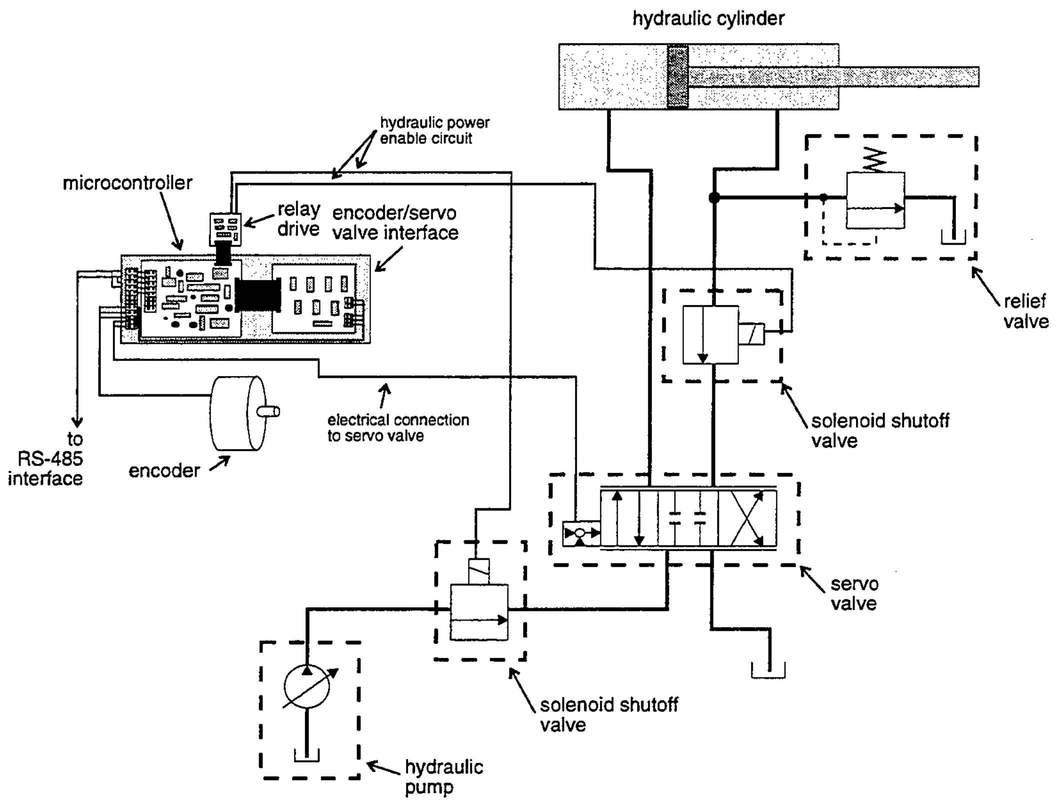

Figure 14: Hydraulic System Shutoff Valves

troller is a special "watch-dog" timer that must be reset every 2.6 milliseconds by special CPU instructions. Should the CPU be incapicitated or disabled due to memory faults, electrical interference, radiation, or other effects, the "watch-dog" will time-out, causing the CPU to be reset. Once the system has been reinitialized, it initiates an automatic shutdown of all hydraulic power. The network command interface will refuse to execute any commands, and return to the hand controller a message that a software induced reset had occured.

3.5.4 Software Fault Tolerance

The last feature for safe operation of the UC Davis robot incorporates software fault tolerance in an effort to guard against human error in coding software. Included with the control software are special software routines called "exeception handlers" that guard against unusual or abnormal software conditions. These conditions include invalid parameters to function calls or random access memory corrupted by stray memory pointers, radiation, or electromagnetic effects. Examples of invalid parameters to function calls are requesting the arc cosine of a value greater than 1.0, or division by zero. These errors occur, however infrequently, since in a real time system, it is impossible beforehand to analyse completely all the operating conditions the software may encounter. Thus, when any of the abnormal software conditions exist and the "exeception handler" is called, the system shuts down the the hydraulic power, and automatically reinitializes the system. The network command interface will refuse to execute any commands, and returns to the hand controller a message indicating a software fault had occured.

4 Conclusions

Due to careful design considerations, the AHMCT center at UC Davis has created a robust and low cost robotic stenciling system. In addition, highway worker safety is greatly increased since the workers are no longer exposed to hazardous situations on the open road.

University of California at Davis
California Department of Transportation

THE BIG ARTICULATED STENCILING ROBOT (BASR)*

Volume II

Phillip W. Wong, P.E.
Professor Bahram Ravani
Richard Blank
Jeff Hemenway
Richard McGrew
Ulrich Mueller
Dr. Walter Nederbragt
Robert Olshausen
Ken Sprott

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Final Report of Contract
RTA-65X936

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DISCLOSURE STATEMENT

Development of an Articulating Robotic Arm for Spray Painting on Roadways

BY

ROBERT HENRY OLSHAUSEN

B. S. (California Polytechnic State University, San Luis Obispo) 1988

THESIS

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DAVIS

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[illegible]

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Robert H. Olshausen
September 1996
Engineering

Development of an Articulating Robotic Arm for Spray Painting on Roadways

ABSTRACT

This thesis discusses the conceptual design of the Big Articulating Stenciling Robot (BASR) Arm that is currently under development at the University of California, Davis. This robotic arm is intended to be used to replace manual methods of spray painting words and symbols on roadways. This will eliminate the hazards of exposing maintenance workers to fast moving traffic and flying debris. Automation of this process can vastly improve maintenance worker safety and reduce restriction of highway traffic.

This thesis deals with mechanical design of BASR which is a long reach articulated robotic arm. A novel linkage design using a pantograph mechanism is used in the design of this arm to eliminate the need for carrying actuators at each joint of the robot. The entire system is designed to operate from the back of a maintenance vehicle and does not need any additional mechanisms for stowing or operating it.

CHAPTER 1 - INTRODUCTION

Highway maintenance operations are some of the most dangerous duties performed to keep the highways safe and functional. Between the years 1972 and 1988, in the state of California alone, there were 4800 highway workers seriously injured enough to keep them out of work [1]. The risks are so great that between the years 1972 and 1991 there were 47 deaths of California highway maintenance workers. One such death occurred on July 29, 1992, to a worker painting surveying markers on a section of Highway 14 in Southern California. This was a manual job that requires a worker to exit the vehicle and expose himself to traffic flow. In response to accidents like this, the Advanced Highway Maintenance and Construction Technology (AHMCT) Center at UC Davis has embarked on projects to automate highway maintenance tasks in order to remove the worker from the pavement. This thesis presents a mechanical design that can perform spray painting of words and symbols on the roadbed with the worker inside the vehicle. Accordingly, the Big Articulating Stenciling Robot (BASR), designed and developed as part of this thesis, will greatly reduce the risks to highway maintenance workers.

This thesis presents the mechanical design and development of the robotic arm, not the entire robot. To this end, parts of the robot not included will be mentioned for clarity but not discussed in-depth.

The following document is broken up into five major sections plus appendices. The first chapter will introduce the current methods for roadway stenciling that are currently in use. Additionally, this chapter will detail the objectives of the thesis. The

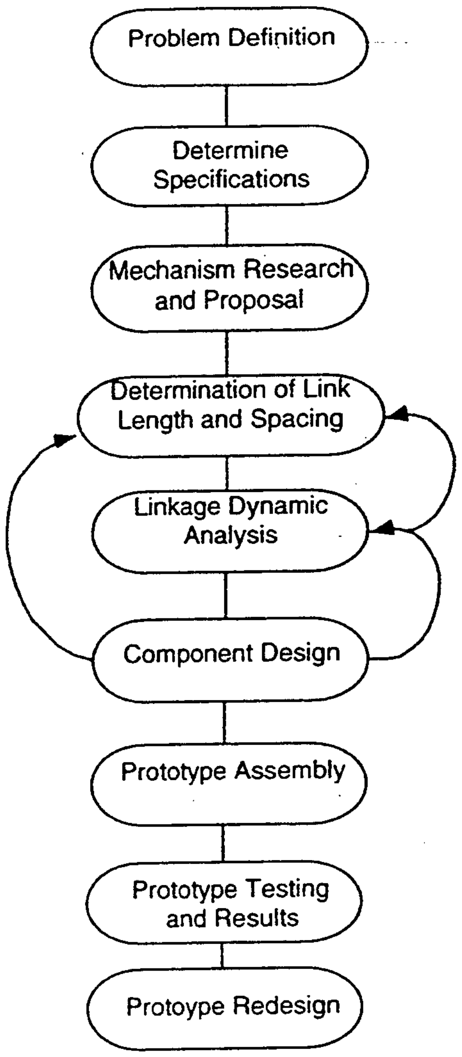

Figure 1.1 *Big Articulating Stenciling Arm Design Flowchart*

second chapter will cover the development of functional specifications and give a general description of the BASR. Chapter three discusses the researching of different configurations for the BASR arm and the acceptance of the final design. Chapter four covers the detailed design, assembly, testing, and modification of the BASR arm. Finally, the last chapter discusses conclusions and recommendations of the project. Figure 1.1 shows the overall design flow chart.

1.1 Literature Search

After a lengthy search, only two other stenciling robots were found to exist. One was created here at the Advanced Highway Maintenance and Construction Technology (AHMCT) Center and the other was created by the Pavement Marking Technologies. They both use gantry type robots to move the end-effector through the painting path. The configurations are discussed below.

The stenciling robot created by AHMCT was designed specifically for painting the aerial surveying premarks [2]. The premarks are 1.2 m x 1.2 m (4ft x 4ft) square and all features of the mark are in a straight line. The premark has a black background with white foreground. An example of a surveying premark is shown in Figure 1.2. This type of mark is ideal for the gantry configuration due to the smaller mark which is much narrower than the 2.4m (8.0 ft) vehicle width. The robot is housed inside a trailer along with its support equipment. The Stenciling Trailer is shown in Figure 1.3.

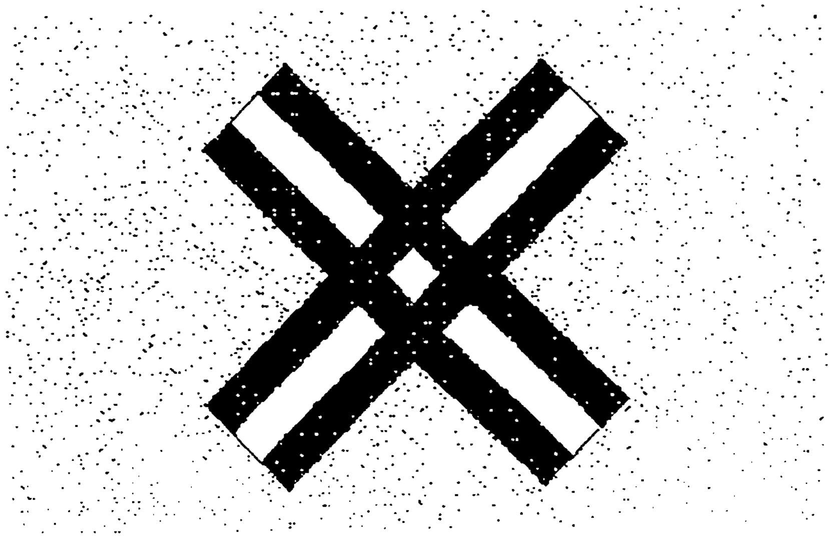

Figure 1.2 *Example of an Aerial Premark*

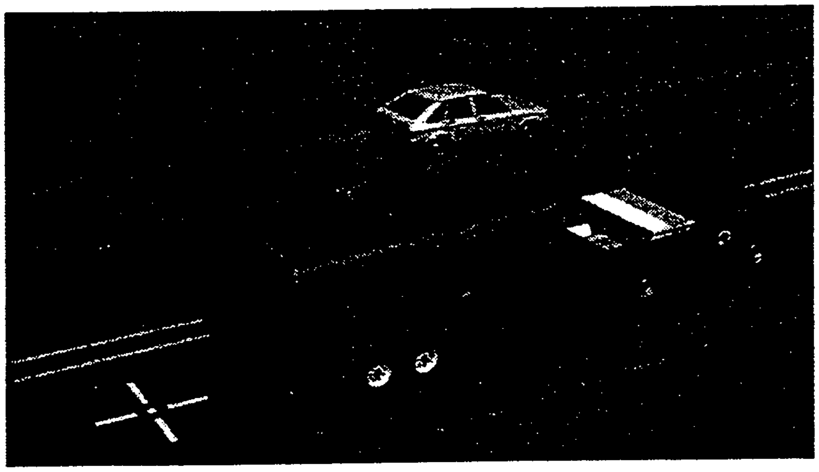

Figure 1.3 *AHMCT's pre-existing Stenciling Trailer*

The stenciling robot developed by Pavement Marking Technologies is designed to spray paint words and symbols on the roadbed. Horizontal positioning of the paint head is controlled by the gantry. Elevation and orientation of the end effector are controlled by a linear positioner and rotary positioner respectfully. All motivation power is electric. The frame of the gantry extends outside of the workspace due to the use of a gantry type robot [3].

1.2 Current In-Use Spray Painting Methods

Many different words and symbols are painted on the roadbed to warn or inform drivers of upcoming events. These words and symbols have a limited life due to vehicular traffic and weather and must be periodically replaced or painted over. To do this, the maintenance worker lays down a stencil of the symbol on the roadbed, aligns it with the existing deteriorated symbol, and then either sprays paint or lays a liquid thermoplastic material over the stencil. The stencil is then removed and the media is allowed to dry. An example of replacement using thermoplastic is shown in Figure 1.4. The area remains coned off until the media is dry enough to resist automobile traffic. This operation is currently performed by a 2 person crew in one to two vehicles. One vehicle must carry a wide variety and size of stencils in order to maintain the wide variety and size of words and symbols on the highway.

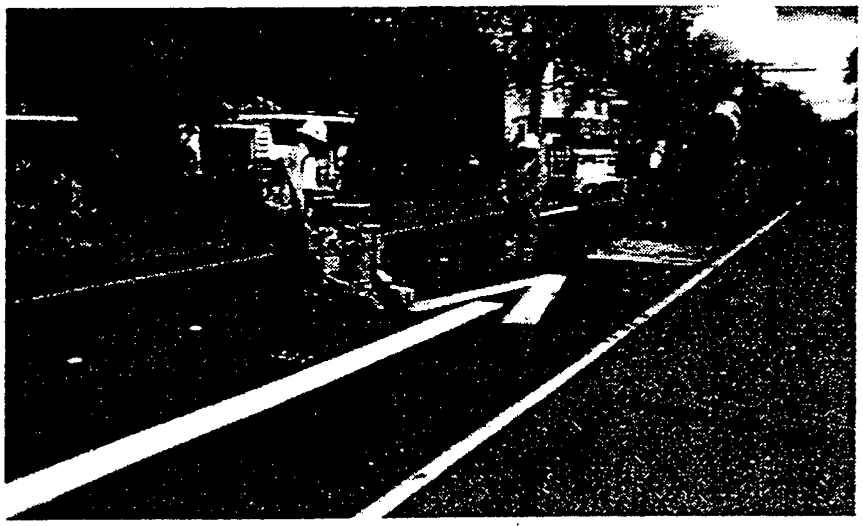

Figure 1.4 *Example of Arrow Replacement Using Thermoplastic Material*

1.3 Problem Description and Objectives

The purpose of this project is to develop a robotic arm to aid in the automation of highway maintenance, specifically the painting of words and symbols on the roadbed. This arm will be designed around a set of specifications which will be defined in Chapter 2. The arm will be designed for static and dynamic loading with sufficient safety factors. Concern will be placed on arm deflection but the arm will not be specifically designed for deflection. Small amounts of deflections will be countered by the active height control incorporated in the end-effector [4]. Numerous tasks performed on the roadway cover a large workspace requiring a large robot to cover all portions of the workspace. A robotic arm that can efficiently reach all portions of the workspace and retract into a manageable size would greatly increase the efficiency of highway maintenance automation.

CHAPTER 2 SPECIFICATIONS OF THE BASR-ARM

2.1 Functional Specifications

Specifications for the Big Articulating Stenciling Robot (BASR) Arm were developed to ensure that the majority of words and symbols on the roadbed could be painted with the same or better quality than is currently obtained manually using stencils. Specifications include workspace size, end-effector speed, end-effector maximum weight, arm rigidity, arm stowed envelop, and simplified control laws.

To effectively cover all words and symbols painted on the roadway, the workspace must be large enough so that a majority of words and symbols are included within that workspace. The majority of words and symbols can all be contained within a 3.7 m by 3.7 m (12 ft x 12 ft) workspace. Some symbols, such as the type III direction arrow [5], are 8 m (24 ft) in length, but these marks are much less prevalent than the marks less than 3.7 m (12 ft) in length. Marks larger 3.7 m (12 ft) can be painted with the support truck moving after the first half of the mark has been painted. Figure 2.1 shows the workspace requirements.

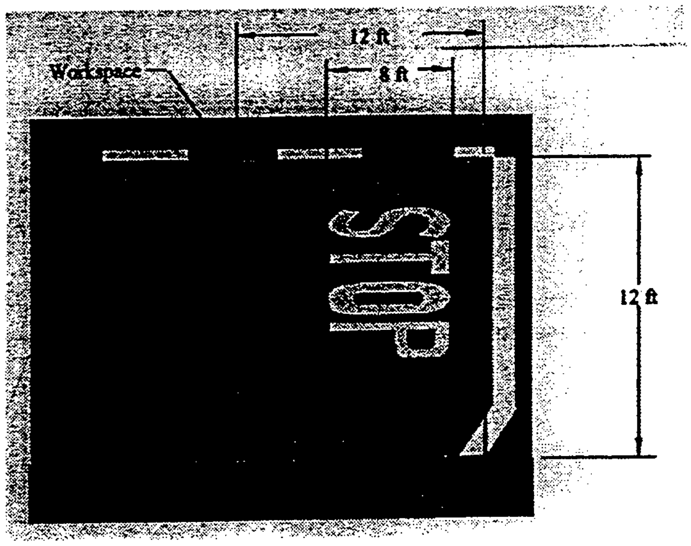

Figure 2.1 *Workspace Requirements*

Painting of words and figures on the roadway is done by high pressure (20.6 MPa or 3000 psi) paint spraying out of an airless nozzle. Tests show that the necessary spray head velocity is approximately 0.3 m/sec (1 ft/sec) with an acceleration of 2 m/sec^2 (6 ft/sec^2) [6]. Therefore, the BASR Arm must be designed to meet these speeds and accelerations from a structural standpoint.

The BASR Arm will be mounted on a support truck and that truck will need to conform with maximum vehicle dimensions. According to the California vehicle codes, standard vehicles must be no wider that 2.4 m (8 ft) and no higher than 4.3 m (14 ft) [5]. The arm can extend from the maximum dimensions when it is in use but must be within these dimensions when stowed. It is desired, but not required that the arm not need any special stowage and handling equipment. Stowing must be performed automatically without the operator exiting the support vehicle.

At the time the specifications were written, the spray painting end-effector had not yet been designed and a weight had not been determined. Therefore, it was estimated that the end-effector would weigh 890 N (200 lbf).

2.2 General Descriptions of the Big Articulated Stenciling Robot

In order to perform the desired spray painting tasks, the robot needs much more than an arm. Much support equipment and structures must be developed and constructed. The BASR is made up of a power unit which provides air, DC and AC voltage and hydraulics for the robot and support systems. The paint is provided by a hydraulically powered positive displacement Binks paint pump. Only one color of paint will be needed since all marks are only painted with one color. Reflective glass beads are provided to the end-effector by placing them under a blanket of compressed air. The end-effector will spray the paint and beads and is capable of three degrees of freedom [4]. The end-effector also has the ability to for active height control. All of the support equipment is mounted in the back of the support vehicle, a flat bed pickup truck. The arm can be mounted on either the front or the back depending on the needs of the local maintenance yard. The support vehicle has front and rear stabilizers to prevent the truck from moving when the robotic arm is moving due to the flexibility in the vehicles suspension. Figure 2.2 shows a sketch of the completed stenciling truck. As discussed in the Introduction (Chapter 1), this thesis presents the mechanical design and development of the robotic arm, not the support equipment and support structures.

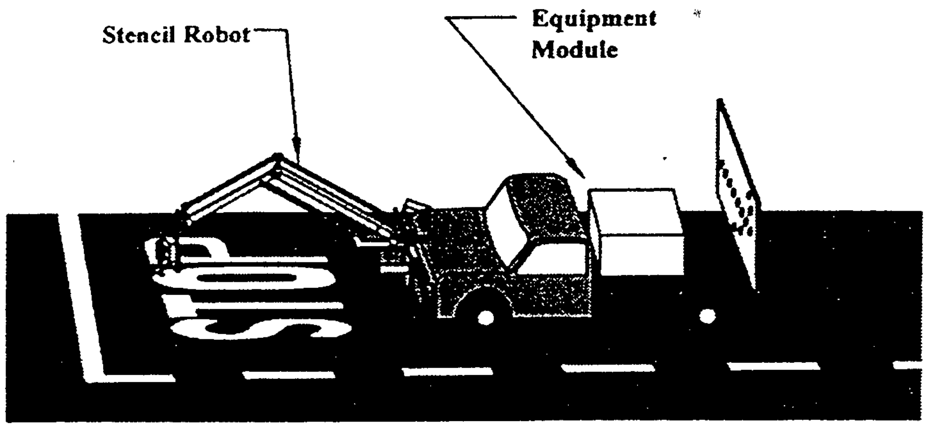

Figure 2.2 *Figure of the Completed Stenciling Truck*

CHAPTER 3 MECHANISM RESEARCH AND PROPOSAL

3.1 Mechanism Research and Configuration Benefits

There were three different configurations considered for the BASR arm. Because of the weight, workspace and speed requirements, gantry, backhoe, and the pantograph types were considered. The following section discusses the each type of configuration and goes over the disadvantages and advantages of each configuration. All of the advantages and disadvantages are summarized in Table 3.1 near the end of this chapter.

3.1.1 Gantry Configuration

This configuration would use two sets of powered linear slides oriented perpendicular to each other. The linear slides would make up a frame around the workspace with the end-effector inside the frame. Figure 3.1 shows the typical gantry configuration. The linear slides can be powered by electric or hydraulic motors. This type of configurations provides for simple reverse kinematics and good position accuracy [3]. Additionally, the end-effector would not need any mechanism to maintain a vertical orientation. The downfall is that the gantry frame must extend outside the workspace, making the frame greater than both the maximum vehicle width (2.4 m or 8 ft) and maximum lane width (3.7m or 12 ft). During transportation, a complex folding mechanism could be employed to reduce the gantry width less than the maximum vehicle width but the gantry would still be wider than the lane width during the painting operation. The large gantry size causes problems with transportation and stowage.

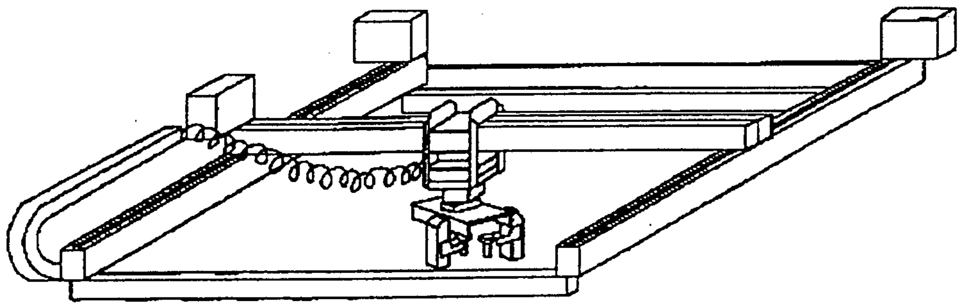

Figure 3.1 *Typical Gantry Frame Configuration*

3.1.2 Backhoe Configuration

The backhoe type mechanism is a familiar sight at many highway maintenance or construction sights. The backhoe operates in the radial coordinate system, thus making the reverse kinematics more complicated than with the gantry configuration. Figure 3.2 shows the typical backhoe configuration. Rotation is accomplished by a revolving base which could be powered by a hydraulic rotary actuator. Displacement is accomplished by a shoulder and a elbow joint. Rotation of these joints would provide for the radial displacement and be accomplished by two hydraulic linear cylinders or rotary hydraulic actuators, one of which must be placed at the elbow joint. This arrangement does not provide for straight line motion at the end-effector within the plane of the workspace. Rotation of both shoulder and elbow joints must be closely coordinated through position sensing and fine position control for straight line motion at the end-effector. This coordination must be carried out by the controller which complicates the control scheme. Additionally, this method requires an actuator at the end-effector to maintain proper end-effector orientation with respect to the workplane. The backhoe does yield a proven mechanical design that is popular in the manual control arena.

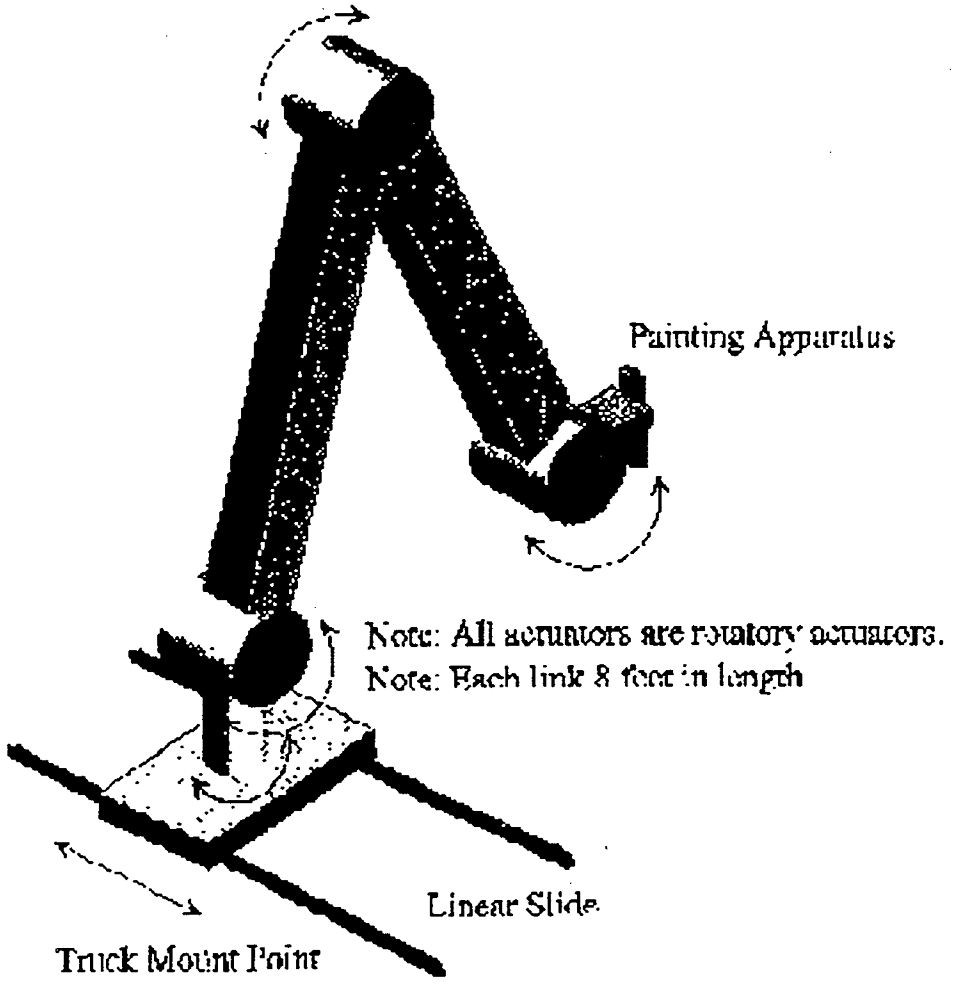
Painting Apparatus
Note: All actuators are rotatory actuators.
Note: Each link 8 feet in length
Linear Slide
Truck Mount Point

Figure 3.2 *Typical Backhoe Configuration*

3.1.3 Pantograph Configuration.

Figure 3.3 shows a simple pantograph mechanism. Input motion is applied at joint C and the output (end-effector, joint F) moves following the same path as the input but this motion is scaled depending on the linkage configuration (see Section 4.1.1). If the input is constrained to move in straight line motion, then the output must also move in a straight line motion greatly simplifying the reverse kinematics of the robot [7]. A pantograph robot would use radial coordinates. The workspace coverage is shown in Figure 3.4. The base could be rotated by a hydraulic rotary actuator similar to the backhoe configuration. Unlike the backhoe configuration, the pantograph would only need one hydraulic linear actuator which could be located at the base to reduce the moment caused by its weight and reducing the radial inertia. Since the arm is articulating, it can reach long distances and then fold up to a small package in its stowed position, as shown in Figure 3.3. In order to give the straight line motion and constant ratio of output to input, the pantograph mechanism must be made to close tolerances which could increase productions costs.

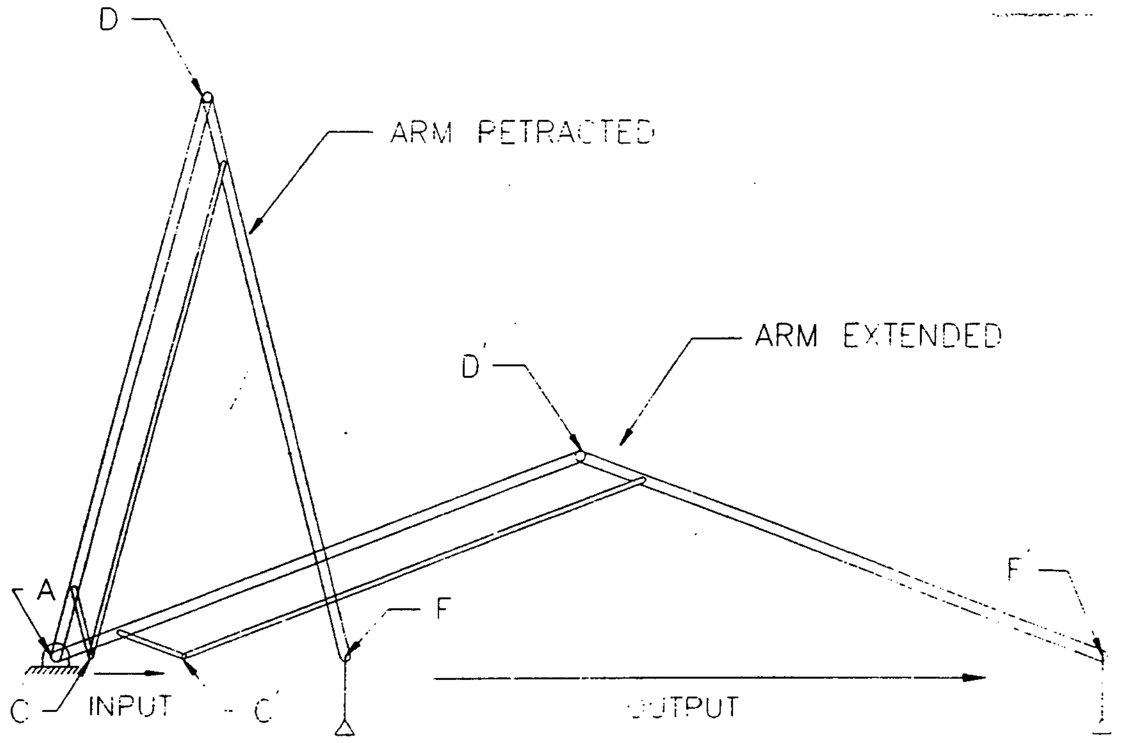

Figure 3.3 *Explanation of Simple Pantographic Motion*

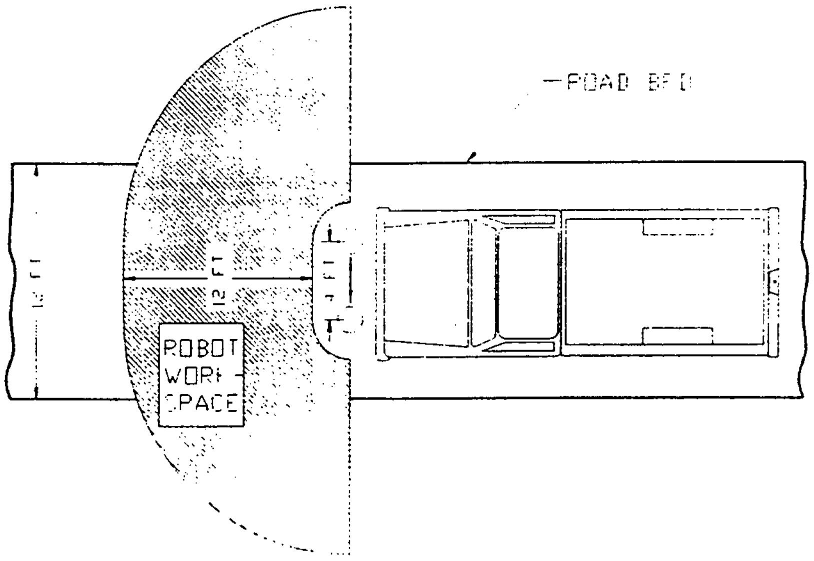

Figure 3.4 *Workspace Coverage with a Pantograph Arm*

To summarize the advantages and disadvantages of each configurations, they are listed in Table 3.1.

Configuration Type	Mechanism Advantage	Mechanism Disadvantage
Gantry	-Linear motion -Simple reverse kinematics -Low height	-Frame is too large to fit in traffic lane -Requires complex stowage mechanism
Backhoe	-Mechanically proven design -Drivers passing by on the road are familiar with the backhoe shape	-Non-linear motion -Difficult reverse kinematics -Elbow actuator not at base -Requires actuator to maintain end-effector orientation
Pantograph	-Linear motion -Simple reverse kinematics -Stowes into small package -All actuators located at base -Simple mechanical linkage provides end-effector orientation	-Tall structure -Not a normal structure

Table 3.1 *Advantages and Disadvantages of Each Arm Configuration*

3.2 Configuration Proposal and Acceptance

On November 30, 1994, the different configurations were presented to the California Department of Transportation (Caltrans). The relative merits and disadvantages of each configuration were discussed and it was decided that the pantograph configuration would be accepted [8].

CHAPTER 4 PROTOTYPE DESIGN AND ANALYSIS

4.1 Component Design and Analysis

Once the general configuration of the BASR arm was determined, detailed design of the prototype could begin. The detailed design started with determination of the main link lengths but the design was an iterative process (reference BASR Design Flowchart, Figure 1.1). With a chosen link length, the resultant forces had to be calculated and then checked to see if they were acceptable. If not, the lengths had to be changed. Additionally, stresses in the links had to be checked when the component design was in process. If the stresses were unacceptable, either the component or the link length had to be changed, adding another iteration to the design process. The following sections show each step of this iterative process.

For reference, Figure 4.1 shows the general configuration of the arm with the letter designations given to each joint.

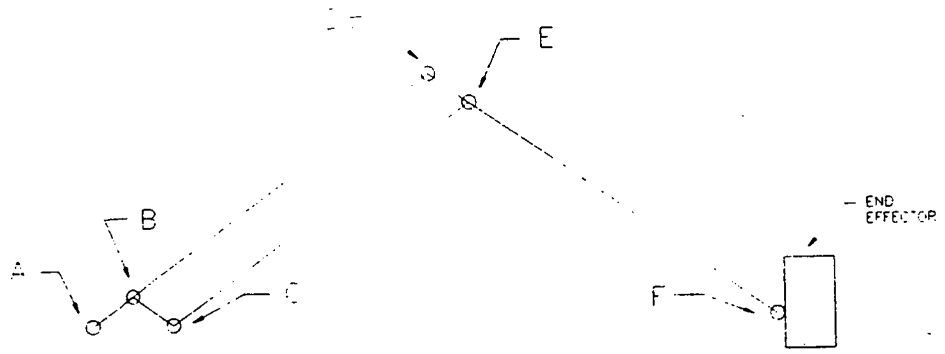

Figure 4.1 *General Arm Configuration with Joints Labeled*

4.1.1 Determination of Linkage Length and Spacing

In order for the BASR arm to reach all areas within the workspace, the arm rotates and extends as discussed in Section 3.1.3. To further enlarge the workspace without requiring a larger arm, the base of the arm can translate 61 cm (2 ft) perpendicular the support truck centerline. Figure 4.2 shows the increase in workspace coverage with and without a translating base. The translating base also helps in stowage of the arm. Stowage of the arm will be discussed in section 4.4.2.

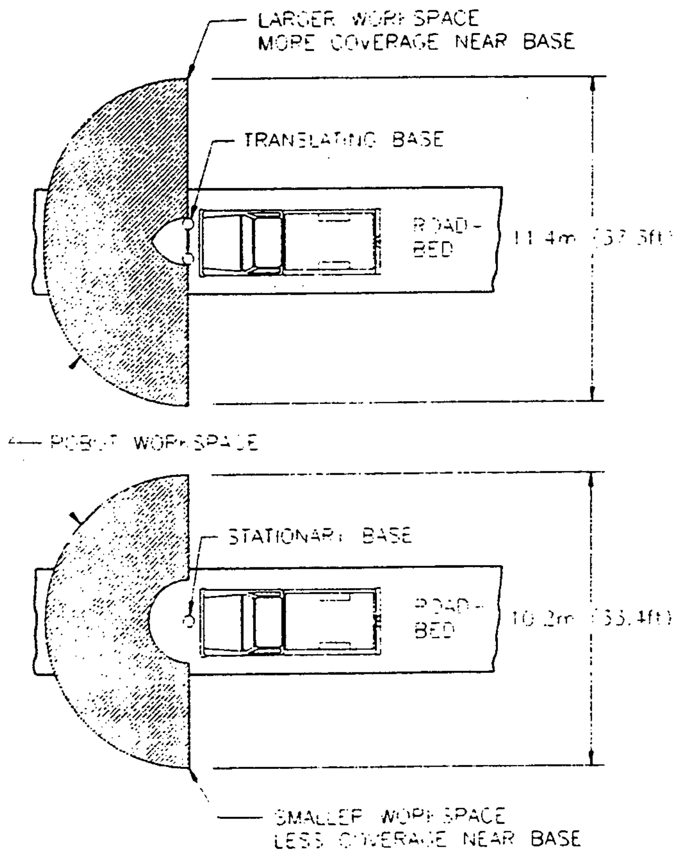

Figure 4.2 *Robotic Reach With and Without Translating Base*

Determination of link length was an iterative process. The Arm is restricted from retracting beyond a minimum angle. This restriction is caused by the interaction between the links, joints, and hydraulic cylinder. Experiments with different configurations showed that the Arm should retract no less than 15° from vertical. This angle is defined as θ_{min}. With θ_{min} known, the minimum retracted distance can be determined depending on the length of links ABD and DEF. This distance is defined as X_{min}. From X_{min}, the Arm must be able to extend out to the farthest corner of the workspace. This distance is defined as X_{max}. Figures 4.3 and 4.4 help define these terms.

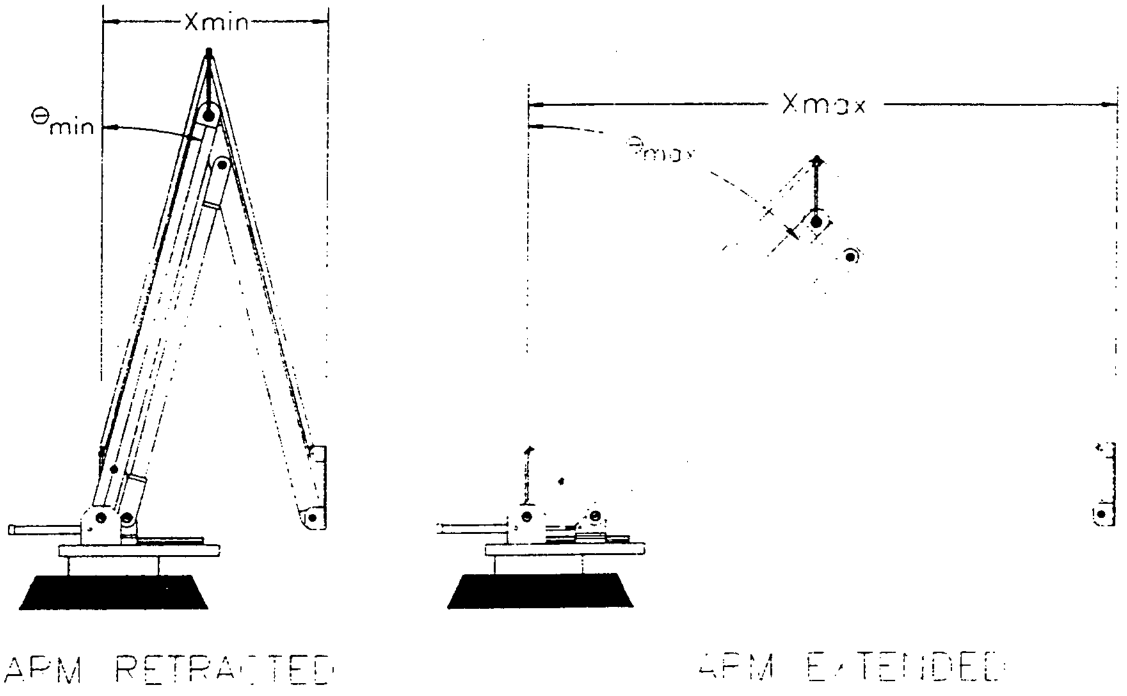

Figure 4.3 *Explanation of Extension and Retraction in Terms of X and* θ

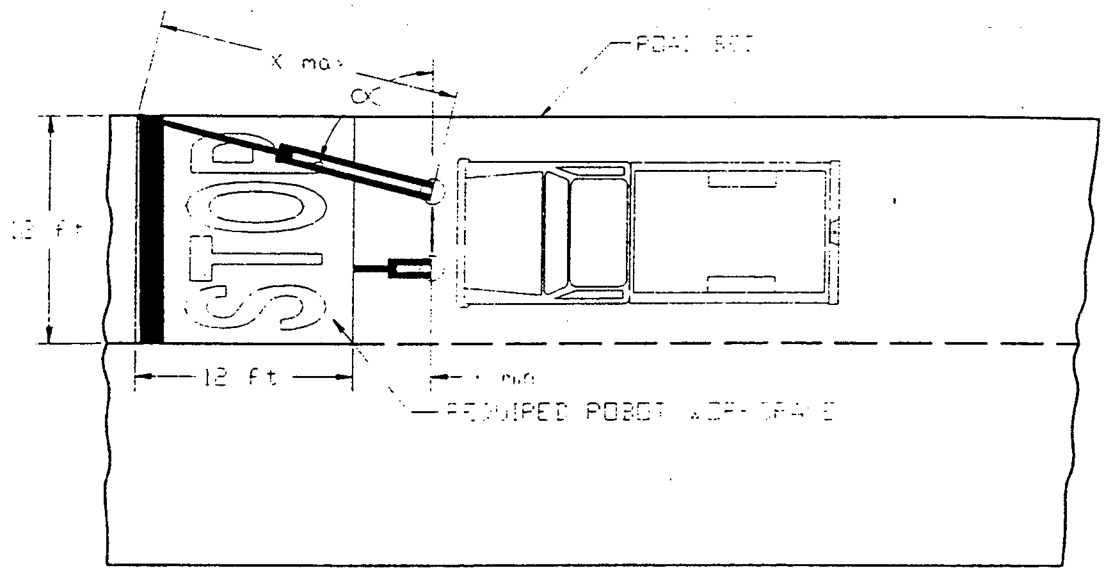

Figure 4.4 *Explanation of Minimum and Maximum Arm Extension in Terms of X and* α

Using these relationships, θ_{max} can be determined for a given length of link ABD and DEF. Iterating through with different link lengths, θ_{max} can be examined to determine the acceptable values for θ_{max} and length of links ABD and DEF. This iterative process is shown on Table 4.1. The term #NUM! in the Theta Max column means that the value can not be calculated. In this case, the arm can not reach all areas within the workspace. The column Max Height is the vertical height of the robot arm in the maximum retracted position (θ=15°).

Theta Minimum (deg)	15.00	0.26	(rads)		
Workspace Width (feet)	12.00	144.00	(inches)		
Workspace Length (feet)	12.00	144.00	(inches)		
Link Length (inches)	X min	X max	Theta Max	Alpha Max	Max Height
101	52.28	202.41	#NUM!	52.85	97.56
102	52.80	202.89	84.03	52.58	98.52
103	53.32	203.38	80.85	52.31	99.49
104	53.83	203.87	78.56	52.04	100.46
105	54.35	204.35	76.68	51.77	101.42
106	54.87	204.84	75.07	51.51	102.39
107	55.39	205.33	73.63	51.25	103.35
108	55.90	205.82	72.34	50.99	104.32
109	56.42	206.30	71.15	50.73	105.29
110	56.94	206.79	70.04	50.47	106.25
111	57.46	207.28	69.02	50.22	107.22
112	57.98	207.77	68.05	49.96	108.18
113	58.49	208.26	67.14	49.71	109.15
114	59.01	208.74	66.28	49.46	110.12
115	59.53	209.23	65.47	49.21	111.08
116	60.05	209.72	64.69	48.97	112.05
117	60.56	210.21	63.94	48.73	113.01
118	61.08	210.70	63.23	48.48	113.98
119	61.60	211.19	62.54	48.24	114.95
120	62.12	211.68	61.88	48.01	115.91
121	62.63	212.17	61.25	47.77	116.88

Table 4.1 *Determination of Link ABD and DEF Length and* θ_{max}

From this data it can be seen that the main links (link ABD and DEF) must be at least 2.60 m (102 in) long in order to reach all areas within the workspace. However, at that link length, the robot arm is nearly horizontal (θ_{max} is 84°, 6° from horizontal). This is not acceptable because the forces in the links and joints would be far too great that close to the horizontal. Table 4.2 shows the forces in the links, joints and hydraulic actuator (F_{act}) if the links are allowed to extend close to the horizontal. Notice the forces at E, D and C at an angle of 85° (5° from horizontal). Appendix A explains the symbology used in Table 4.2.

FORCE CALCULATIONS AT EACH JOINT											
CONSTANTS:			(feet)		(slugs)		(pounds)	------	(slugs*ft^2)		
		Ra=	4.34	Mabd=	6.24	Wabd=	201.26	Iabd=	78.64		
		Rb=	3.24	Mce=	2.37	Wce=	76.35	Ice=	20.41		
		Rc=	3.63	Mdef=	3.12	Wdef=	100.63	Idef=	39.32		
		Rd=	4.83	Meff=	6.21	Weff=	200.00				
		Rd1=	4.34								
		Re=	4.43		VARIABLE:		(ft/sec^2)		(ft/sec)		
		Re1=	3.24			Aeff=	6.00	Veff=	0.00		
		Rf=	4.83								
		Rlink=	9.17								
THETA	Fex	Fey	Fdx	Fdy	Fcx	Fcy	Fbc	Fax	Fay	Fact	Fnormal
(deg)	(pounds)	(pounds)	(pounds)	(pounds)	(pounds)	(pounds)	(pounds)	(pounds)	(pounds)	(pounds)	(pounds)
15.00	467.46	1722.46	416.41	1423.15	471.98	1798.06	443.34	-292.80	1853.76	-357.24	2226.29
20.00	567.86	1535.33	516.80	1236.49	572.38	1610.65	716.16	-263.00	1912.69	-327.44	2283.62
25.00	674.76	1420.60	623.71	1122.27	679.28	1495.64	905.20	-232.29	1946.80	-296.73	2316.03
30.00	790.64	1342.01	739.59	1044.23	795.17	1416.73	1061.04	-200.21	1968.23	-264.65	2335.62
35.00	918.71	1283.99	867.66	986:81	923.23	1358.36	1207.46	-166.23	1982.10	-230.67	2347.45
40.00	1063.31	1238.73	1012.26	942.23	1067.84	1312.71	1359.18	-129.74	1990.86	-194.17	2353.91
45.00	1230.59	1201.88	1179.54	906.18	1235.12	1275.41	1528.29	-90.02	1995.70	-154.46	2356.07
50.00	1429.62	1170.80	1378.57	876.05	1434.14	1243.79	1727.62	-46.28	1997.10	-110.71	2354.28
55.00	1674.48	1143.77	1623.43	850.18	1679.01	1216.10	1973.80	2.27	1994.96	-62.16	2348.22
60.00	1988.46	1119.60	1937.41	827.51	1992.98	1191.07	2291.51	55.96	1988.61	-8.48	2336.82
65.00	2413.14	1097.36	2362.08	807.30	2417.66	1167.66	2721.29	113.11	1976.37	48.67	2317.73
70.00	3030.96	1076.23	2979.91	789.15	3035.48	1144.84	3336.31	164.06	1954.58	99.63	2285.92
75.00	4032.09	1055.23	3981.04	772.99	4036.62	1121.06	4282.12	164.03	1914.36	99.59	2229.35
80.00	5976.04	1032.36	5924.98	759.68	5980.56	1092.72	5866.89	138.36	1828.72	202.80	2111.50
85.00	11530.65	999.23	11479.60	754.94	11535.17	1043.36	8094.65	3406.89	1561.72	3471.33	1748.86

Table 4.2 *Forces in the Links and Joints When Arm is Extended Past 70°*

If the link lengths were 2.79 m (110 in) then the arm would only extend down to 70° from vertical which yields acceptable forces. Link ABD and DEF will be 2.79 m (110 in) in length. It should be noted at this point that without the translating base the main link lengths would have to be at least 3.05 m (120 in), a 10% increase in length.

The length of the shorter links, link AB, BC and DE can now be determined. While the main links define the reach of the robot, the relationship between longer and shorter links define the amplification factor (output/input) of the pantograph mechanism [7]. When joint A is pinned and joint C (refer to Figure 4.1) is allowed to translate, joint F will translate a distance according to the following linear relationship:

$$OUTPUT = INPUT\frac{LENGTH\ AD}{LENGTH\ AB} \text{ or,} \tag{1}$$

$$AMPLIFICATION\ FACTOR = \frac{OUTPUT}{INPUT} = \frac{LENGTH\ AD}{LENGTH\ AB}. \tag{2}$$

It would be ideal to have a very high amplification factor. To accomplish this, the short links (link AB, BC and DE) must be much shorter than main link. Unfortunately there is a limit to how small the short links may be made. If the short links are made too small, the spacing between the parallel links ABD and CE will be too small when fully retracted and extended, causing interference between the links. Figure 4.3 shows the arm fully retracted and it can be seen if the arm was retracted any further, that link ABD and CE would interfere. The short links must be big enough to allow for spacing and provide for an adequate amplification. If the amplification factor is not high enough, a long stroke hydraulic cylinder must be used to provide actuation over the required travel of joint C. Table 4.3 shows the trade off parameters for the determination of the short link length.

Short Link Length cm (in)	Amplification Factor	Required Hydraulic Cylinder Stroke for X_{min} cm (in)	Acceptable Clearance Between Links YES/NO?
25.4 (10.0)	11.0	33.3 (13.1)	NO
27.9 (11.0)	10.0	36.6 (14.4)	NO
30.5 (12.0)	9.17	39.9 (15.8)	NO
33.5 (13.2)	8.33	43.9 (17.3)	YES
35.6 (14.0)	7.86	46.6 (18.3)	YES
38.1 (15.0)	7.33	49.9 (19.6)	YES

Table 4.3 *Determination of Link AB, BC, and DE Length*

From the information provided from Table 4.2, it was determined that the correct length for the small links (links AB, BC and DE) would be 33.53 cm (13.20 in) providing for an amplification factor of 8.33.

4.1. 2 Linkage Dynamic Analysis

With the length of each link known and the specifications for workspace, end-effector speed and acceleration, and end-effector weight known, the forces in each link can be found. To determine these forces, equilibrium equations were written for each link resulting in twelve linear equations with twelve unknown variables. The equations were solved for a given end-effector weight, acceleration and velocity while varying end-effector position. The resultant forces in each link and joint were calculated along with the maximum stresses in each link. The free body diagrams, equations and spread sheets containing the data are shown in detail in Appendix A. It is easily seen that the maximum forces are caused at the maximum extension of the arm, so all links must be designed with these values as worst case. The maximum stress in each critical position are shown in Table 4.4.

Critical Location	Stress Mpa (psi)	Arm Position	Arm Dynamics m/sec^2 (ft/sec^2)
Link ABD, Joint B	35.53 (5157)	70° (extended)	Accel= -2 (-6) Vel=anything
Link BC	8.082 (1173)	70° (extended)	Accel= -2 (-6) Vel=anything
Link CE	5.953 (864)	70° (extended)	Accel= +2 (+6) Vel=anything
Link DEF, Joint E	19.23 (2971)	70° (extended)	Accel= +2 (+6) Vel=anything

Table 4.4 *Maximum Stresses in the Critical Links*

4.1.3 Linkage Type and Configuration

The links must maintain the proper distance between the joints and limit deflections due to bending stress. Maintaining proper spacing between joints ensures that the arm will provide output motion that is linear with respect to the input. Additionally, the proper distance will allow the linkage configuration to remain intact providing for straight line motion of the end-effector. If the links are allowed to bend or deflect, the ability of the linkage to provide straight line linear motion will be degraded.

Since link weight was needed to be kept to a minimum, rectangular extruded aluminum tubes were used. These tubes are one third the weight of steel tubes, with almost the same strength, 340 MPa (50 kpsi) vs. 275 Mpa (40 kpsi) [9]. The main links were made up of 10cm x 15cm (4in x 6in) by 6.4mm (0.25in) thick stock.

In order to fasten the shafts or bearing cups to the tubes, solid aluminum inserts were connected to each end of the links in the area of the joint. These inserts were bonded to the tubes by the use of high strength adhesive made by 3M Corporation. The adhesive was 1838-L B/A Scotch weld two-part epoxy with a 21 Mpa (3.0 kpsi) [10]. Using adhesive to attach the inserts into the tubes precludes the deformation and stresses associated with welding. Additionally, the long set up time of the adhesive (8-12 hours) allows the inserts to be placed in position and then verified for correct position before the adhesive has set.

Link CE was made up of smaller outside dimension tubing since it is the only link, besides link BC, that is in pure compression. The main portion of the link is made up of 10cm x 10cm (4in x 4in) by 6.4mm (0.25in) stock. Link CE also has side arms so that it can mount at joints C and E. Link BC is the shortest link and was made up of solid aluminum for ease of manufacturing.

4.1.4 Joint System

An important part of maintaining the robotic motion linear and repeatable is the pinned joints. Each joint must handle the loading due to the weight of the links and the end-effector while still allowing the joint to rotate with a minimum amount of friction. Also, the joint must be resistant to any displacement or deflection other than rotation it is designed to allow. To meet these requirements, opposed angular contact roller bearings where used [11]. Figure 4.5 shows a typical bearing arrangement.

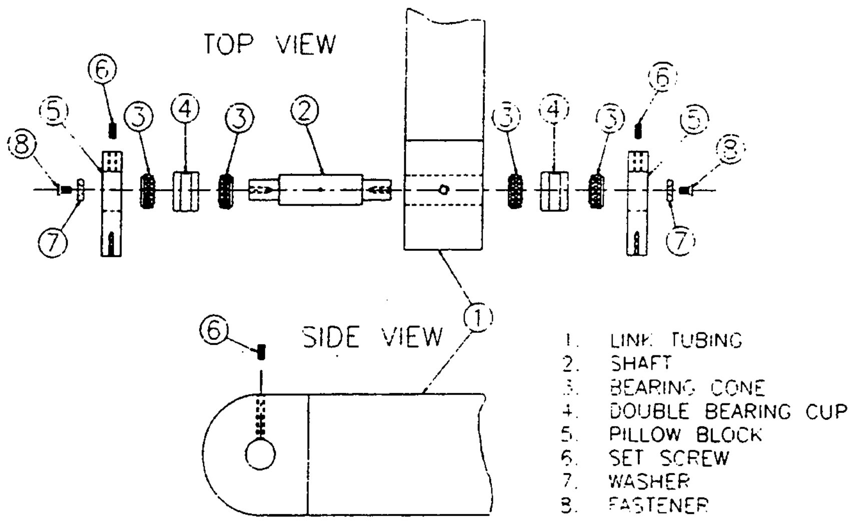

Figure 4.5 *Typical Bearing Arrangement.*

Angular contact roller bearings are able to take both radial and axial loading. In this bearing arrangement, the majority of the loading will come from the pin loading, acting on the bearing in a radial direction. This is consistent with angular contact roller bearing design since angular contact roller bearings are designed to carry the majority of loading in the radial direction[11]. Axial loading of the bearing will come from any side loading and joint preloading. Side loading comes from rotary acceleration or deceleration of the robotic arm, end-effector and payload. Joint preloading is necessary to ensure that there is no play in the joints. Play would allow for displacement of the joints in a direction other than rotation, reducing the placement accuracy of the end-effector.

4.1.5 Linear Slide

Joint C must be constrained to translate in only one degree of freedom in order for the end-effector to maintain its straight line motion. This constraint is obtained by mounting the shaft at joint C on a carriage of a linear slide assembly. The linear slide would have to be strong enough to withstand the vertical force created by the weight of the linkage and payload at the end-effector. The force was calculated to be 11,800 N (2670 lb). Various linear slides were investigated and a INA KUSE35L linear slide was found to meet these requirements.

Joint C must also provide for an attachment point for the end of the linear hydraulic actuator. The actuator is attached to the pillow block through a pin and rod end system at joint C and a trunion mount at joint A. This allows the cylinder to rotate and align itself due to any shifting or bending in the support which isolates the cylinder from any bending moment which would degrade the seals.

4.1.6 Parallel Mechanism

The use of the pantograph mechanism allows the extension actuator to be mounted at the base saving weight hydraulic lines running out the arm all of the while giving straight line linear motion at the end-effector. This is very advantageous but does not guarantee proper orientation of the end-effector with respect to the road surface. In order to maintain the proper orientation, a mechanical linkage or actuator could be used to maintain the orientation.

If the end-effector was hard mounted directly to link DEF, its orientation with respect to the road surface would change as link DEF rotates as it is extended or retracted. One way to maintain the proper end-effector orientation is to mount an actuator between link DEF and the end-effector mount. The actuator would be given a position command based on the angular displacement of link ABD. This would require more weight at the end of the arm and more electrical or hydraulic cables to be routed out to the actuator. Additionally, any misalignment caused by the actuator system would cause error in the end-effector.

Another alternative is to use identical gears at joints A, C, and F. The gear at joint A would be fixed to the base while the gears at joints C and F would be free to rotate with respect to the links. If the gears are connected with chains, the gear at joint F would maintain its orientation with respect to the gear at joint A and in doing so, maintain its orientation with respect to the base. The gears and chains are heavy, adding too much weight to the arm. Some weight savings could be achieved by replacing the gears with pulleys and chains with belts. This alternative would still weigh too much and be susceptible to stretching. A better, lighter, and less complex system was needed.

Further research discovered a reliable and simple system to maintain the end-effector orientation. Based on the principle that ends of a parallelogram stay parallel due to the opposite sides being equal length, a linkage mechanism could be mounted above links ABD and DEF to maintain end-effector orientation. Light weight links made of composite materials could be used to save weight and still provide the required strength. No actuation would be necessary since the action of the arm would maintain the position. Figure 4.6 shows the parallel linkage.

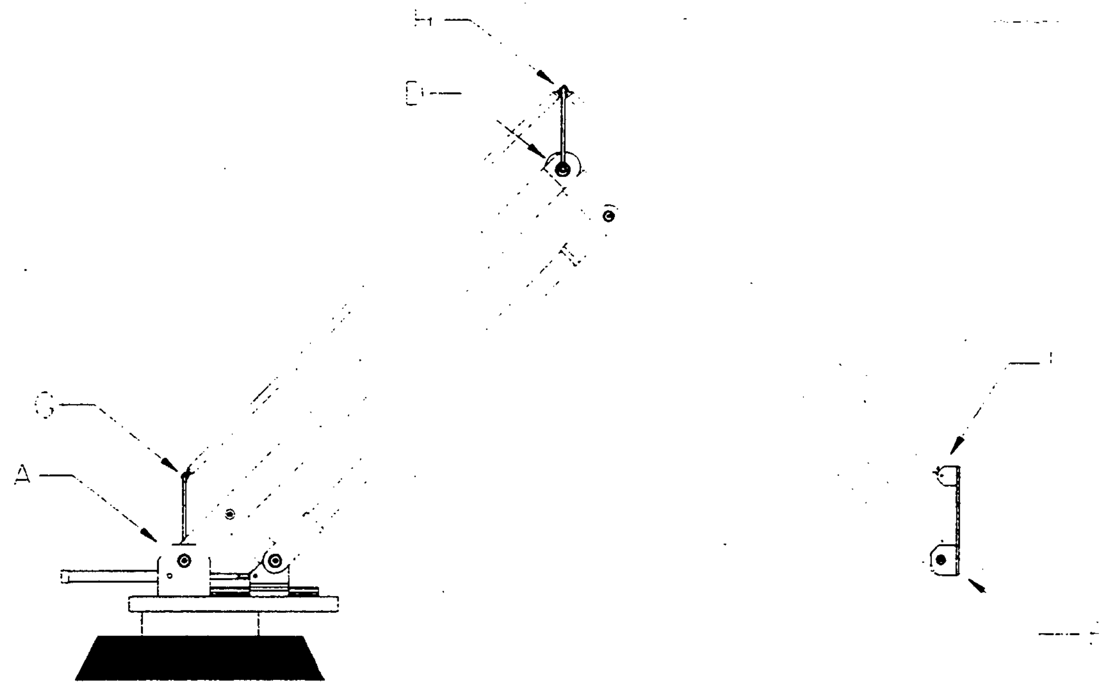

Figure 4.6 *View of the BASR arm with the Parallel Linkage Attached*

The parallel links were made from carbon graphite tubes with aluminum plugs epoxied at both ends. The plugs were drilled and tapped to allow spherical rod ends to be threaded into the plugs. This thread gives minor adjustments in length which is needed when maintaining the links the same length. The shorter links of the parallel linkage parallelogram, links AG, DH, and FI are made up of links 43.18 cm (17.00 in) long. Link AG maintains the orientation of the parallel mechanism and is hard mounted to the inside base pillow blocks. Link DH is mounted to the shaft at joint D but is free to rotate independently of the shaft. This rotation is accomplished by more spherical rod end bearings. The universal end-effector mount provides for the remaining side of the parallel linkage parallelogram. These parallel links maintain the end-effector in the correct orientation without any control scheme or actuation required.

4.1.7 Universal End-effector Mount

The end-effector is mounted to the end of link DEF through the universal end-effector mount. This mount is made up of 6.4 mm (0.25 in) aluminum plate which is fastened to two sets of pillow blocks. The lower set houses the tapered roller bearings at joint F and the upper set houses the pin for joint I. The plate also provides for spacing of the link FI in the parallel linkage. Four fasteners secure the end-effector to the universal end-effector mount. Figure 4.7 shows the side and front views of the universal end-effector mount.

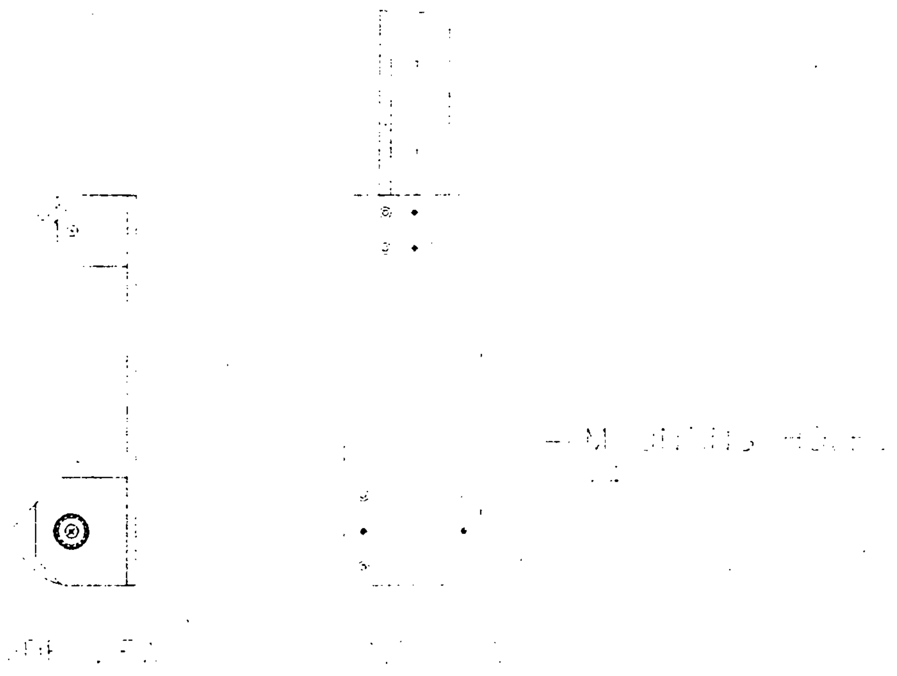

Figure 4.7 *Universal End-Effector Mount*

4.2 Prototype Assembly

The first major parts of the BASR arm to be assembled were the main links. Before the links could be assembled, the bearing cups were pressed into the ABD inserts at joint D. In parallel with this, the aluminum tubes were accurately machined to length in order to provide the correct spacing between joints. Once all of the aluminum tubes were machined to length and the corresponding plugs were completed, tubes and plugs were epoxied and clamped together to form the main links. A jig was used to check and maintain the correct distance between joints.

With the links assembled, the entire Arm could also be assembled. During the first stage, links ABD and DEF were assembled horizontally. The left hand side link ABD was first placed on the turntable bearing interface by securing the link to its pillow blocks (Pillow Block, Joint A) and securing the pillow blocks to the interface. Joint D shaft was fastened to link DEF and then attached to the left hand link ABD through the bearings in Link ABD at joint D. The right hand link ABD was then attached at joints A (by the pillow blocks), B (by the shaft at joint B), and D (by the shaft and bearings). The link was not securely fastened yet because the shaft at joint B had to be slipped through left and right link ABD and the bearings for link BC at joint B. Once the shaft was secured and the tapered roller bearings on link BC at joint B were properly preloaded by shims, the remaining joints on link ABD could be secured.

Before anymore assembly could continue, joint D had to be raised so that the main links were in the normal operating position and then held there until the remaining links and joints were attached. With joint D raised such that link ABD was about 20° from vertical, joint C and the linear slide could be assembled by slipping the shaft at joint C through the sliding carriage and tapered roller bearings on link BC at joint C. Link CE was then assembled by placing the two side arms on either side of the sliding carriage at joint C and tightening the bolts that secure the joint. The side arms at joint E are placed on the shaft at joint E and then the joint was secured to link DEF. The end plates are secured to the side arms and then the tube between the end plates was secured to the plates which completed link CE and the assembling of the BASR arm.

4.3 Prototype Testing and Results

Once the Arm was assembled, testing to ensure that it met the design requirements could be conducted. At the time of writing this thesis, the Arm had not been actuated under closed loop electronic control. Testing was accomplished using static and some open loop (manual) control.

4.3.1 Arm Deflection Under Design Loading

Deflection of the Arm was tested by incrementally extending the Arm with and without the end-effector payload. To measure deflection, a laser level was shined horizontally from the base interface (joints A and C) onto the end-effector. Any deflection in the Arm was measured by noting the displacement in the laser light beam. The results from the testing are presented in Table 4.5.

Arm Extension meter (ft)	No Load Deflection cm (in)	Full Load Deflection cm (in)
0.30 (1.00)	0 (0)	0.16 (0.063)
0.61 (2.00)	0 (0)	0.48 (0.19)
1.22 (4.00)	0.078 (0.031)	0.40 (0.16)
1.83 (6.00)	0.16 (0.063)	0.64 (0.25)
2.48 (8.00)	0.32 (0.13)	0.80 (0.31)
3.05 (10.00)	0.48 (0.19)	1.51 (0.60)
3.66 (12.00)	0.56 (0.22)	1.91 (0.75)

Table 4.5 *Results from the Arm Deflection Test*

Although the maximum under load deflection was not specified at the conception of this project, the actual deflections fall well within practical limits. The largest deflection recorded was 1.91 cm (0.75 in) which is well within the end-effector's active height control ability.

4.4 Prototype Redesign

Through design, assembly and testing, it was noticed that portions of the design could be modified to improve performance and safety. Some modifications would require significant redesign of the existing prototype design and therefore will be postponed until the second stage prototype is designed. The following modifications will be implemented to the existing prototype to improve performance and safety.

4.4.1 Parallel Linkage Redesign

Originally, the parallel links were placed above links ABD and DEF. This posed a height restriction as the link DH was 43.18 cm (17.00 in) above joint D. See Figure 4.8 for an illustration of the overall height of BASR. If the parallel linkage could be placed below the main links the overall height of BASR could be significantly reduced. It was decided to move the parallel linkage mechanism below the main links.

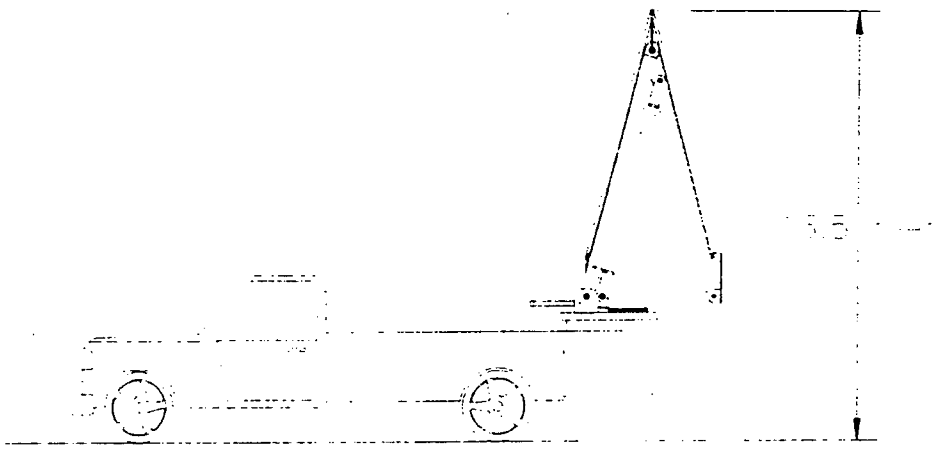

Figure 4.8 *BASR Overall Height with the Arm Retracted*

Joint G was moved from above joint A to below Joint A. The parallel link GH is mounted at joint G 22.84 cm (8.993 in) below joint A on the turntable bearing interface. This is the maximum spacing between joints A and G before the link GH will interfere with the rotating base of the robot. Because of the smaller spacing between the main links and the parallel links, larger tension and compressive forces will be seen in the links therefore two sets of parallel links will be used, one on either side of the main links.

Link DH must be free to rotate around the center of joint D but be constrained from moving in other directions. The shaft at joint D already had a 5/8-16 UNF tapped hole at both ends. If the proper mechanism could be found to use this thread and allow the one degree of freedom (rotation about the axis of joint D), the lower parallel linkage design would be essentially complete. It was found that a cam follower would thread into the threaded joint D and if link DH was pressed onto the bearing surface of the cam follower, the link would be properly constrained. This approach was used with a 1.59 cm bolt passing through joint H and holding links GH and HI. There is no connection between the left and right hand sides of joint H because this connection would interfere with the main links when the arm was retracted towards the stowed position.

There was not much change made to joint I. The universal end-effector mount was rotated so that it was hanging below joint F. The pillow block for joint I were move so that they met the same spacing from joint F as joints A and G were spaced. Since there were two parallel links HI now versus one on centerline, the length of the shaft at joint G had to be lengthened to accommodate the width of the spacing between both links. Figures 4.9 and 4.10 show the final configuration of the parallel linkage mechanism.

Figure 4.9 *Side View of the Modified Parallel Linkage*

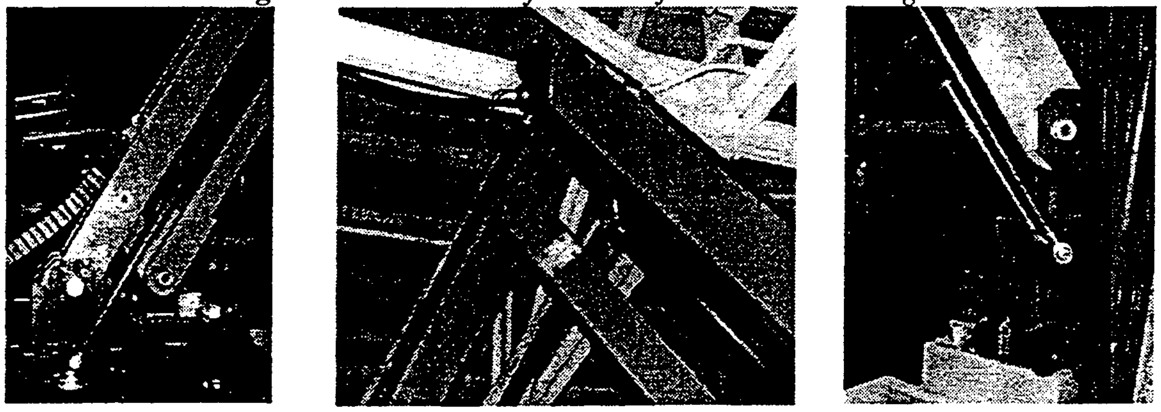

Figure 4.10 *Side View of Base, Joint H, and End-Effector Respectfully*

An added advantage of placing the parallel links below the main links is that the universal end-effector mount is now mounted mostly below joint F. Rotating the mount and mounting it below joint F lowers the center of the universal end-effector mount and therefore also lowering the height above the pavement of the paint head. Additionally, the universal end-effector mount does not have to be as long now that the parallel links are only spaced 22.84 cm (8.993 in) apart. Shortening the mount from 55.9 cm (22.0 in) to 27.9 cm (11.0 in) reduces its weight by 50 percent.

4.4.2 End-effector Retraction for Stowage Redesign

It was decided that the BASR arm have the ability to stow the end-effector within the bed of the support truck. As BASR is transported between work sites, it would be safer to have the arm rotated around and over the bed of the truck so that it is completely within the confines of the truck bed and that the paint head is rotated to horizontal so that it is not in danger of striking objects on the roadway. Different schemes were investigated for merit. The optimum retraction scheme is shown in Figure 4.11.

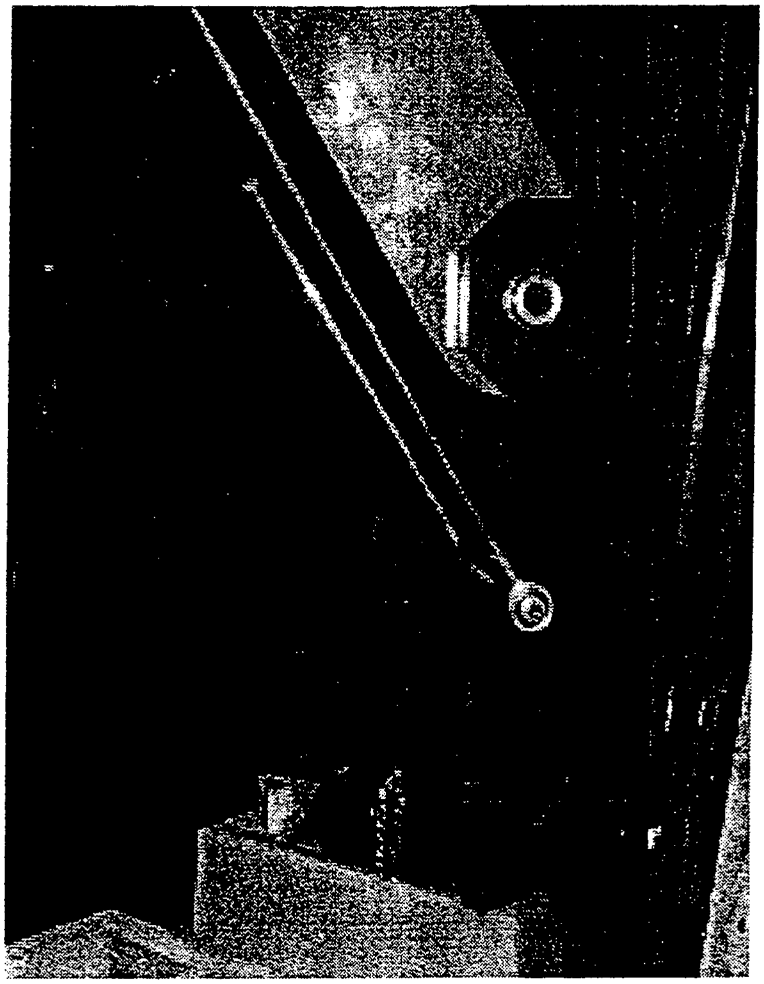

Figure 4.11 *End-effector Retraction Mechanism*

The end-effector is retracted by changing the length of parallel links HI. In the normal working (non-retracted) position, link HI is the original 27.94 m (110 in) length. To rotate and retract the end-effector, link HI shortens 33 cm (13 in). When the end-effector is needed in its working position, the link extends to its original length. This extension and retraction is accomplished by an air cylinders imbedded in the end of the two link HI's. When the cylinder is retracted, the link is short and when the cylinder extends to full stroke, the link expands to its full 27.94 m (110 in) length. The air cylinders are actuated by 1.03 MPa (150 psi) air which was already available to the end-effector. The status of the end-effector rotation is sensed by hall effect switches mounted on each pneumatic cylinder. When the end-effector is retracted over the truck bed, air to the air cylinders is vented allowing the end-effector to rest in restraints provided in the truck bed.

5 CONCLUSIONS

5.1 Conclusions

This thesis discusses the multiple developmental stages involved in the mechanical design of the Big Articulating Stenciling Robot (BASR) Arm. Current methods and mechanisms used to paint words and symbols on the roadway are presented to establish the direction that was taken towards the generation of overall conceptual designs. The previous chapters include general descriptions of the individual systems that constitute the BASR as well as more detailed descriptions of the BASR Arm. The generation of multiple arm concepts and the impartial trade-off process provide a logical means of selecting the most effective design while identifying the strengths and weaknesses of each design. The development of the Arm as presented in Chapter 4 and Appendix A is also presented to show the step by step process used to design the accepted concept.

5.2 Recommendations

During initial prototype testing, it was determined that the overall arm height above the roadbed while retracted was too tall and should be reduced. Contributing to the overall height was the parallel linkage mechanism. If the mechanism height could be reduced, the overall performance of the arm would be greatly improved. Modifications to the linkage were undertaken and the initial modifications are discussed in Section 4.4.1. Further modifications could improve the parallel linkage even further. Experimentation with other mechanisms and geometry may yield a parallel linkage extends along link DEF only, eliminating the linkages along link ABD.

Approximately 30 - 40% of the stress in the links and shafts is due to the weight of the links and joint materials. To reduce this contribution to the overall stress, the Arm was made from heat treated aluminum. Although aluminum is lighter than steel, it is not as stiff as steel, lowering the natural frequency of the structure. Alternative materials to aluminum should be investigated to further reduce the weight of the structure while increasing natural frequency of the structure. An alternative material to aluminum is carbon fiber composites.

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APPENDIX A
FORCE, MOMENT, AND STRESS CALCULATIONS

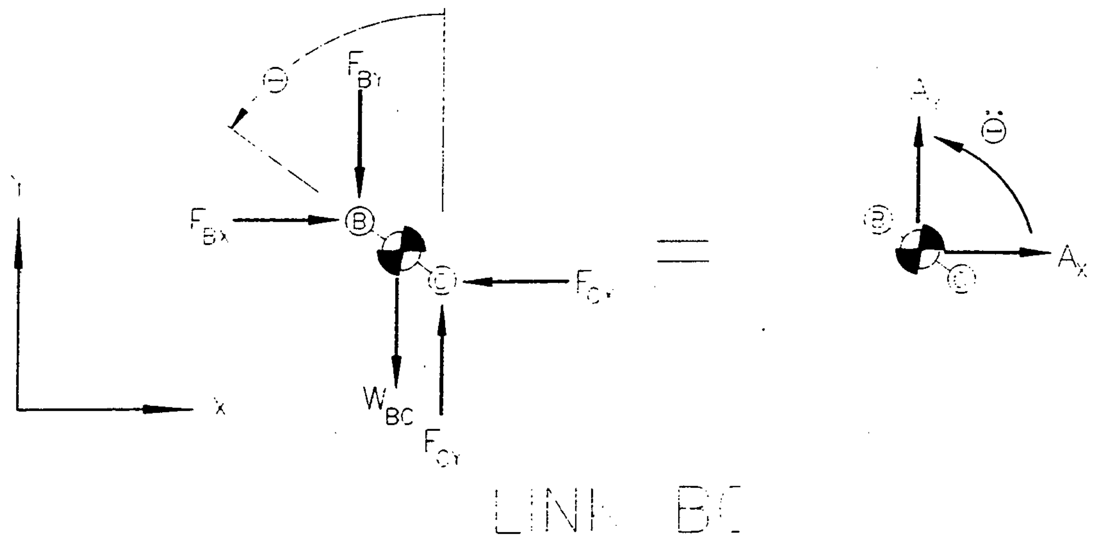

Figure A.1 *Link BC Free Body Diagram*

FORCE IN LINK BC

Assume that link BC is massless (less than 10lbf)

$$\sum F = M_{BC}A = (O)A = 0$$
$$\Rightarrow \sum F = 0, \quad so,$$

(1)

$$\overset{+}{\rightarrow} \sum F_X = 0$$
$$F_{BX} - F_{CX} = 0 \quad \Rightarrow \quad F_{BX} = F_{CX} \tag{2}$$

$$+\uparrow \sum F_Y = 0$$
$$-F_{BY} + F_{CY} = 0 \quad \Rightarrow \quad F_{BY} = F_{CY}$$

Force acts along the link axis and the force is just F_{BC} at angle Θ as shown in Figure A.2.

APPENDIX A
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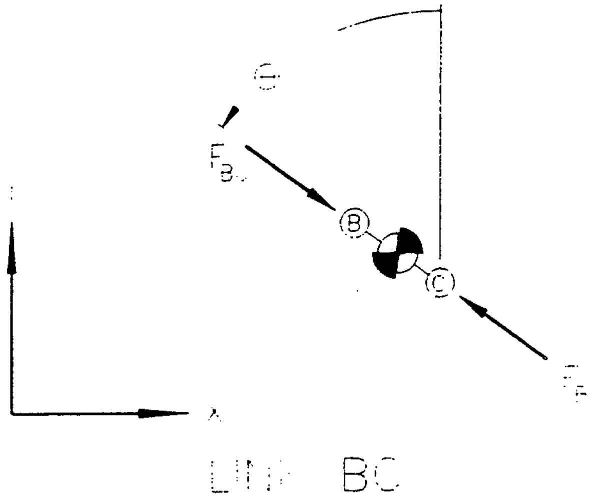

Figure A.2 *Link BC Free Body Diagram Showing Forces in Line with Link*

STRESS IN LINK BC

Since the link is just in compression without any bending moment, determine just compresive stress due to F_{BC}.

$$\sigma_{BC} = \frac{F_{BC}}{A_{BC}} \qquad \text{Where } A_{BC} \equiv \text{Cross sectional area of link BC} \qquad (3)$$

NOTE 1: Cross sectional area of the link is defined as the minimum cross section area minus material removed for the shaft or bearing at that joint.

NOTE 2: In this link, buckling is ignored due to its short length (low L / k).

APPENDIX A
FORCE, MOMENT, AND STRESS CALCULATIONS

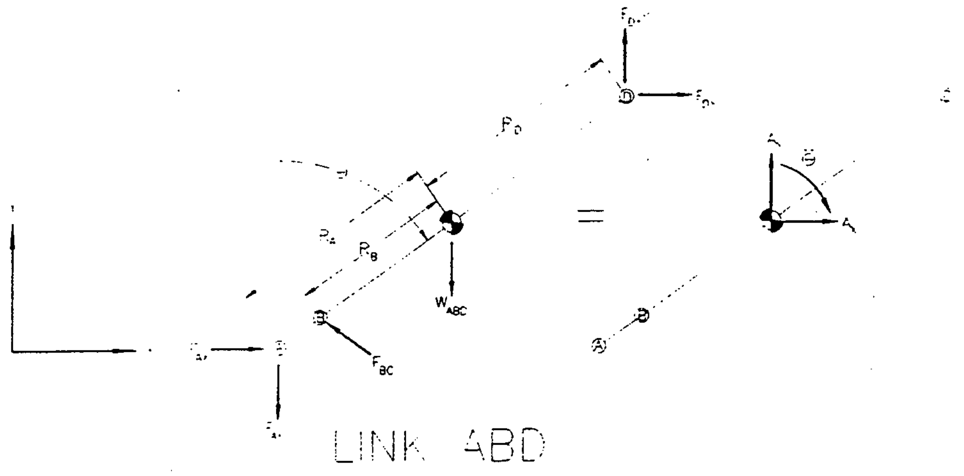

Figure A.3 *Link ABD Free Body Diagram*

FORCE AND MOMENT IN LINK ABD

$$\overset{+}{\rightarrow}\sum F_X = MA_X$$

$$F_{AX} - F_{BC}\sin(\Theta) + F_{DX} = M_{ABD}\left(A_{ABD}\right)_X \qquad (4)$$

$$+\uparrow\sum F_Y = MA_Y$$

$$-F_{AY} + F_{BC}\cos(\Theta) + F_{DY} = M_{ABD}(A_{ABD})_Y \qquad (5)$$

$$\overset{\rightarrow}{\underset{\leftarrow}{+}}\sum M_{CG} = I_{ABD}\ddot{\Theta}$$

$$-F_{AX}R_{AY} - F_{AY}R_{AX} + F_{BC}R_B\cos(2\Theta-90) + F_{DX}R_{DY} - F_{DY}R_{DX} = I_{ABD}\ddot{\Theta} \qquad (6)$$

STRESS IN LINK ABD Find the stress in link at joint B (tensile). Joint B has the max stress due to max bending moment and minimum cross sectional area.

$$M_B = \frac{F_{BC}\cos(2\Theta-90)R_{AB}R_{BD}}{R_{LINK}} \qquad \text{Where } R_{AB} = R_A - R_B \text{ and } R_{BD} = R_B + R_D \qquad (7)$$

$$F_B = F_{DX}\sin(\Theta) + F_{DY}\cos(\Theta) \qquad (8)$$

$$\sigma_B = \frac{M_B C}{I_{ABD}} + \frac{F_B}{A_{ABD}} \qquad (9)$$

Where $A_{ABD} \equiv$ Cross sectional area of link ABD

(without hole for joint)

APPENDIX A
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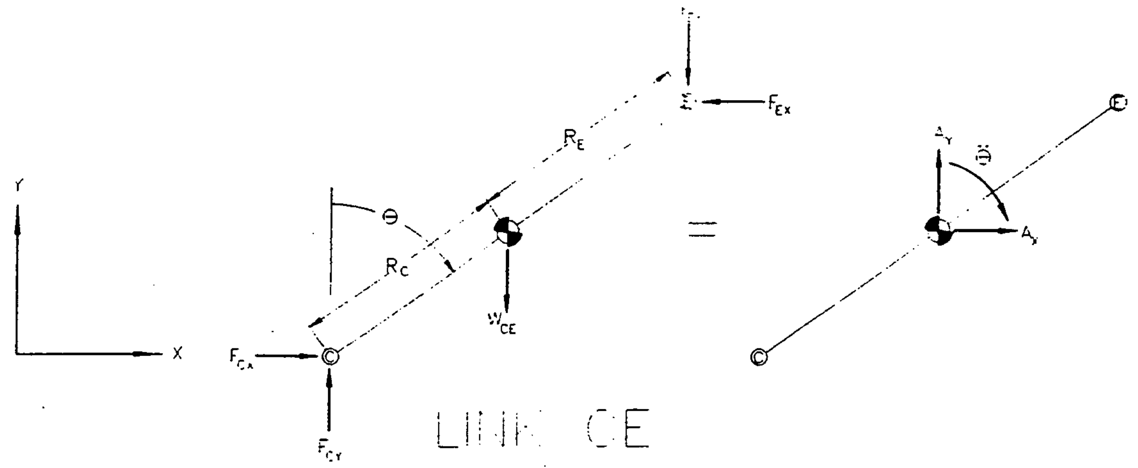

Figure A.4 *Link CE Free Body Diagram*

FORCE AN MOMENT IN LINK CE

$\overset{+}{\rightarrow} \sum F_X = MA_X$

$F_{CX} - F_{EX} = M_{CD}(A_{CE})_X$ (10)

$+\uparrow \sum F_Y = MA_Y$

$F_{CY} - F_{EY} - W_{CE} = M_{CE}(A_{CE})_y$ (11)

$+\sum M_{CG} = I_{CE}\ddot{\Theta}$

$-F_{CX}R_{CY} + F_{CY}R_{CX} - F_{EX}R_{EY} + F_{EY}R_{EX} = I_{CE}\ddot{\Theta}$ (12)

STRESS IN LINK CE (Compression)

Assume that F_{CE} is in line with link axis

$\sigma_{CE} = \dfrac{F_{CE}}{A_{CE}}$ Where $A_{CE} \equiv$ Cross sectional area of link CE (13)

Buckling for this link is evaluated near the end of this section.

APPENDIX A
FORCE, MOMENT, AND STRESS ~~CALCUL~~ATIONS

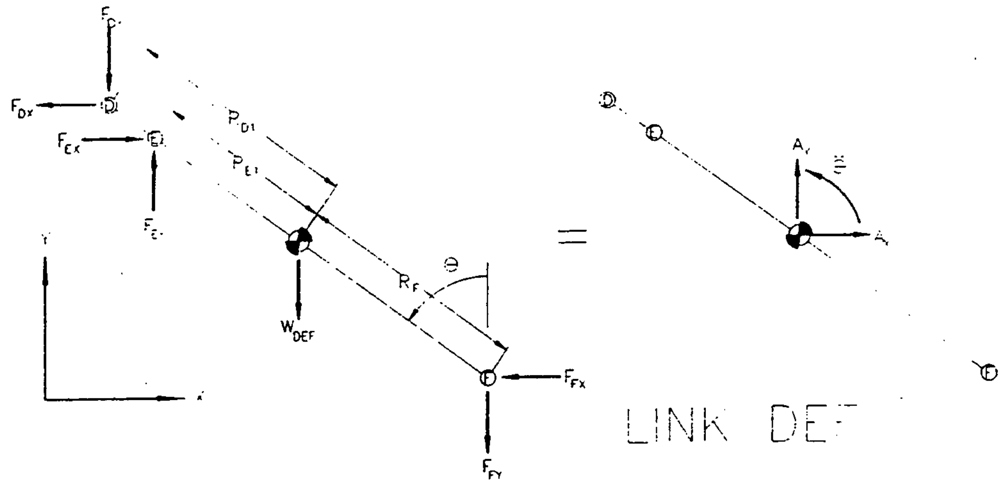

Figure A.5 *Link DEF Free Body Diagram*

FORCE AND MOMENT IN LINK DEF

$\overset{+}{\rightarrow}\sum F_X = MA_X$

$-F_{DX} + F_{EX} - F_{FX} = M_{DEF}(A_{DEF})_X$ (14)

$+\uparrow\sum F_Y = MA_Y$

$-F_{DY} + F_{EY} - F_{FY} - W_{DEF} = M_{DEF}(A_{DEF})_Y$ (15)

$+\sum M_{CG} = I_{DEF}\ddot{\Theta}$

$F_{DX}R_{D1Y} + F_{DY}R_{D1X} - F_{EX}R_{E1Y} - F_{EY}R_{E1X} - M_{EEF}A_{EEF}R_{FY} - W_{EEF}R_{FX} = I_{DEF}\ddot{\Theta}$ (16)

STRESS IN LINK DEF

Maximum stress occurs at joint E (tensile) due to max bending moment and force at minimum cross section.

$M_E = R_{EF}(F_{EY}\sin(\Theta) + F_{EX}\cos(\Theta)) + R_{E1}W_{DEF}\sin(\Theta)$ Where $R_{EF} = R_{E1} + R_F$ (17)

$F_{E(TENSION)} = W_{DEF}\cos(\Theta) - F_{FX}\sin(\Theta) + F_{FY}\cos(\Theta)$ (18)

$\sigma_{E(TENSILE)} = \dfrac{M_E C_{CE}}{I_{CE}} + \dfrac{F_{E(TENSION)}}{A_{DEF}}$ Where $A_{DEF} \equiv$ Cross sectional area of link DEF (19)

APPENDIX A
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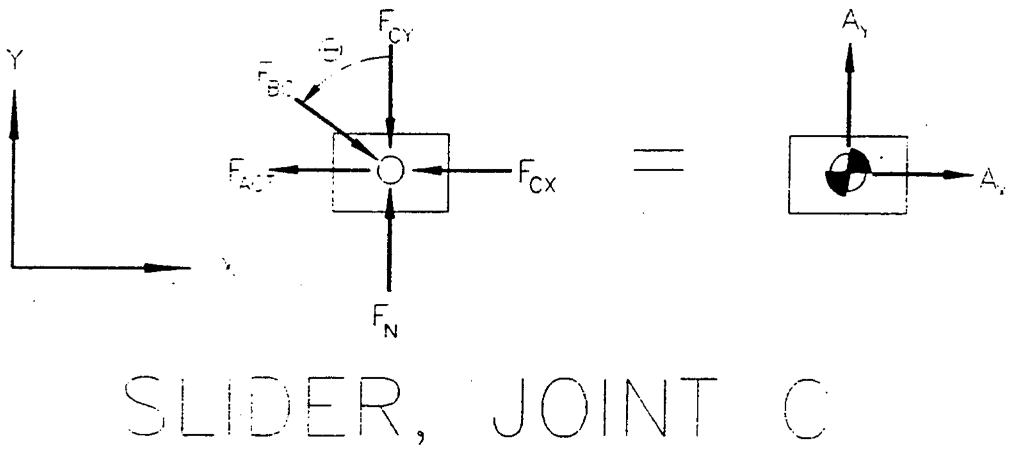


Figure A.6 *Slider, Joint C Free Body Diagram*

JOINT C SLIDER

Assume that the mass of the Slider is zero and no friction in the linear slide. Additionally, assume that the Slider is constrained to move in X direction only ($A_Y = 0$).

$$\sum F = MA = (0)A = 0$$
$$\Rightarrow \sum F = 0 \quad so,$$

$$\overset{+}{\rightarrow} \sum F_X = 0$$
$$F_{BC}\sin(\Theta) - F_{CX} - F_{ACT} = 0 \tag{20}$$

$$+\uparrow \sum F_Y = 0$$
$$-F_{BC}\cos(\Theta) - F_{CY} + F_N = 0 \tag{21}$$

APPENDIX A
FORCE, MOMENT, AND STRESS CALCULATIONS

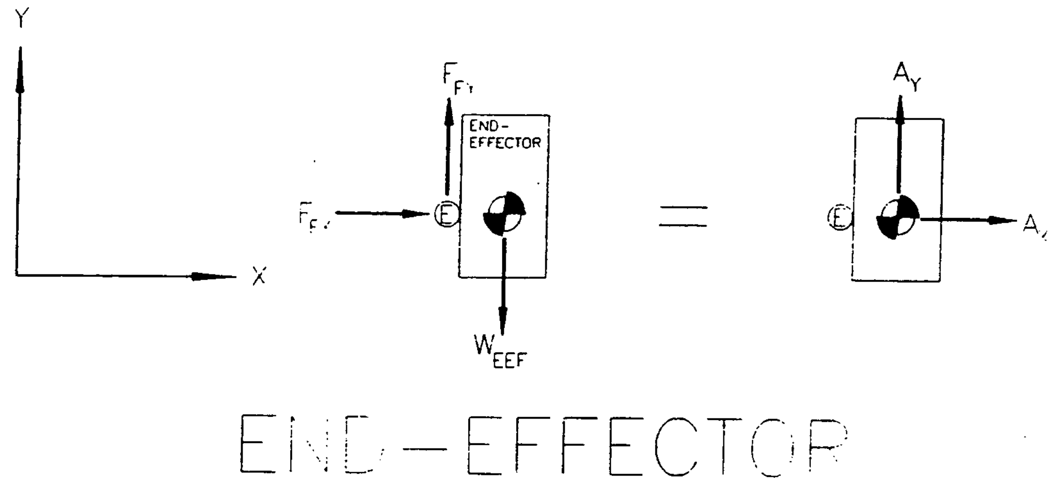


Figure A.7 *End-Effector Free Body Diagram*

END – EFFECTOR

Assume that the end - effector moves in X direction only due to the input (Slider) constrained to move in X direction.

$\sum F_Y = M_{EEF}(A_{EEF})_Y = M_{EEF}(0) = 0$

$\Rightarrow \sum F_Y = 0$

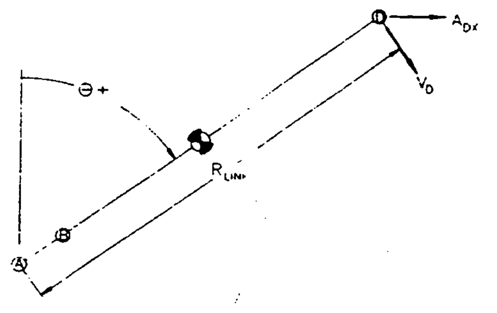
$\overset{+}{\rightarrow} \sum F_X = M_{EEF}(A_{EEF})_X$, but $(A_{EEF})_X = A_{EEF}$

$F_{FX} = M_{EEF} A_{EEF}$ (22)

$+\uparrow \sum F_Y = 0$

$F_{FY} - W_{EEF} = 0 \quad \Rightarrow \quad F_{FY} = W_{EEF}$ (23)

APPENDIX A
FORCE, MOMENT, AND STRESS CALCULATIONS



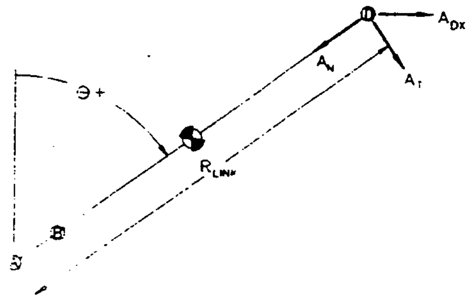
Determination of angular velocity

$$V_{DX} = \dot{\Theta} R_{LINK} \cos(\Theta) \quad and \quad V_{DX} = \frac{1}{2} V_{EEF}$$

$$\Rightarrow \quad V_{EFF} = 2\dot{\Theta} R_{LINK} \cos(\Theta)$$

$$or.. \quad \dot{\Theta} = \frac{V_{EEF}}{2R_{LINK}\cos(\Theta)} \quad and \tag{24}$$

$$\dot{\Theta}^2 = \frac{V_{EEF}^2}{4R_{LINK}^2 \cos^2(\Theta)}$$



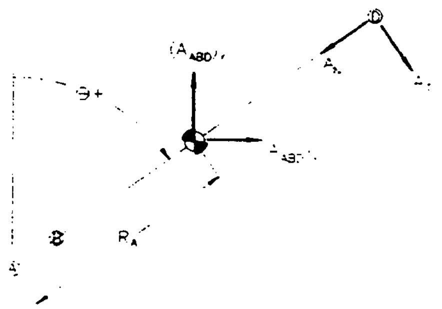
Determination of angular acceleration

$$A_{DX} = \ddot{\Theta} R_{LINK} \cos(\Theta) - \dot{\Theta}^2 R_{LINK} \sin(\Theta)$$

$$and \quad A_{DX} = \frac{1}{2} A_{EEF},$$

$$\Rightarrow \quad A_{EEF} = 2(\ddot{\Theta} R_{LINK} \cos(\Theta) - \dot{\Theta}^2 R_{LINK} \sin(\Theta)) \tag{25}$$

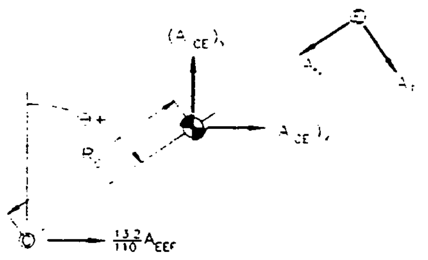
$$or.. \quad \ddot{\Theta} = \frac{A_{EEF}}{2R_{LINK}\cos(\Theta)} + \frac{V_{EEF}^2 \tan(\Theta)}{4R_{LINK}^2 \cos^2(\Theta)} \tag{26}$$



Determination of link ABD accelerations

$$A_{ABD})_X = \frac{1}{2}\frac{R_A}{R_{LINK}} A_{EEF} = 0.2367 A_{EEF} \tag{27}$$

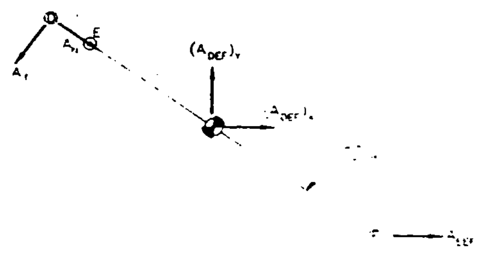
$$(A_{ABD})_Y = -R_A(\ddot{\Theta}\sin(\Theta) + \dot{\Theta}^2 \cos(\Theta)) \tag{28}$$



Determination of link CE accelerations

$$A_{CE})_X = \frac{13.2}{110} A_{EEF} + R_C(\ddot{\Theta}\cos(\Theta) - \dot{\Theta}^2 \sin(\Theta)) \tag{29}$$

$$(A_{CE})_Y = -R_C(\ddot{\Theta}\sin(\Theta) + \dot{\Theta}^2 \cos(\Theta)) \tag{30}$$



Determination of link DEF accelerations

$$(A_{DEF})_X = (\frac{R_{D1} + R_{LINK}}{2R_{LINK}}) A_{EEF} = 0.737 A_{EEF} \tag{31}$$

$$(A_{DEF})_Y = -R_F(\ddot{\Theta}\sin(\Theta) + \dot{\Theta}^2 \cos(\Theta)) \tag{32}$$

Figure A.8 *Determination of Link Velocity and Accelerations*

APPENDIX A
FORCE, MOMENT, AND STRESS CALCULATIONS

The previous free body diagrams give us twelve equations and twelve unknowns. The values for link length, link weight, position, velocity and acceleration are known or specified. To determine the unknowns, solve individual equations for one unknown and substitute into other equations. This reduces equation (16) to one unknown, Force at E in the Y direction. Equation (33) shows the relation.

$$F_{EY} = \frac{B + 7.334(A)}{16.13\sin(\Theta)} \quad \text{Where} \tag{33}$$

$$A = \left[M_{EEF}A_{EEF} + M_{DEF}(A_{DEF})_X\right]R_{D1Y} + \left[W_{EEF} + W_{DEF} + M_{DEF}(A_{DEF})_Y\right]R_{D1X} + M_{EEF}A_{EEF}R_{FY} + W_{EEF}R_{FX} + I_{DEF}\ddot{\Theta} \tag{34}$$

And

$$B = I_{CE}\ddot{\Theta} + M_{CE}(A_{CE})_X R_{CY} - \left[M_{CE}(A_{CE})_Y + W_{CE}\right]R_{CX} \tag{35}$$

Substituting the value for F_{EY} found with equation (33) into a simplified equation (16) yields the following equation.

$$F_{EX} = \frac{A}{1.1\cos(\Theta)} - F_{EY}\tan(\Theta) \tag{36}$$

Substituting F_{EX} and F_{EY} into equations (14) and (15) respectfully yields the following two equations.

$$F_{DX} = F_{EX} - M_{EEF}A_{EEF} - M_{DEF}(A_{DEF})_X \tag{37}$$

$$F_{DY} = F_{EY} - W_{EEF} - W_{DEF} - M_{DEF}(A_{DEF})_Y \tag{38}$$

Substituting F_{EX} and F_{EY} into equations (10) and (11) respectfully yields the following two equations.

$$F_{CX} = F_{EX} + M_{CE}(A_{CE})_X \tag{39}$$

$$F_{CY} = F_{EY} + M_{CE}(A_{CE})_Y + W_{CE} \tag{40}$$

APPENDIX A
FORCE, MOMENT, AND STRESS CALCULATIONS

To solve for F_{BC}, solve equations (4) and (5) for F_{AX} and F_{AY} respectfully and then substitute into equation (6) and solve the resultant equation for F_{BC}.

$$F_{BC} = \frac{C + \left[-F_{DX}\cos(\Theta) + F_{DY}\sin(\Theta)\right]R_D}{-2R_A\left[\cos(\Theta)\sin(\Theta)\right] + R_B\cos(2\Theta - 90)} \quad \text{Where} \tag{41}$$

$$C = I_{ABD}\ddot{\Theta} + R_A\left\{\left[M_{ABD}(A_{ABD})_X - F_{DX}\right]\cos(\Theta) + \left[-M_{ABD}(A_{ABD})_Y + F_{DY}\right]\sin(\Theta)\right\} \tag{42}$$

Substituting F_{BC} into equations (4) and (5) yields the following two equations which give the last two unknowns.

$$F_{AX} = M_{ABD}(A_{ABD})_X + F_{BC}\sin(\Theta) - F_{DX} \tag{43}$$

$$F_{AY} = M_{ABD}(A_{ABD})_Y + F_{BC}\cos(\Theta) + F_{DY} \tag{44}$$

APPENDIX A
FORCE, MOMENT, AND STRESS CALCULATIONS

RESULTS:

Critical Location	Stress	Arm Position	Arm Dynamics
[illegible]	5157 psi	70° (extended)	Accel= -6 ft/sec/sec Vel=anything
[illegible]	1173 psi	70° (extended)	Accel= -6ft/sec/sec Vel=anything
[illegible]	864 psi	70° (extended)	Accel= +6 ft/sec/sec Vel=anything
[illegible]	2971 psi	70° (extended)	Accel= +6 ft/sec/sec Vel=anything

Table A.1 *Maximum Stresses in the Links*

The maximum stress in each critical location are shown in Table A.1 below.

APPENDIX A
FORCE, MOMENT, AND STRESS CALCULATIONS

DETERMINATION OF CRITICAL LOADING FOR LINK CE

Since link CE is in compression without any external loads or bending moments, buckling of the column is a concern that needs to be addressed. Determination of the critical loading is shown below. The calculations are taken from Mechanical Engineering Design [8]. It must be determined if the column is a short or a long column and use the appropriate equations to determine the critical load. The figure below shows the regions.

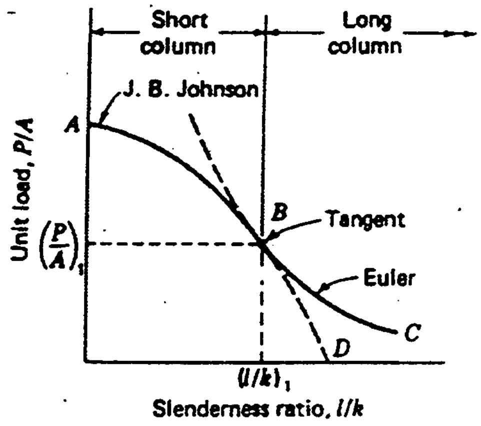


Figure A.9 *Determination of Column Loading Type*

J. B. Johnson formula:

$$\frac{P_{CR}}{A} = S_Y - \left(\frac{S_Y}{2\pi}\right)^2 \left(\frac{1}{CE}\right)\left(\frac{L}{k}\right)^2$$

Euler Formula:

$$\frac{P_{CR}}{A} = \frac{C\pi^2 E}{(L/k)^2} \qquad (44) \text{ and } (45)$$

Where:

$P_{CR} =$ Critical Loading

$A =$ Cross Sectional Area of Link CE

$S_Y =$ Yield Strength

$C =$ Distance from Neutral Axis to Outside of CE

$E =$ Modulus of Elasticity

$L =$ Length of the Column (Length of CE) = R_{CE}

$$k = \text{Spring Constant of the Column} = \frac{AE}{L} = \frac{AE}{R_{CE}} \qquad (46)$$

APPENDIX A
FORCE, MOMENT, AND STRESS CALCULATIONS

Assume that the link is the static case so that transverse (small) load causing bending due to inertia loads can be ignored.

First we must determine $(L/k)_1$. From Mechanical Engineering Design

$$(L/k)_1 = \sqrt{\frac{2\pi^2 CE}{S_Y}} \qquad (47)$$

$$= \sqrt{\frac{2\pi^2(1)(10x10^6)}{40x10^3}} = 70.2\ in^2/lb$$

Now calculate (L/k)

$$(L/k) = \frac{R_{CE}}{\left(\frac{AE}{R_{CE}}\right)} = \frac{R_{CE}^2}{AE} \qquad (48)$$

$$= \frac{96.8^2}{(4^2 - 3.5^2)(10x10^6)} = 2.49x10^{-3} << 70.2\ in^2/lb$$

Since $(L/k) << (L/k)_1$, we must therefore use J. B. Johnson formula

$$\frac{P_{CR}}{A} = S_Y - \left(\frac{S_Y}{2\pi}\right)^2\left(\frac{1}{CE}\right)\left(\frac{L}{k}\right)^2$$

$$= S_Y - \left(\frac{S_Y}{2\pi}\right)\left(\frac{1}{(1)(10x10^6)}\right)(2.49x10^{-3})^2 = S_Y - S_Y(9.9x10^{-14})$$

$$\Rightarrow \frac{P_{CR}}{A} \cong S_Y \qquad (49)$$

Use S_Y as the design stress with applicable factor of safety.

APPENDIX A
FORCE, MOMENT, AND STRESS CALCULATIONS

FORCE CALCULATIONS AT EACH JOINT
CONSTANTS:

	(feet)		(slugs)		(pounds)		(slugs*ft^2)
Ra=	4.34	Mabd=	6.24	Wabd=	201.26	Iabd=	78.64
Rb=	3.24	Mce=	2.37	Wce=	76.35	Ice=	20.41
Rc=	3.63	Mdef=	3.12	Wdef=	100.63	Idef=	39.32
Rd=	4.83	Meff=	6.21	Weff=	0.00		
Rd1=	4.34						
Re=	4.43						
Re1=	3.24						
Rf=	4.83						
Rlink=	9.17						

VARIABLE:

	(ft/sec^2)		(ft/sec)
Aeff=	0.00	Veff=	0.00

THETA (deg)	Fex (pounds)	Fey (pounds)	Fdx (pounds)	Fdy (pounds)	Fcx (pounds)	Fcy (pounds)	Fbc (pounds)	Fax (pounds)	Fay (pounds)	Fact (pounds)	Fnormal (pounds)
15.00	57.78	181.33	57.78	80.70	57.78	257.68	581.38	92.70	642.27	92.70	819.25
20.00	78.48	181.33	78.48	80.70	78.48	257.68	597.80	125.98	642.45	125.98	819.43
25.00	100.55	181.33	100.55	80.70	100.55	257.68	619.95	161.46	642.57	161.46	819.55
30.00	124.49	181.33	124.49	80.70	124.49	257.68	648.89	199.96	642.66	199.96	819.64
35.00	150.98	181.33	150.98	80.70	150.98	257.68	686.11	242.56	642.73	242.56	819.71
40.00	180.93	181.33	180.93	80.70	180.93	257.68	733.76	290.72	642.79	290.72	819.77
45.00	215.62	181.33	215.62	80.70	215.62	257.68	795.00	346.53	642.85	346.53	819.83
50.00	256.97	181.33	256.97	80.70	256.97	257.68	874.64	413.05	642.91	413.05	819.89
55.00	307.94	181.33	307.94	80.70	307.94	257.68	980.29	495.07	642.98	495.07	819.96
60.00	373.47	181.33	373.47	80.70	373.47	257.68	1124.69	600.54	643.05	600.54	820.03
65.00	462.40	181.33	462.40	80.70	462.40	257.68	1330.83	743.74	643.14	743.74	820.12
70.00	592.41	181.33	592.41	80.70	592.41	257.68	1644.79	953.19	643.26	953.19	820.24

THETA (deg)	Mb (in lb)	Stress B. (psi)	Stress BC (psi)	Stress CE (psi)	Me (in lb)	Stress E (psi)
15.00	3376.63	451.17	142.70	70.42	1012.37	155.32
20.00	4463.54	592.16	146.74	71.83	1337.81	196.22
25.00	5516.56	729.49	152.17	73.76	1653.07	235.62
30.00	6527.67	862.20	159.28	76.31	1955.74	273.23
35.00	7489.19	989.44	168.41	79.64	2243.54	308.76
40.00	8393.83	1110.42	180.11	83.96	2514.26	341.94
45.00	9234.72	1224.52	195.14	89.60	2765.84	372.51
50.00	10005.49	1331.29	214.69	97.04	2996.37	400.25
55.00	10700.35	1430.60	240.62	107.07	3204.10	424.95
60.00	11314.09	1522.78	276.06	121.00	3387.45	446.41
65.00	11842.21	1609.11	326.66	141.16	3545.01	464.47
70.00	12281.03	1692.80	403.73	172.27	3675.60	479.00

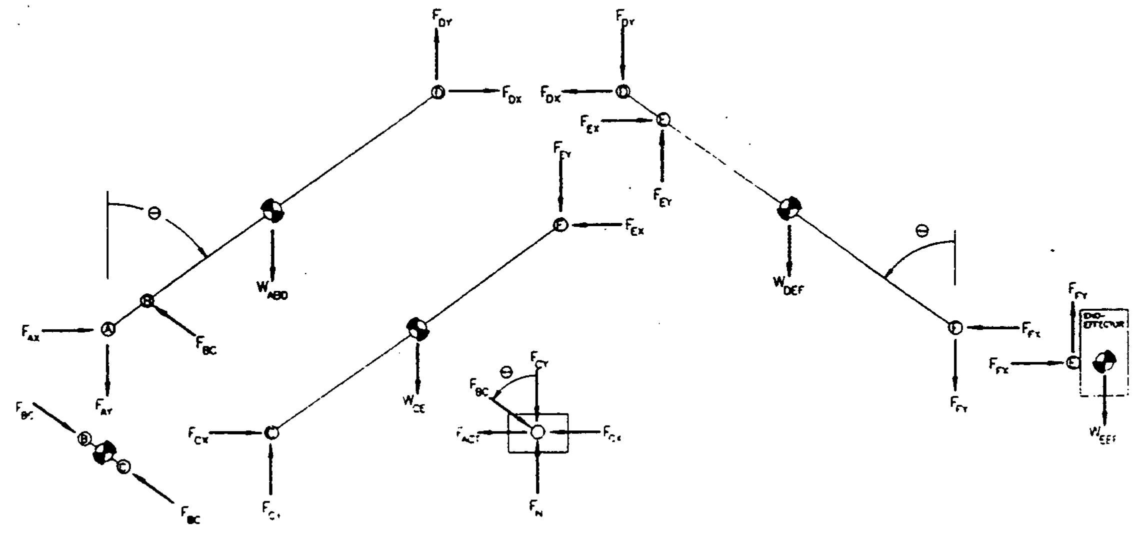


Table A.2 *Link Forces and Stresses with Weef=0, Velocity=0, and Acceleration=0*

APPENDIX A
FORCE, MOMENT, AND STRESS CALCULATIONS

FORCE CALCULATIONS AT EACH JOINT
CONSTANTS:

	(feet)		(slugs)		(pounds)		(slugs*ft^2)
Ra=	4.34	Mabd=	6.24	Wabd=	201.26	Iabd=	78.64
Rb=	3.24	Mce=	2.37	Wce=	76.35	Ice=	20.41
Rc=	3.63	Mdef=	3.12	Wdef=	100.63	Idef=	39.32
Rd=	4.83	Meff=	6.21	Weff=	200.00		
Rd1=	4.34						
Re=	4.43	VARIABLE:			(ft/sec^2)		(ft/sec)
Re1=	3.24			Aeff=	0.00	Veff=	0.00
Rf=	4.83						
Rlink=	9.17						

THETA (deg)	Fex (pounds)	Fey (pounds)	Fdx (pounds)	Fdy (pounds)	Fcx (pounds)	Fcy (pounds)	Fbc (pounds)	Fax (pounds)	Fay (pounds)	Fact (pounds)	Fnormal (pounds)
15.00	281.00	1014.92	281.00	714.29	281.00	1091.27	1441.07	91.98	2106.26	91.98	2483.24
20.00	381.70	1014.92	381.70	714.29	381.70	1091.27	1481.78	125.10	2106.71	125.10	2483.69
25.00	489.02	1014.92	489.02	714.29	489.02	1091.27	1536.69	160.41	2107.00	160.41	2483.98
30.00	605.47	1014.92	605.47	714.29	605.47	1091.27	1608.42	198.74	2107.22	198.74	2484.20
35.00	734.31	1014.92	734.31	714.29	734.31	1091.27	1700.68	241.16	2107.40	241.16	2484.38
40.00	879.97	1014.92	879.97	714.29	879.97	1091.27	1818.78	289.12	2107.55	289.12	2484.53
45.00	1048.71	1014.92	1048.71	714.29	1048.71	1091.27	1970.59	344.71	2107.70	344.71	2484.68
50.00	1249.80	1014.92	1249.80	714.29	1249.80	1091.27	2168.00	410.99	2107.85	410.99	2484.83
55.00	1497.71	1014.92	1497.71	714.29	1497.71	1091.27	2429.88	492.73	2108.01	492.73	2484.99
60.00	1816.41	1014.92	1816.41	714.29	1816.41	1091.27	2787.80	597.89	2108.18	597.89	2485.16
65.00	2248.96	1014.92	2248.96	714.29	2248.96	1091.27	3298.76	740.74	2108.40	740.74	2485.38
70.00	2881.30	1014.92	2881.30	714.29	2881.30	1091.27	4076.99	949.82	2108.70	949.82	2485.68

THETA (deg)	Mb (in lb)	Stress B (psi)	Stress BC (psi)	Stress CE (psi)	Me (in lb)	Stress E (psi)
15.00	8369.76	1230.41	353.72	300.50	6023.10	847.33
20.00	11063.92	1583.01	363.72	308.29	7959.32	1092.72
25.00	13674.05	1927.65	377.19	318.89	9834.96	1329.79
30.00	16180.32	2262.18	394.80	332.79	11635.74	1556.74
35.00	18563.68	2584.71	417.45	350.75	13347.98	1771.84
40.00	20806.02	2893.76	446.44	373.83	14958.62	1973.46
45.00	22890.35	3188.36	483.70	403.60	16455.43	2160.07
50.00	24800.90	3468.34	532.16	442.45	17826.99	2330.23
55.00	26523.26	3734.81	596.44	494.16	19062.89	2482.65
60.00	28044.55	3991.09	684.29	565.07	20153.70	2616.19
65.00	29353.63	4244.72	809.71	666.60	21091.13	2729.81
70.00	30441.35	4512.53	1000.73	821.61	21868.05	2822.65

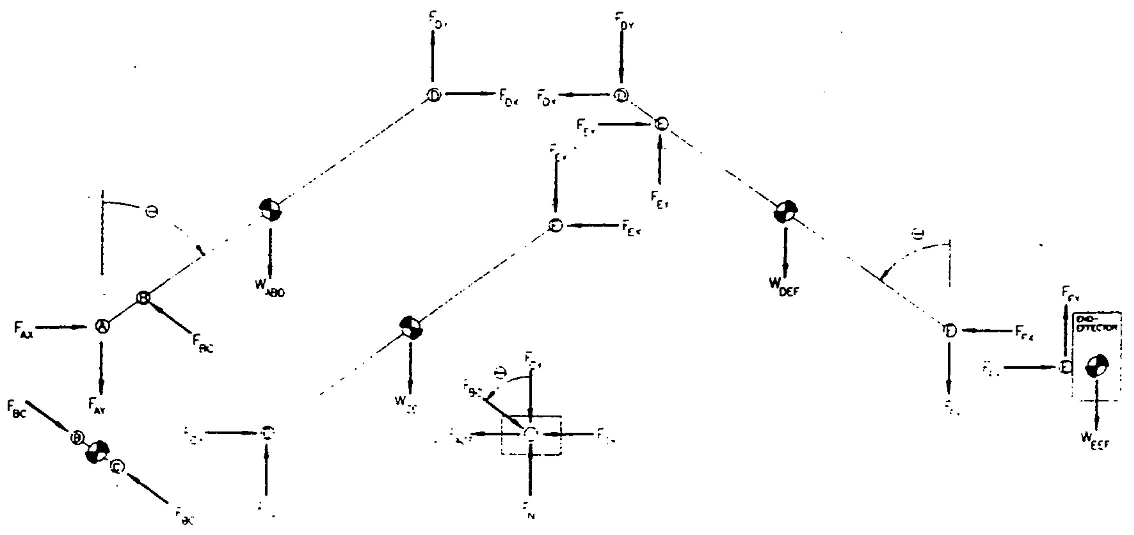


Table A.3 *Link Forces and Stresses with Weef=200, Velocity=0, and Acceleration=0*

APPENDIX A
FORCE, MOMENT, AND STRESS CALCULATIONS

FORCE CALCULATIONS AT EACH JOINT

CONSTANTS:

	(feet)		(slugs)		(pounds)		(slugs*ft^2)
Ra=	4.34	Mabd=	6.24	Wabd=	201.26	Iabd=	78.64
Rb=	3.24	Mce=	2.37	Wce=	76.35	Ice=	20.41
Rc=	3.63	Mdef=	3.12	Wdef=	100.63	Idef=	39.32
Rd=	4.83	Meff=	6.21	Weff=	200.00		
Rd1=	4.34						
Re=	4.43						
Re1=	3.24						
Rf=	4.83						
Rlink=	9.17						

VARIABLE:

	(ft/sec^2)		(ft/sec)
Aeff=	6.00	Veff=	0.00

THETA (deg)	Fex (pounds)	Fey (pounds)	Fdx (pounds)	Fdy (pounds)	Fcx (pounds)	Fcy (pounds)	Fbc (pounds)	Fax (pounds)	Fay (pounds)	Fact (pounds)	Fnormal (pounds)
15.00	467.46	1722.46	416.41	1423.15	471.98	1798.06	443.34	-292.80	1853.76	-357.24	2226.29
20.00	567.86	1535.33	516.80	1236.49	572.38	1610.65	716.16	-263.00	1912.69	-327.44	2283.62
25.00	674.76	1420.60	623.71	1122.27	679.28	1495.64	905.20	-232.29	1946.80	-296.73	2316.03
30.00	790.64	1342.01	739.59	1044.23	795.17	1416.73	1061.04	-200.21	1968.23	-264.65	2335.62
35.00	918.71	1283.99	867.66	986.81	923.23	1358.36	1207.46	-166.23	1982.10	-230.67	2347.45
40.00	1063.31	1238.73	1012.26	942.23	1067.84	1312.71	1359.18	-129.74	1990.86	-194.17	2353.91
45.00	1230.59	1201.88	1179.54	906.18	1235.12	1275.41	1528.29	-90.02	1995.70	-154.46	2356.07
50.00	1429.62	1170.80	1378.57	876.05	1434.14	1243.79	1727.62	-46.28	1997.10	-110.71	2354.28
55.00	1674.48	1143.77	1623.43	850.18	1679.01	1216.10	1973.80	2.27	1994.96	-62.16	2348.22
60.00	1988.46	1119.60	1937.41	827.51	1992.98	1191.07	2291.51	55.96	1988.61	-8.48	2336.82
65.00	2413.14	1097.36	2362.08	807.30	2417.66	1167.66	2721.29	113.11	1976.37	48.67	2317.73
70.00	3030.96	1076.23	2979.91	789.15	3035.48	1144.84	3336.31	164.06	1954.58	99.63	2285.92

THETA (deg)	Mb (in lb)	Stress B (psi)	Stress BC (psi)	Stress CE (psi)	Me (in lb)	Stress E (psi)
15.00	2574.92	641.22	108.82	495.73	9506.97	1290.07
20.00	5347.27	965.33	175.79	455.82	11348.57	1522.54
25.00	8054.82	1299.21	222.19	438.05	13103.80	1743.42
30.00	10673.77	1632.59	260.44	433.23	14759.30	1951.03
35.00	13179.95	1959.65	296.38	437.98	16302.47	2143.80
40.00	15548.40	2276.38	333.62	451.25	17721.57	2320.25
45.00	17752.60	2579.68	375.13	473.45	19005.80	2479.03
50.00	19763.12	2867.05	424.06	506.23	20145.38	2618.96
55.00	21544.94	3136.56	484.49	552.84	21131.64	2738.95
60.00	23052.01	3386.91	562.47	619.14	21957.08	2838.09
65.00	24215.06	3617.75	667.97	715.96	22615.42	2915.64
70.00	24910.98	3830.53	818.93	865.12	23101.63	2971.00

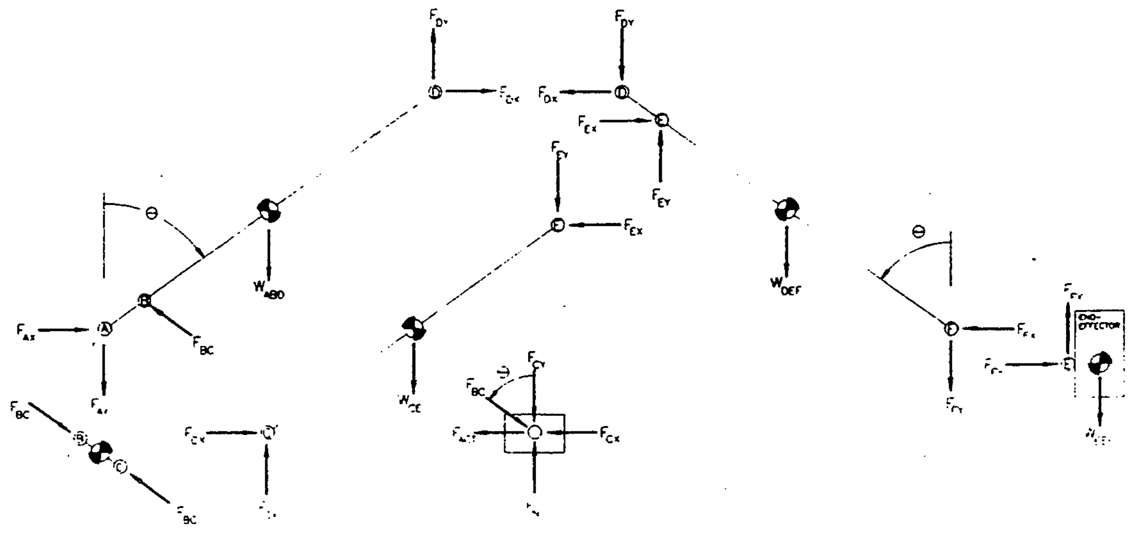


Table A.4 *Link Forces and Stresses with Weef=200, Velocity=0, and Acceleration=6*

APPENDIX A
FORCE, MOMENT, AND STRESS CALCULATIONS

FORCE CALCULATIONS AT EACH JOINT

CONSTANTS:

	(feet)		(slugs)		(pounds)		(slugs*ft^2)
Ra=	4.34	Mabd=	6.24	Wabd=	201.26	Iabd=	78.64
Rb=	3.24	Mce=	2.37	Wce=	76.35	Ice=	20.41
Rc=	3.63	Mdef=	3.12	Wdef=	100.63	Idef=	39.32
Rd=	4.83	Meff=	6.21	Weff=	200.00		
Rd1=	4.34						
Re=	4.43						
Re1=	3.24						
Rf=	4.83						
Rlink=	9.17						

VARIABLE:

	(ft/sec^2)		(ft/sec)
Aeff=	6.00	Veff=	1.00

THETA (deg)	Fex (pounds)	Fey (pounds)	Fdx (pounds)	Fdy (pounds)	Fcx (pounds)	Fcy (pounds)	Fbc (pounds)	Fax (pounds)	Fay (pounds)	Fact (pounds)	Fnormal (pounds)
15.00	467.44	1722.43	416.39	1423.18	471.97	1798.00	442.73	-292.94	1853.28	-357.38	2225.65
20.00	567.84	1535.30	516.79	1236.52	572.36	1610.59	715.48	-263.22	1912.17	-327.65	2282.92
25.00	674.73	1420.57	623.68	1122.30	679.26	1495.57	904.41	-232.60	1946.22	-297.03	2315.25
30.00	790.60	1341.97	739.55	1044.26	795.13	1416.65	1060.09	-200.64	1967.56	-265.08	2334.72
35.00	918.65	1283.94	867.60	986.84	923.18	1358.27	1206.28	-166.85	1981.32	-231.29	2346.39
40.00	1063.23	1238.67	1012.18	942.28	1067.76	1312.60	1357.64	-130.64	1989.90	-195.08	2352.61
45.00	1230.47	1201.81	1179.42	906.23	1234.99	1275.27	1526.16	-91.39	1994.48	-155.83	2354.43
50.00	1429.42	1170.70	1378.37	876.12	1433.94	1243.60	1724.50	-48.46	1995.47	-112.90	2352.09
55.00	1674.14	1143.64	1623.09	850.28	1678.67	1215.83	1968.89	-1.41	1992.67	-65.85	2345.13
60.00	1987.84	1119.39	1936.79	827.66	1992.36	1190.66	2283.00	49.21	1985.15	-15.22	2332.16
65.00	2411.86	1097.02	2360.81	807.55	2416.39	1166.98	2704.63	99.27	1970.65	34.83	2310.01
70.00	3027.89	1075.59	2976.83	789.62	3032.41	1143.55	3297.45	130.62	1943.78	66.18	2271.35

THETA (deg)	Mb (in lb)	Stress B (psi)	Stress BC (psi)	Stress CE (psi)	Me (in lb)	Stress E (psi)
15.00	2571.38	640.78	108.67	495.71	9506.97	1290.07
20.00	5342.18	964.68	175.62	455.81	11348.57	1522.54
25.00	8047.82	1298.32	222.00	438.03	13103.80	1743.42
30.00	10664.27	1631.37	260.21	433.21	14759.30	1951.03
35.00	13167.07	1958.00	296.09	437.95	16302.47	2143.80
40.00	15530.75	2274.12	333.24	451.21	17721.57	2320.25
45.00	17727.91	2576.51	374.61	473.40	19005.80	2479.03
50.00	19727.51	2862.48	423.30	506.16	20145.38	2618.96
55.00	21491.34	3129.66	483.28	552.72	21131.64	2738.95
60.00	22966.45	3375.87	560.38	618.94	21957.08	2838.09
65.00	24066.77	3598.58	663.87	715.58	22615.42	2915.64
70.00	24620.84	3792.87	809.39	864.23	23101.63	2971.00

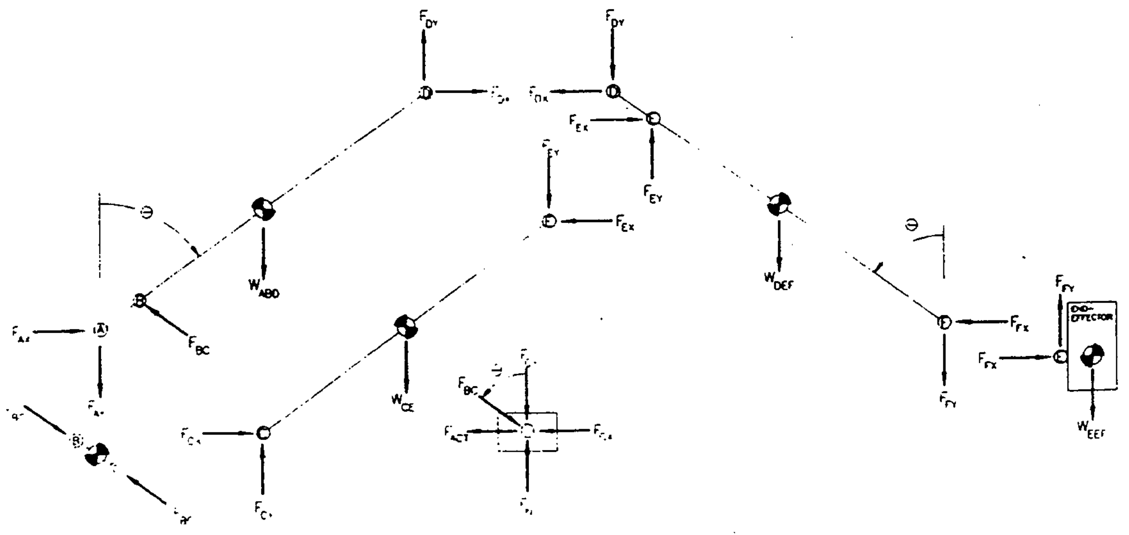


Table A.5 *Link Forces and Stresses with Weef=200, Velocity=1, and Acceleration=6*

APPENDIX A
FORCE, MOMENT, AND STRESS CALCULATIONS

FORCE CALCULATIONS AT EACH JOINT
CONSTANTS:

	(feet)		(slugs)		(pounds)		(slugs*ft^2)
Ra=	4.34	Mabd=	6.24	Wabd=	201.26	Iabd=	78.64
Rb=	3.24	Mce=	2.37	Wce=	76.35	Ice=	20.41
Rc=	3.63	Mdef=	3.12	Wdef=	100.63	Idef=	39.32
Rd=	4.83	Meff=	6.21	Weff=	200.00		
Rd1=	4.34						
Re=	4.43						
Re1=	3.24						
Rf=	4.83						
Rlink=	9.17						

VARIABLE:	(ft/sec^2)		(ft/sec)
Aeff=	-6.00	Veff=	1.00

THETA (deg)	Fex (pounds)	Fey (pounds)	Fdx (pounds)	Fdy (pounds)	Fcx (pounds)	Fcy (pounds)	Fbc (pounds)	Fax (pounds)	Fay (pounds)	Fact (pounds)	Fnormal (pounds)
15.00	94.53	307.34	145.58	5.44	90.00	384.42	2438.20	476.61	2358.27	541.05	2739.53
20.00	195.52	494.47	246.57	192.10	190.99	571.82	2246.73	512.99	2300.21	577.43	2683.05
25.00	303.25	609.19	354.30	306.33	298.73	686.82	2167.39	552.82	2266.63	617.25	2651.15
30.00	420.26	687.78	471.31	384.37	415.74	765.72	2154.86	597.26	2245.55	661.70	2631.89
35.00	549.86	745.80	600.91	441.80	545.33	824.08	2192.72	647.92	2231.91	712.36	2620.24
40.00	696.54	791.05	747.59	486.38	692.01	869.70	2276.84	707.07	2223.29	771.51	2613.87
45.00	866.69	827.88	917.74	522.45	862.16	906.97	2410.76	778.06	2218.48	842.50	2611.64
50.00	1069.78	858.93	1120.83	552.60	1065.25	938.55	2605.27	866.06	2216.98	930.50	2613.18
55.00	1320.60	885.92	1371.65	578.49	1316.07	966.16	2881.05	979.51	2218.76	1043.95	2618.66
60.00	1643.74	910.03	1694.80	601.22	1639.22	991.06	3275.58	1133.08	2224.31	1197.52	2628.85
65.00	2083.51	932.13	2134.56	621.53	2078.98	1014.19	3859.57	1354.54	2234.72	1418.98	2645.31
70.00	2728.56	952.96	2779.61	639.90	2724.04	1036.41	4778.81	1702.14	2252.02	1766.58	2670.86

THETA (deg)	Mb (in lb)	Stress B (psi)	Stress BC (psi)	Stress CE (psi)	Me (in lb)	Stress E (psi)
15.00	14161.05	1819.14	598.48	105.28	2539.23	404.58
20.00	16775.48	2200.05	551.48	160.77	4570.06	662.89
25.00	19286.28	2555.20	532.01	199.73	6566.11	916.15
30.00	21677.38	2890.55	528.93	232.35	8512.19	1162.45
35.00	23934.53	3208.13	538.22	263.51	10393.49	1399.89
40.00	26046.00	3508.88	558.87	296.38	12195.68	1626.68
45.00	28003.42	3793.87	591.74	333.70	13905.06	1841.10
50.00	29803.07	4065.05	639.49	378.59	15508.61	2041.50
55.00	31447.98	4326.17	707.18	435.37	16994.13	2226.36
60.00	32951.55	4584.24	804.02	510.81	18350.32	2394.28
65.00	34343.91	4852.51	947.37	616.84	19566.84	2543.97
70.00	35681.57	5156.88	1173.00	777.21	20634.46	2674.31

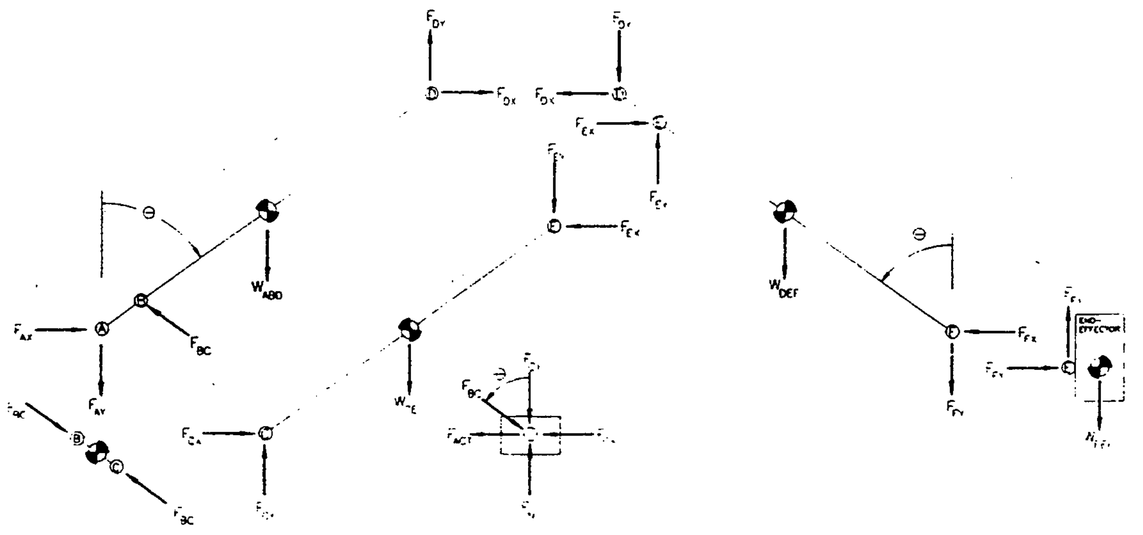


Table A.6 *Link Forces and Stresses with Weef=200, Velocity=1, and Acceleration=-6*

APPENDIX A
FORCE, MOMENT, AND STRESS ~~CALCULATIONS~~

FORCE CALCULATIONS AT EACH JOINT

CONSTANTS:

	(feet)		(slugs)		(pounds)		(slugs*ft^2)
Ra=	4.34	Mabd=	6.24	Wabd=	201.26	Iabd=	78.64
Rb=	3.24	Mce=	2.37	Wce=	76.35	Ice=	20.41
Rc=	3.63	Mdef=	3.12	Wdef=	100.63	Idef=	39.32
Rd=	4.83	Meff=	6.21	Weff=	200.00		
Rd1=	4.34						
Re=	4.43						
Re1=	3.24						
Rf=	4.83						
Rlink=	9.17						

VARIABLE:

	(ft/sec^2)		(ft/sec)
Aeff=	6.00	Veff=	-1.00

THETA (deg)	Fex (pounds)	Fey (pounds)	Fdx (pounds)	Fdy (pounds)	Fcx (pounds)	Fcy (pounds)	Fbc (pounds)	Fax (pounds)	Fay (pounds)	Fact (pounds)	Fnormal (pounds)
15.00	467.44	1722.43	416.39	1423.18	471.97	1798.00	442.73	-292.94	1853.28	-357.38	2225.65
20.00	567.84	1535.30	516.79	1236.52	572.36	1610.59	715.48	-263.22	1912.17	-327.65	2282.92
25.00	674.73	1420.57	623.68	1122.30	679.26	1495.57	904.41	-232.60	1946.22	-297.03	2315.25
30.00	790.60	1341.97	739.55	1044.26	795.13	1416.65	1060.09	-200.64	1967.56	-265.08	2334.72
35.00	918.65	1283.94	867.60	986.84	923.18	1358.27	1206.28	-166.85	1981.32	-231.29	2346.39
40.00	1063.23	1238.67	1012.18	942.28	1067.76	1312.60	1357.64	-130.64	1989.90	-195.08	2352.61
45.00	1230.47	1201.81	1179.42	906.23	1234.99	1275.27	1526.16	-91.39	1994.48	-155.83	2354.43
50.00	1429.42	1170.70	1378.37	876.12	1433.94	1243.60	1724.50	-48.46	1995.47	-112.90	2352.09
55.00	1674.14	1143.64	1623.09	850.28	1678.67	1215.83	1968.89	-1.41	1992.67	-65.85	2345.13
60.00	1987.84	1119.39	1936.79	827.66	1992.36	1190.66	2283.00	49.21	1985.15	-15.22	2332.16
65.00	2411.86	1097.02	2360.81	807.55	2416.39	1166.98	2704.63	99.27	1970.65	34.83	2310.01
70.00	3027.89	1075.59	2976.83	789.62	3032.41	1143.55	3297.45	130.62	1943.78	66.18	2271.35

THETA (deg)	Mb (in lb)	Stress B (psi)	Stress BC (psi)	Stress CE (psi)	Me (in lb)	Stress E (psi)
15.00	2571.38	640.78	108.67	495.71	9506.97	1290.07
20.00	5342.18	964.68	175.62	455.81	11348.57	1522.54
25.00	8047.82	1298.32	222.00	438.03	13103.80	1743.42
30.00	10664.27	1631.37	260.21	433.21	14759.30	1951.03
35.00	13167.07	1958.00	296.09	437.95	16302.47	2143.80
40.00	15530.75	2274.12	333.24	451.21	17721.57	2320.25
45.00	17727.91	2576.51	374.61	473.40	19005.80	2479.03
50.00	19727.51	2862.48	423.30	506.16	20145.38	2618.96
55.00	21491.34	3129.66	483.28	552.72	21131.64	2738.95
60.00	22966.45	3375.87	560.38	618.94	21957.08	2838.09
65.00	24066.77	3598.58	663.87	715.58	22615.42	2915.64
70.00	24620.84	3792.87	809.39	864.23	23101.63	2971.00

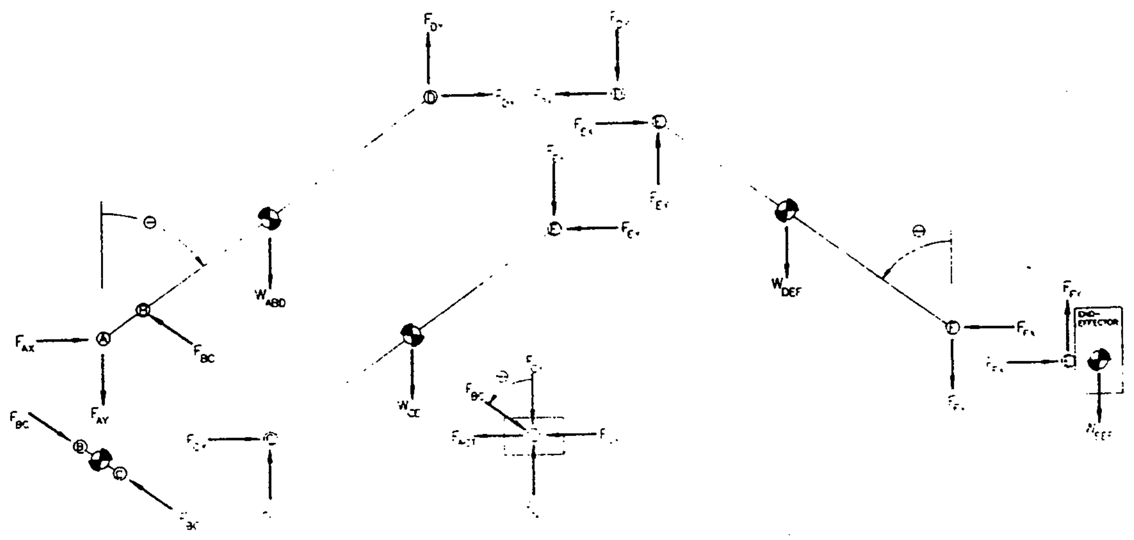


Table A.7 *Link Forces and Stresses with Weef=200, Velocity=-1, and Acceleration=6*

APPENDIX A
FORCE, MOMENT, AND STRESS CALCULATIONS

FORCE CALCULATIONS AT EACH JOINT
CONSTANTS:

	(feet)		(stugs)		(pounds)		(slugs*ft^2)
Ra=	4.34	Mabd=	6.24	Wabd=	201.26	Iabd=	78.64
Rb=	3.24	Mce=	2.37	Wce=	76.35	Ice=	20.41
Rc=	3.63	Mdef=	3.12	Wdef=	100.63	Idef=	39.32
Rd=	4.83	Meff=	6.21	Weff=	200.00		
Rd1=	4.34						
Re=	4.43						
Re1=	3.24						
Rf=	4.83						
Rlink=	9.17						

VARIABLE:

	(ft/sec^2)		(ft/sec)
Aeff=	-6.00	Veff=	-1.00

THETA (deg)	Fex (pounds)	Fey (pounds)	Fdx (pounds)	Fdy (pounds)	Fcx (pounds)	Fcy (pounds)	Fbc (pounds)	Fax (pounds)	Fay (pounds)	Fact (pounds)	Fnormal (pounds)
15.00	94.53	307.34	145.58	5.44	90.00	384.42	2438.20	476.61	2358.27	541.05	2739.53
20.00	195.52	494.47	246.57	192.10	190.99	571.82	2246.73	512.99	2300.21	577.43	2683.05
25.00	303.25	609.19	354.30	306.33	298.73	686.82	2167.39	552.82	2266.63	617.25	2651.15
30.00	420.26	687.78	471.31	384.37	415.74	765.72	2154.86	597.26	2245.55	661.70	2631.89
35.00	549.86	745.80	600.91	441.80	545.33	824.08	2192.72	647.92	2231.91	712.36	2620.24
40.00	696.54	791.05	747.59	486.38	692.01	869.70	2276.84	707.07	2223.29	771.51	2613.87
45.00	866.69	827.88	917.74	522.45	862.16	906.97	2410.76	778.06	2218.48	842.50	2611.64
50.00	1069.78	858.93	1120.83	552.60	1065.25	938.55	2605.27	866.06	2216.98	930.50	2613.18
55.00	1320.60	885.92	1371.65	578.49	1316.07	966.16	2881.05	979.51	2218.76	1043.95	2618.66
60.00	1643.74	910.03	1694.80	601.22	1639.22	991.06	3275.58	1133.08	2224.31	1197.52	2628.85
65.00	2083.51	932.13	2134.56	621.53	2078.98	1014.19	3859.57	1354.54	2234.72	1418.98	2645.31
70.00	2728.56	952.96	2779.61	639.90	2724.04	1036.41	4778.81	1702.14	2252.02	1766.58	2670.86

THETA (deg)	Mb (in lb)	Stress B (psi)	Stress BC (psi)	Stress CE (psi)	Me (in lb)	Stress E (psi)
15.00	14161.05	1819.14	598.48	105.28	2539.23	404.58
20.00	16775.48	2200.05	551.48	160.77	4570.06	662.89
25.00	19286.28	2555.20	532.01	199.73	6566.11	916.15
30.00	21677.38	2890.55	528.93	232.35	8512.19	1162.45
35.00	23934.53	3208.13	538.22	263.51	10393.49	1399.89
40.00	26046.00	3508.88	558.87	296.38	12195.68	1626.68
45.00	28003.42	3793.87	591.74	333.70	13905.06	1841.10
50.00	29803.07	4065.05	639.49	378.59	15508.61	2041.50
55.00	31447.98	4326.17	707.18	435.37	16994.13	2226.36
60.00	32951.55	4584.24	804.02	510.81	18350.32	2394.28
65.00	34343.91	4852.51	947.37	616.84	19566.84	2543.97
70.00	35681.57	5156.88	1173.00	777.21	20634.46	2674.31

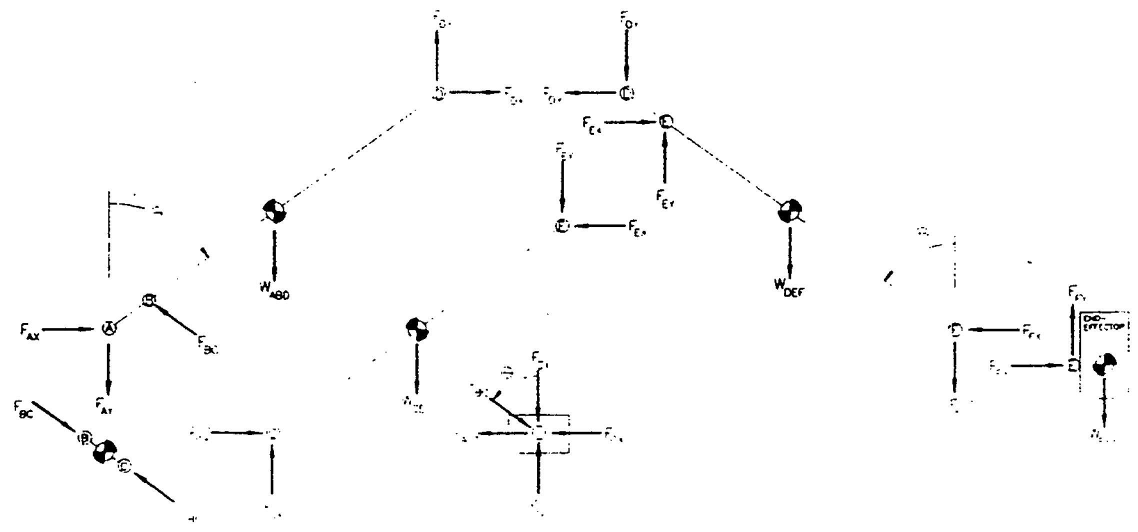
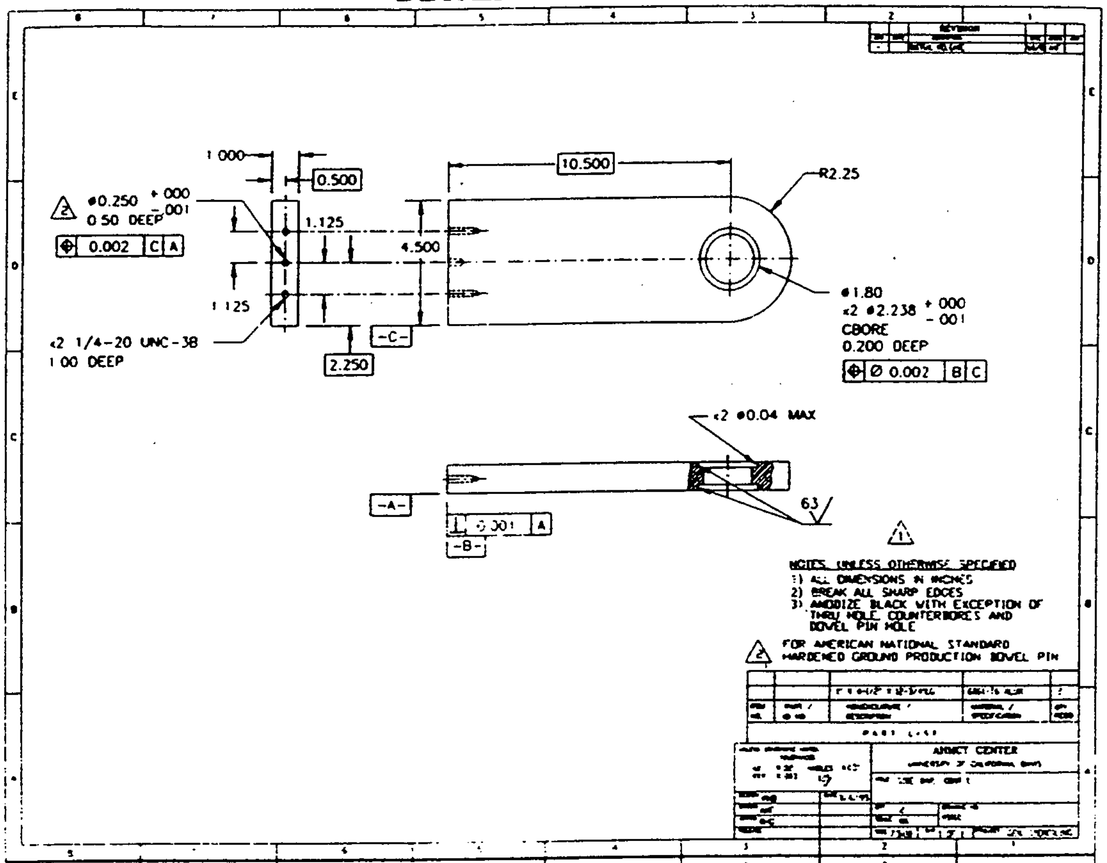
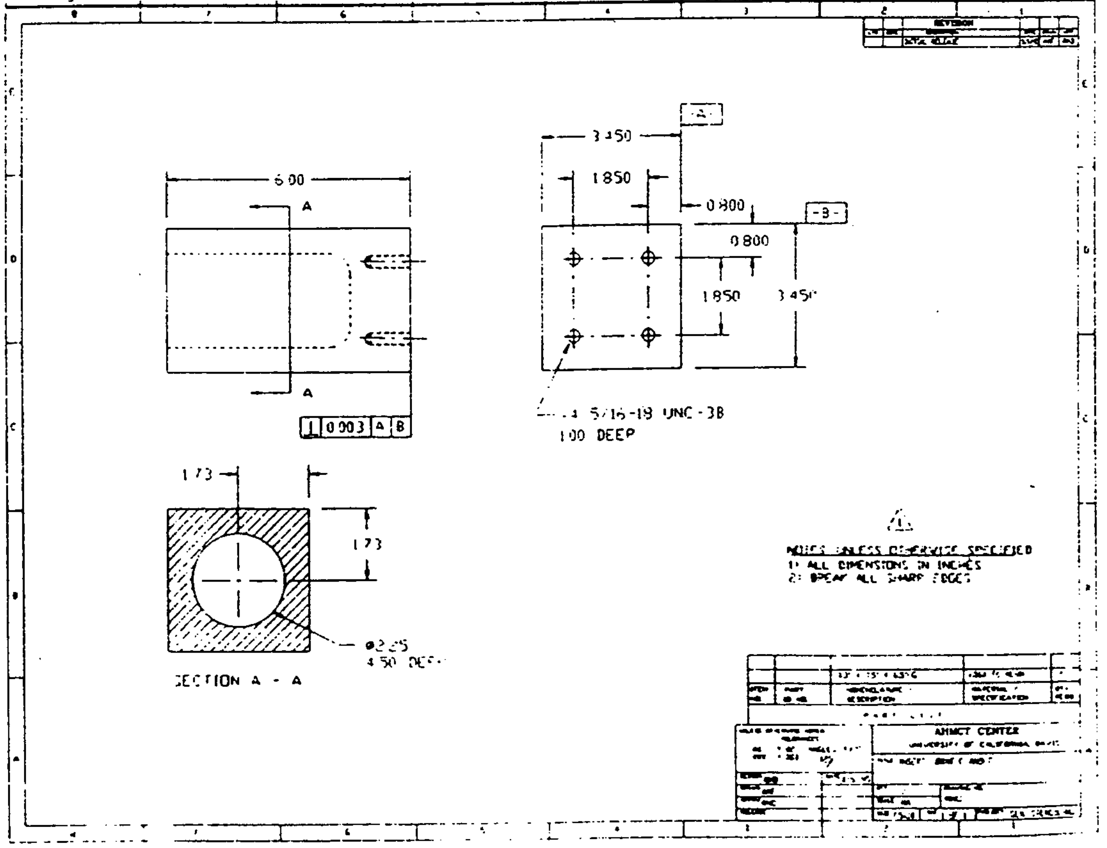


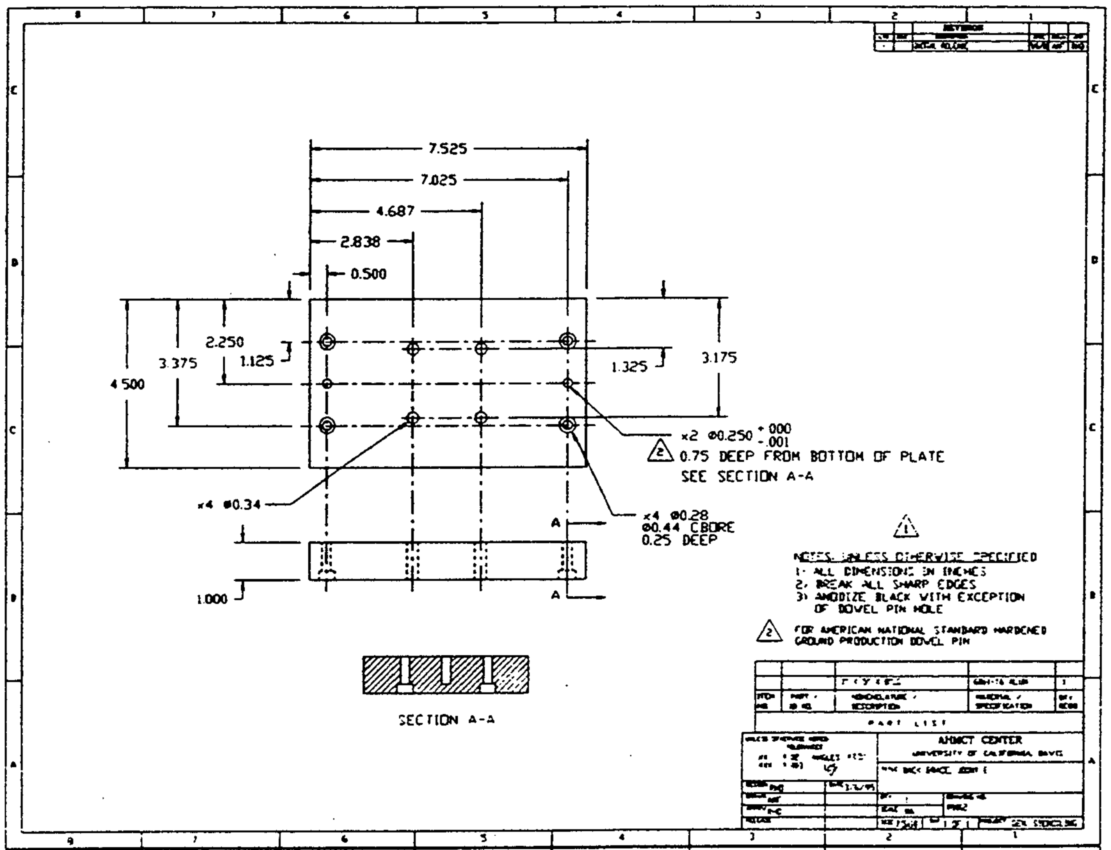
Table A.8 *Link Forces and Stresses with Weef=200, Velocity=-1, and Acceleration=-6*

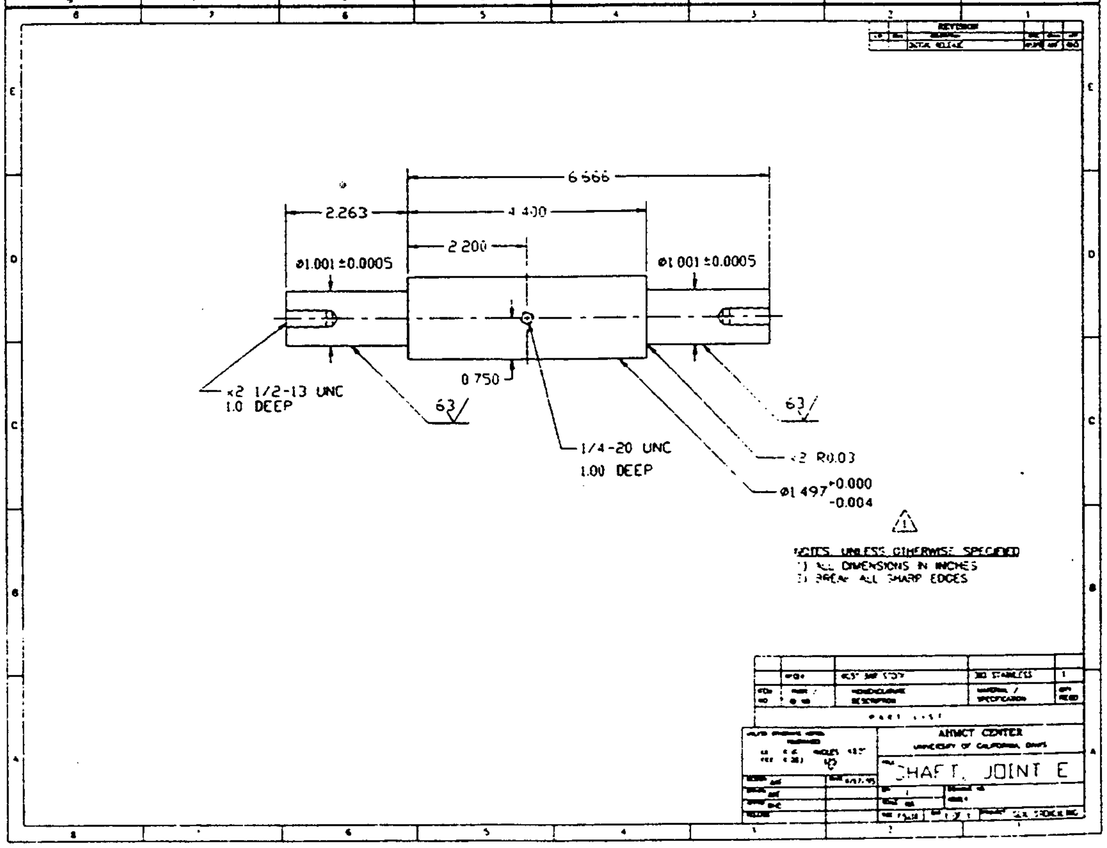
APPENDIX B
DETAILED DRAWINGS



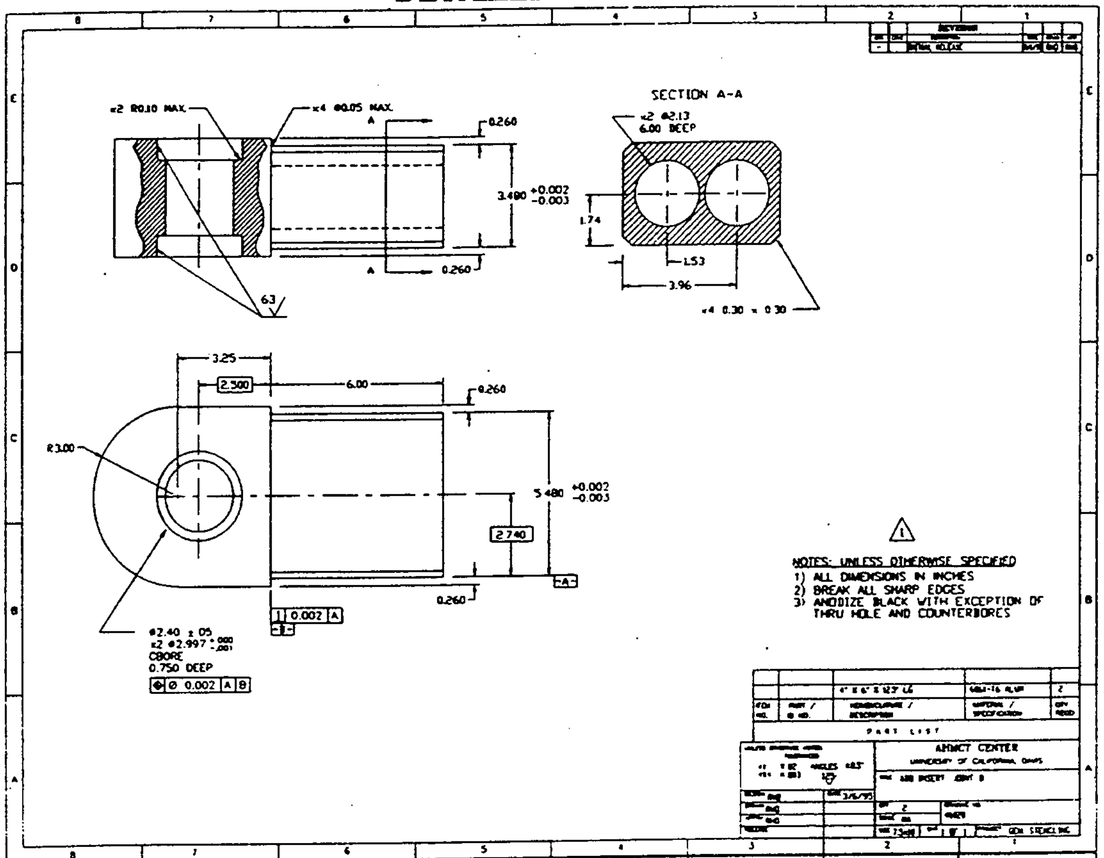


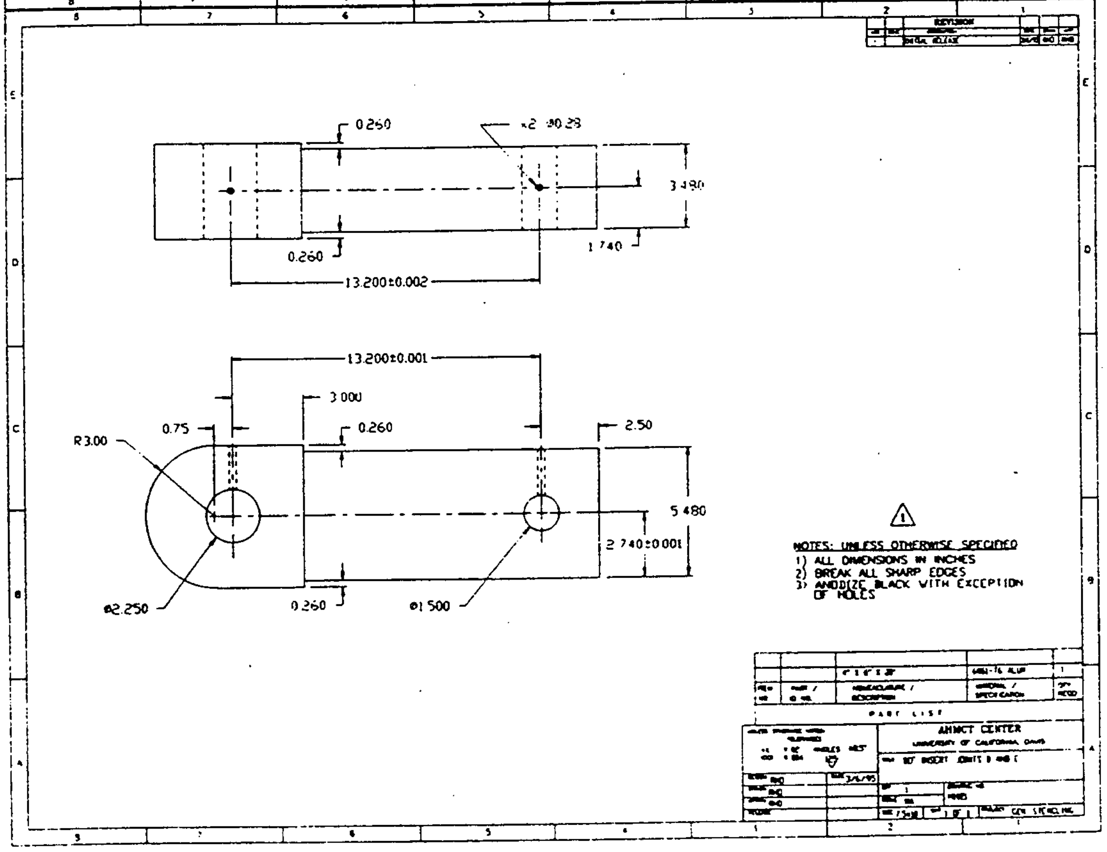
APPENDIX B
DETAILED DRAWINGS


7.525
7.025
4.687
2.838
0.500
2.250
3.375
1.125
4.500
1.325
3.175
x2 Ø0.250 +.000 -.001
0.75 DEEP FROM BOTTOM OF PLATE
SEE SECTION A-A
x4 Ø0.34
x4 Ø0.28
Ø0.44 CBORE
0.25 DEEP
1.000
SECTION A-A
NOTES: UNLESS OTHERWISE SPECIFIED
1. ALL DIMENSIONS IN INCHES
2. BREAK ALL SHARP EDGES
3. ANODIZE BLACK WITH EXCEPTION OF DOWEL PIN HOLE
FOR AMERICAN NATIONAL STANDARD HARDENED GROUND PRODUCTION DOWEL PIN
AHMCT CENTER
UNIVERSITY OF CALIFORNIA, DAVIS

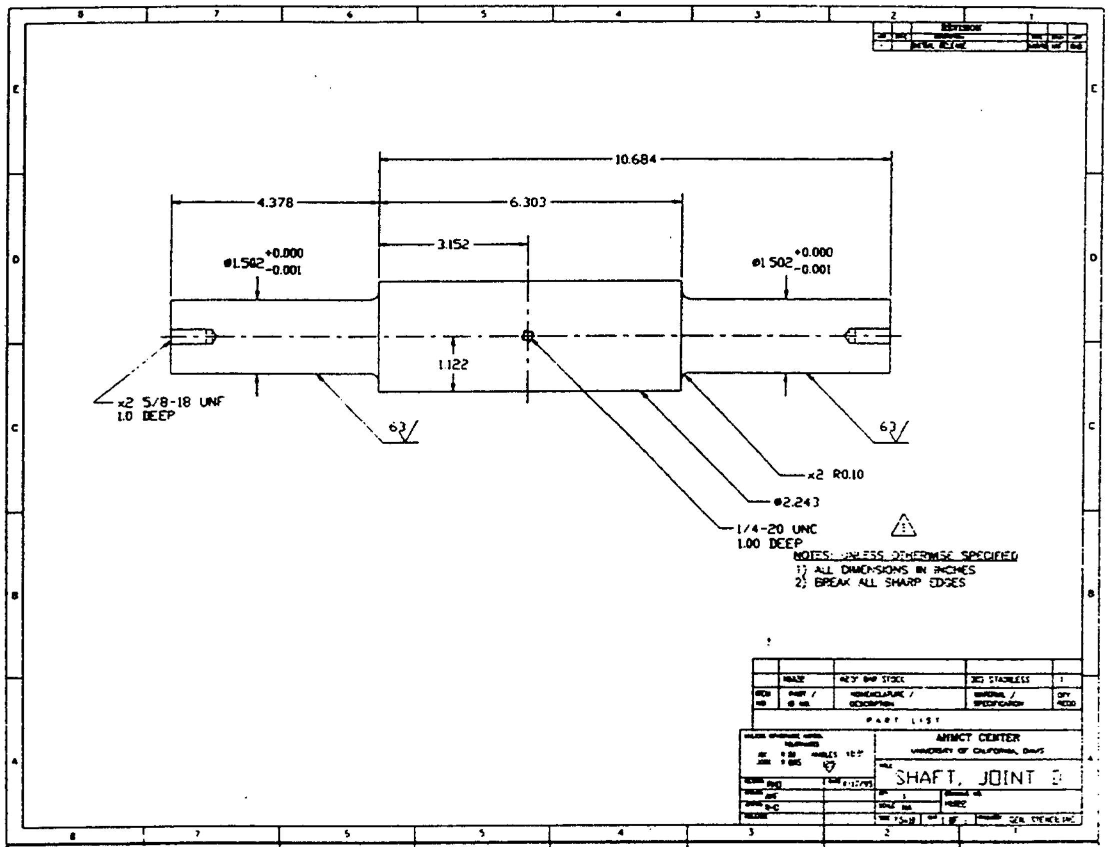


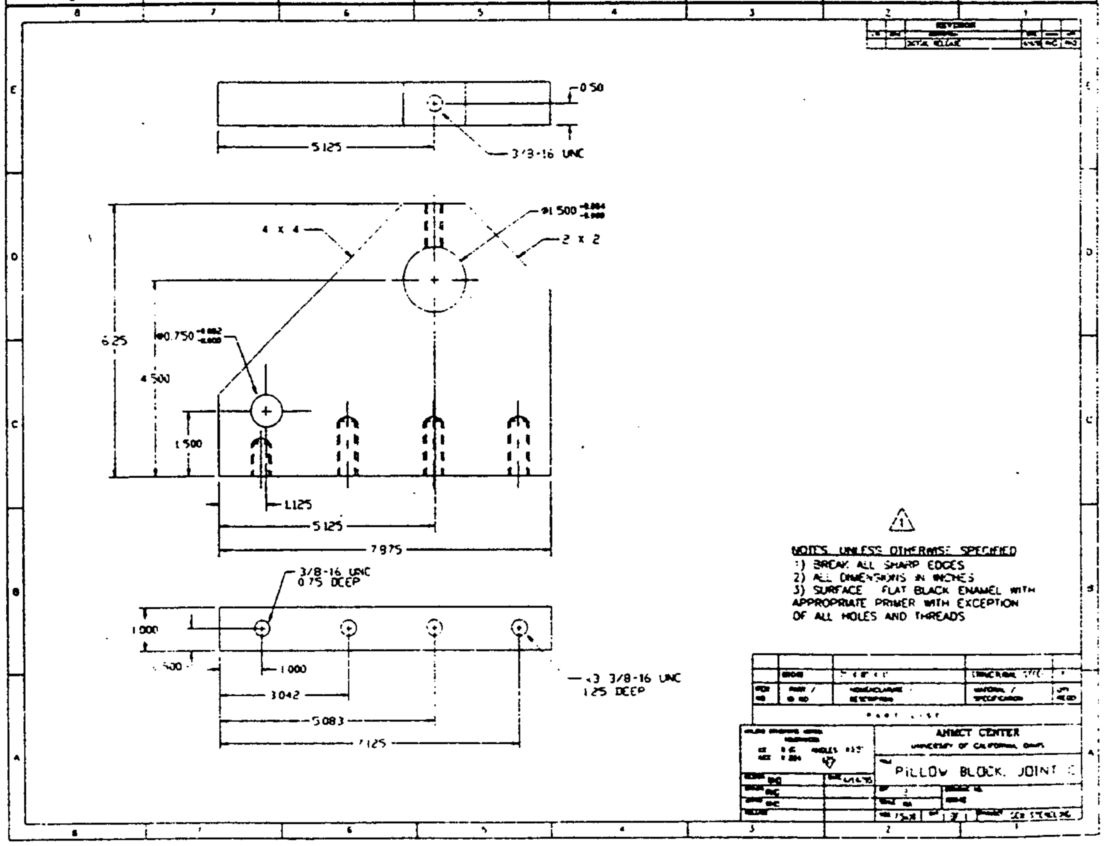
APPENDIX B
DETAILED DRAWINGS



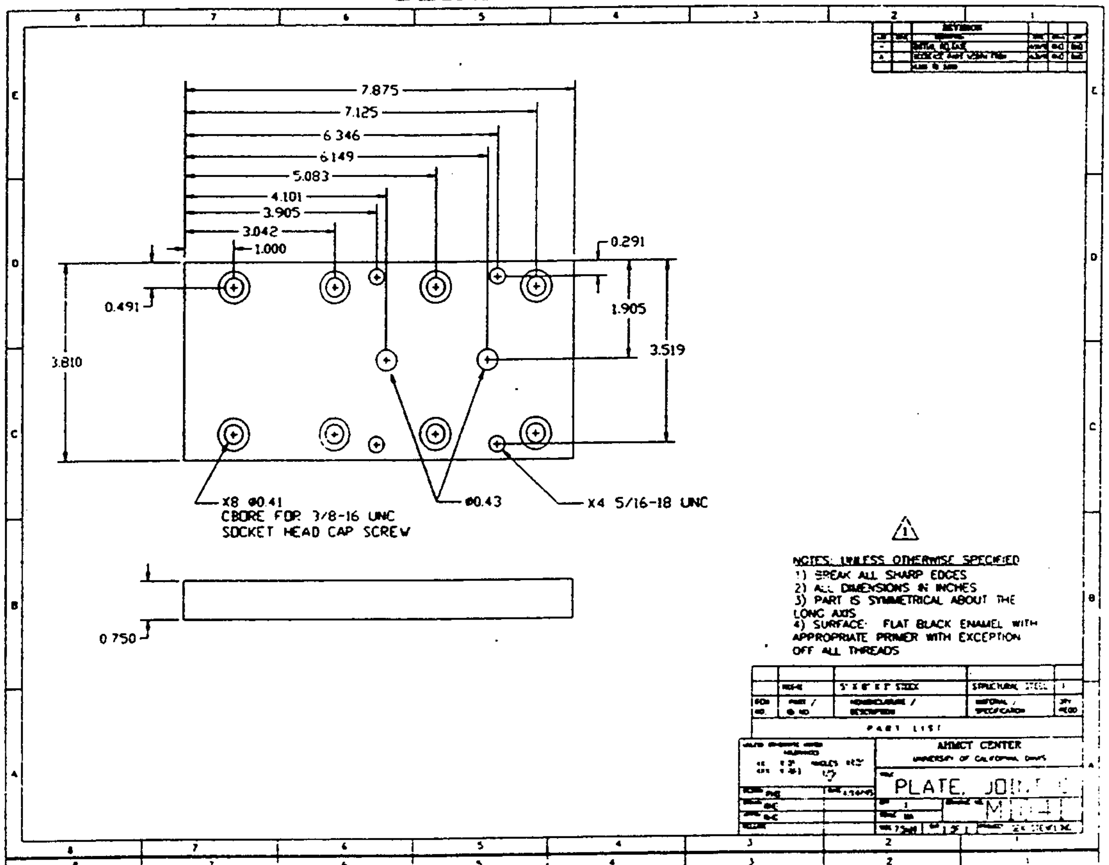


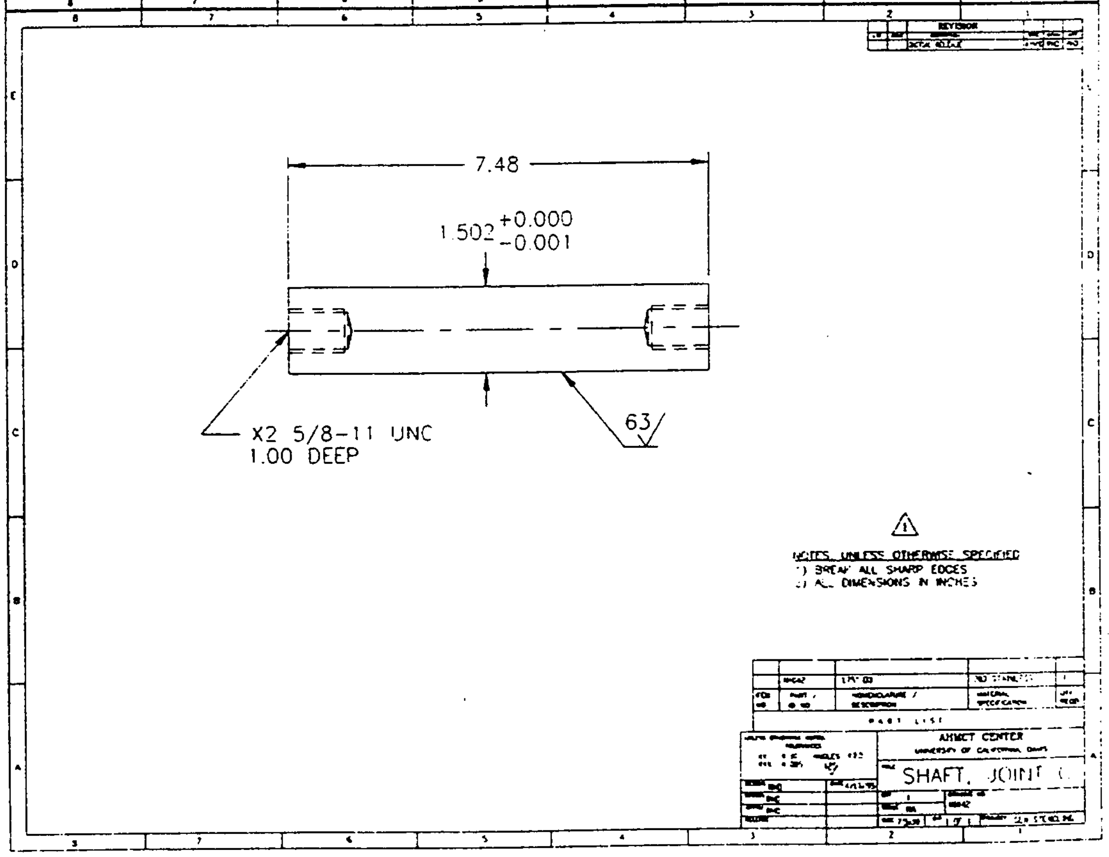
APPENDIX B
DETAILED DRAWINGS



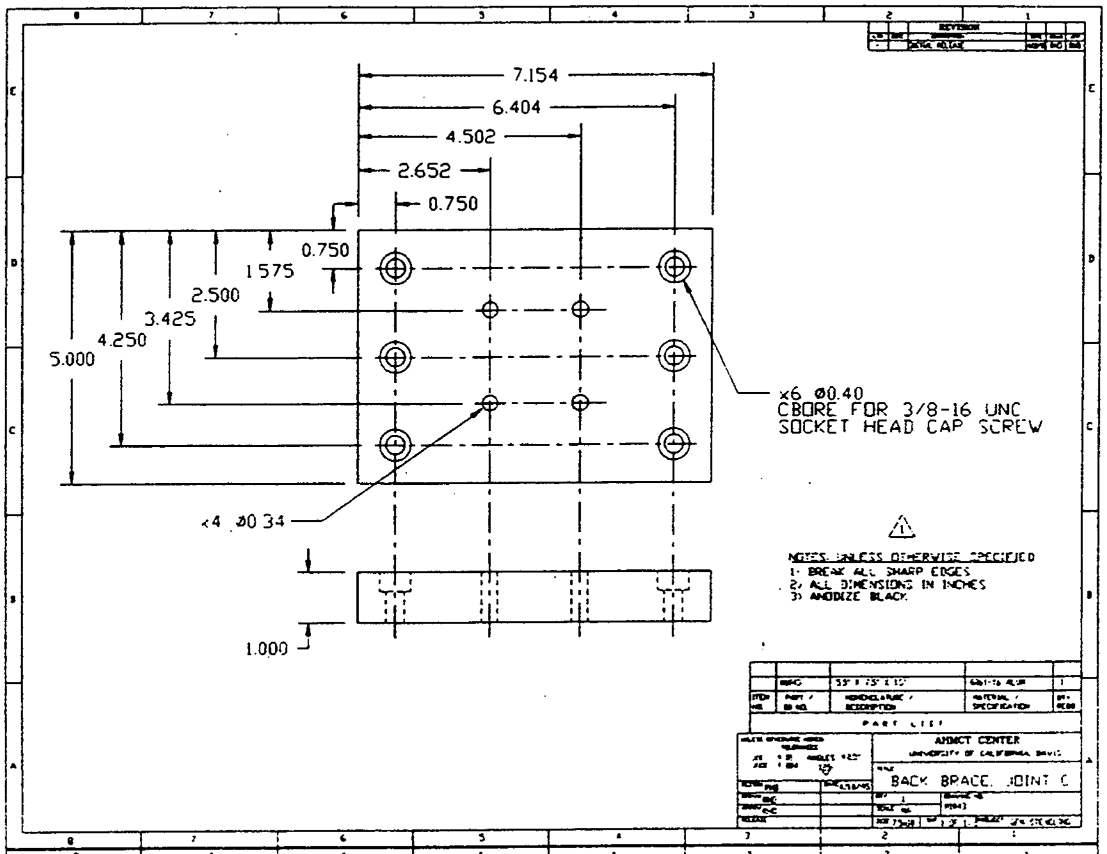


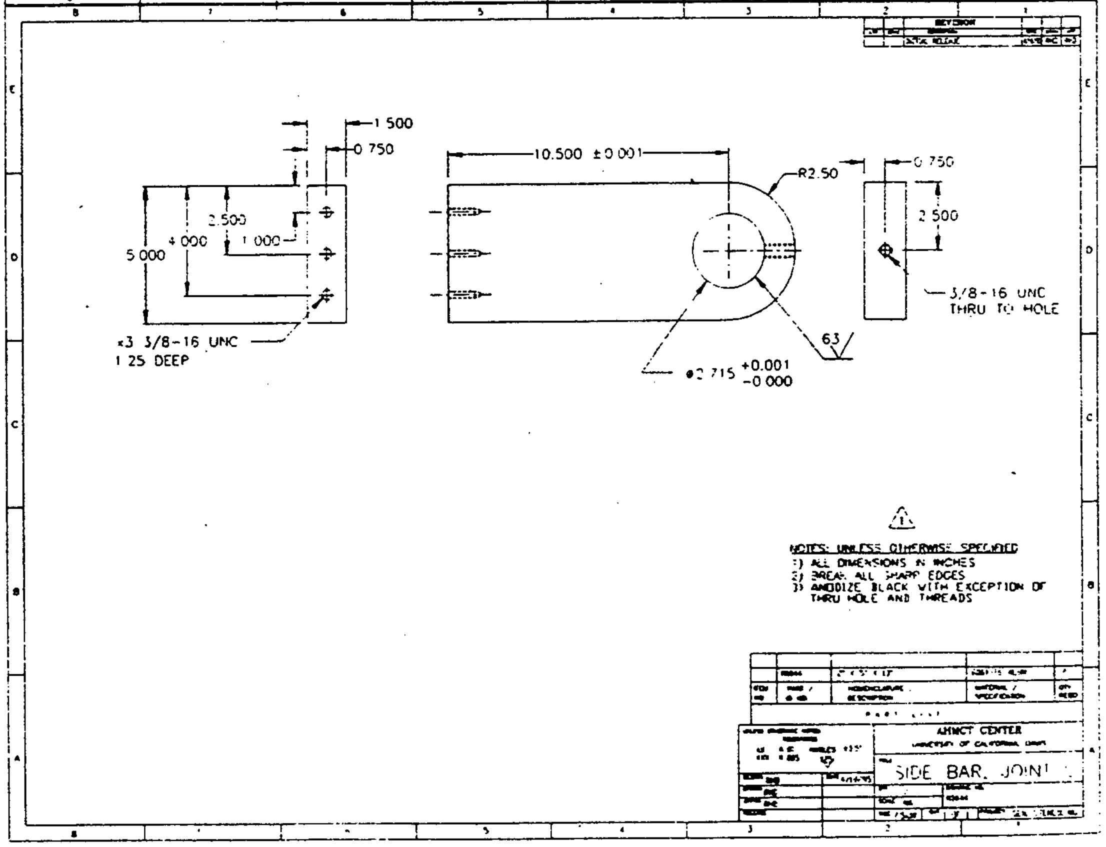
APPENDIX B
DETAILED DRAWINGS


7.875
7.125
6.346
6.149
5.083
4.101
3.905
3.042
1.000
0.291
0.491
1.905
3.810
3.519
X8 ⌀0.41
CBORE FOR 3/8-16 UNC
SOCKET HEAD CAP SCREW
⌀0.43
X4 5/16-18 UNC
0.750
NOTES: UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
2) ALL DIMENSIONS IN INCHES
3) PART IS SYMMETRICAL ABOUT THE LONG AXIS
4) SURFACE: FLAT BLACK ENAMEL WITH APPROPRIATE PRIMER WITH EXCEPTION OFF ALL THREADS
STRUCTURAL STEEL
PART LIST
AHMCT CENTER
UNIVERSITY OF CALIFORNIA, DAVIS
PLATE, JOINT

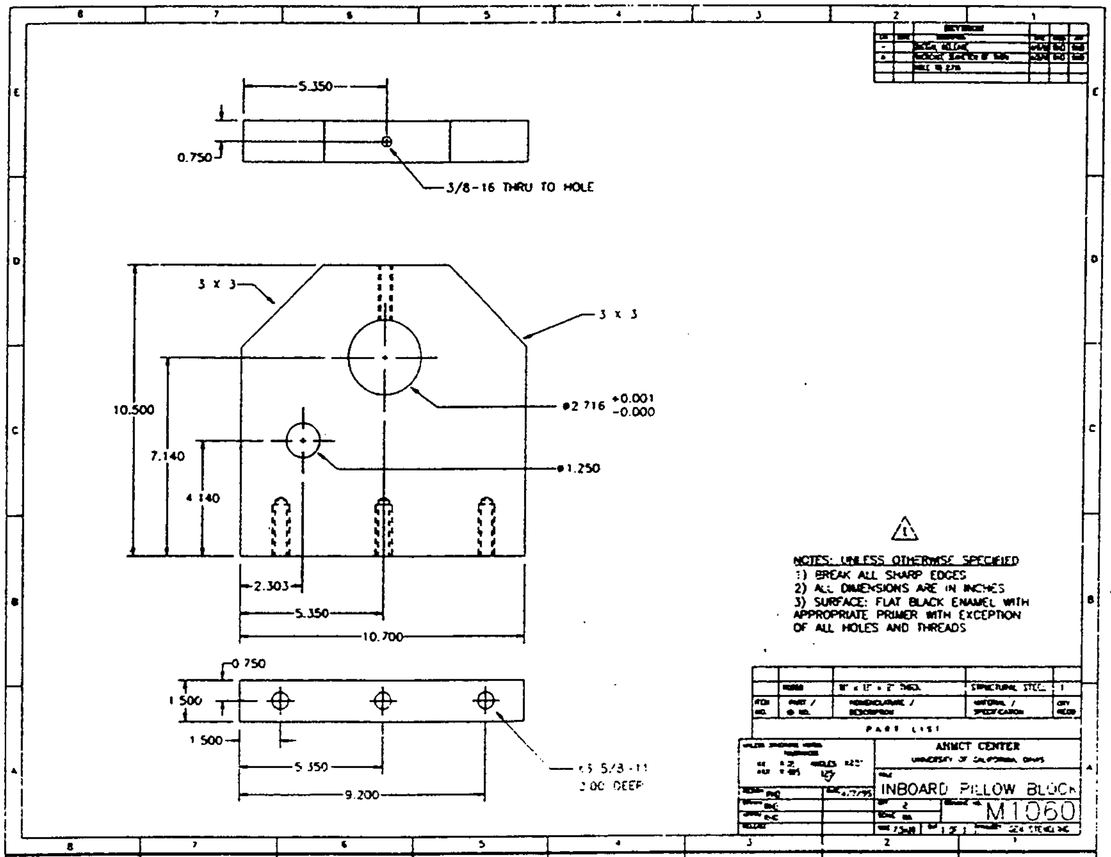


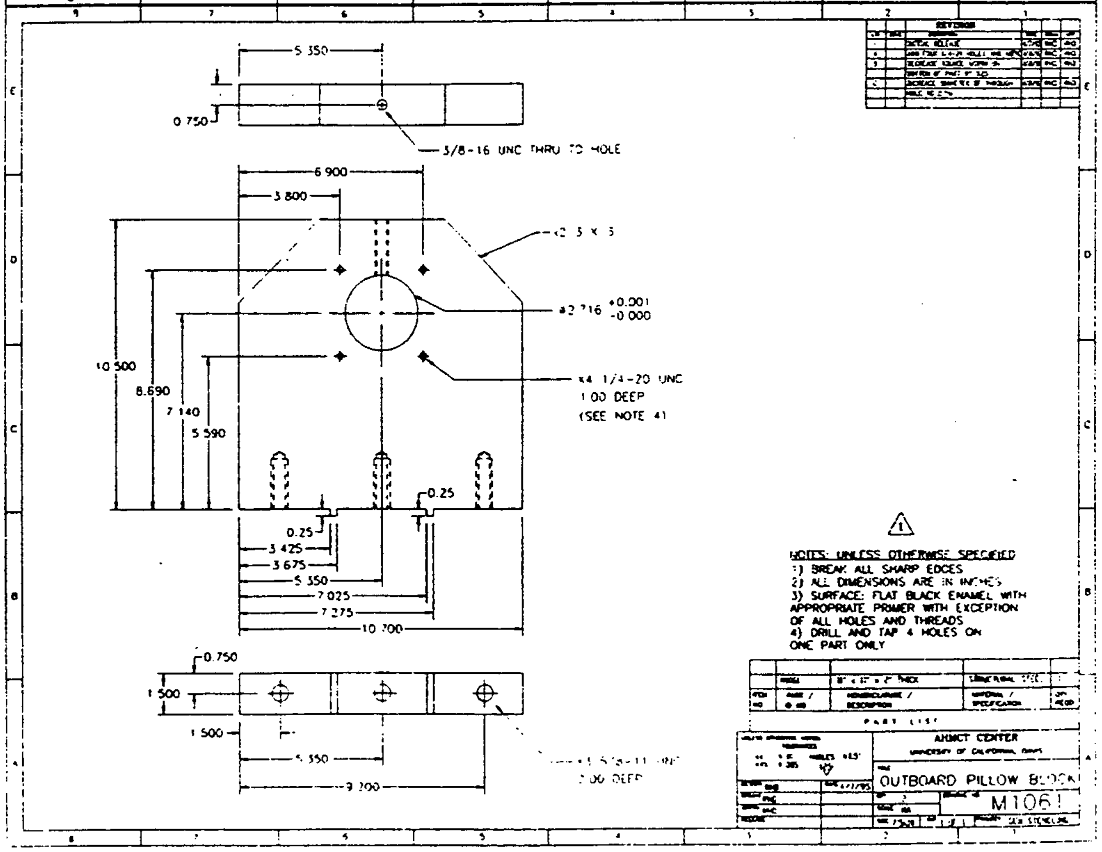
APPENDIX B
DETAILED DRAWINGS



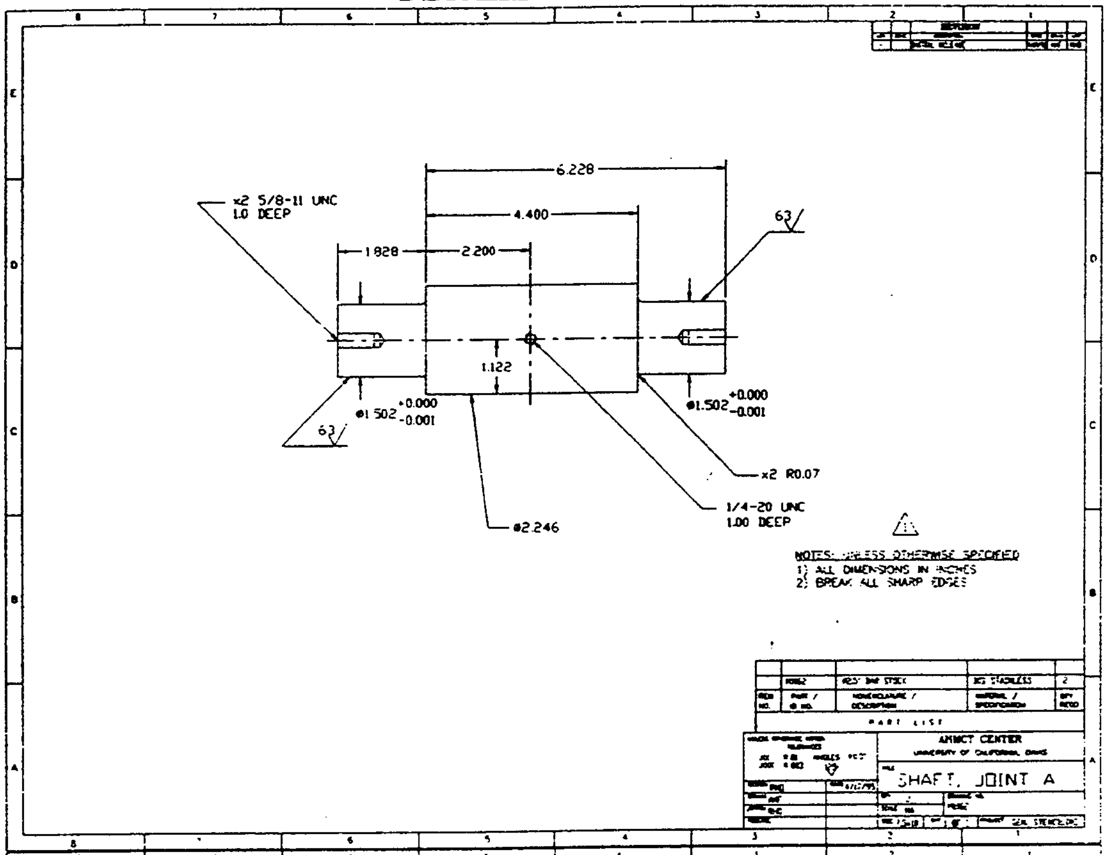


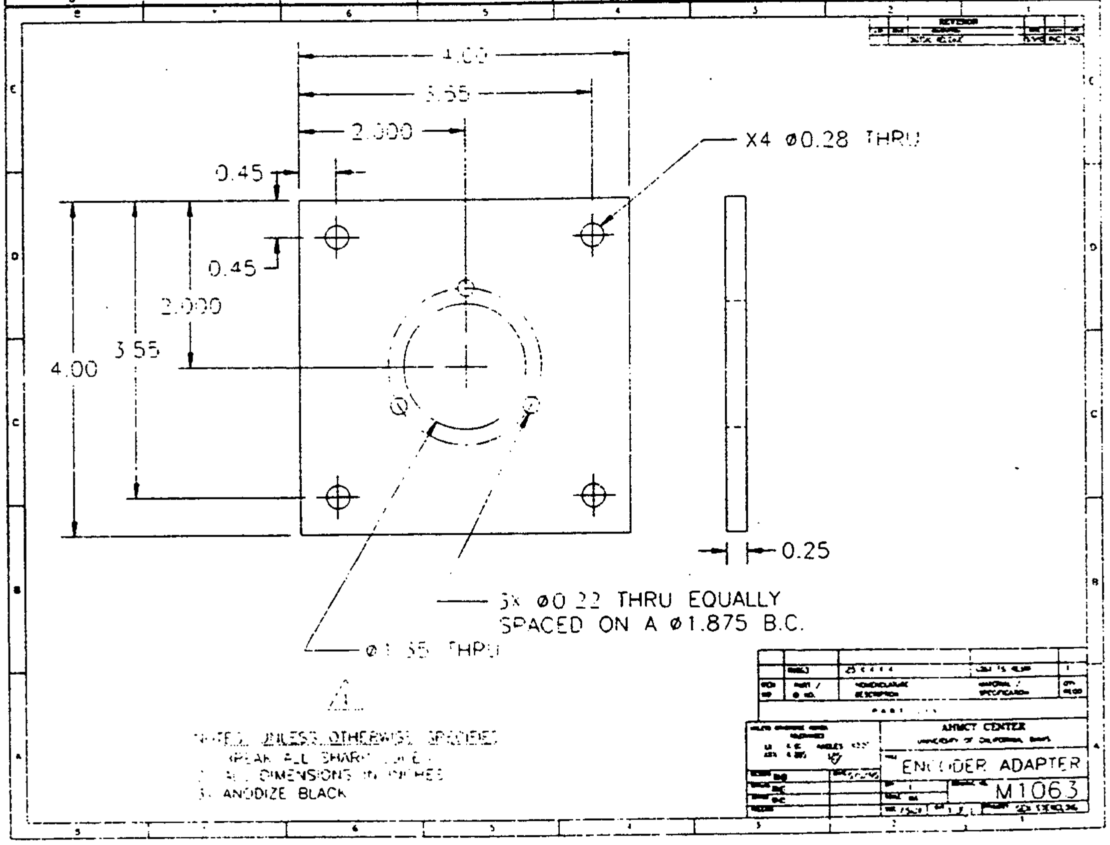
APPENDIX B
DETAILED DRAWINGS



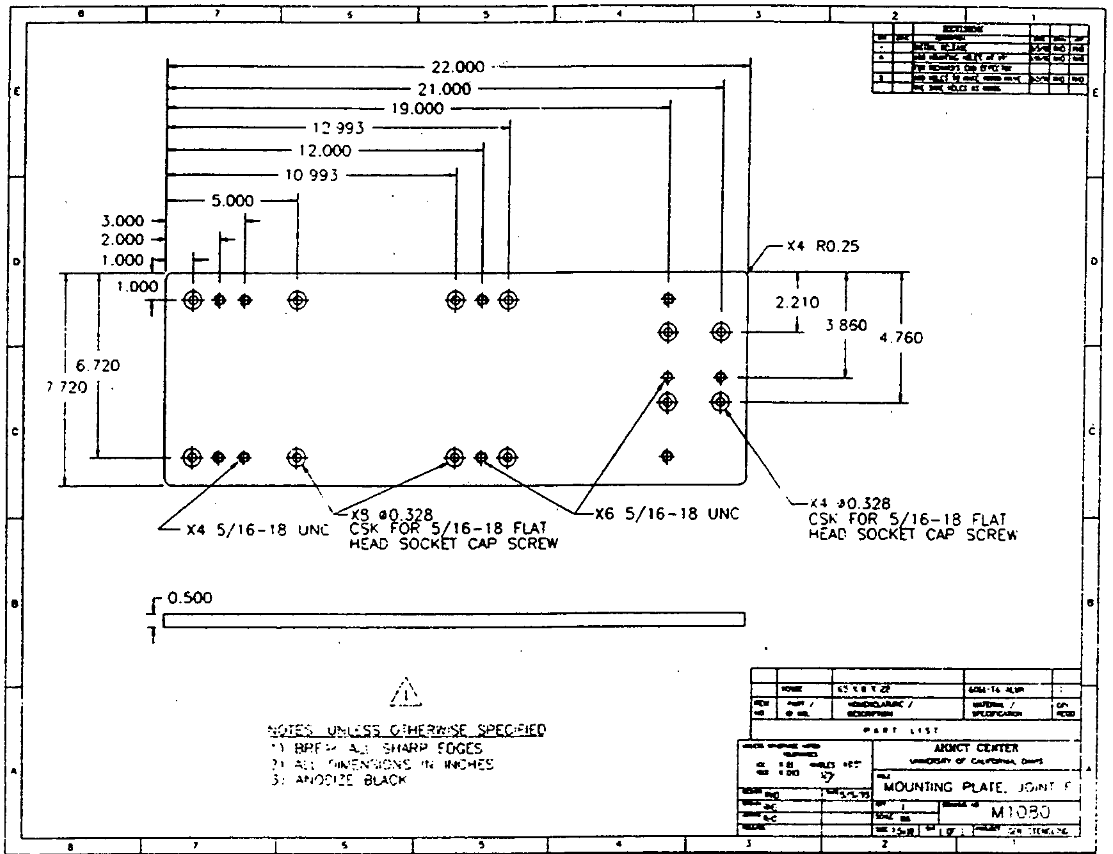


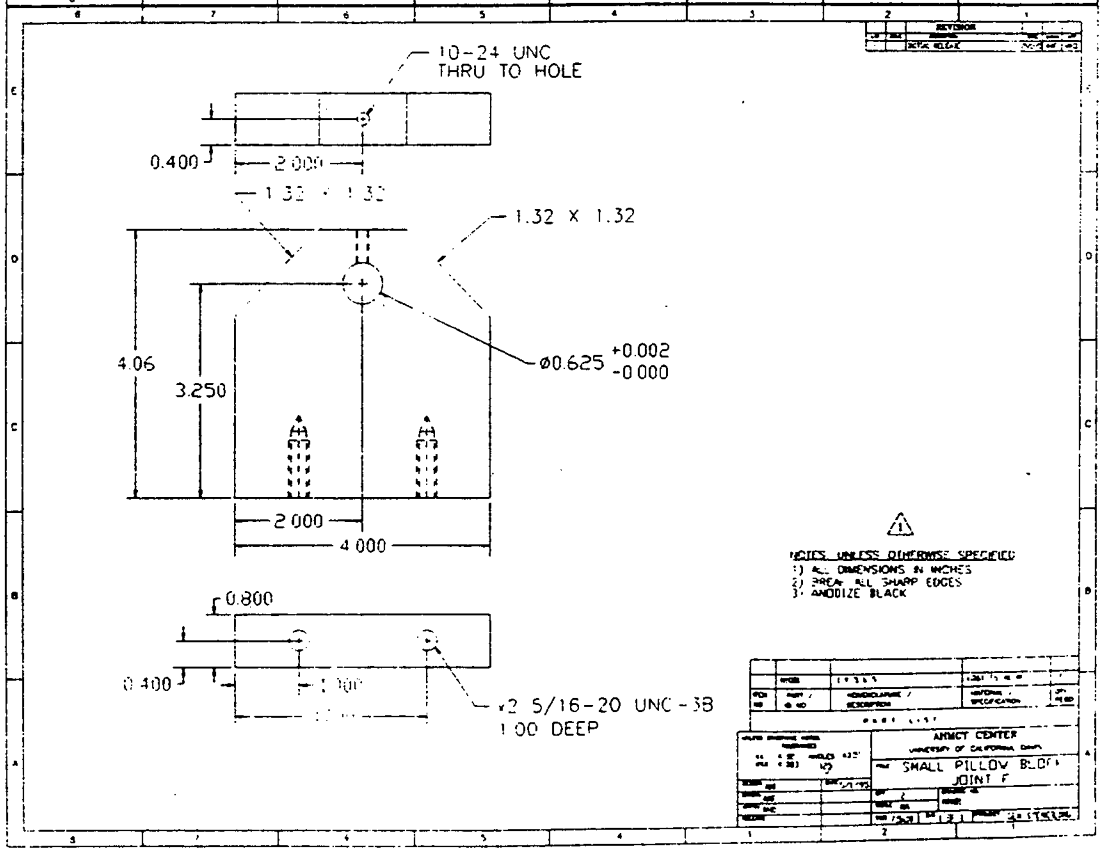
APPENDIX B
DETAILED DRAWINGS



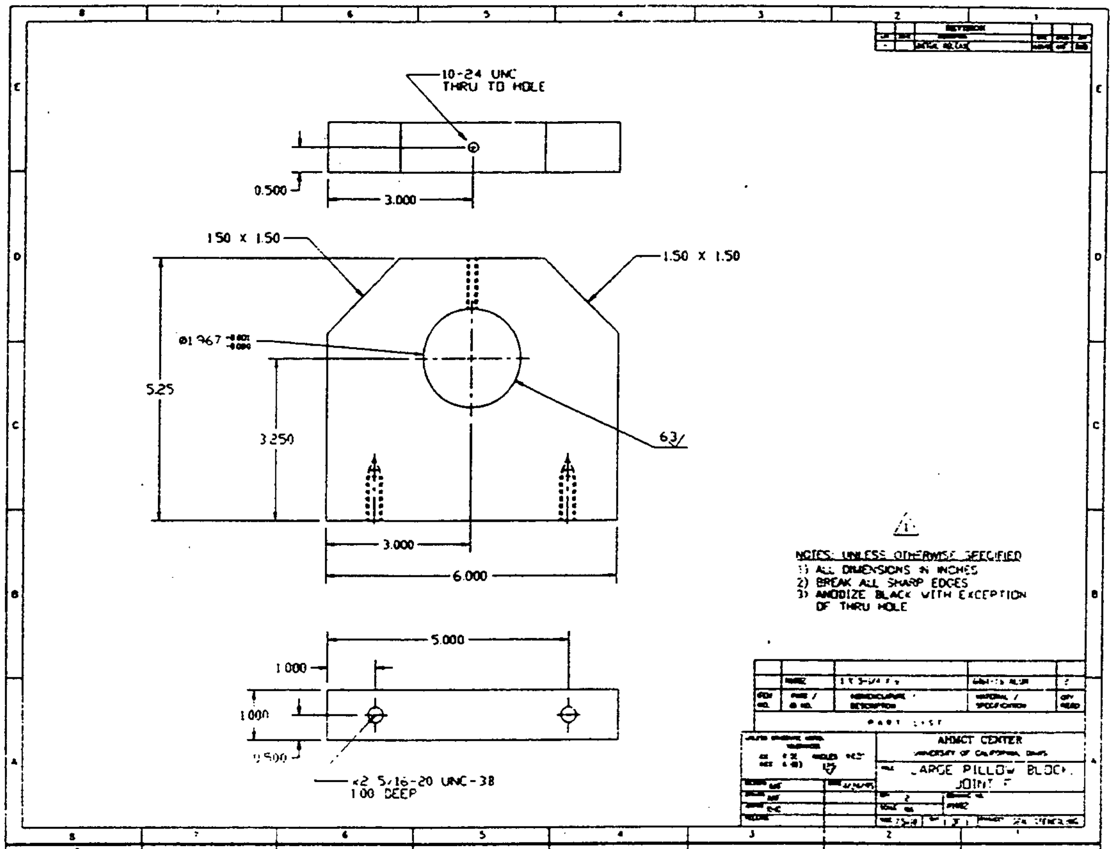


APPENDIX B
DETAILED DRAWINGS

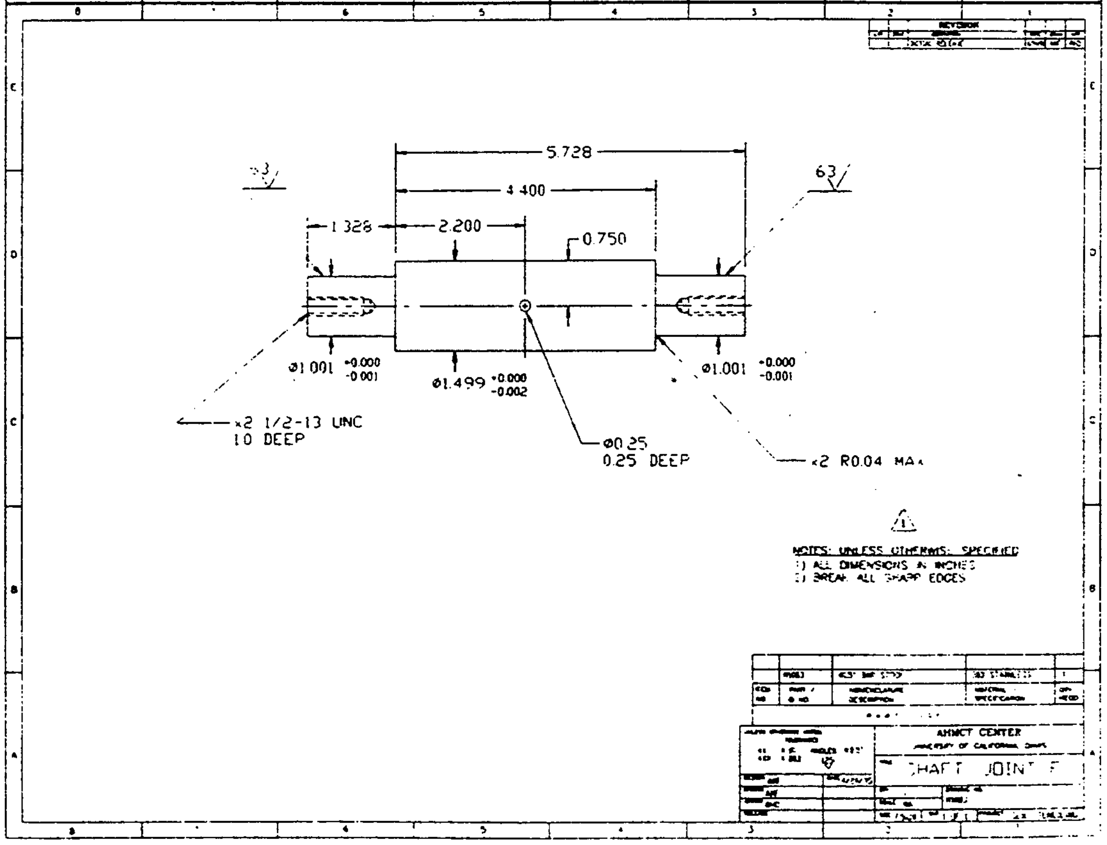




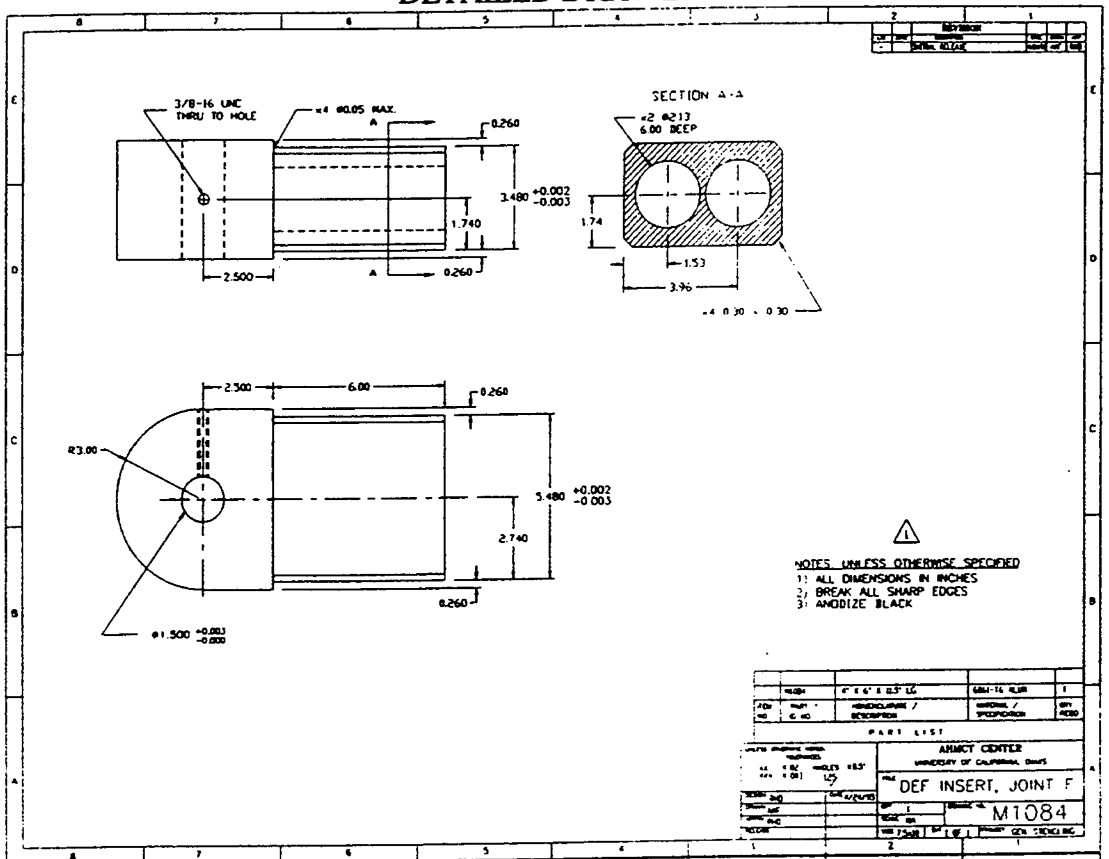
APPENDIX B
DETAILED DRAWINGS

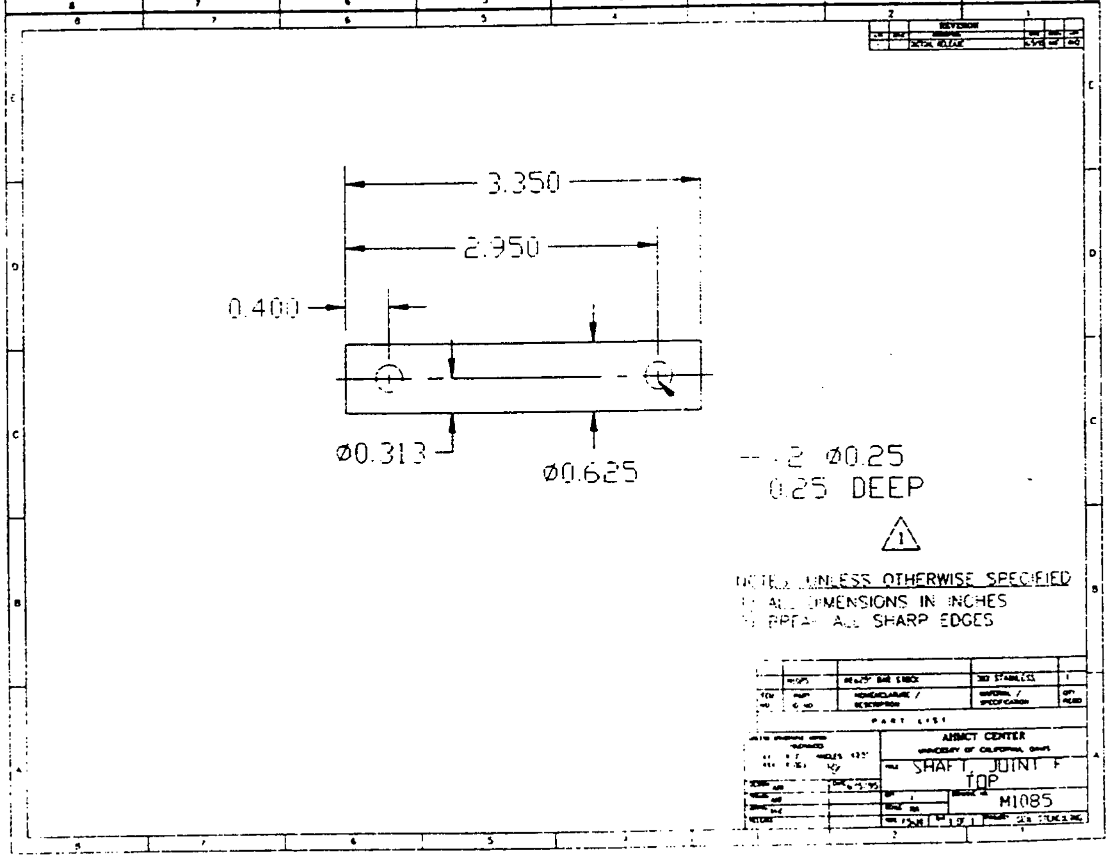


10-24 UNC THRU TO HOLE
0.500
3.000
1.50 X 1.50
1.50 X 1.50
Ø1.967
5.25
3.250
63/
3.000
6.000
5.000
1.000
1.000
0.500
x2 5/16-20 UNC-3B 1.00 DEEP
NOTES: UNLESS OTHERWISE SPECIFIED
1) ALL DIMENSIONS IN INCHES
2) BREAK ALL SHARP EDGES
3) ANODIZE BLACK WITH EXCEPTION OF THRU HOLE
AHMCT CENTER
UNIVERSITY OF CALIFORNIA, DAVIS
LARGE PILLOW BLOCK, JOINT F

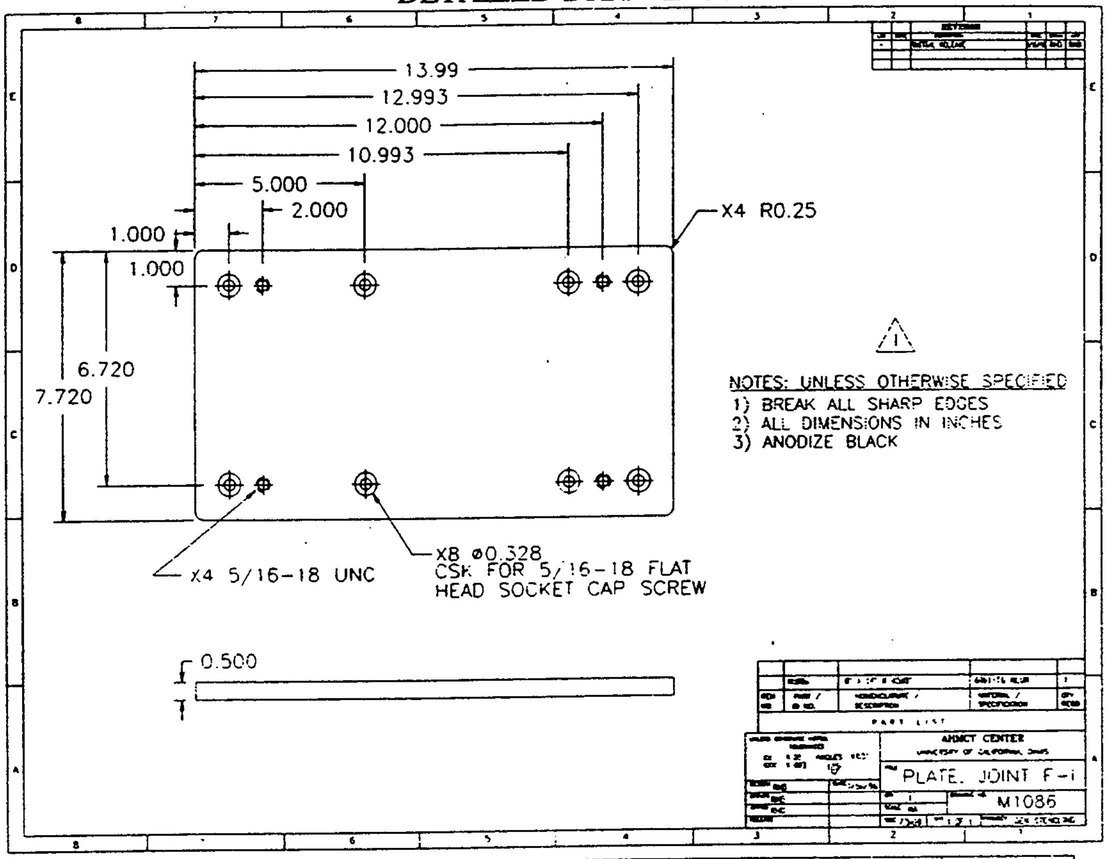


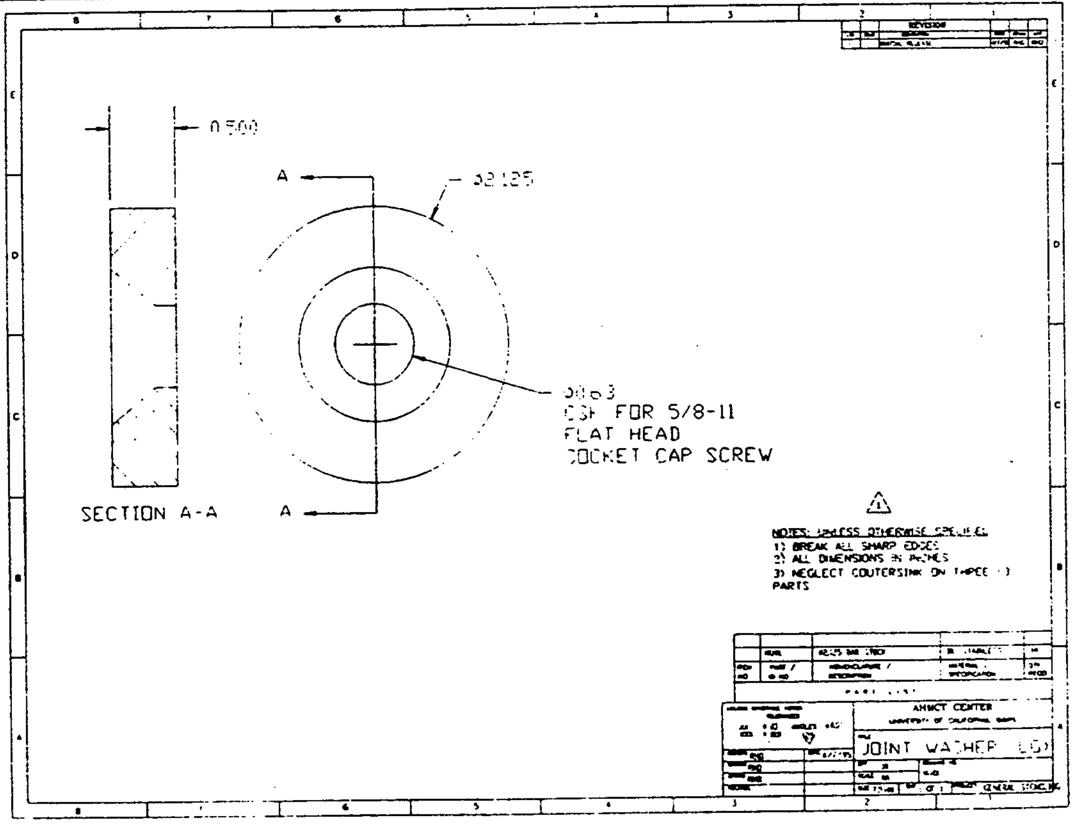
APPENDIX B
DETAILED DRAWINGS



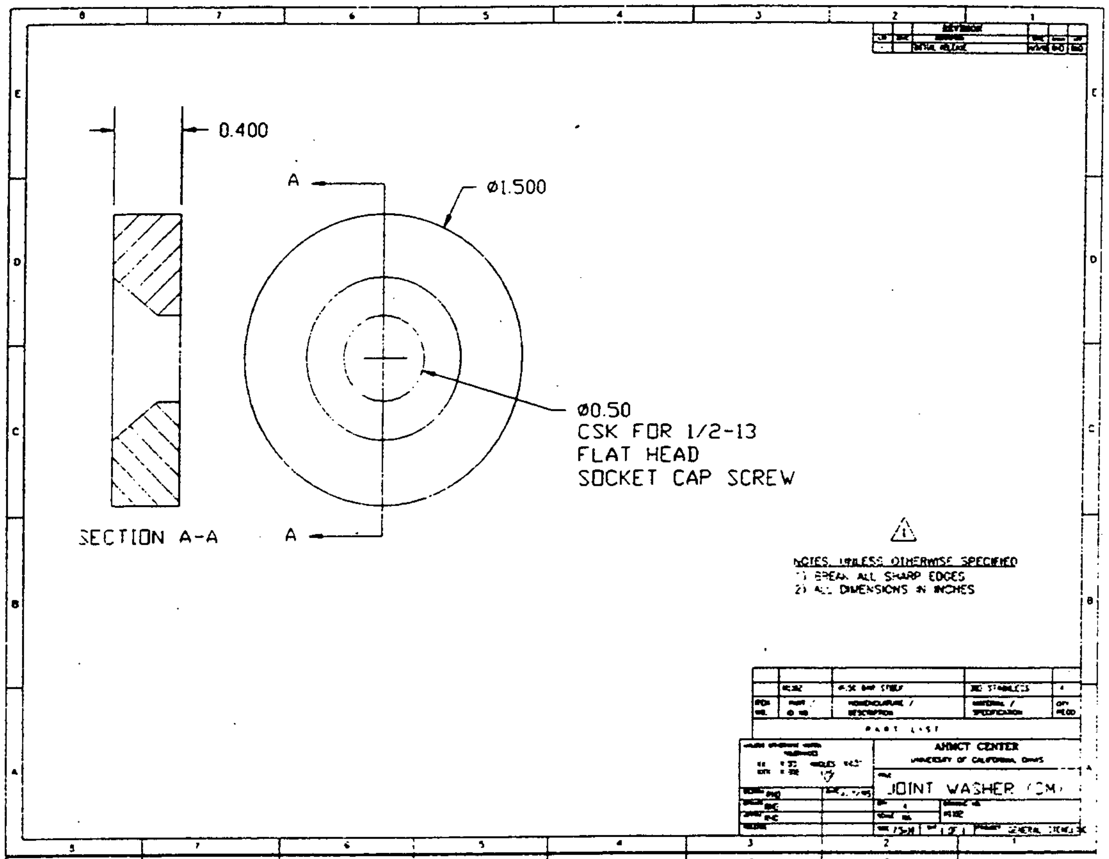


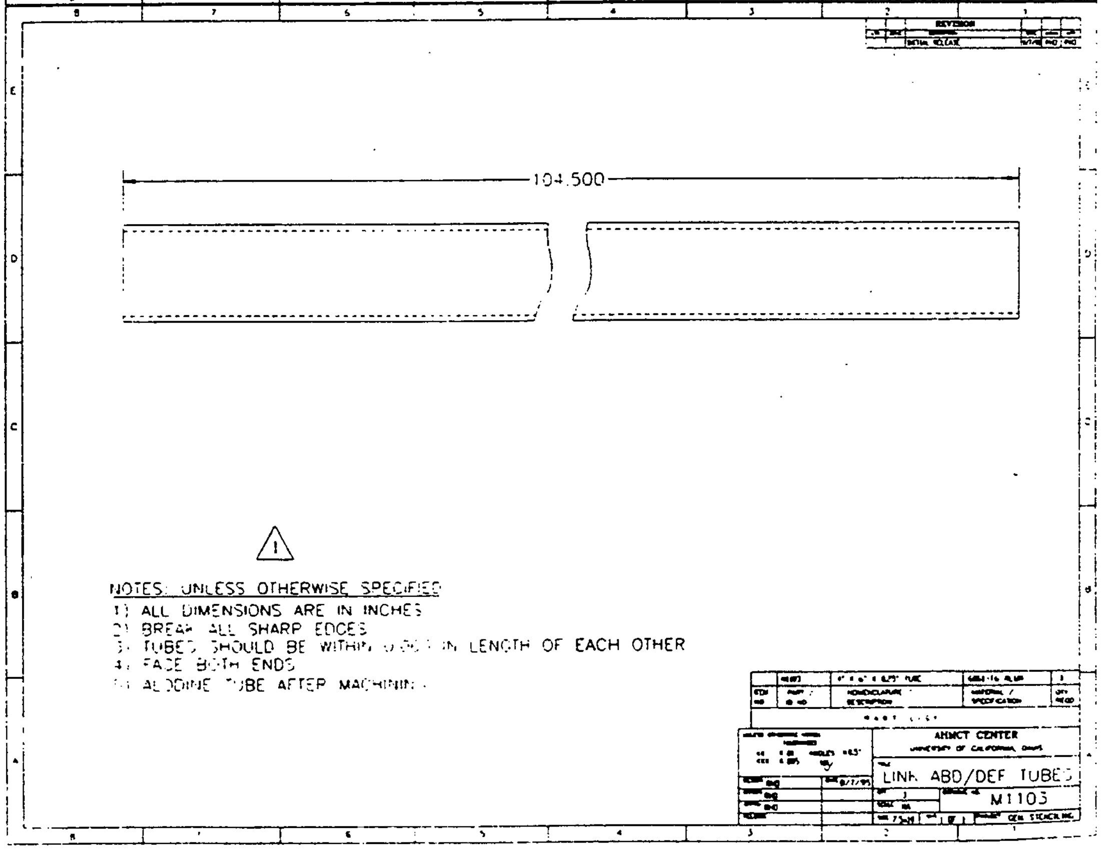
APPENDIX B
DETAILED DRAWINGS



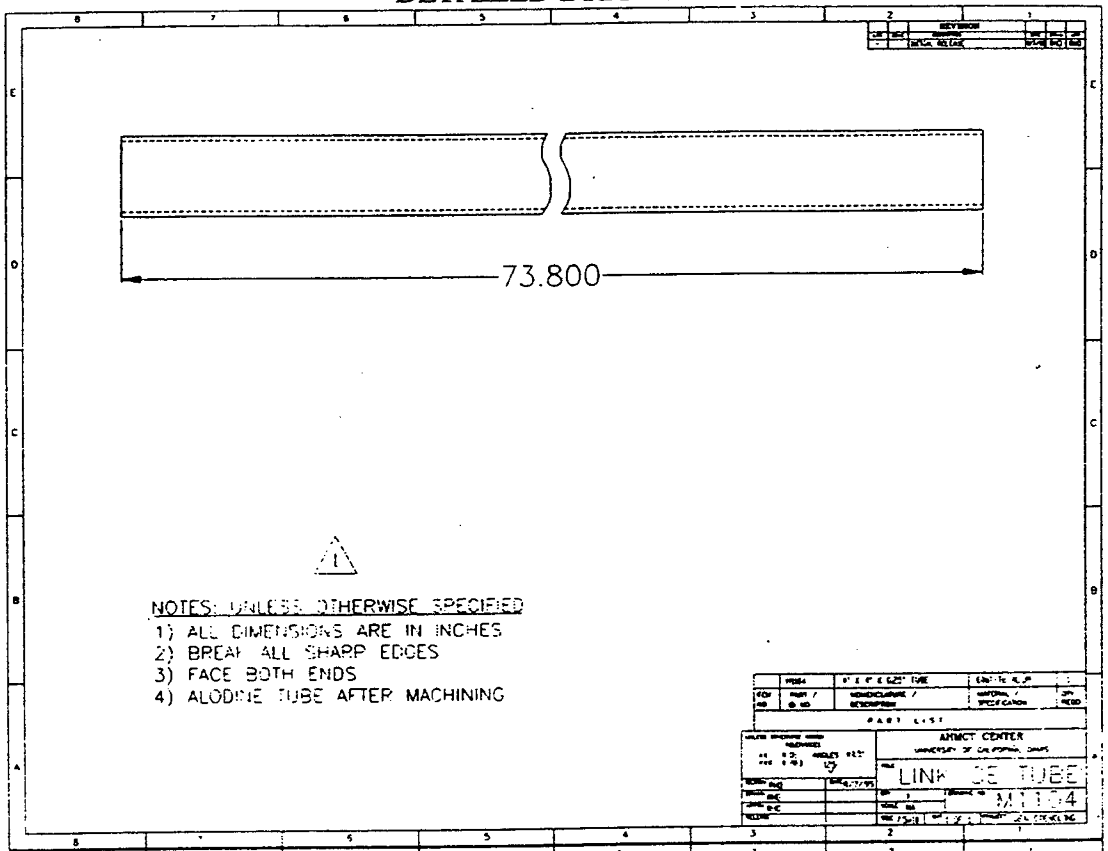


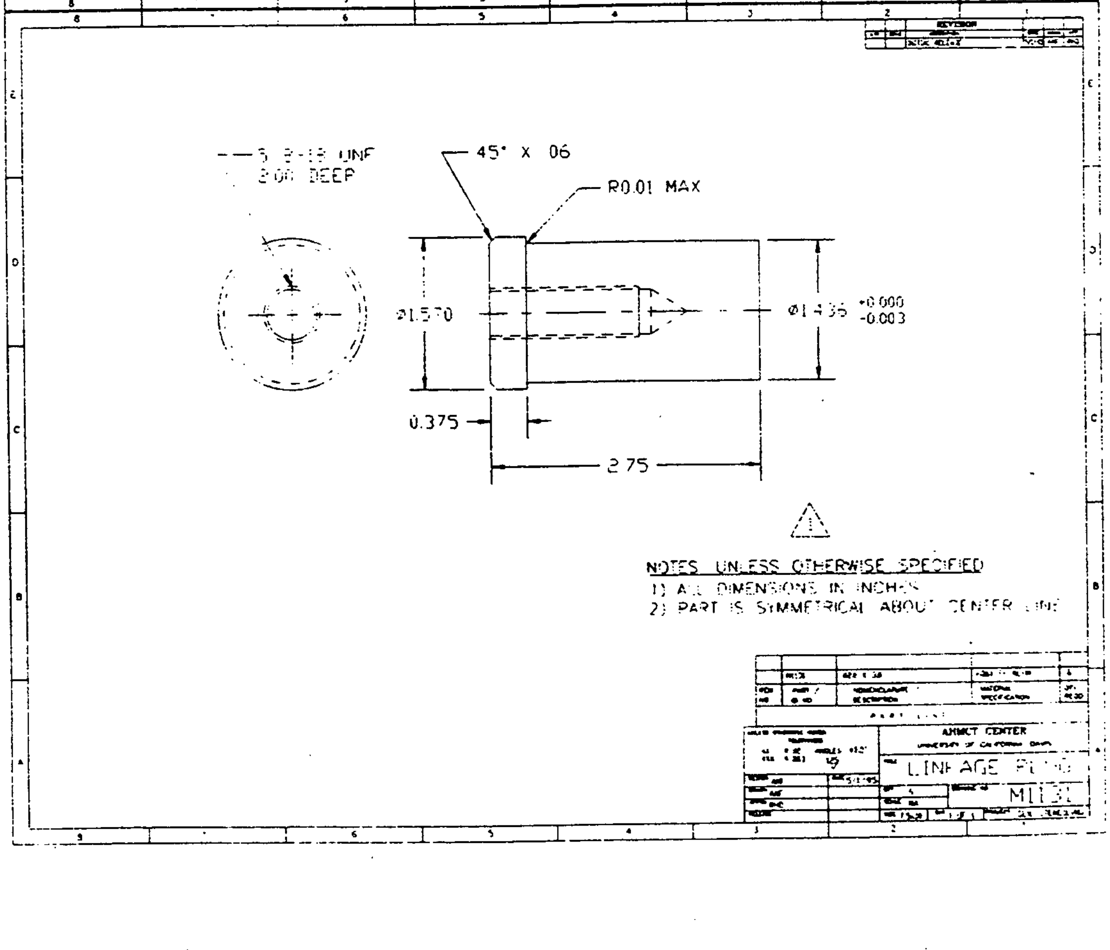
APPENDIX B
DETAILED DRAWINGS



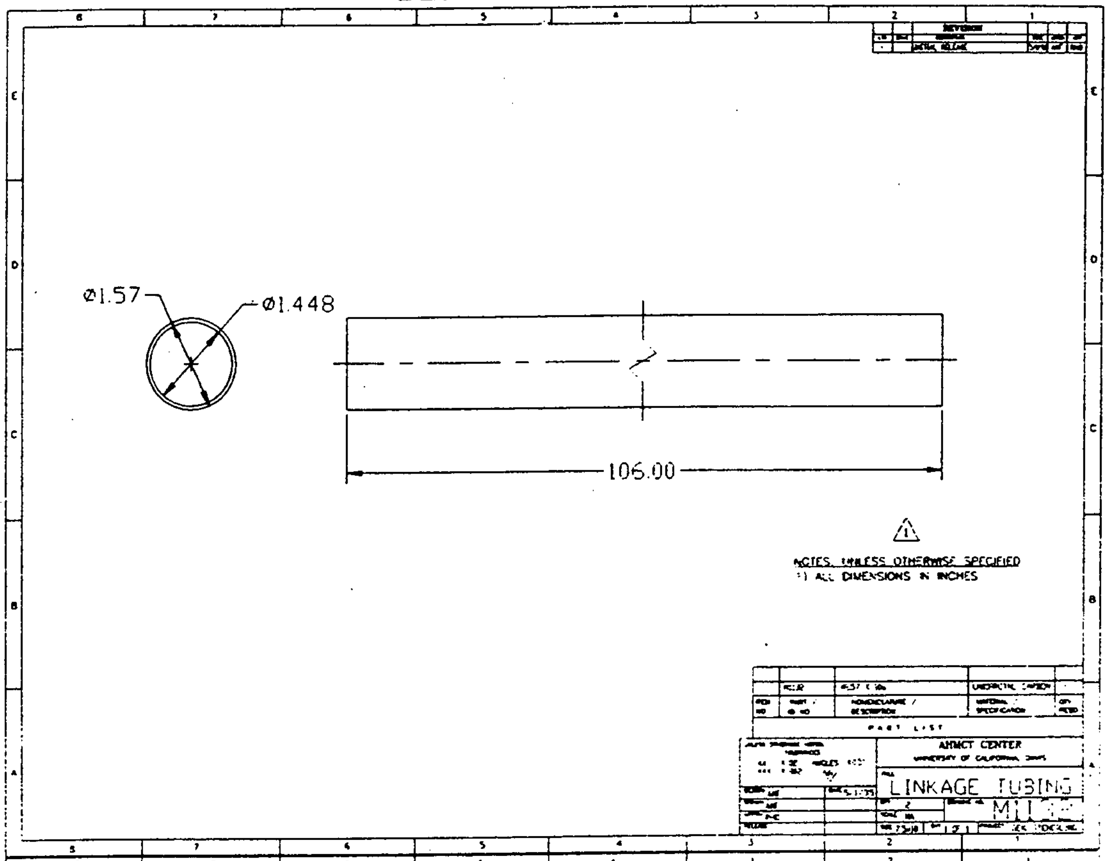

104.500
NOTES: UNLESS OTHERWISE SPECIFIED
1) ALL DIMENSIONS ARE IN INCHES
2) BREAK ALL SHARP EDGES
3) TUBES SHOULD BE WITHIN [illegible] IN LENGTH OF EACH OTHER
4) FACE BOTH ENDS
5) ALODINE TUBE AFTER MACHINING
AHMCT CENTER
UNIVERSITY OF CALIFORNIA, DAVIS
LINK ABD/DEF TUBES
M1103

APPENDIX B
DETAILED DRAWINGS

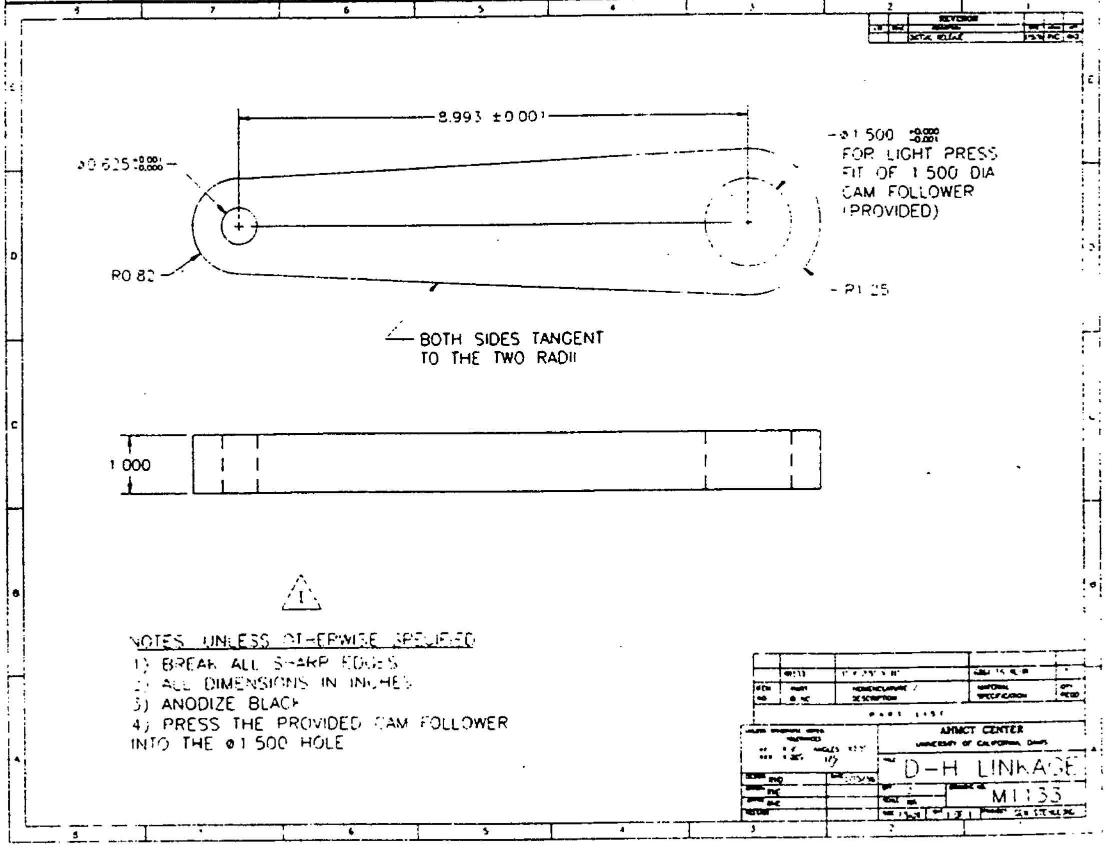

73.800
NOTES: UNLESS OTHERWISE SPECIFIED
1) ALL DIMENSIONS ARE IN INCHES
2) BREAK ALL SHARP EDGES
3) FACE BOTH ENDS
4) ALODINE TUBE AFTER MACHINING
PART LIST
AHMCT CENTER
LINK OE TUBE
M1104



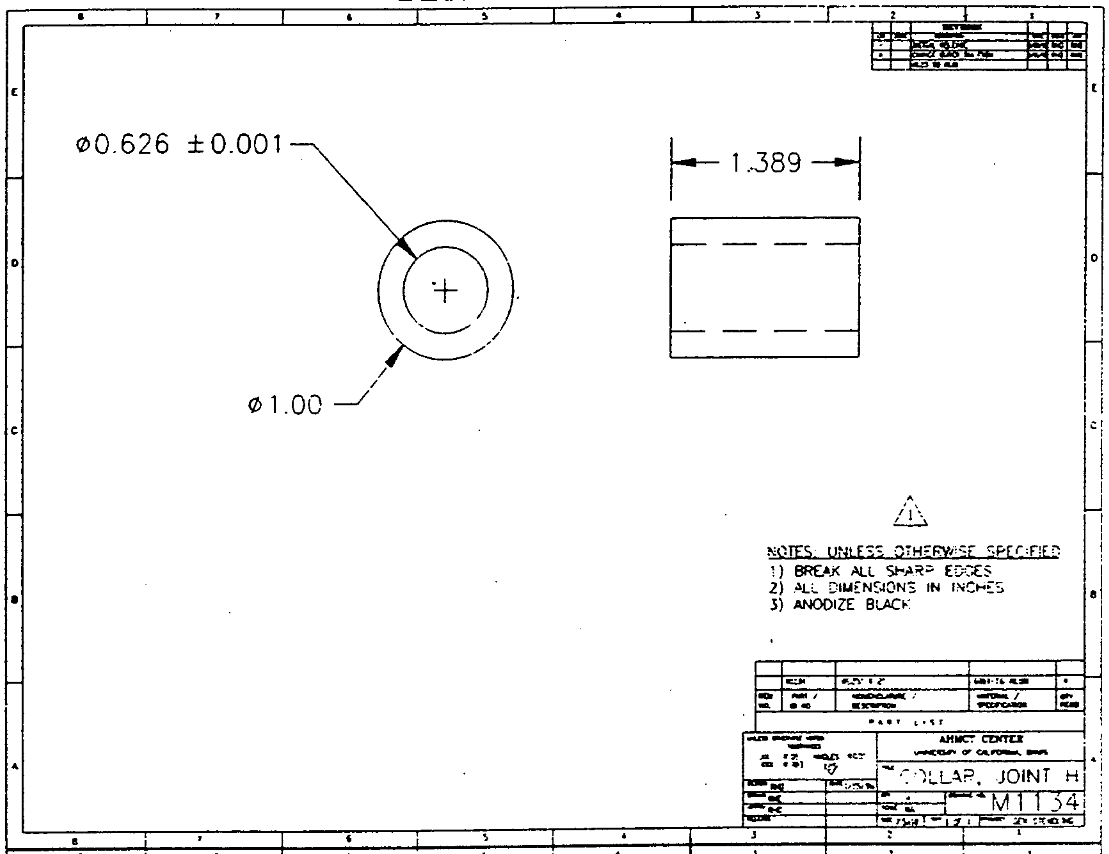
APPENDIX B
DETAILED DRAWINGS

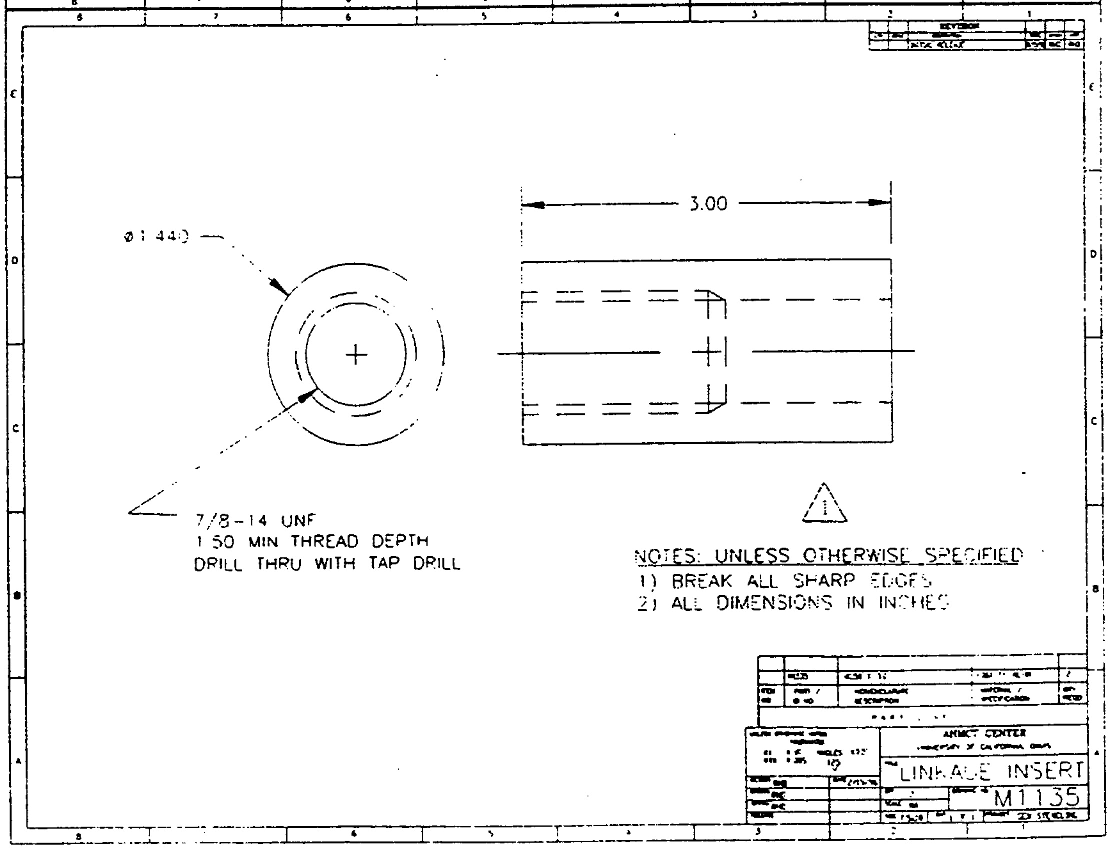


Ø1.57
Ø1.448
106.00
NOTES, UNLESS OTHERWISE SPECIFIED
1) ALL DIMENSIONS IN INCHES
AHMCT CENTER
LINKAGE TUBING
M11

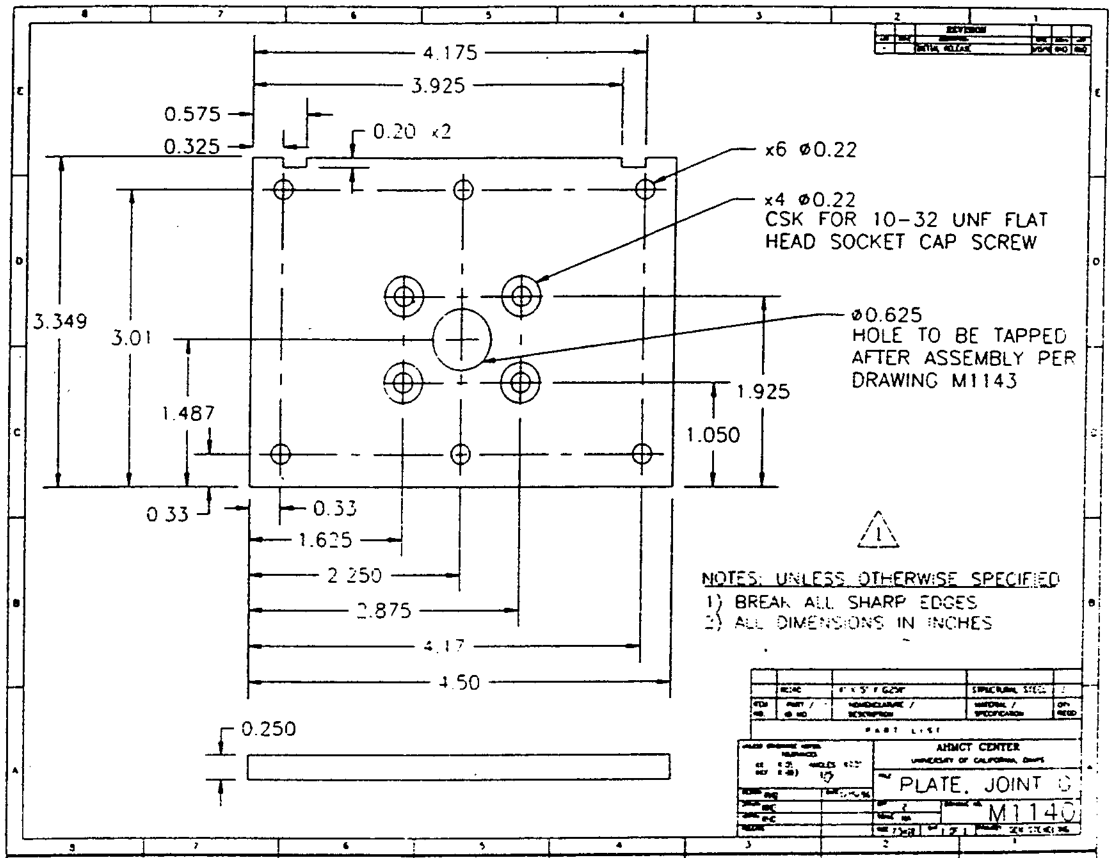


APPENDIX B
DETAILED DRAWINGS

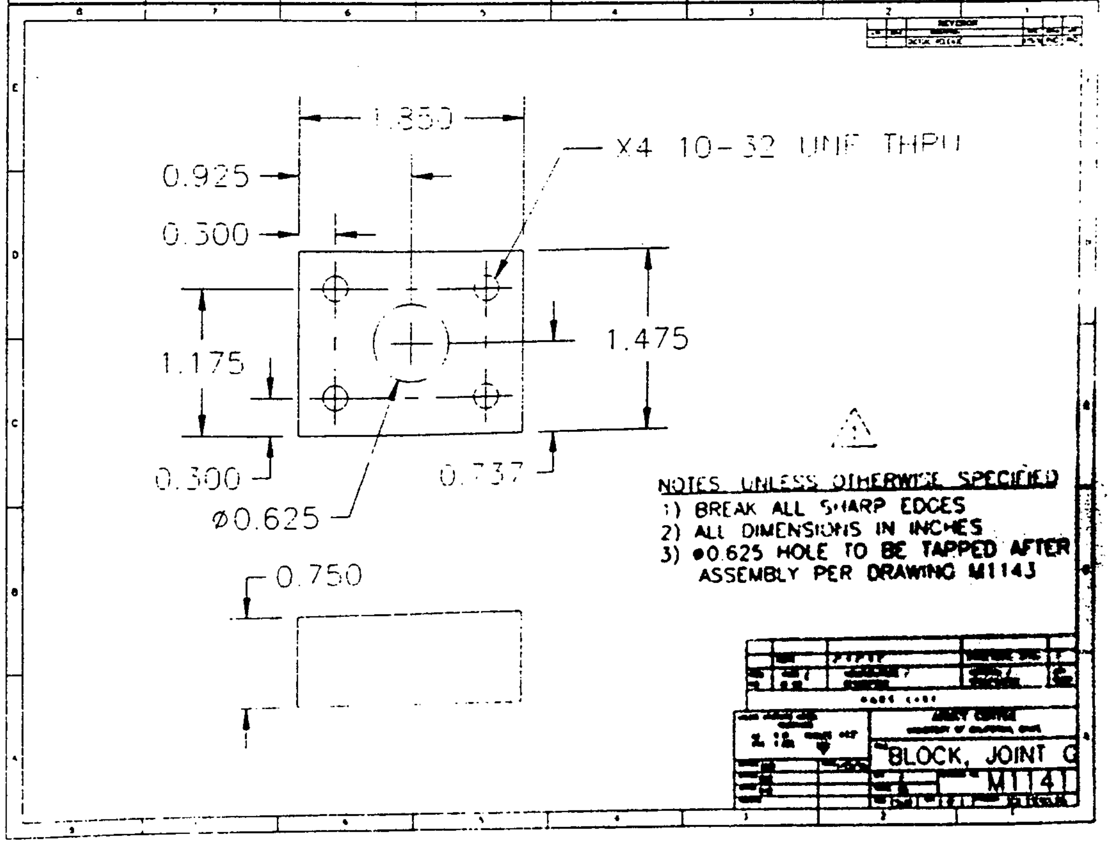




APPENDIX B DETAILED DRAWINGS

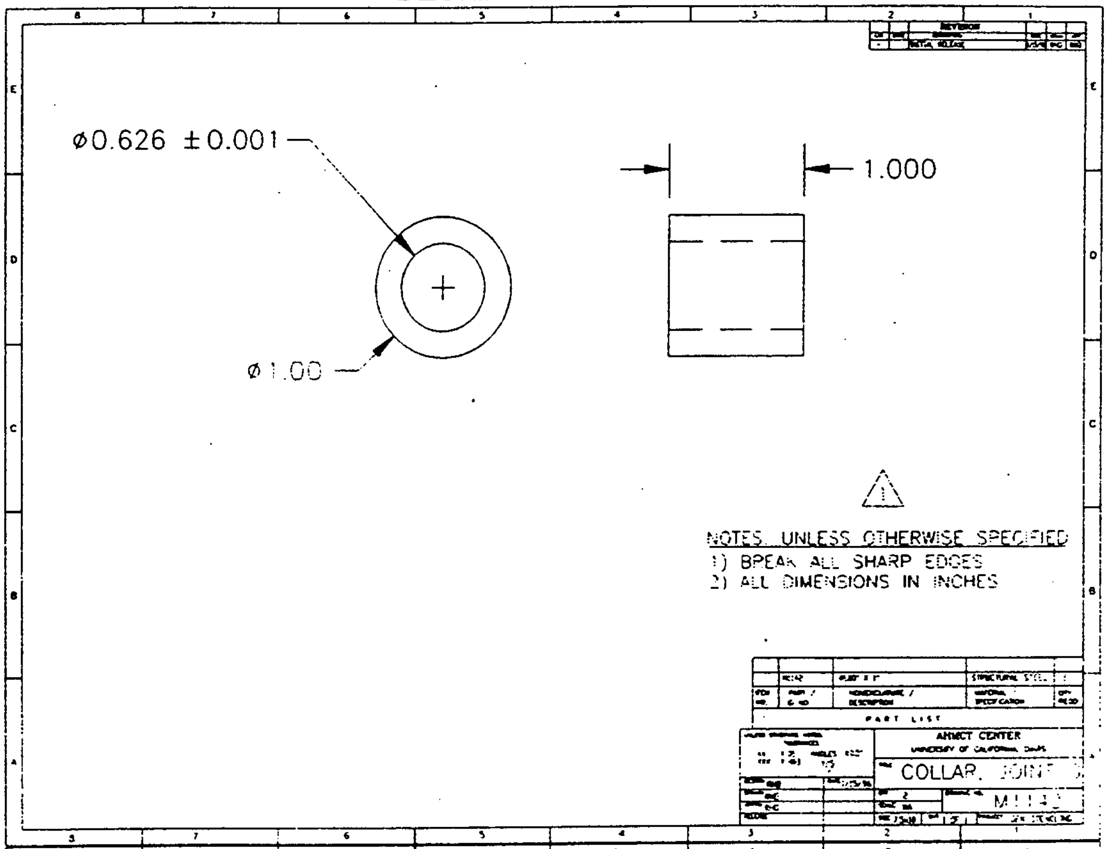


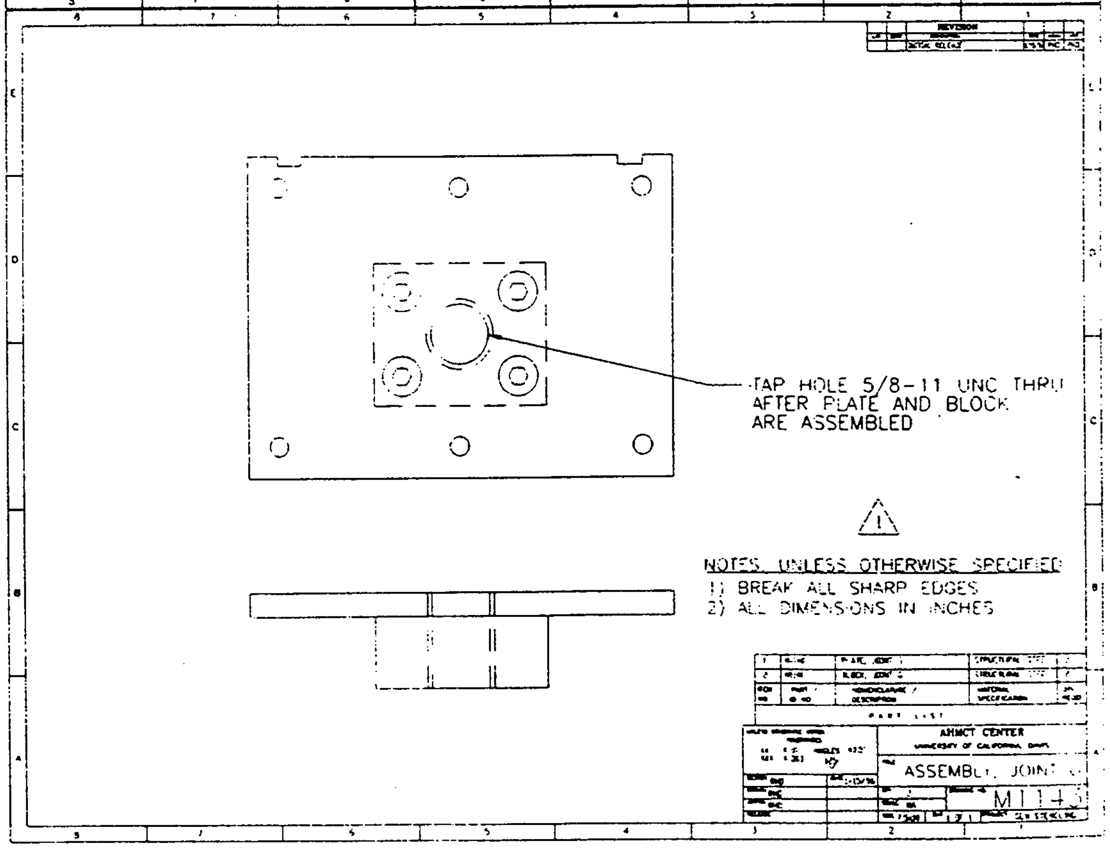
4.175
3.925
0.575
0.325
0.20 x2
x6 ⌀0.22
x4 ⌀0.22
CSK FOR 10-32 UNF FLAT HEAD SOCKET CAP SCREW
⌀0.625
HOLE TO BE TAPPED AFTER ASSEMBLY PER DRAWING M1143
3.349
3.01
1.487
1.925
1.050
0.33
0.33
1.625
2.250
2.875
4.17
4.50
0.250
NOTES: UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
2) ALL DIMENSIONS IN INCHES
AHMCT CENTER
UNIVERSITY OF CALIFORNIA, DAVIS
PLATE, JOINT G
M1140



1.850
X4 10-32 UNF THRU
0.925
0.300
1.175
1.475
0.300
0.737
⌀0.625
0.750
NOTES UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
2) ALL DIMENSIONS IN INCHES
3) ⌀0.625 HOLE TO BE TAPPED AFTER ASSEMBLY PER DRAWING M1143
AHMCT CENTER
BLOCK, JOINT G
M1141

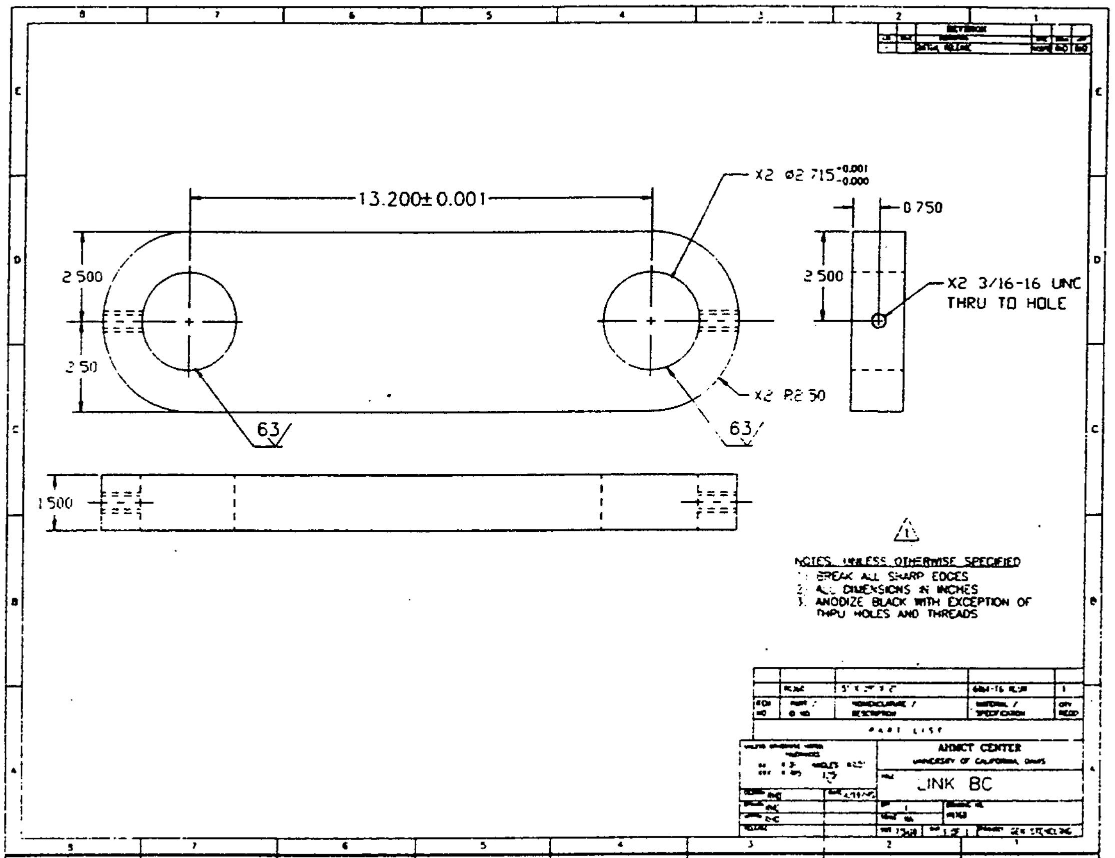
APPENDIX B
DETAILED DRAWINGS

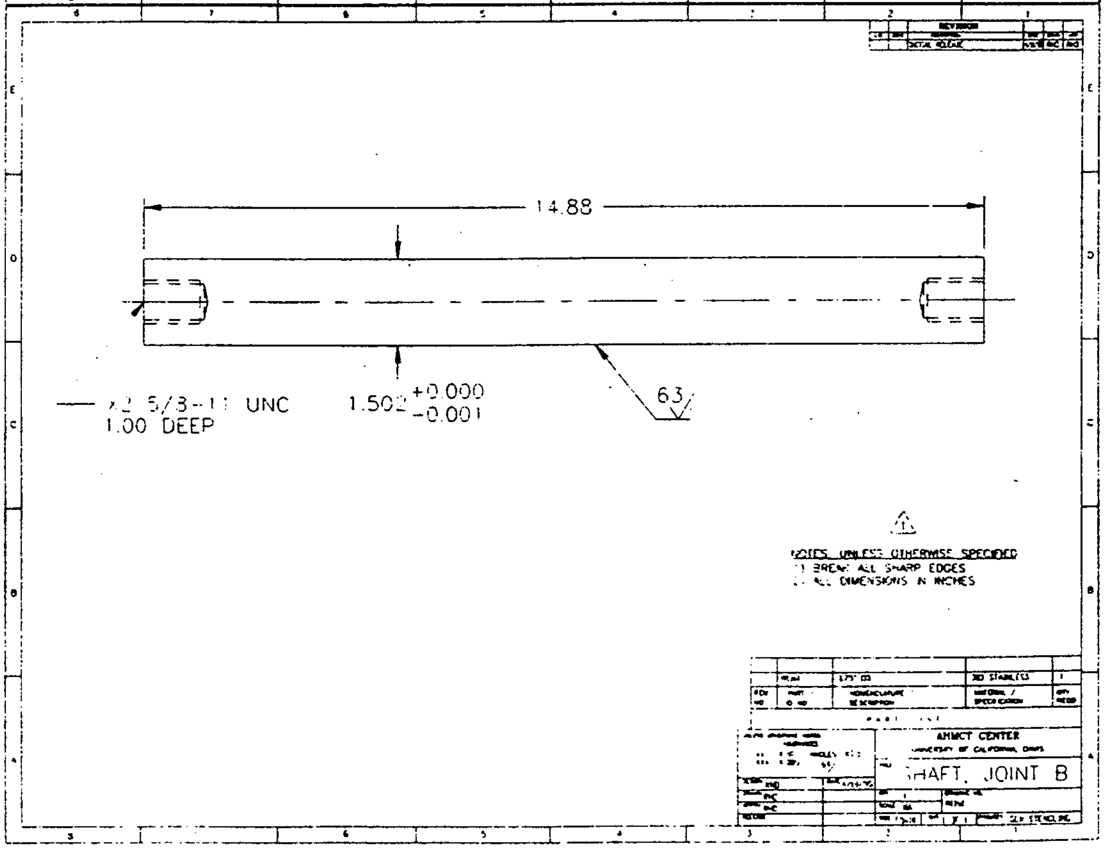




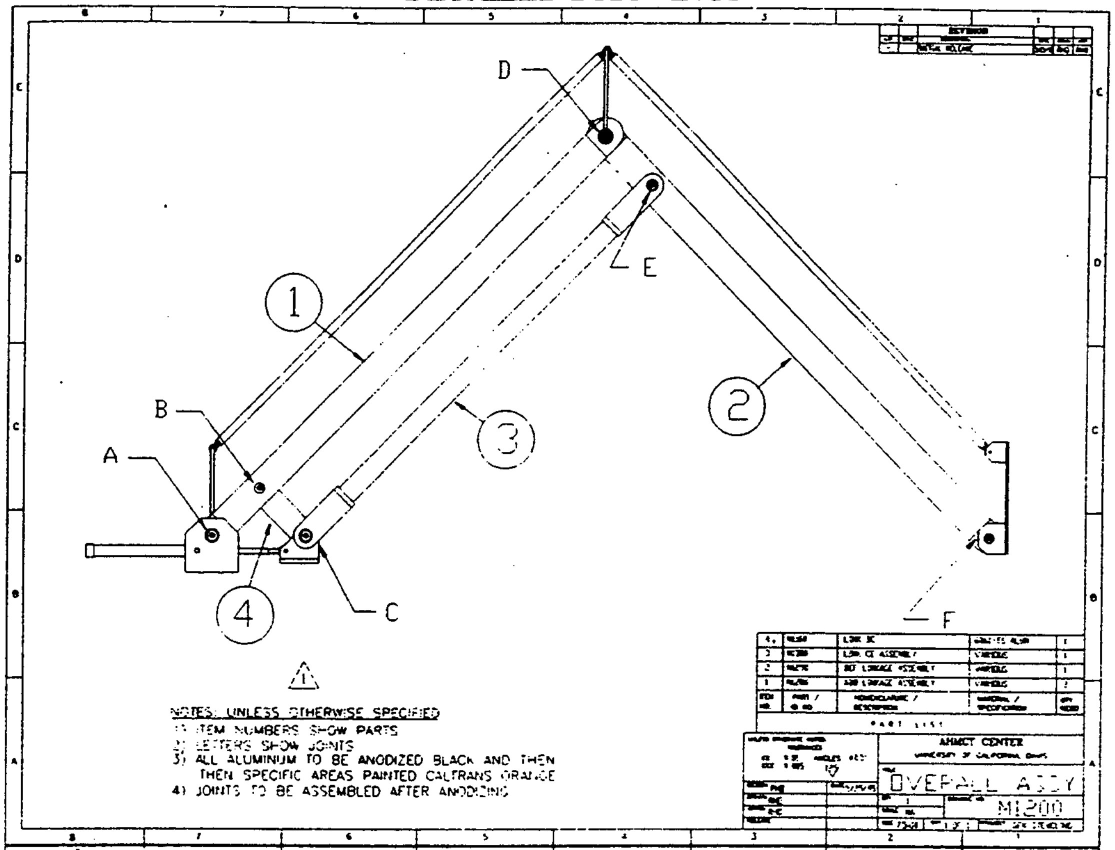
TAP HOLE 5/8-11 UNC THRU AFTER PLATE AND BLOCK ARE ASSEMBLED
NOTES: UNLESS OTHERWISE SPECIFIED
1) BREAK ALL SHARP EDGES
2) ALL DIMENSIONS IN INCHES
PART LIST
AHMCT CENTER
UNIVERSITY OF CALIFORNIA, DAVIS
ASSEMBLY, JOINT
M1143

APPENDIX B
DETAILED DRAWINGS


13.200± 0.001
X2 Ø2.715 +0.001 -0.000
0.750
2.500
2.500
X2 3/16-16 UNC THRU TO HOLE
2.50
X2 R2.50
63
1.500
NOTES, UNLESS OTHERWISE SPECIFIED
1. BREAK ALL SHARP EDGES
2. ALL DIMENSIONS IN INCHES
3. ANODIZE BLACK WITH EXCEPTION OF THRU HOLES AND THREADS
AHMCT CENTER
UNIVERSITY OF CALIFORNIA, DAVIS
LINK BC



APPENDIX B
DETAILED DRAWINGS



NOTES: UNLESS OTHERWISE SPECIFIED
1) ITEM NUMBERS SHOW PARTS
2) LETTERS SHOW JOINTS
3) ALL ALUMINUM TO BE ANODIZED BLACK AND THEN THEN SPECIFIC AREAS PAINTED CALTRANS ORANGE
4) JOINTS TO BE ASSEMBLED AFTER ANODIZING

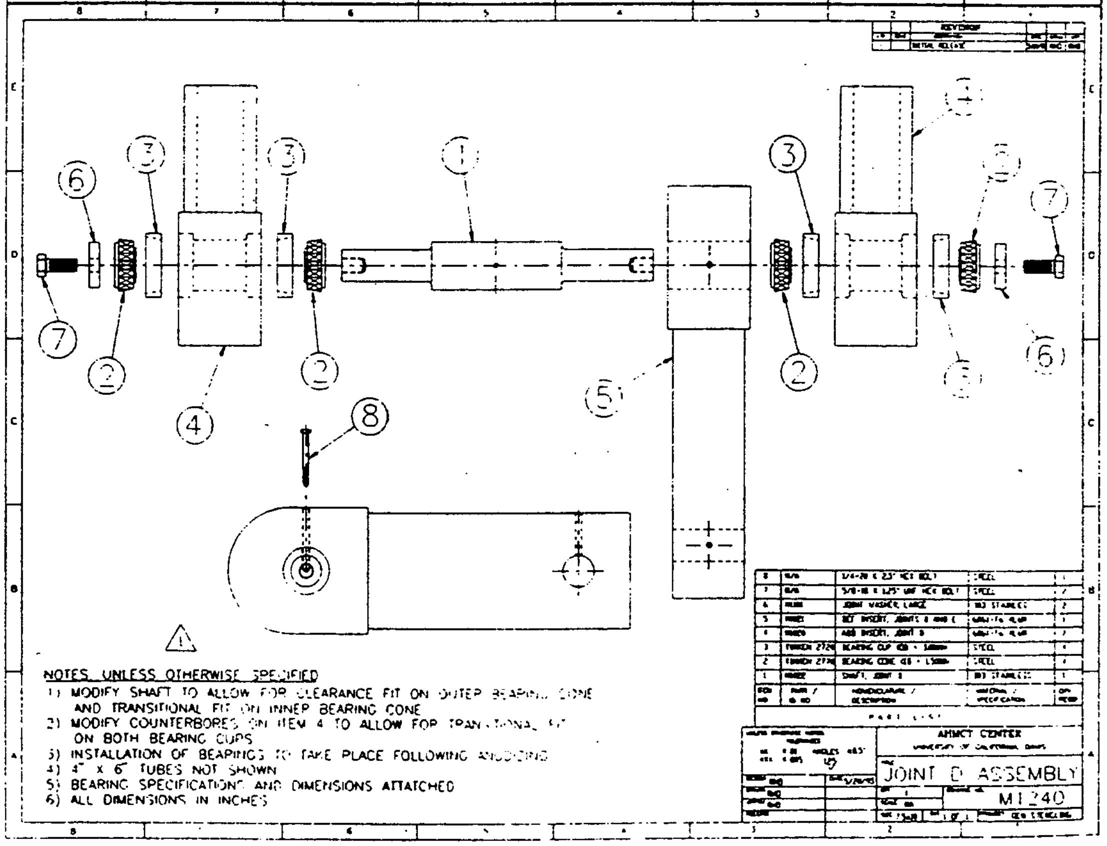
ITEM NO.	PART / ID NO	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD
4	[illegible]	LINK 3C	6061-T6 ALUM	1
3	[illegible]	LINK CE ASSEMBLY	VARIOUS	1
2	[illegible]	BOT LINKAGE ASSEMBLY	VARIOUS	1
1	[illegible]	ARM LINKAGE ASSEMBLY	VARIOUS	2

PART LIST

AHMCT CENTER
UNIVERSITY OF CALIFORNIA, DAVIS

OVERALL ASSY

M1200



NOTES: UNLESS OTHERWISE SPECIFIED
1) MODIFY SHAFT TO ALLOW FOR CLEARANCE FIT ON OUTER BEARING CONE AND TRANSITIONAL FIT ON INNER BEARING CONE
2) MODIFY COUNTERBORES ON ITEM 4 TO ALLOW FOR TRANSITIONAL FIT ON BOTH BEARING CUPS
3) INSTALLATION OF BEARINGS TO TAKE PLACE FOLLOWING ANODIZING
4) 4" X 6" TUBES NOT SHOWN
5) BEARING SPECIFICATIONS AND DIMENSIONS ATTATCHED
6) ALL DIMENSIONS IN INCHES

ITEM NO.	PART / ID NO	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD
8	N/A	1/4-20 X 2.5" HEX BOLT	STEEL	1
7	N/A	5/8-18 X 1.25" UNF HEX BOLT	STEEL	2
6	[illegible]	JOINT WASHER, LARGE	303 STAINLESS	2
5	[illegible]	BOT INSERT, JOINTS B AND C	6061-T6 ALUM	1
4	[illegible]	ARM INSERT, JOINT D	6061-T6 ALUM	2
3	TIMKEN 2720	BEARING CUP [illegible]	STEEL	4
2	TIMKEN 2720	BEARING CONE [illegible]	STEEL	4
1	[illegible]	SHAFT, JOINT D	303 STAINLESS	1

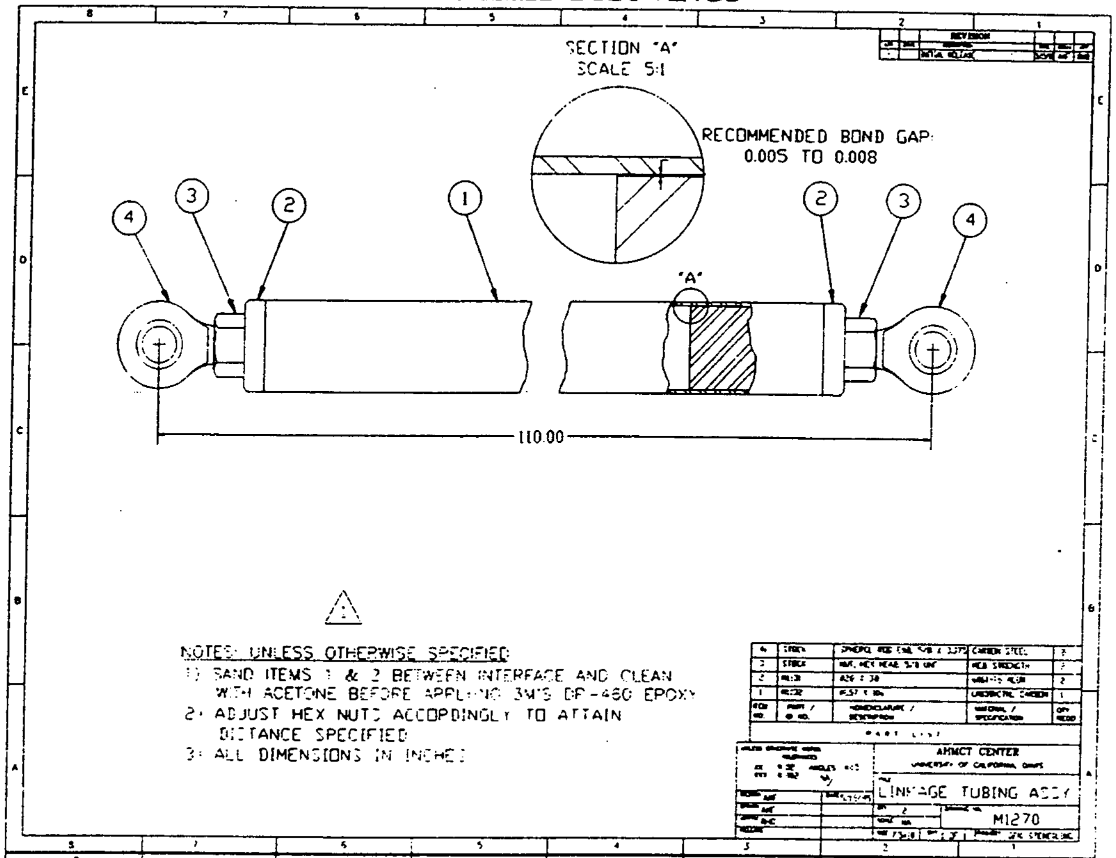
PART LIST

AHMCT CENTER
UNIVERSITY OF CALIFORNIA, DAVIS

JOINT D ASSEMBLY

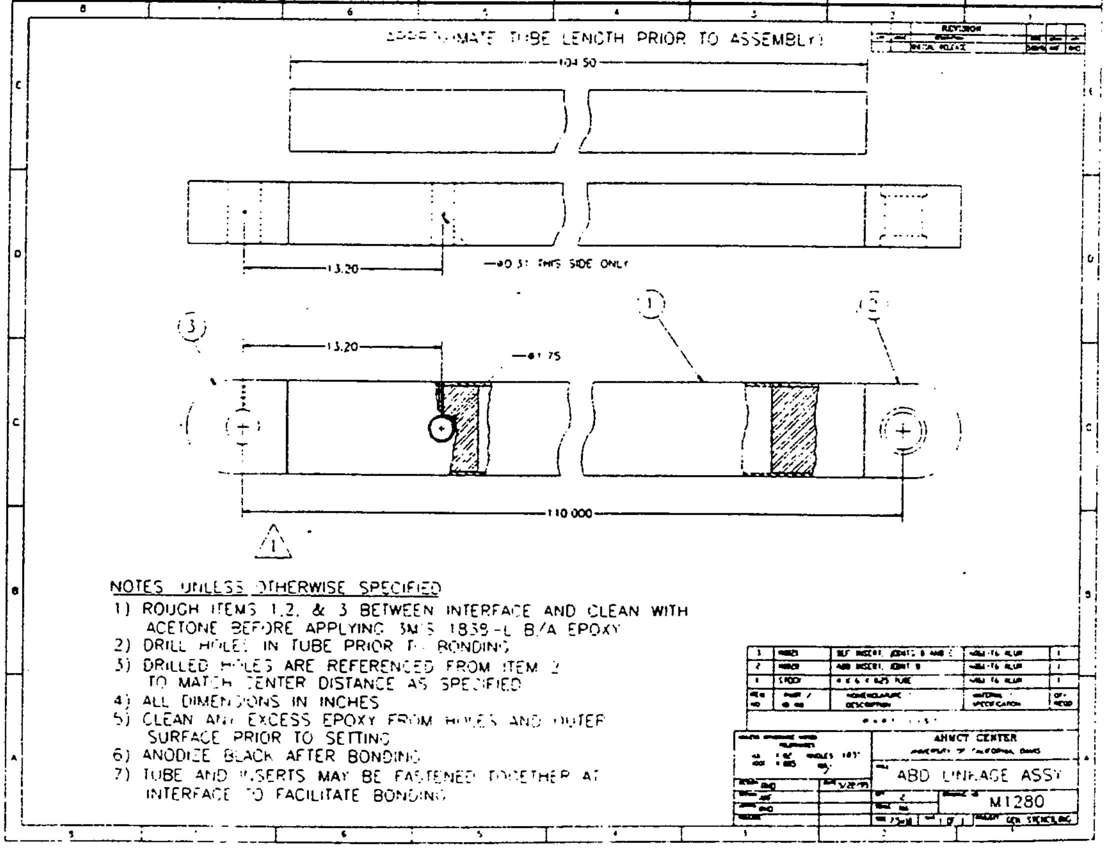
M1240

APPENDIX B
DETAILED DRAWINGS



NOTES: UNLESS OTHERWISE SPECIFIED
1) SAND ITEMS 1 & 2 BETWEEN INTERFACE AND CLEAN WITH ACETONE BEFORE APPLYING 3M'S DP-460 EPOXY
2) ADJUST HEX NUTS ACCORDINGLY TO ATTAIN DISTANCE SPECIFIED
3) ALL DIMENSIONS IN INCHES

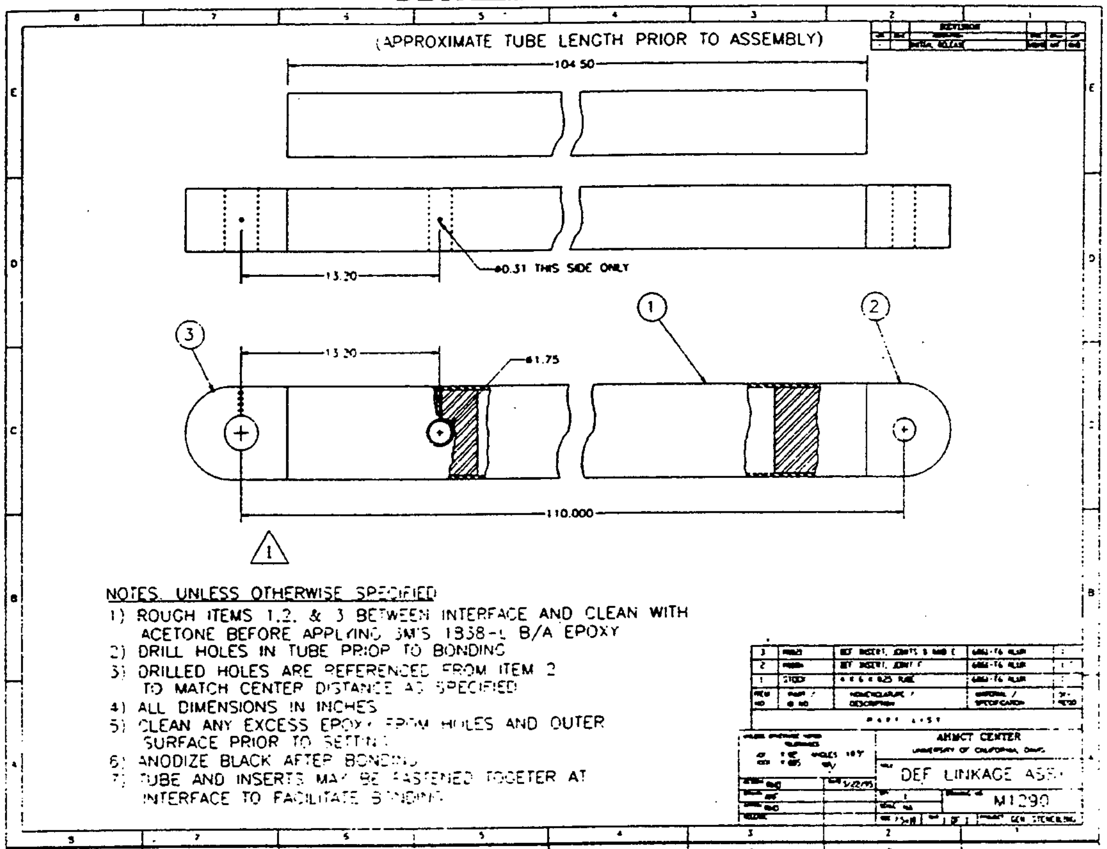
ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD
4	STOCK	SPHERICAL ROD END, 5/8 X 3.272	CARBON STEEL	2
3	STOCK	NUT, HEX HEAD, 5/8 UNF	HIGH STRENGTH	2
2	[illegible]	A26 X 38	[illegible]	2
1	[illegible]	[illegible]	UNIDIRECTIONAL CARBON	1

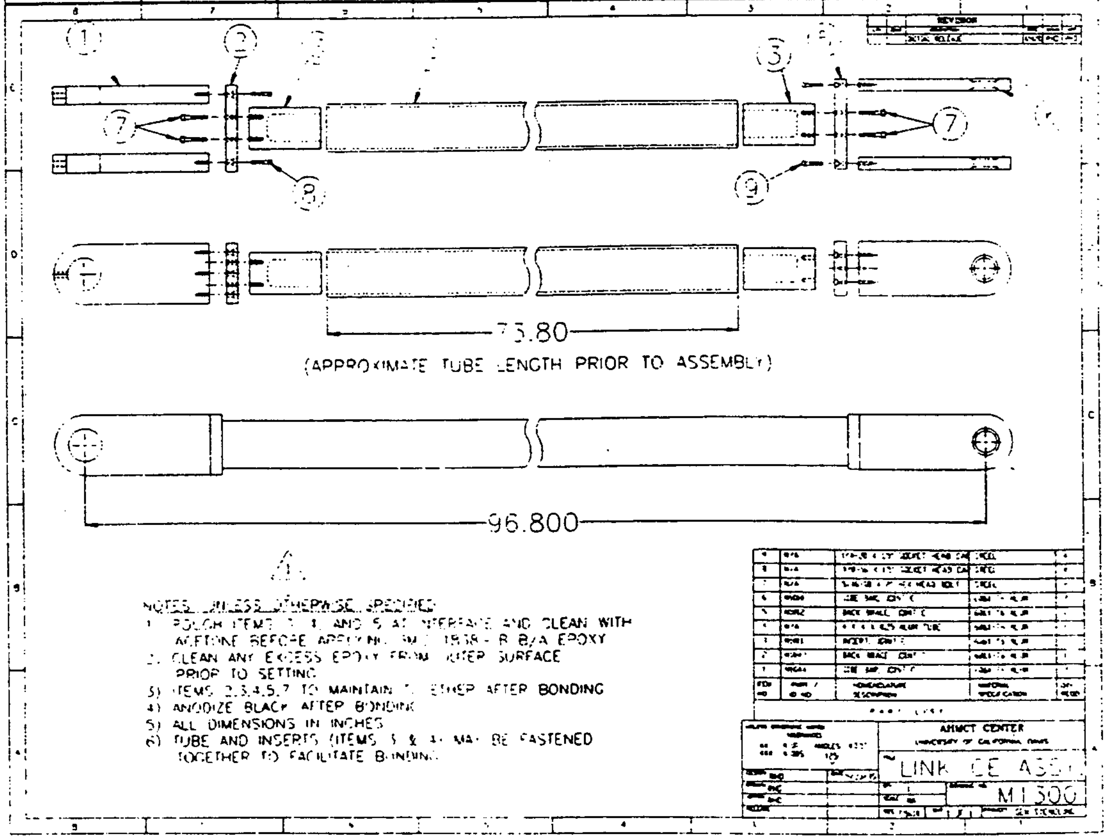


NOTES: UNLESS OTHERWISE SPECIFIED
1) ROUGH ITEMS 1, 2, & 3 BETWEEN INTERFACE AND CLEAN WITH ACETONE BEFORE APPLYING 3M'S 1838-L B/A EPOXY
2) DRILL HOLES IN TUBE PRIOR TO BONDING
3) DRILLED HOLES ARE REFERENCED FROM ITEM 2 TO MATCH CENTER DISTANCE AS SPECIFIED
4) ALL DIMENSIONS IN INCHES
5) CLEAN ANY EXCESS EPOXY FROM HOLES AND OUTER SURFACE PRIOR TO SETTING
6) ANODIZE BLACK AFTER BONDING
7) TUBE AND INSERTS MAY BE FASTENED TOGETHER AT INTERFACE TO FACILITATE BONDING

ITEM NO.	PART / ID NO.	NOMENCLATURE / DESCRIPTION	MATERIAL / SPECIFICATION	QTY REQD
3	[illegible]	SELF INSERT, JOINTS B AND C	6061-T6 ALUM	1
2	[illegible]	ABD INSERT, JOINT B	6061-T6 ALUM	1
1	STOCK	[illegible] TUBE	6061-T6 ALUM	1

APPENDIX B
DETAILED DRAWINGS


(APPROXIMATE TUBE LENGTH PRIOR TO ASSEMBLY)
104.50
13.20
⌀0.31 THIS SIDE ONLY
⌀1.75
110.000
NOTES: UNLESS OTHERWISE SPECIFIED
1) ROUGH ITEMS 1,2, & 3 BETWEEN INTERFACE AND CLEAN WITH ACETONE BEFORE APPLYING 3M'S 1838-L B/A EPOXY
2) DRILL HOLES IN TUBE PRIOR TO BONDING
3) DRILLED HOLES ARE REFERENCED FROM ITEM 2 TO MATCH CENTER DISTANCE AS SPECIFIED
4) ALL DIMENSIONS IN INCHES
5) CLEAN ANY EXCESS EPOXY FROM HOLES AND OUTER SURFACE PRIOR TO SETTING
6) ANODIZE BLACK AFTER BONDING
7) TUBE AND INSERTS MAY BE FASTENED TOGETER AT INTERFACE TO FACILITATE BONDING
AHMCT CENTER
DEF LINKAGE ASSY
M1290


73.80
(APPROXIMATE TUBE LENGTH PRIOR TO ASSEMBLY)
96.800
NOTES: UNLESS OTHERWISE SPECIFIED
1) ROUGH ITEMS 3, 4, AND 5 AT INTERFACE AND CLEAN WITH ACETONE BEFORE APPLYING 3M'S 1838-B B/A EPOXY
2) CLEAN ANY EXCESS EPOXY FROM OUTER SURFACE PRIOR TO SETTING
3) ITEMS 2,3,4,5,7 TO MAINTAIN TOGETHER AFTER BONDING
4) ANODIZE BLACK AFTER BONDING
5) ALL DIMENSIONS IN INCHES
6) TUBE AND INSERTS (ITEMS 3 & 4) MAY BE FASTENED TOGETHER TO FACILITATE BONDING
AHMCT CENTER
LINK CE ASSY
M1300