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Implementation of a System for Controlling the Lateral Position of a Moving Vehicle

State Job No. 14598(0)

and

Field Testing of ODOT Sensor-Assisted Steering System

State Job No. 14640(0)

FINAL REPORT

July 2002

Prepared by:

Dennis R. Pugh and James V. Nivens

Prepared in cooperation with the Ohio Department of Transportation and the U. S. Department of Transportation, Federal Highway Administration.

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16. Abstract

The overall objective was to design, implement, and test sensor-assisted driver control of an ODOT dump truck. Requirements included repeatably steering a loaded or unloaded truck over embedded sensors to a lateral accuracy of +/- one inch, time-sharing the truck with normal uses, and providing for safe operation.

The design and implementation of the Sensor-Assisted Steering System described in this report has verified that the suite of sensors, actuators, and computation resources can be packaged in and powered from a standard ODOT dump truck at a reasonable component cost.

The required lateral positioning accuracy of +/- one inch was achieved via servomotor control of the steering column of a conventional dump truck. The "dead-reckoning" portion of the vehicle lateral position observer, based on an angular rate sensor and a vehicle velocity sensor, worked very well.

The human-in-the-loop, video-based lateral positioning system performed well under the conditions for which it was designed. However, the assumption of a perfectly straight edge line was not realized, and may not be practical. Indeed, some portions of the test highway are not straight, but have gentle curves. Overall, the video-based edge-line tracking system, designed to correct longer-term drift of the "dead-reckoning" subsystem, was found to be insufficiently robust.

To further pursue this type of automatic steering, it is recommended that an active position-sensing technology be employed that does not rely on natural ambient lighting.

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INTRODUCTION

AMT Systems Engineering, Inc. (formerly Adaptive Machine Technologies, Inc.) designed a system to automatically control the lateral position of a moving vehicle.

In Phase I, (State Job Number 14598(0)), a study was performed to support investigation of the durability of various highway construction techniques that will be used to build the experimental section of highway on US 23 north of Delaware, Ohio. The specific objective of the study was to determine the feasibility and cost of instrumenting and controlling a loaded ODOT dump truck in order that it can be driven over sensors embedded in the test highway, while maintaining with a lateral position accuracy of +/- one inch or better.

The major task to be accomplished in Phase I was determination of the feasibility and cost of using a computerized image processing system to accurately determine vehicle lateral position, given a video signal from a vehicle-mounted camera aimed at the highway edge line. With the help of an image processor vendor, this was accomplished with much less effort than expected. The Phase I study was therefore expanded to include experimental investigation of direct driver control using video image feedback, and subsequent analysis of gyro-assisted driver control.

The video image processing approach was shown to provide ample resolution, accuracy, and data rates for this application. However, it is relatively expensive, with an off-the-shelf hardware and software component cost of about $20,000, exclusive of the required application-specific engineering.

Experiments with an ODOT dump truck and driver showed that a driver using only video-image feedback could not reliably maintain lateral positioning accuracies of better than +/- 6 inches at highway speeds. This was observed to be primarily due to the reaction time of a human driver, which is too slow to adequately reject heading disturbances caused by road imperfections. From this experiment, it was concluded that automatic servo control of the vehicle steering would be required, regardless of the type of feedback devices used.

Because of the relatively high cost of the computerized image processing system, it was decided to investigate the use of an angular rate sensor to sense vehicle yaw rate; this information would be used as an input to the steering servo controller. This approach will allow high-frequency disturbances to be compensated for automatically, reducing the driver's task to controlling the vehicle lateral position at a much lower frequency. Because the rate sensor is relatively inexpensive and will assist achieving accurate control even if an image processor is employed, it was decided to pursue an incremental system development plan in which the image processing system will be added only if gyro-assisted driver control fails to provide adequate accuracy, or if automatic verification of lateral positioning accuracy is deemed essential.

During Phase II, (also State Job Number 14598(0)), all systems needed for gyro-assisted driver control were designed, integrated, and installed, and preliminary testing was performed.

In Phase III, (State Job Number 14640(0)), field testing of the full system was performed.

RESEARCH OBJECTIVES

The overall objective was to design, implement, and test sensor-assisted driver control of an ODOT dump truck. Requirements included repeatably steering a loaded or unloaded truck over embedded sensors to a lateral accuracy of +/- 1 inch, time-sharing the truck with normal uses, and providing for safe operation. General tasks include control system design, software design and implementation, final component selection, custom mounting and packaging (see Appendix 1 for drawings), wiring harness design and fabrication (see Appendix 2 for schematics), and system integration. The various required subsystems include a sensing subsystem, servo-actuator subsystem, control computer, control software, and operator display controls. The design and implementation of these subsystems is described in the following section.

GENERAL DESCRIPTION OF THE RESEARCH

Servoactuator Subsystem

Accurate lateral positioning at highway speeds depends directly on the speed and acceleration capability of the steering actuator. Preliminary calculations indicated that a servomotor of approximately 3/4 horsepower may be required at higher speeds. A larger motor would be expensive to provide with electrical power, and would be difficult for the driver to overpower in the event of an emergency.

The major servoactuator subsystems were selected as follows: A 1/2 horsepower DC servomotor / 20:1 gearhead / optical encoder / DC tachometer assembly, an electromechanical motor clutch to disengage the actuator system when not in use, a timing belt and pulley system to drive the steering column, a DC servo amplifier, a 48V DC power supply, a 12V input / 1 KVA power inverter to provide adequate power at 115 VAC.

Custom bracketry was fabricated to mount the servo mechanism (including the DC motor, gearhead, encoder, tachometer, clutch, timing belt, and pulley system). This entire assembly mounts on the floor of the truck cab directly beside the steering column and the brake pedal of the vehicle. (See Appendix 4 for a photo).

Control Computer Subsystem

The control computer subsystem provides the processing power, data storage, and sensor interface circuitry for the system. Specific components include a mobile PC enclosure/backplane, a single-board 486 computer which includes watchdog timer circuitry, a 3 1/2" floppy disk drive, a multifunction analog and digital input/outboard board, and a quadrature decoder board to read the motor position sensor.

Operator Display and Controls

A camera was mounted on the test vehicle outboard of the front bumper, and aimed downward at the edge line (see Appendix 4 for a photo). A flat-screen monitor was installed on the vehicle dashboard, to show the image of the edge line from the camera. A vehicle operator, seated in the passenger seat, can see the precise lateral position of the vehicle by watching the edge line image on the video monitor.

A small control pendant was designed to allow the operator to control the vehicle. A switch on the pendant allows the operator to switch between automatic steering control and manual steering (using the normal vehicle steering wheel). When the controller is in automatic steering mode, the operator positions a computer-generated cursor over the edge-line image, using a rotary knob on the pendant. Thus the operator serves as part of a video-based, human-in-the-loop lateral position sensor. Finally, an LED on the pendant gives feedback to the operator as to the status of the automatic steering controller.

Sensor Subsystem

In addition to the video camera and position-cursor subsystem, dead-reckoning and inertial sensors were incorporated in the vehicle. A solid-state angular-rate sensor was incorporated in order to provide high-bandwidth vehicle yaw-rate information. Circuitry was also designed and implemented to determine the vehicle longitudinal velocity, based on the frequency of an electrical signal from a vehicle-transmission sensor.

Lateral Position Confirmation System

In order to provide independent verification of vehicle lateral positioning accuracy, a separate video camera, VCR, and associated electronics were added to the system. The second camera was positioned such that the edge line is in view as it passes under the rear wheels of the truck. The signal from this camera can be recorded on the VCR.

Safety Features

Automatic control of a large vehicle traveling at highway speeds presents safety issues that must be taken very seriously. Various automatic error-detection systems were incorporated, and high-reliability interlocks were provided to disengage the automatic steering if the driver or the operator performs natural emergency reflex actions. Specifically, the following safety features were incorporated into the system:

1. A normally-disengaged electromagnetic clutch was installed between the steering column and the servomotor. When electrical power is removed from the clutch, the automatic steering servomechanism is disengaged, and the steering operates normally.

2. Servomotor, amplifier, and gearing were sized to permit the driver to overpower the servomotor. A force of approximately 20 pounds, applied to the rim of the steering wheel, is sufficient to overpower the servomotor. Thus the driver can still safely control the vehicle, under the worst-case scenario of a simultaneous control system and clutch failure.

3. A watchdog timer circuit was incorporated within the control computer. All critical software processes must report normal operation every few milliseconds, or else this circuit disengages the servomotor clutch, disables the automatic steering controller, and removes power from the servomotor. This circuit also disengages the clutch in the event of a computer power failure.

4. If the driver grabs the steering wheel in an emergency, he will quickly overpower the servomotor; thus causing a servo error. The computer will detect this servo error, disengaging the servomotor clutch and removing power from the servomotor.

5. The values of the yaw rate sensor measurement and the vehicle speed sensor measurement are constantly tested for reasonableness. Thus a serious sensor failure will be detected by the computer, which will then disengage the servomotor clutch and remove power from the servomotor.

6. The operator yaw rate command (from the rotary knob on the operator control pendant) is constantly checked for reasonableness. If the command is not reasonable (due to controller equipment failure or to operator error), the computer will then disengage the servomotor clutch and remove power from the servomotor.

Control Software

Software was designed and implemented to execute the steering control algorithm, to execute many of the safety checks, and to perform the overall simulation for testing. The automatic steering control algorithm was the major technical challenge in this program. The first step was to analyze the system mathematically. From this, a vehicle dynamics model was used to design the control algorithm. Next, it was coded in software and tested in simulation, controlling a computer-simulated vehicle.

The vehicle-control problem was divided into two major issues: 1) determining the lateral position and velocity of the vehicle (relative to the edge line), and 2) controlling the steering actuator so as to maintain the desired position.

A vehicle lateral-state observer was designed, using as inputs the vehicle yaw rate, vehicle forward speed, and the edge-line position from the human-in-the-loop video positioning system. Because of the reaction time of the human operator, the feedback from the video subsystem was considered to have zero drift, but very limited bandwidth. The yaw sensor provides good high-bandwidth signals, but is subject to drift. Kalman filtering techniques were employed to combine the accurate signal frequency bands from each source, while rejecting the inaccurate signal frequency bands, resulting in an accurate observed vehicle state.

Given an accurate vehicle state, a state-feedback control law was used to determine the desired steering angle of the vehicle's front wheels. From this, the desired steering-column angle was computed and used as the input to the servomotor position control loop.

SYSTEM TESTING

Preliminary Testing

During Phase II of this project, a simulation of the lateral dynamics of a truck was developed, coded, implemented on a stand-alone PC, interfaced to the vehicle control computer, and tested for basic functionality. Actual vehicle tests were conducted at low parking-lot speeds, with good results. The computer recorded all variables of interests, which were analyzed subsequent to the tests.

Field Testing

In Phase III of this project, full-systems tests were conducted. During October and November of 1996, approximately 100 test runs were made on the test section of U.S. 23 north of Delaware, Ohio. Control parameters were tuned for maximum performance, with good stability, at 60 mph. System performance was verified with the truck in both unloaded and in fully loaded conditions.

In testing, the system performed well if the road had a very straight edge line. As specified, edge lines were to be made perfectly straight with the assistance of laser alignment. Under these conditions, vehicle lateral tracking accuracy was within +/- one inch.

Due to reconstruction of portions of the test highway, however, some sections of the edge line were wavy. With a wavy edge line, it was very difficult for the operator to track with adequate bandwidth, and tracking accuracy suffered. To solve this problem, the human in-the-loop edge-line tracking would have to be replaced with an electronic video image recognition system.

Although the system was architected to incorporate a video image recognition system, field testing showed that reliable results could probably <u>not</u> be achieved under natural-lighting conditions. Specifically, on sunny days, if the edge of the vehicle shadow often fell on the road edge line. When this happened, it was extremely difficult for even a human to discriminate the actual edge line. If a computer-vision system erroneously tracked the shadow instead of the edge line, the vehicle could drive off of the road.

CONCLUSIONS AND RECOMMENDATIONS

The design and implementation of the Sensor-Assisted Steering System described in this report has verified that the suite of sensors, actuators, and computation resources can be packaged in and powered from a standard ODOT dump truck at a reasonable component cost.

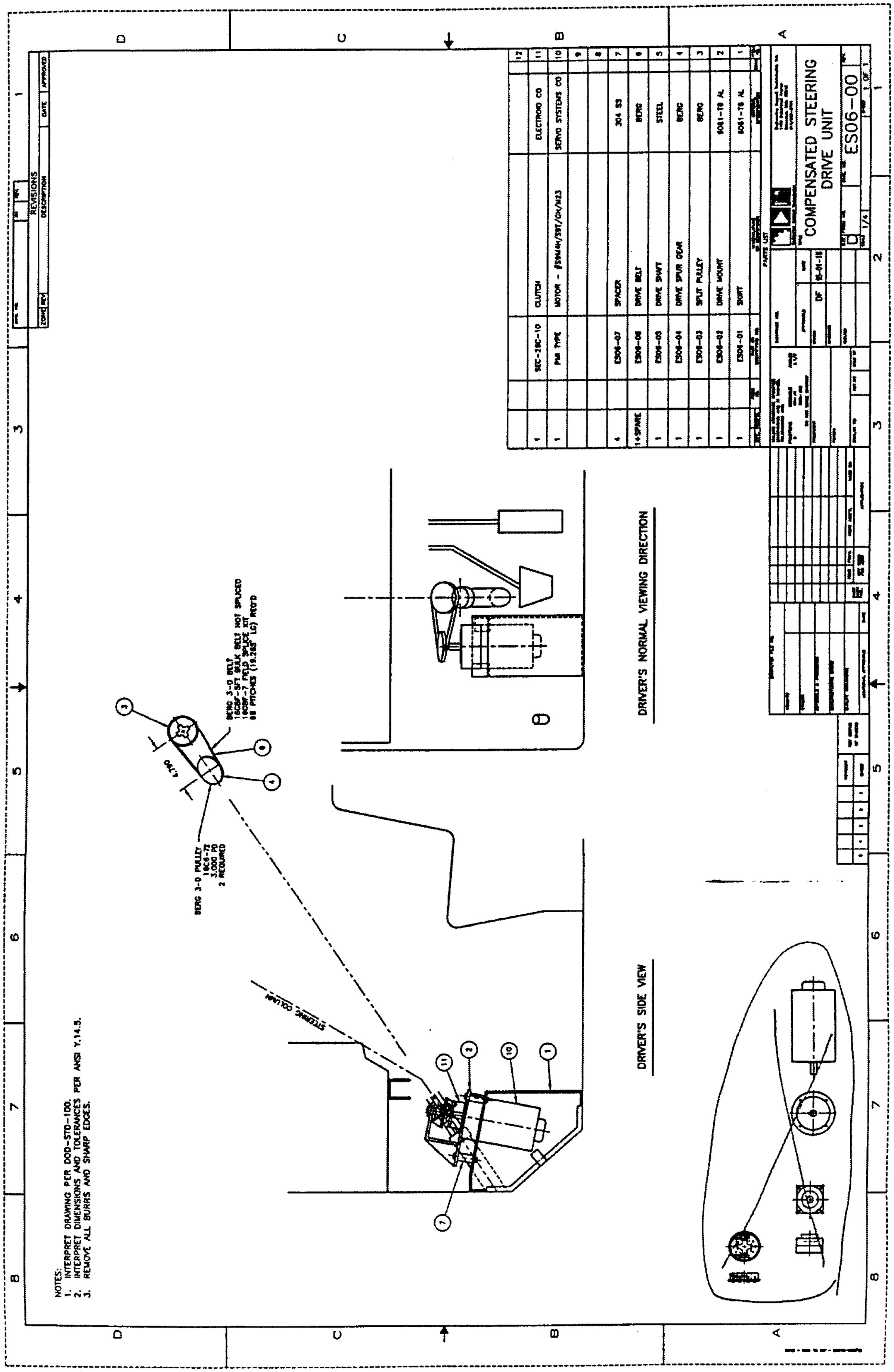
The required lateral positioning accuracy of +/- one inch was achieved via servomotor control of the steering column of a conventional dump truck. The "dead-reckoning" portion of the vehicle lateral position observer, based on an angular rate sensor and a vehicle velocity sensor, worked very well.

The human-in-the-loop, video-based lateral positioning system performed well under the conditions for which it was designed. However, the assumption of a perfectly straight edge line was not realized, and may not be practical. Indeed, some portions of the test highway are not straight, but have gentle curves. Overall, the video-based edge-line tracking system, designed to correct longer-term drift of the "dead-reckoning" subsystem, was found to be insufficiently robust.

The various safety features performed very well. Over the course of about a hundred test runs, there was never an incident in which safety was compromised.

To further pursue this type of automatic steering, it is recommended that an active position-sensing technology be employed that does not rely on natural ambient lighting.

APPENDIX 1: Drawings of Custom Mounting and Packaging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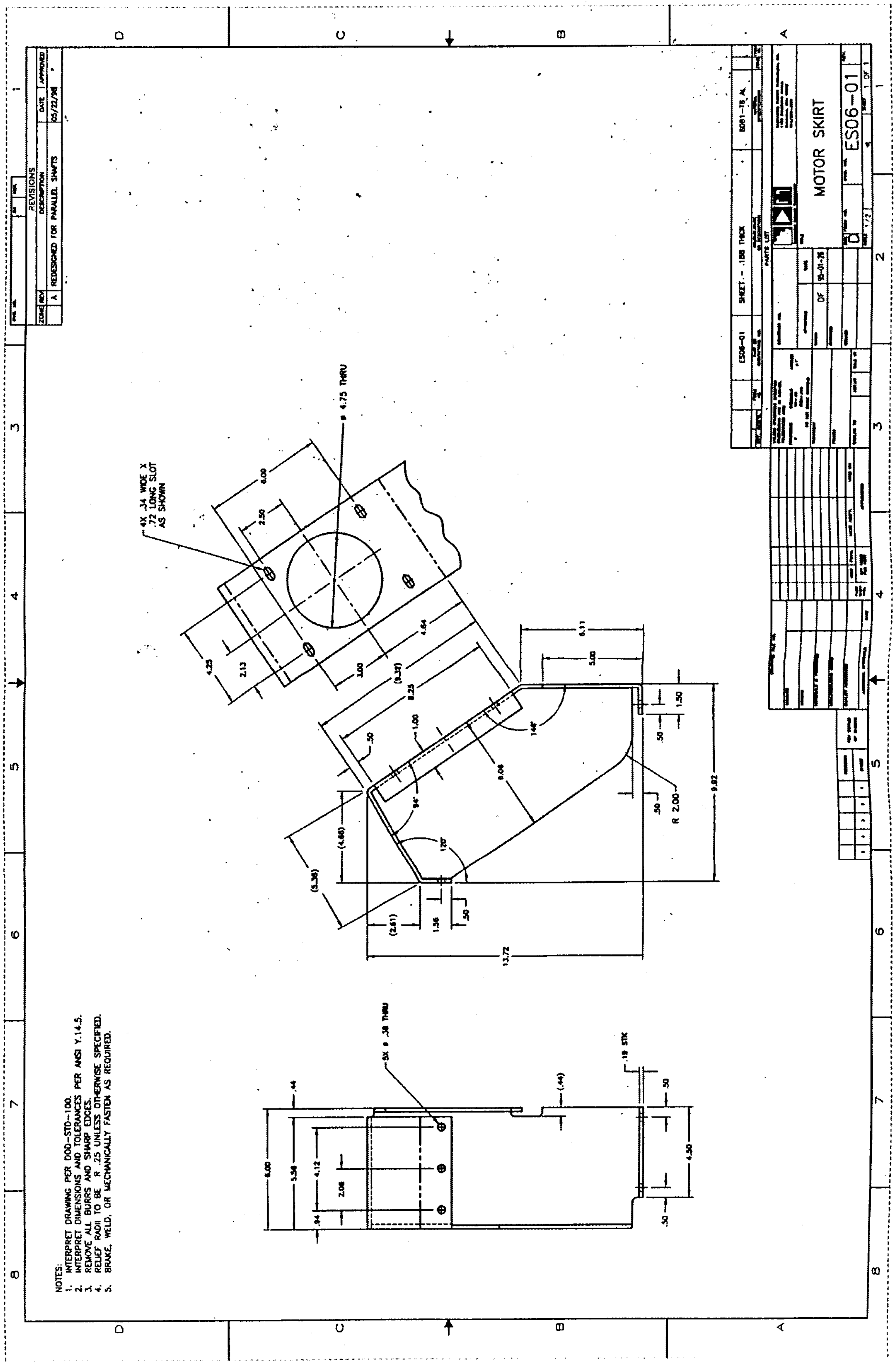
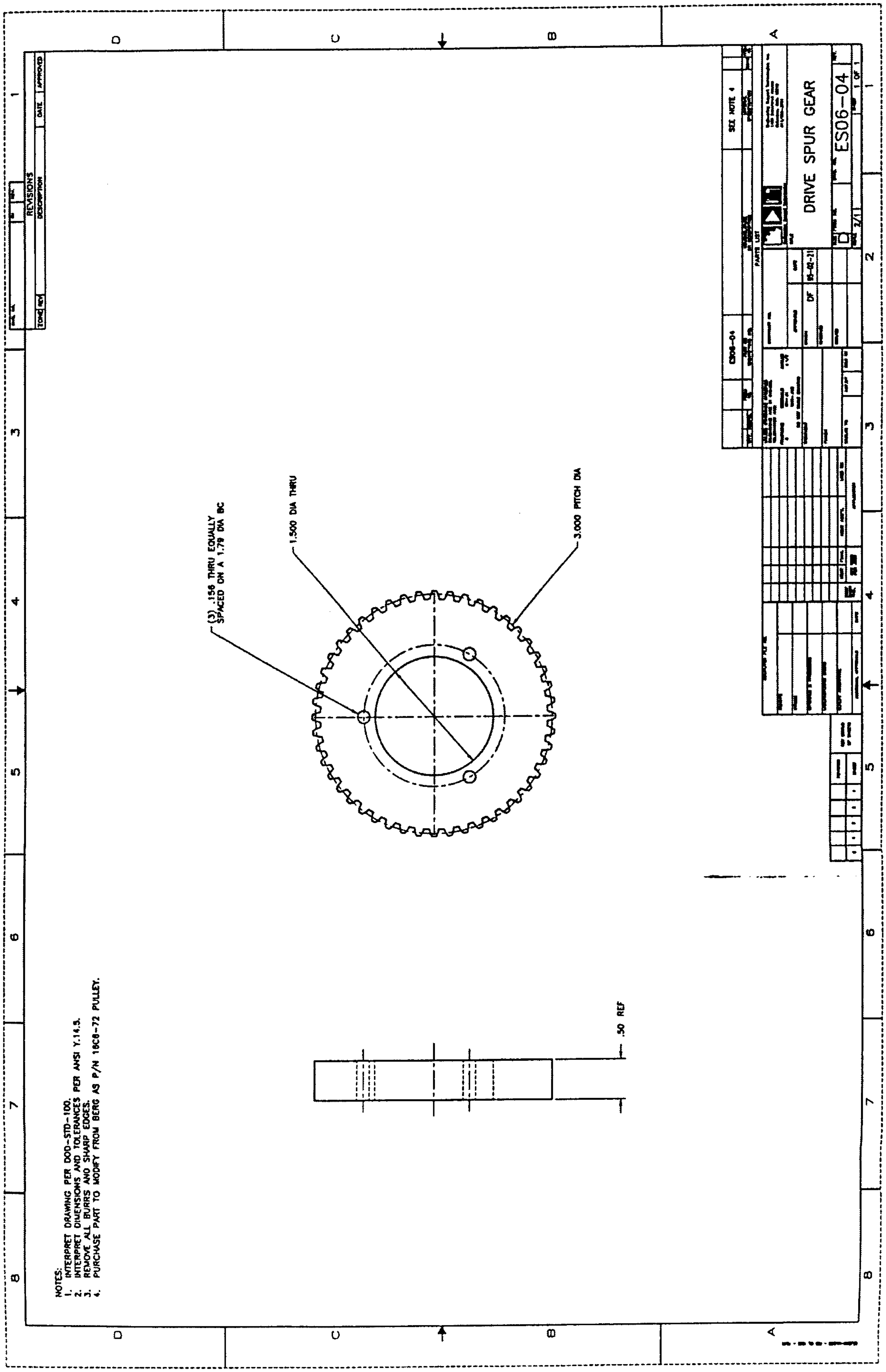
1. INTERPRET DRAWING PER DOD-STD-100.
2. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y.14.5.
3. REMOVE ALL BURRS AND SHARP EDGES.
BERG 3-D PULLEY
3.000 PD
2 REQUIRED
BERG 3-D BELT
88 PITCHES (19.285" LG) REQ'D
STEERING COLUMN
DRIVER'S SIDE VIEW
DRIVER'S NORMAL VIEWING DIRECTION
REVISIONS
11 SEC-28C-10 CLUTCH ELECTROID CO
10 PM TYPE MOTOR SERVO SYSTEMS CO
7 ES06-07 SPACER 304 SS
6 ES06-06 DRIVE BELT BERG
5 ES06-05 DRIVE SHAFT STEEL
4 ES06-04 DRIVE SPUR GEAR BERG
3 ES06-03 SPLIT PULLEY BERG
2 ES06-02 DRIVE MOUNT 6061-T6 AL
1 ES06-01 SKIRT 6061-T6 AL
PARTS LIST
COMPENSATED STEERING
DRIVE UNIT
ES06-00


REVISIONS
REDESIGNED FOR PARALLEL SHAFTS
4X .34 WIDE X .72 LONG SLOT AS SHOWN
Ø 4.75 THRU
5X Ø .38 THRU
.19 STK
NOTES:
1. INTERPRET DRAWING PER DOD-STD-100.
2. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y.14.5.
3. REMOVE ALL BURRS AND SHARP EDGES.
4. RELIEF RADII TO BE R .25 UNLESS OTHERWISE SPECIFIED.
5. BRAKE, WELD, OR MECHANICALLY FASTEN AS REQUIRED.
MOTOR SKIRT
ES06-01


(3) .156 THRU EQUALLY SPACED ON A 1.79 DIA BC
1.500 DIA THRU
3.000 PITCH DIA
.50 REF
NOTES:
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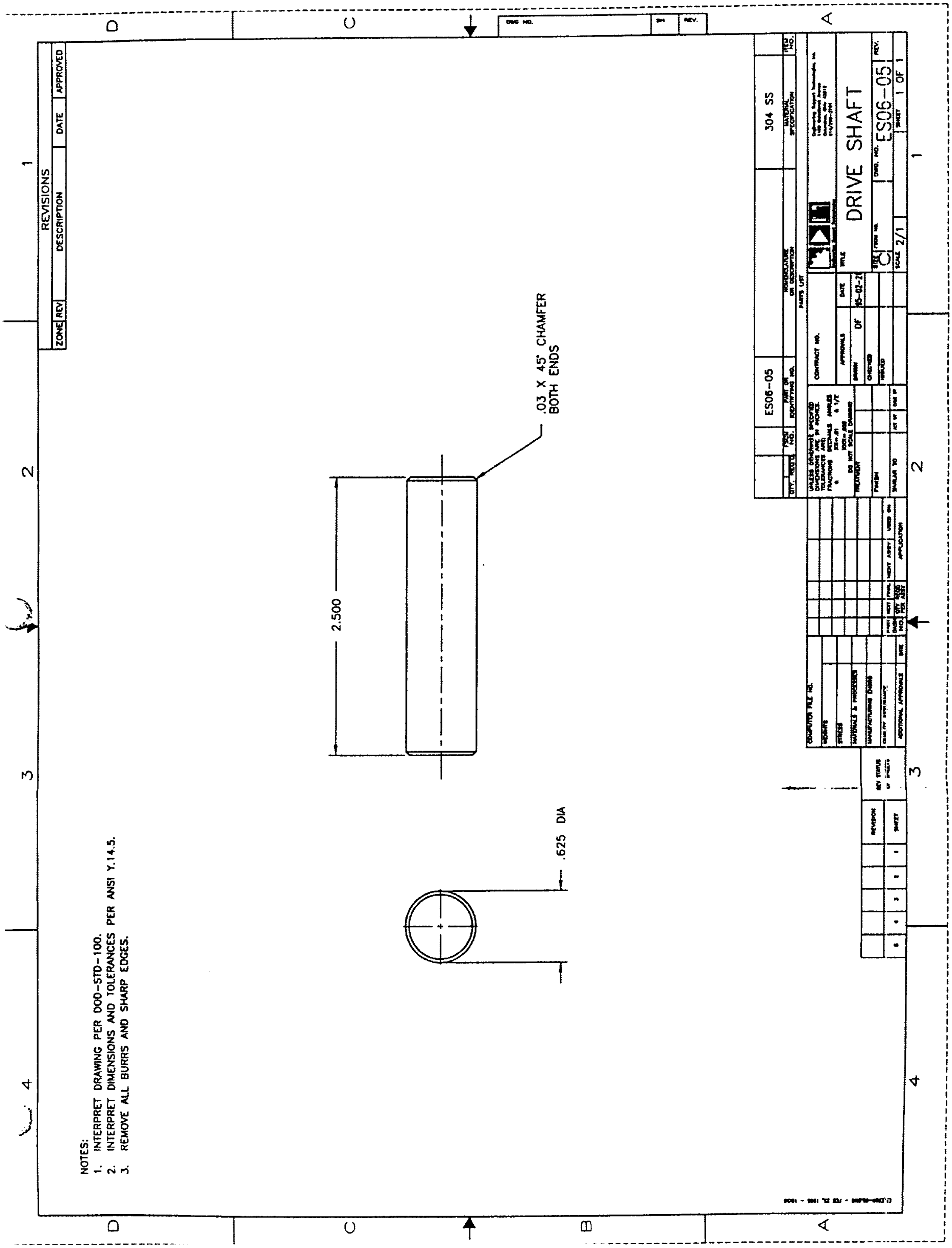
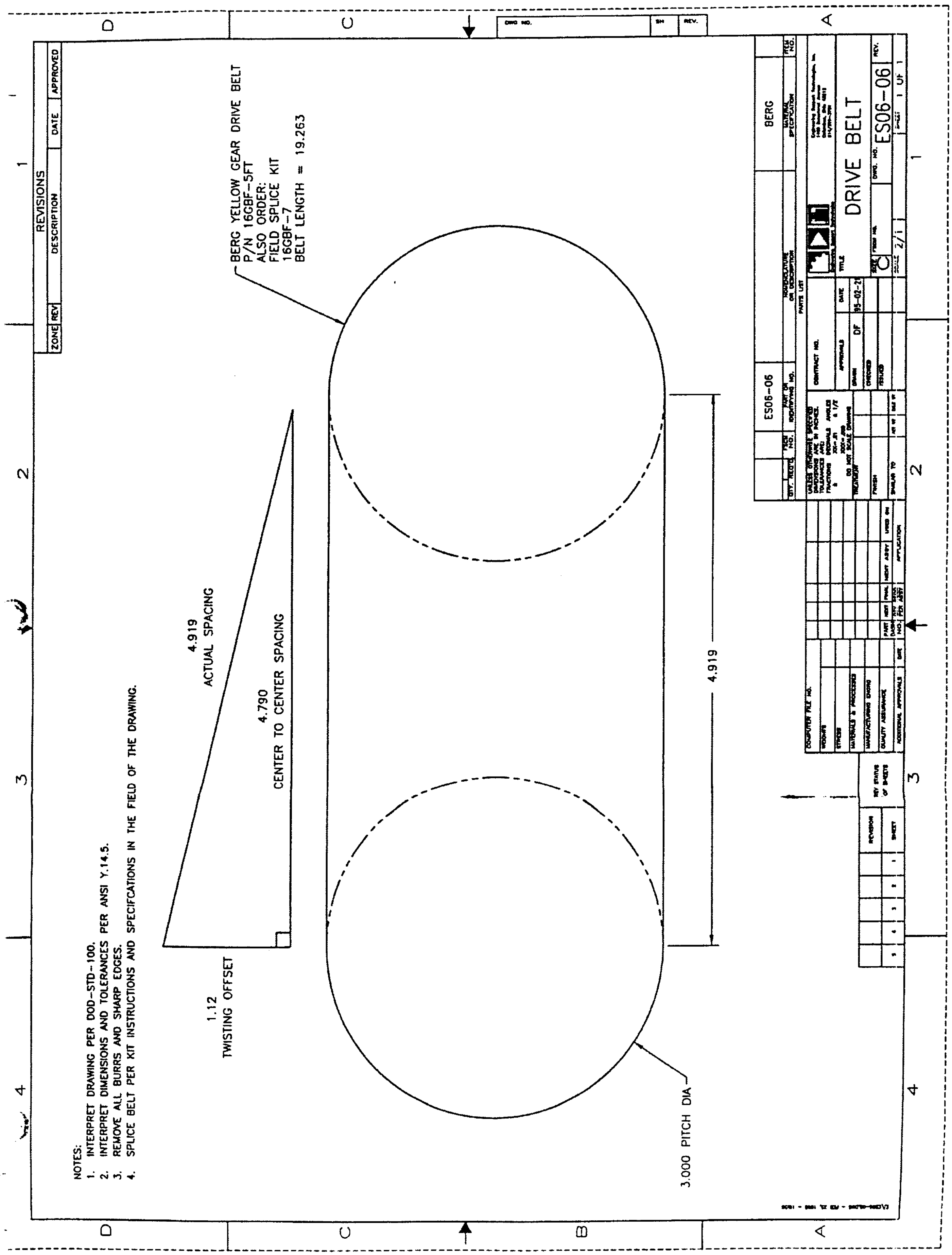
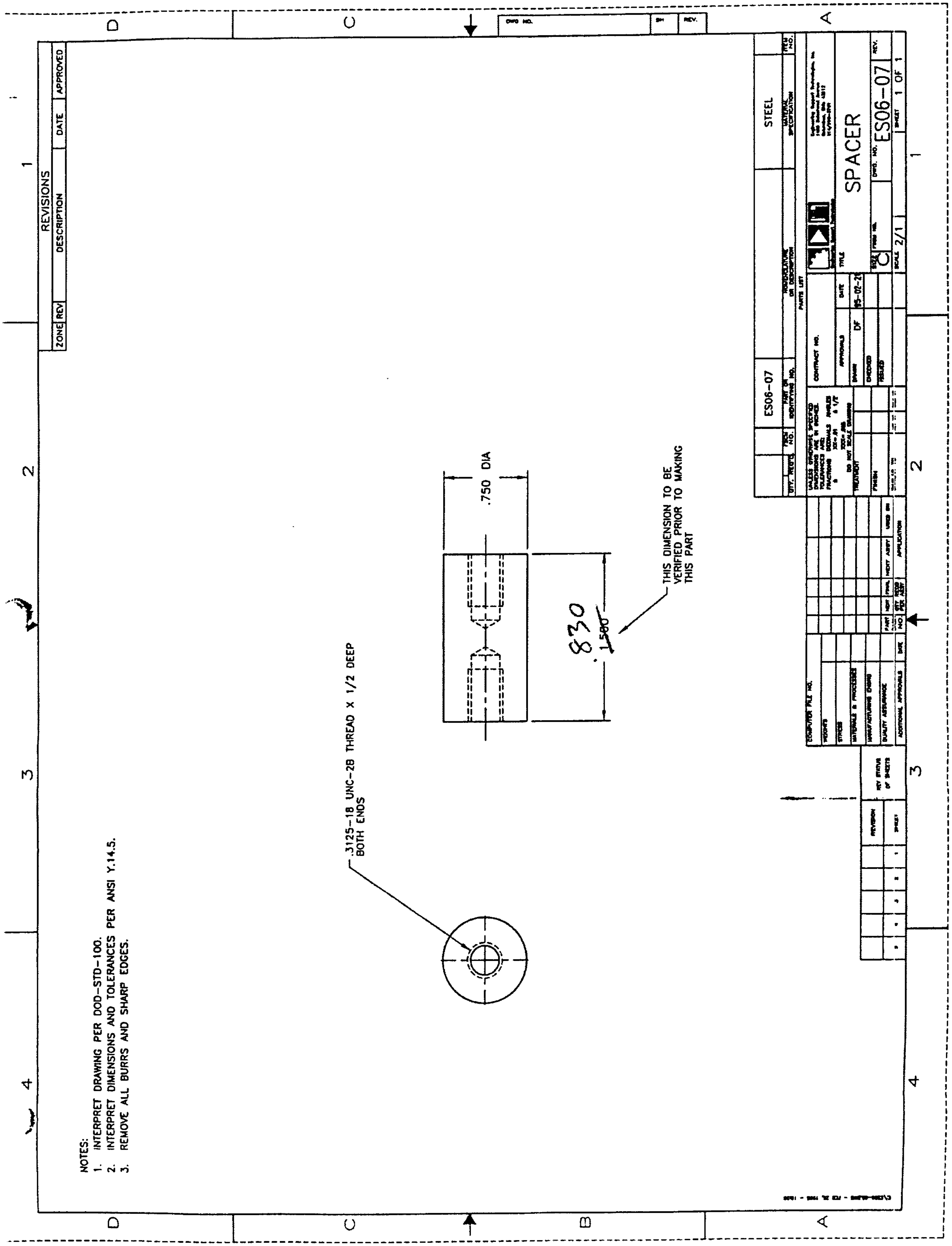
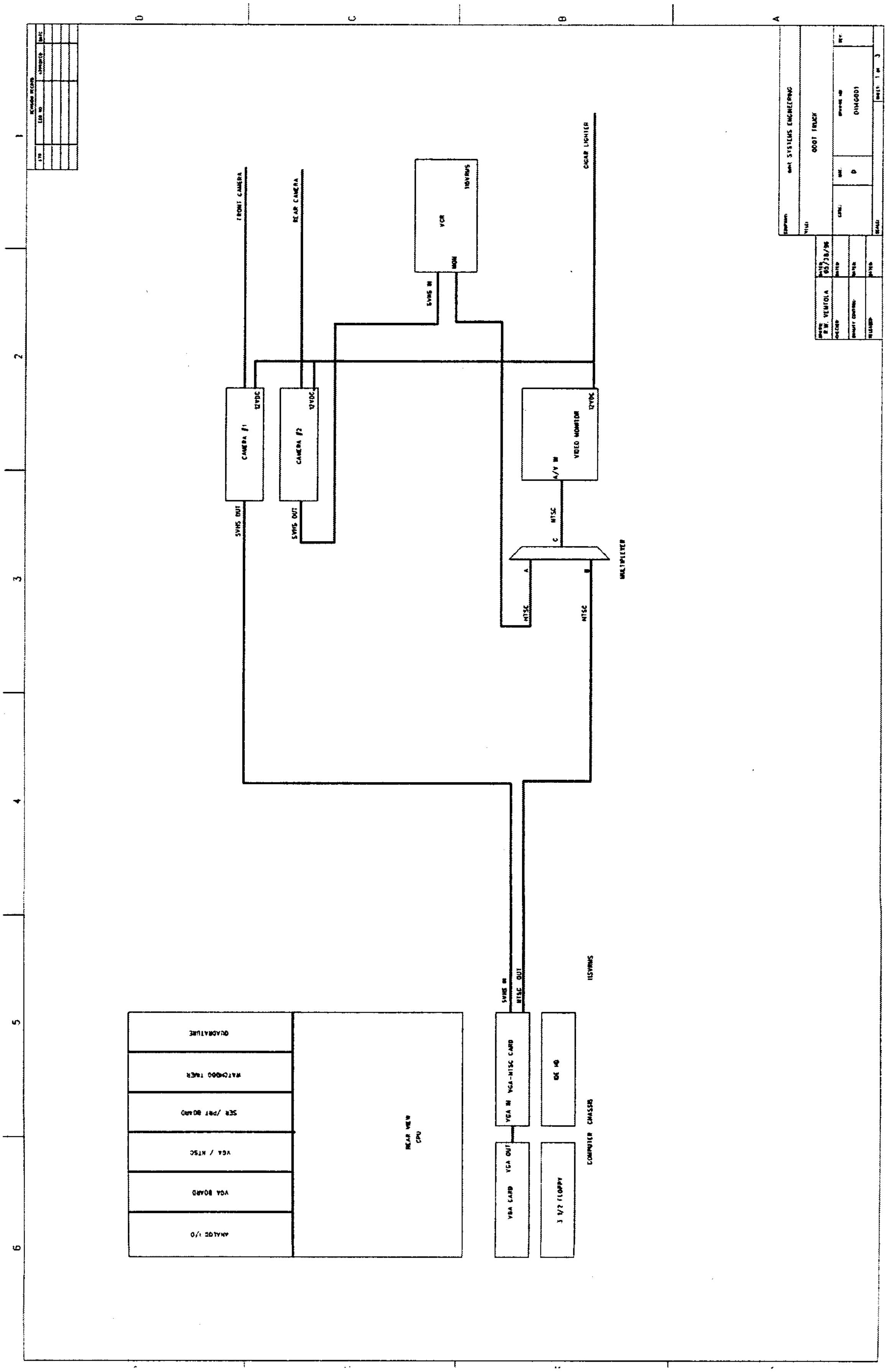
2. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y.14.5.
3. REMOVE ALL BURRS AND SHARP EDGES.
4. PURCHASE PART TO MODIFY FROM BERG AS P/N 18C8-72 PULLEY.
REVISIONS
SEE NOTE 4
ES06-04
DRIVE SPUR GEAR
ES06-04
2/1

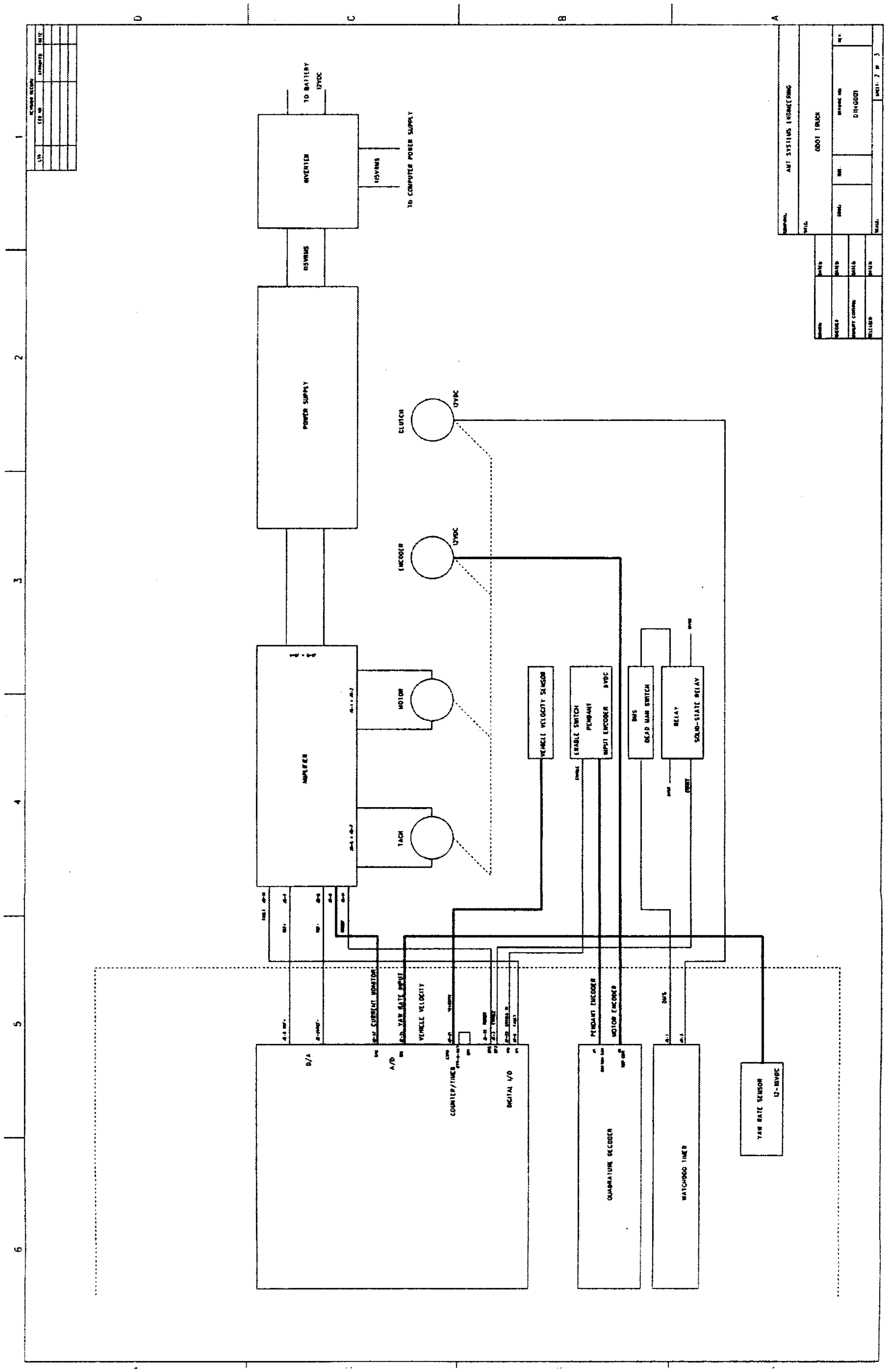

REVISIONS
ZONE
REV
DESCRIPTION
DATE
APPROVED
.03 X 45° CHAMFER
BOTH ENDS
2.500
.625 DIA
NOTES:
1. INTERPRET DRAWING PER DOD-STD-100.
2. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y.14.5.
3. REMOVE ALL BURRS AND SHARP EDGES.
304 SS
ES06-05
DRIVE SHAFT
ES06-05
C
SCALE 2/1
SHEET 1 OF 1

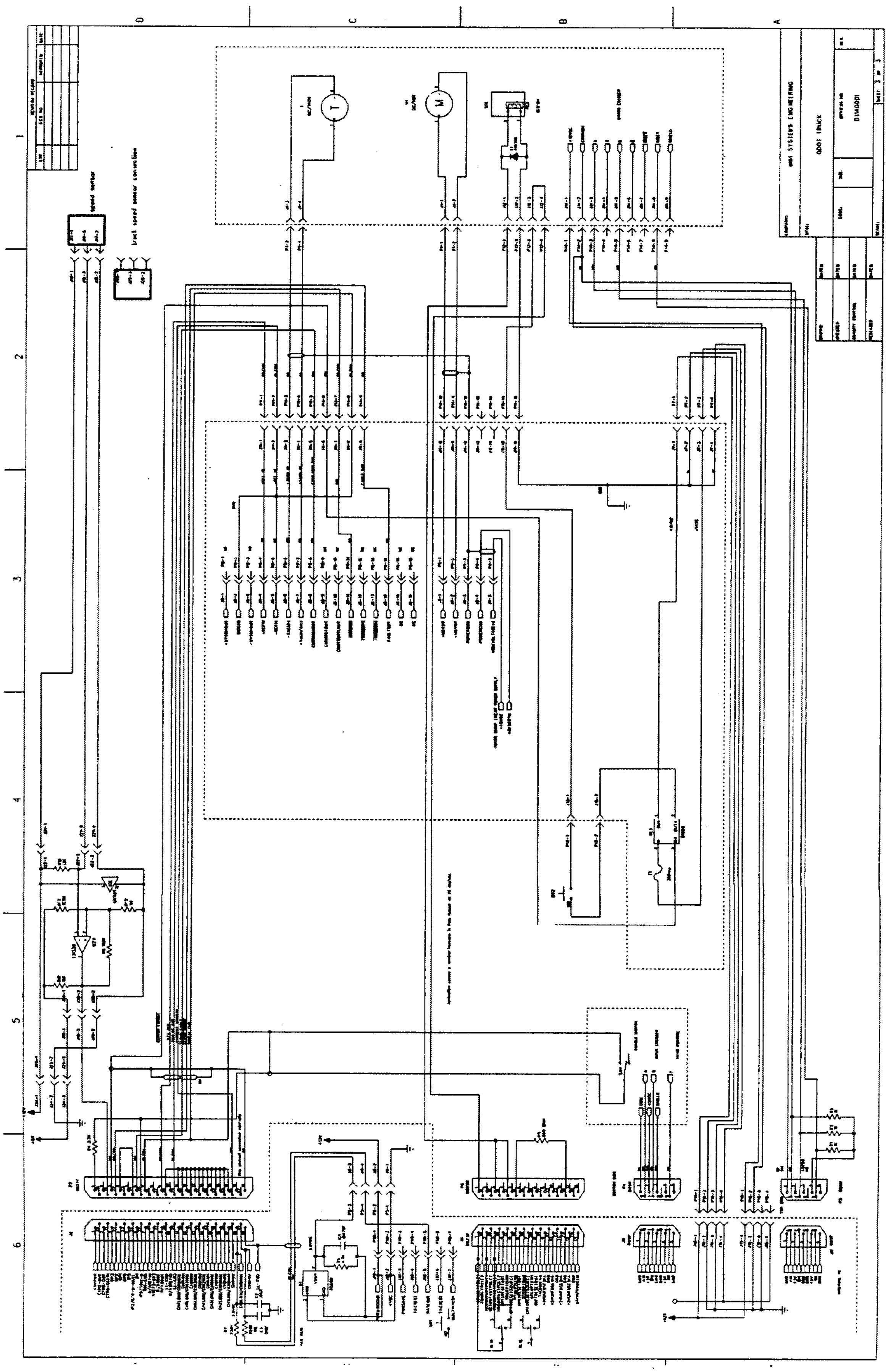

REVISIONS
ZONE
REV
DESCRIPTION
DATE
APPROVED
BERG YELLOW GEAR DRIVE BELT
P/N 16GBF-5FT
ALSO ORDER:
FIELD SPLICE KIT
16GBF-7
BELT LENGTH = 19.263
4.919
ACTUAL SPACING
4.790
CENTER TO CENTER SPACING
4.919
1.12
TWISTING OFFSET
3.000 PITCH DIA
NOTES:
1. INTERPRET DRAWING PER DOD-STD-100.
2. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y.14.5.
3. REMOVE ALL BURRS AND SHARP EDGES.
4. SPLICE BELT PER KIT INSTRUCTIONS AND SPECIFCATIONS IN THE FIELD OF THE DRAWING.
BERG
ES06-06
DRIVE BELT
ES06-06
95-02-21
DF


REVISIONS
ZONE REV DESCRIPTION DATE APPROVED
.750 DIA
.830
1.500
THIS DIMENSION TO BE VERIFIED PRIOR TO MAKING THIS PART
.3125-18 UNC-2B THREAD X 1/2 DEEP BOTH ENDS
NOTES:
1. INTERPRET DRAWING PER DOD-STD-100.
2. INTERPRET DIMENSIONS AND TOLERANCES PER ANSI Y.14.5.
3. REMOVE ALL BURRS AND SHARP EDGES.
STEEL
ES06-07
SPACER
SCALE 2/1
SHEET 1 OF 1

APPENDIX 2: Schematics of Control System and Wiring Harness


FRONT CAMERA
REAR CAMERA
VCR
CIGAR LIGHTER
CAMERA #1
CAMERA #2
12VDC
SVHS OUT
VIDEO MONITOR
NTSC
MULTIPLEXER
QUADRATURE
WATCHDOG TIMER
SER /PRT BOARD
VGA / NTSC
VGA BOARD
ANALOG I/O
REAR VIEW CPU
VGA-NTSC CARD
IDE HD
VGA CARD
3 1/2 FLOPPY
COMPUTER CHASSIS
ODOT TRUCK


TO BATTERY
12VDC
INVERTER
115VRMS
TO COMPUTER POWER SUPPLY
POWER SUPPLY
CLUTCH
ENCODER
AMPLIFIER
MOTOR
TACH
VEHICLE VELOCITY SENSOR
ENABLE SWITCH
PENDANT
INPUT ENCODER
DEAD MAN SWITCH
RELAY
SOLID-STATE RELAY
CURRENT MONITOR
YAW RATE INPUT
VEHICLE VELOCITY
PENDANT ENCODER
MOTOR ENCODER
D/A
A/D
COUNTER/TIMER
DIGITAL I/O
QUADRATURE DECODER
WATCHDOG TIMER
YAW RATE SENSOR
AVT SYSTEMS ENGINEERING
ODOT TRUCK



APPENDIX 3: Operating Instructions

START-UP PROCEDURE

1. Start the truck engine.
2. Turn on the inverter (in the external box behind the cab on driver's side).
3. Plug in the video power cord to the cigarette lighter socket.
4. Set the video selector switch for front camera (position "B" on switch box behind video monitor). Note: Position "A" selects the rear wheel camera.
5. Verify that the small three-position toggle switch on the video overlay board (at the back of the computer) is in the center position.
6. Turn on the computer power switch. Wait for the computer to boot. A plus-shaped cursor will appear on the video screen.
7. If you wish to videotape the rear camera image, operate the VCR as per its operating manual. The rear camera is connected to VCR's SVHS input, which must be selected during VCR setup.

OPERATING PROCEDURE

1. **Operator:** Toggle the enable switch on the operator control pendant and verify that it is in the OUT position.
2. **Driver:** Hold the dead-man switch depressed. Accelerate the vehicle to at least 10 MPH and steer normally until the edge line is visible on the video monitor.
3. **Operator:** Turn the control knob on the pendant to keep the cursor on the edge line. Depress the enable switch to enter sensor-assisted steering (SAS) mode. The cursor will change color if SAS mode is entered successfully. Tell the driver that you now have control.
4. **Driver:** Remove your hands from the steering wheel. ***You have primary responsibility for vehicle safety.*** Release the dead-man switch at any time to resume manual steering of the vehicle.
5. **Operator:** Keep the cursor on the edge line for the duration of the test. You can return to manual steer mode by toggling the enable switch to the OUT position. *Inform the driver before doing this!*

Note: You can re-enter SAS mode as many times as you want, but you must start over at Step #1 each time.

SHUT-DOWN PROCEDURE

1. Turn off the computer power switch.
2. Unplug the video power cord from the cigarette lighter socket.
3. Turn off the inverter.

Rev 5/28/97

APPENDIX 4: Photos of the Installed System

Photo of the servoactuator subsystem mounted to the steering column.

Photo of camera mounted to the front of the dump truck.

END OF DOCUMENT