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THE DEVELOPMENT OF A FIBER OPTICS COMMUNICATION NETWORK FOR CONTROLLING A MULTIDEGREE-OF-FREEDOM SERPENTINE TRUSS

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ABSTRACT

The problem addressed by this report is the large size and heavy weight of the cable bundle, used for controlling a Multidegree-Of-Freedom Serpentine Truss Manipulator arm, which imposes limitations on the manipulator arm maneuverability. This report covers a design of an optical fiber network to replace the existing copper wire network of the Serpentine Truss Manipulator. This report proposes a fiber network design which significantly reduces the bundle size into two phases. The first phase does not require any modifications for the manipulator architecture, while the other requires major modifications. Design philosophy, hardware details and schematic diagrams are presented.

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I. INTRODUCTION

The Serpentine Truss is an eight degrees of freedom (DOF) robot manipulator which is presently in the KSC Robotic Applications Development Laboratory. This truss is used as a development prototype. The problem addressed by this project is the large size and heavy weight of the cable bundle which imposes limitations on the manipulator arm maneuverability. This problem could be avoided by developing an optical-fiber communications link between the robot central controller, actuators and sensors. Optical-fibers are characterized with several advantages, some of them are the following:

- **Weight**

  Because of their small volume and lower density, optical-fiber cables enjoy considerable weight advantages over typical copper cables. Hence, optical-fibers will certainly reduce the weight and the size of the cable bundle of the present Serpentine Truss.

- **Immunity to Electromagnetic Interference**

  Since optical fibers are nonconducting, they will neither **generate** nor **receive** *electromagnetic interference* (EMI). The final Serpentine Truss is planned to operate in the vicinity of the Space Orbiter where electromagnetic emissions may be high or/and restricted. Therefore, a transmission system which neither generate nor receive electromagnetic interference is highly desirable.

- **Lack of Sparking**

  For special purpose applications that require transmission of information through hazardous places (such as The Space Orbiter Cargo Bay), fibers offer a potential advantage of not sparking in case of breakage in the transmission line.

- **Bandwidth**

  Optical-fibers are characterized with very wide bandwidth. Historically, bandwidth requirements for communications have shown increasing trend. The traditional way of meeting this requirement has been to increase the carrier frequency, as the information bandwidth is constrained to be, at most, equal to the carrier or some fraction of the carrier frequency. Hence, to meet the increase bandwidth demands, information carriers have transitioned from HF to VHF to UHF to microwave to millimeter waves and finally, to light waves. Wide bandwidth may not be crucial for the present prototype Serpentine Truss, but with the addition of more degrees of freedom (DOF), proximity sensors, and distributed controllers, the demand for a wider bandwidth is expected to increase.

- **Compatibility with Solid-State Sources**
  The physical dimensions of the fiber-optic sources, detectors, and connectors, as well as the fiber itself, are compatible with modern miniaturized electronics. Most components are available in dual in-line packaging (DIP packs), making mounting on a printed board extremely easy.
- **No Emission Licenses**
  Since fiber optics is a nonradiating means of information transfer, no special licenses are required to implement a network for controlling the Serpentine Truss.

Along with the several advantages of optical-fibers, come some potential disadvantages. These include **radiation darkening.** Optical glass darkens under the exposure to nuclear radiation. Although the specifics of the interaction depend on the dose rate and time history of the dose, as well as the type of radiation and the material dopants of the glass, optical-fibers are generally susceptible to interruption to nuclear radiation. Hence, precautions should be taken in similar situations.

II. PRESENT SYSTEM

The serpentine truss system has eight feedback loops six of them are to control six truss arm *servo systems*. Each servo system consists of a DC motor, fail-safe brake, a primary position sensor, and a secondary absolute position sensor. All DC motors are powered by pulse-width modulated (PWM) amplifiers located at the central control and processing unit. On the truss arm, the primary position sensor is a linear quadrature encoder. The secondary absolute position sensor is a linear film potentiometer.

Each servo system is connected to the central control and processing unit via a bundle of wire busses (sixteen wires per servo system). A detailed description for this bundle is as follows:

Device	Number of wires used
DC motor	2
Fail-safety brakes	2
Linear film potentiometer sensor	3
Linear quadrature encoder	9
Total	**16**

This bundle consists of two types of busses:

1. Power bus; the type of signal carried by this bus is a power signal. The following wires belong to this bus type:

   • two lines from the PWM amplifier in the central control and processing unit to the DC motor,

   • two lines from the DC output module (OPTO-22) to the DC motor,

   • two lines from *Power One* power supply to the linear film potentiometer sensor (± 10 V),

   • one line to analog input *Keithley DAS-15* from the linear film potentiometer sensor, and

   • two lines, from encoder input *Tech 80* board to *Futaba* linear quadrature encoder (+5 V and ground)

2. Timing bus; this bus is intended to carry timing information back from the *Futaba* linear quadrature encoder to the *Tech 80* encoder inputs at the central processing unit. Six wires out from the quadrature encoder are of the timing bus type (the rest are of the power bus type). The six wires consists of; three analog timing signals A, B, and Z and their compliments $\bar{A}$, $\bar{B}$, and $\bar{Z}$. Timing relationship between the three signals A, B, and Z, determines the direction and the relative location of displacement.

III. DESIGN PHILOSOPHY

Present Serpentine Truss moves data from sensors to the central control and processing unit using multiple wire lines (parallel bus). Parallel bus provides, fast data transfer and compatibility with most computer architecture. However, it is bulky, and it has low performance issues such as crosstalk, radio frequency interference (RFI), bit-to-bit skew and other concerns associated with multiple wire interfaces. Serial data links, although simpler and less costly, have not traditionally provided sufficient bandwidth to compete with the high data transfer rates of parallel links. Recent technological advances in optical fibers technology permit very high speed digital transmission over extended distances, at increasingly level of reliability of the connection. In order to maximize the benefits of the bandwidth made available by optical fiber technology, new high speed serial transmission links are being developed. These recent developments have altered the cost/performance trade-off between serial and parallel data transfer techniques.

The optimum and the best design is replacing all copper cables with one optical-fiber network. This requires major modifications of manipulator's architecture from centralized control architecture to distributed control architecture. The intention of this design is to reduce the cable bundle size and weight with the least possible modifications of manipulator's architecture. Network development process will be divided into two phases.

The first phase is to develop fiber serial links to replace all existing Timing Bus parallel wires coming out of the *Futaba* linear encoder. This should reduce the cable bundle size and weight by a factor of almost 30%. The second phase is to replace all other motor controls and sensing signals with another network similar to the one developed for the first phase. The size of the cable bundle of this phase is dominated by the size of the power bus which is directly proportional to the number of actuators. For the present manipulator, with 6 DOF in the arm, cable bundle size is expected not to exceed ~ 1 inch diameter instead of present ~ 3 inch diameter bundle.

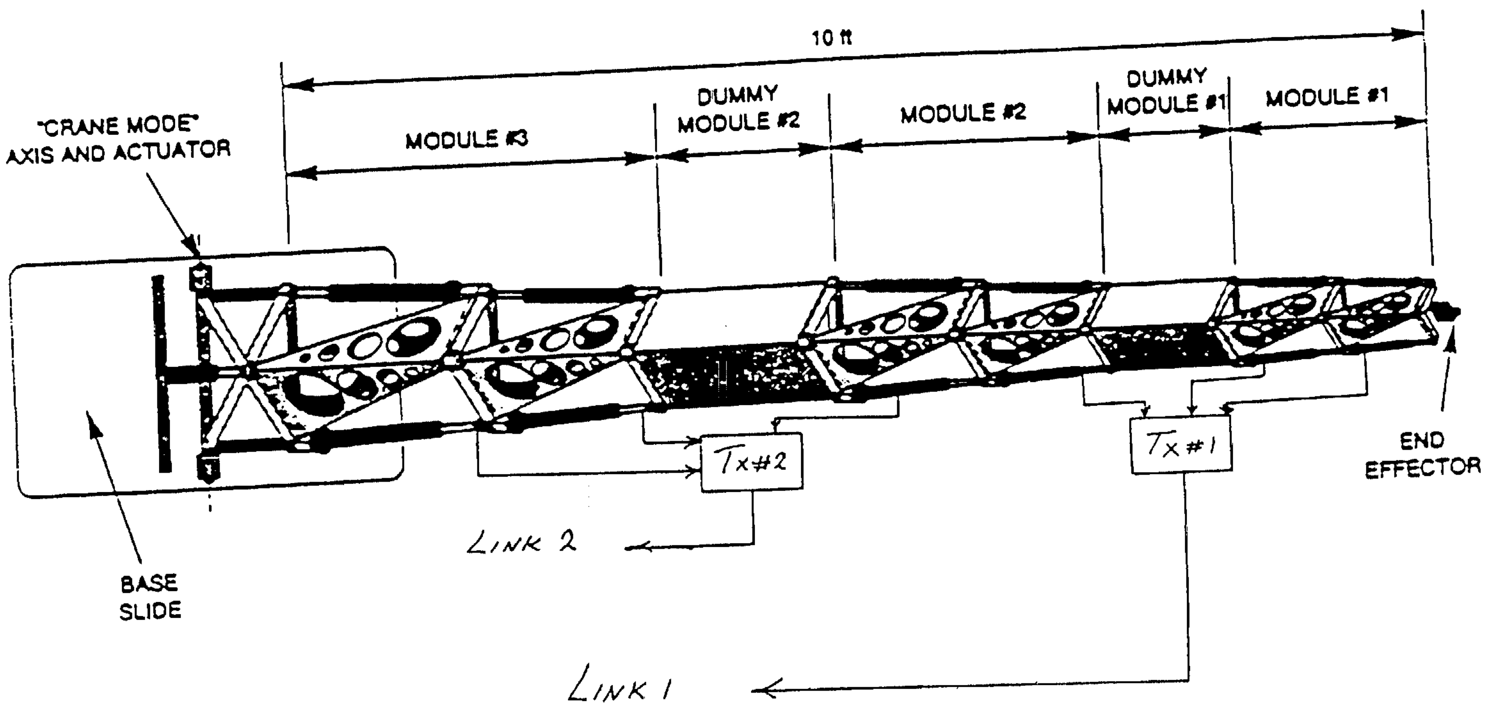


Figure 1: Serpentine Truss with phase 1 fiber links

IV. DESIGN DETAILS

The proposed optical fiber design is divided into two phases; the first phase do not require any modifications to the Truss architecture while the second phase requires major modifications of the Truss.

a. Phase I:

This phase is to replace Timing Bus parallel wires, between the *Futaba* linear encoder and the quadrature encoder board *Tech 80*, with two optical-fiber links.

The quadrature encoder board *Tech 80* accepts quadrature signals in a single-ended mode as well as differential mode. Therefore, the three signals A, B, and Z are sent in a single-ended mode format rather than differential mode format. These are sufficient to completely decode displacement parameters. These three signals are sampled, at the quadrature encoder board *Tech 80*, with a frequency of 0.625 MHz. Three timing signals are multiplexed (each consists of three analog signals A, B, and Z, generated by the *Futaba* quadrature encoder) and transmitted to the central control and processing unit over a digital optical-fiber link. The digital link is transparent, that is to say, the analog signal is over sampled with a rate six times (exactly 6.4x) greater than the sampling rate of the quadrature encoder board.

The link uses a point-to-point configuration using HP FOXIchip™ set (Fiber Optic Xmitter – Receiver Interface with TAXI™). The DLT6000-ST FOXIchip Transmitter and DLR6000-ST Receiver chipset is a general purpose interface for very high-speed interface (up to 12.5 Mbytes/sec) point-to-point communications over fiber-optic make. They include the necessary data handling, timing and control functions together with the optical transducers. The link is unidirectional: a parallel word is sent one end and recovered at the other end. For each point-to-point direction a pair of FOXIs and a separate fiber are required.

(i) *Transmitter:*

The DLT6000-ST data link transmitter provides a high performance transparent fiber optic interface. The DLT6000-ST converts parallel TTL data into serial lightwaves in the 1.3 μm band. When used in conjunction with the complementary DLR6000-ST, in point to point applications, data transfer rates are up to 12.5 Mbytes/sec with minimum power budget of 6 dB. Both, the FOXI parallel interface inputs and the *Futaba* linear quadrature encoder outputs are TTL compatible. Data to be transmitted is latched in the transmitter, encoded, serialized, converted into light, and sent over the fiber.

In the FOXI sense, *"Data"* means a group of 8, 9, or 10 bits (depending on the "*data mode selector*". Another group, called *"Command"*, has 4, 3, or 2 bits, correspondingly. The mode used in this design is 9 *Data* + 3 *Command* mode, accordingly, *"Data Mode Select"* input is connected to V_{cc}.

Present Serpentine Truss arm has six *Futaba* quadrature encoders. Three analog signals A, B, and Z, generated by each encoder, are transmitted, to the central control and processing unit , for a total of 18 signals. Hence, two FOXI links are needed to handle all quadrature encoder signals. Figure 1 illustrates an approximate position for the two transmitters mounted on the two dummy modules. The first FOXI transmitter chip (Tx#1), mounted on dummy module #1, is connected via copper wires to Box1A, Box1B, and Box2A. A block diagram for the Tx#1 is shown in Figure 2a. Pin 17, 16, and 15 are connected to Ch A, Ch B, and Ch Z of Box2A; pin 23, 24, and 25 to Box1B; and pin 26, 27, and 28 to Box1A. The second FOXI transmitter chip (Tx#2), mounted on dummy module #1, is connected via copper wires to Box2B, Box3A, and Box3B. Tx#2 is identical to Tx#1. A block diagram for the Tx#2 is shown in Figure 2b. Pin 17, 16, and 15 are connected to Ch A, Ch B, and Ch Z of Box2B; pin 23, 24, and 25 to Box3A; and pin 26, 27, and 28 to Box3B. In addition to the two fiber links, a +5 V power bus is needed to distribute power to the *Futaba* encoders and the FOXI transmitters.

Detailed schematics for TX#1 and TX#2 are shown in Figure 3a and Figure 3b respectively. For DLT6000 Transmitters, DMS (Data Mode Select) determines the data pattern width. When it is wired to V_{CC}, the DLT600 will assume Data to be nine bits wide, with three bits of command. In this mode, transmitters use one 5B/6B encoder and one 4B/5B encoder to decode nine data bits into an 11-bit pattern. Only Data bits are used and command pins are not connected. TLS (Test Local Select) should always be grounded during normal operation, and CLK output should be always connected to STRB (strobe) input. Furthermore, X1 and X2 are connected to a crystal oscillator with a frequency of 4 MHz, this frequency is FOXI's minimum operating frequency.

(ii) Receiver:

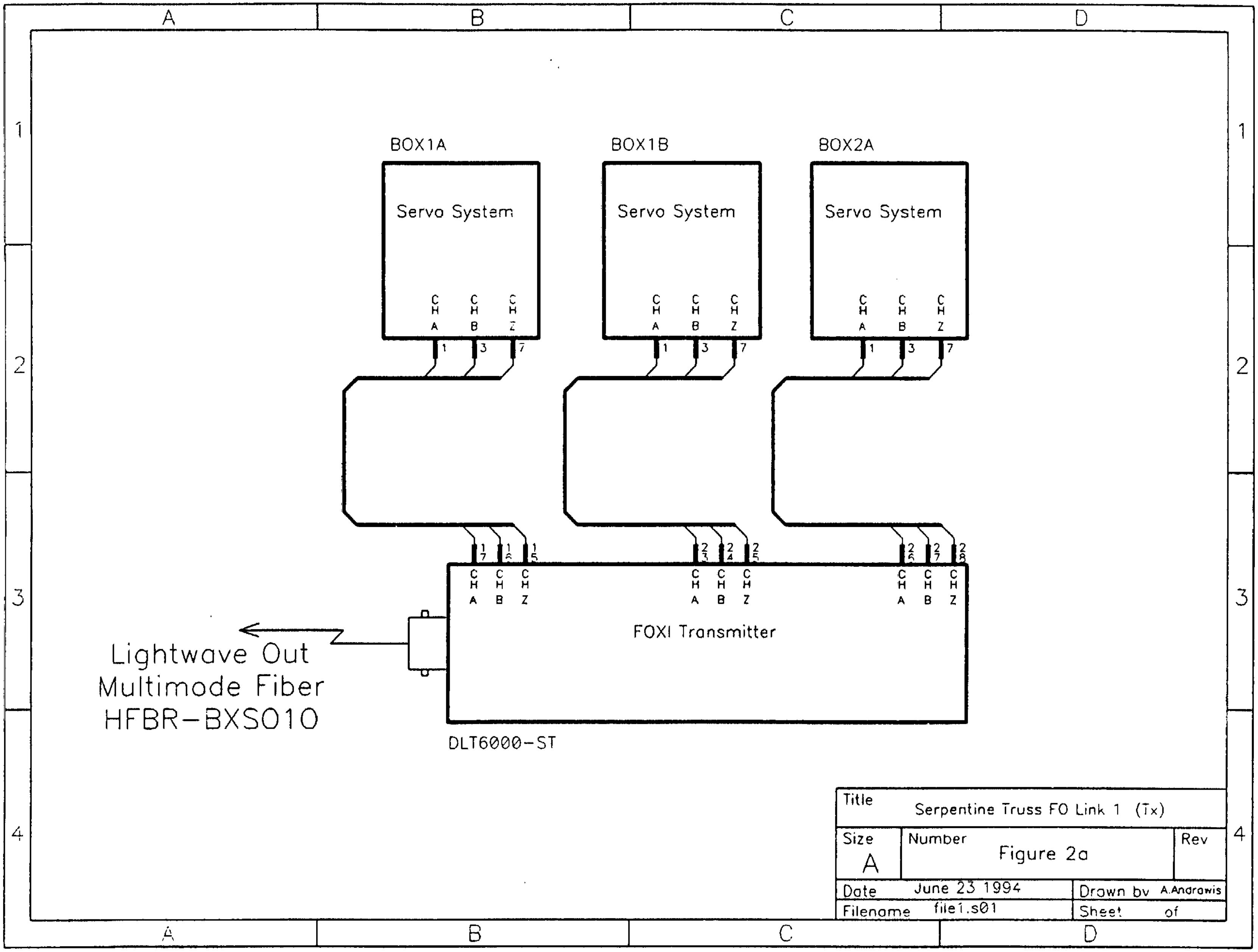
At the receiver end, the serial string of optical symbols is converted into electrical signal, deserialized, decoded and clocked out as parallel words.

Two DLR6000-ST FOXI receivers located in the control rack feed position sensing signals to *Tech 80* encoder inputs. Figure 4a and Figure 4b illustrates block diagrams for the Serpentine Truss Fiber Optic Network Rx1 and Rx2 respectively.

The network features both error detection and error correction capabilities. The capability of detecting simple errors is built in the chip, while correcting errors is done externally.

The receiver logic detects the most common types of transmission errors. It detects these errors by completely decoding the incoming data patterns, and recognizes several types of violations. The rising edge of VLTN (Violation) output signals that a transmission error has been detected. Consequently, SN74116 latches ignore the erroneous word and the previous word is considered valid for one more clock cycle. Meanwhile, the LED connected to the SN74121 Monostable Multivibrator blinks for a duration of one second. If the error rate is bigger than $\sim 2\text{x}10^{-8}$, then the LED will remain on continuously.

LED blinking rate is not a measure of the end-to-end link error rate, but it is a good indication about the condition of the fiber optic part of the link. Only six consecutive violations causes an end-to-end error. In normal operating conditions, the probability of six consecutive violations is negligible.


BOX1A
BOX1B
BOX2A
Servo System
Servo System
Servo System
CH A
CH B
CH Z
FOXI Transmitter
DLT6000-ST
Lightwave Out
Multimode Fiber
HFBR-BXSO10
Title
Serpentine Truss FO Link 1 (Tx)
Size
A
Number
Figure 2a
Rev
Date
June 23 1994
Drawn by
A.Androwis
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file1.s01
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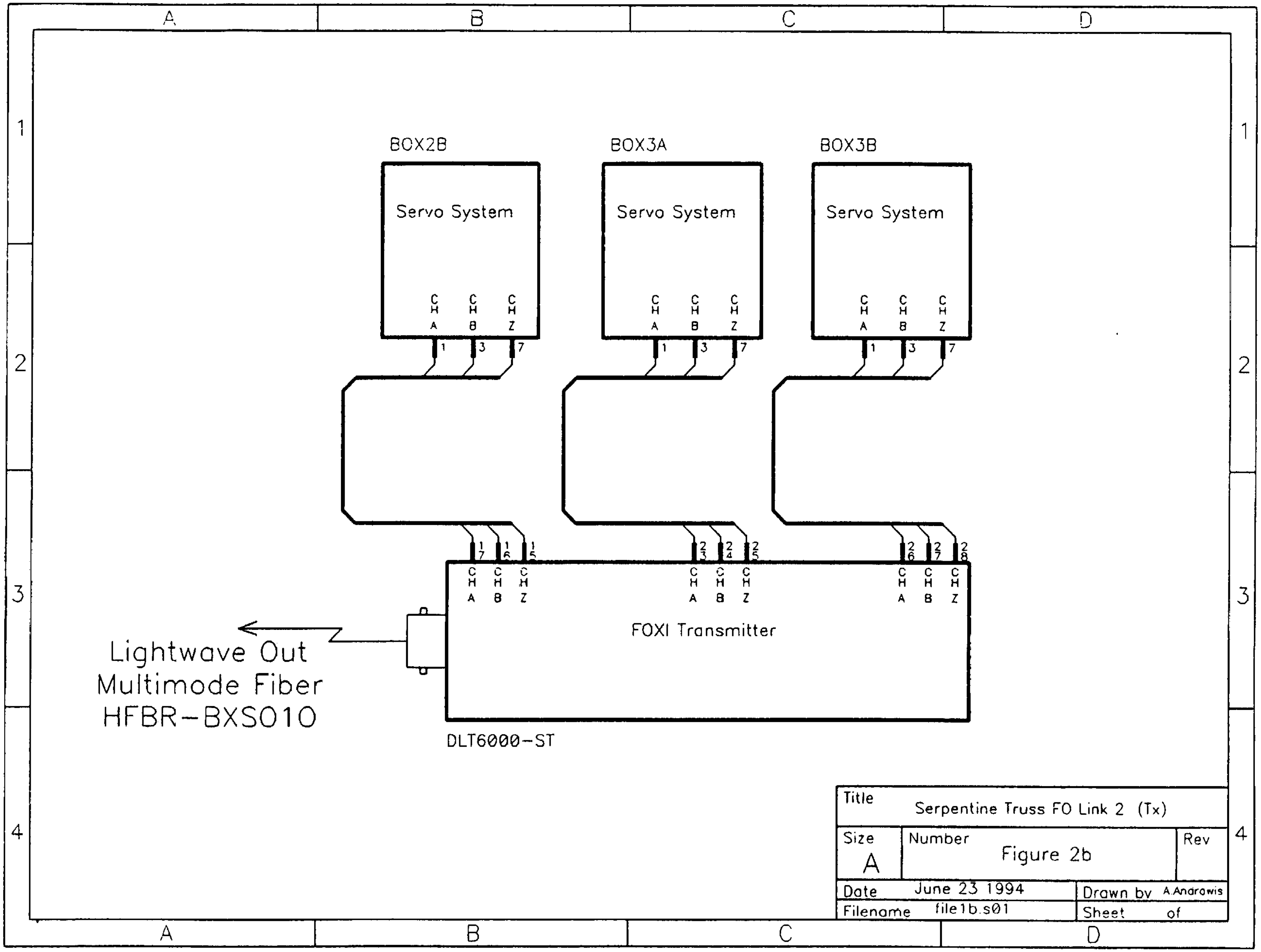
of


A
B
C
D
1
2
3
4
BOX2B
BOX3A
BOX3B
Servo System
Servo System
Servo System
CH A
CH B
CH Z
1
3
7
17
16
15
23
24
25
26
27
28
FOXI Transmitter
Lightwave Out
Multimode Fiber
HFBR-BXS010
DLT6000-ST
Title
Serpentine Truss FO Link 2 (Tx)
Size
A
Number
Figure 2b
Rev
Date
June 23 1994
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A.Androwis
Filename
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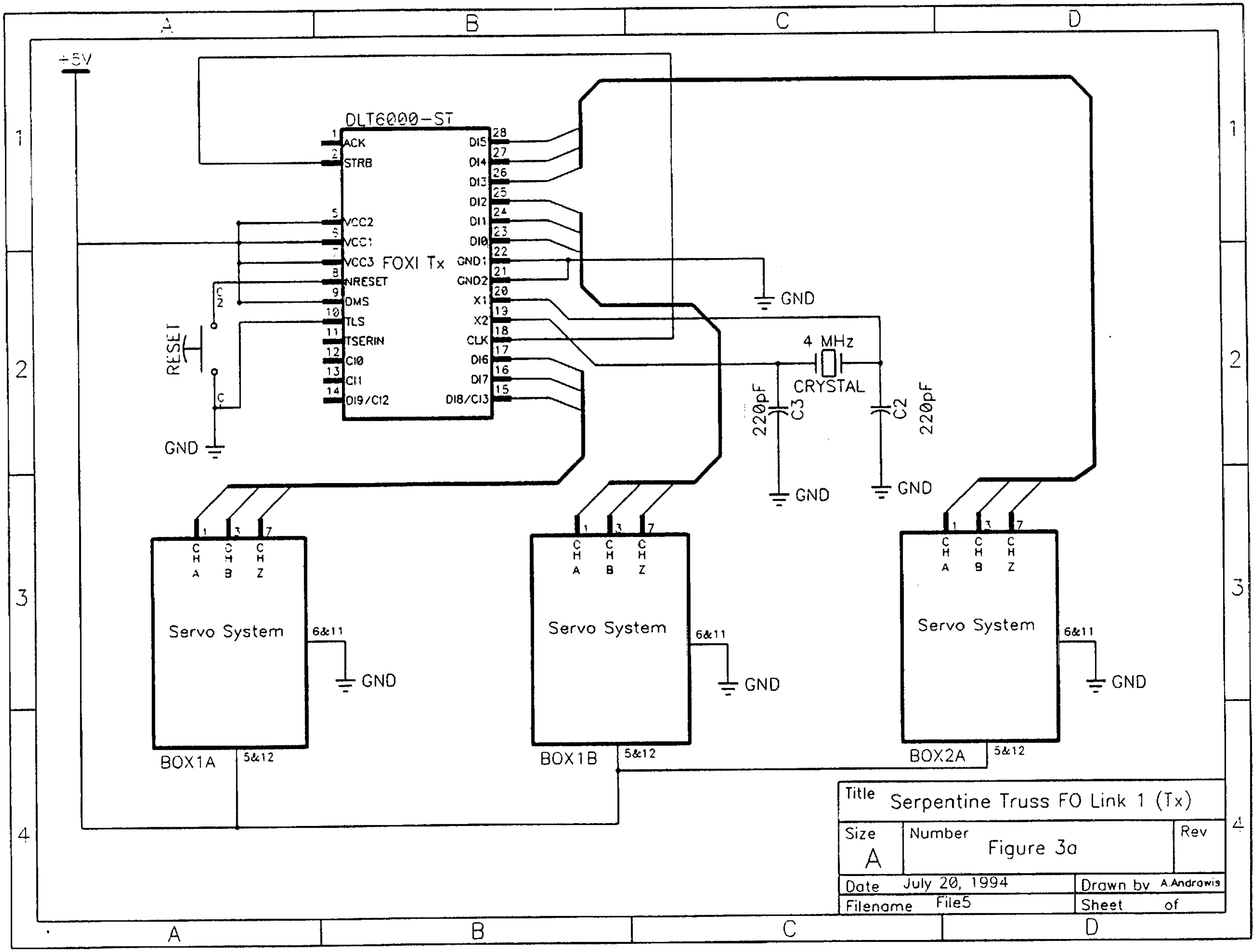
Sheet
of


+5V
DLT6000-ST
FOXI Tx
ACK
STRB
VCC2
VCC1
VCC3
NRESET
DMS
TLS
TSERIN
CI0
CI1
DI9/CI2
DI5
DI4
DI3
DI2
DI1
DI0
GND1
GND2
X1
X2
CLK
DI6
DI7
DI8/CI3
RESET
GND
4 MHz
CRYSTAL
220pF
C3
C2
220pF
Servo System
CH A
CH B
CH Z
6&11
5&12
BOX1A
BOX1B
BOX2A
Title Serpentine Truss FO Link 1 (Tx)
Size A
Number Figure 3a
Rev
Date July 20, 1994
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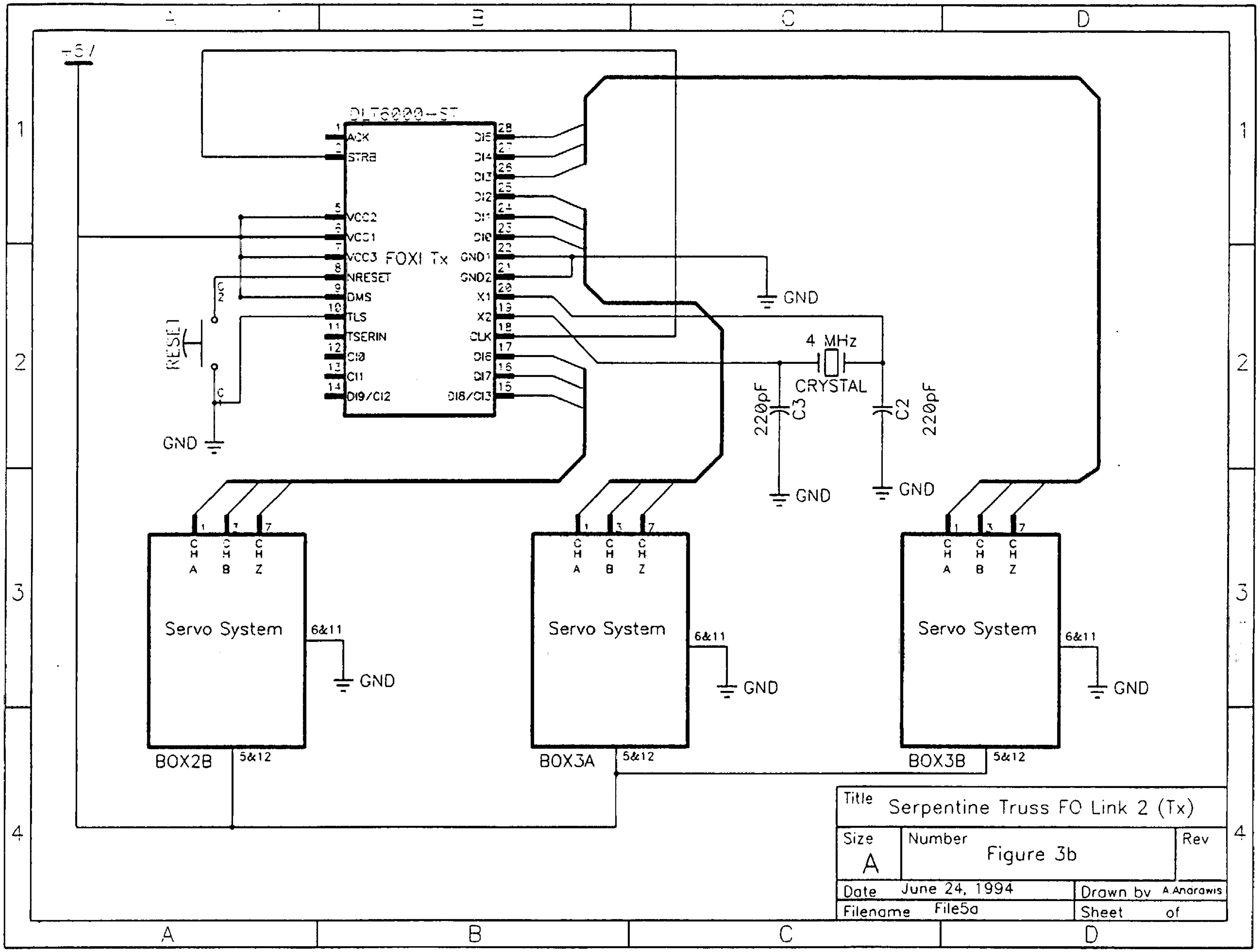
+5V
DLT6000-ST
FOXI Tx
ACK
STRB
VCC2
VCC1
VCC3
NRESET
DMS
TLS
TSERIN
CI0
CI1
DI9/CI2
DI5
DI4
DI3
DI2
DI1
DI0
GND1
GND2
X1
X2
CLK
DI6
DI7
DI8/CI3
RESET
GND
4 MHz
CRYSTAL
220pF
C3
C2
220pF
Servo System
6&11
BOX2B
5&12
BOX3A
BOX3B
Title
Serpentine Truss FO Link 2 (Tx)
Size
A
Number
Figure 3b
Rev
Date June 24, 1994
Drawn by A.Anarawis
Filename File5a
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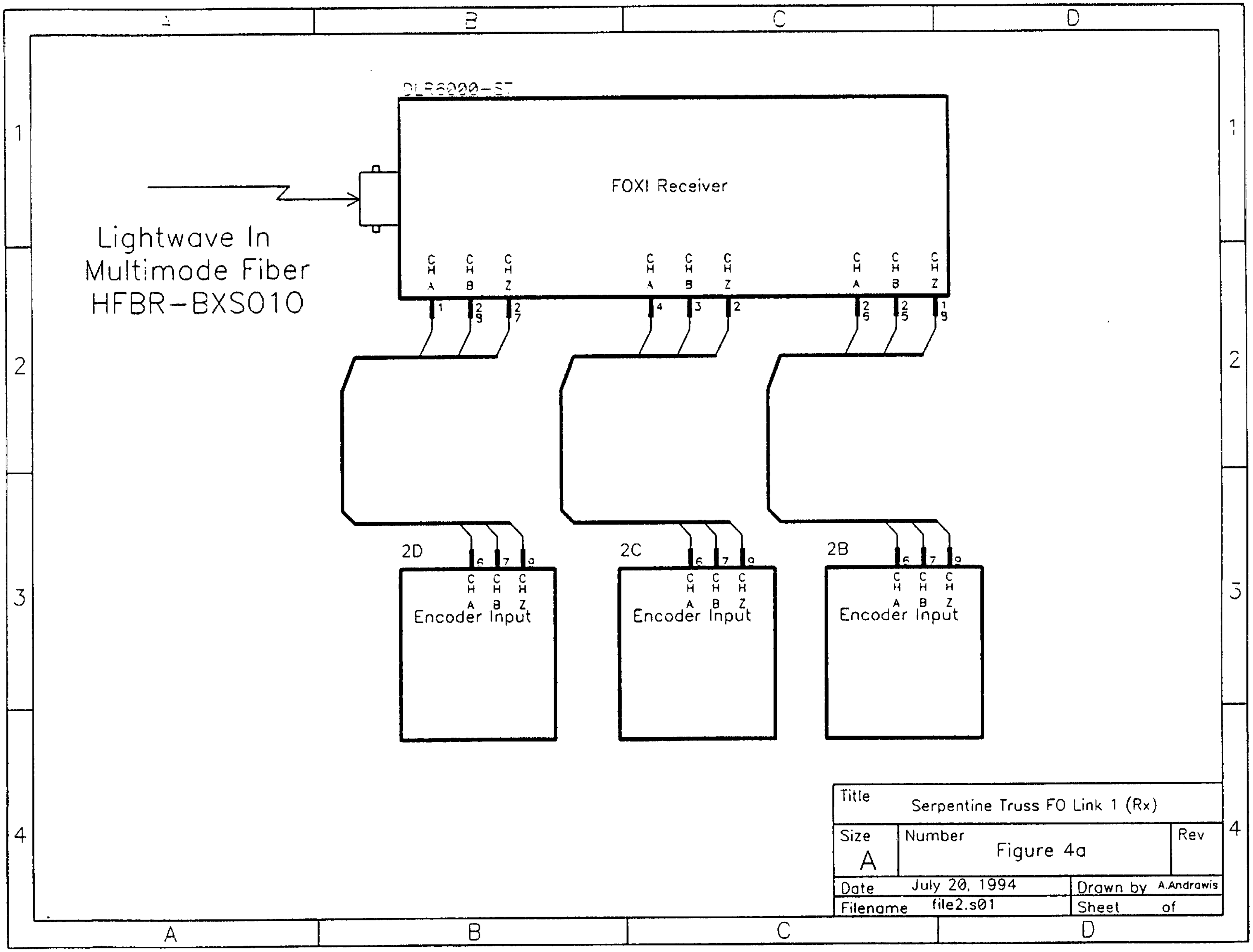

FOXI Receiver
Lightwave In
Multimode Fiber
HFBR-BXS010
CH A
CH B
CH Z
2D
2C
2B
Encoder Input
Encoder Input
Encoder Input
Title Serpentine Truss FO Link 1 (Rx)
Size A
Number Figure 4a
Rev
Date July 20, 1994
Drawn by A.Andrawis
Filename file2.s01
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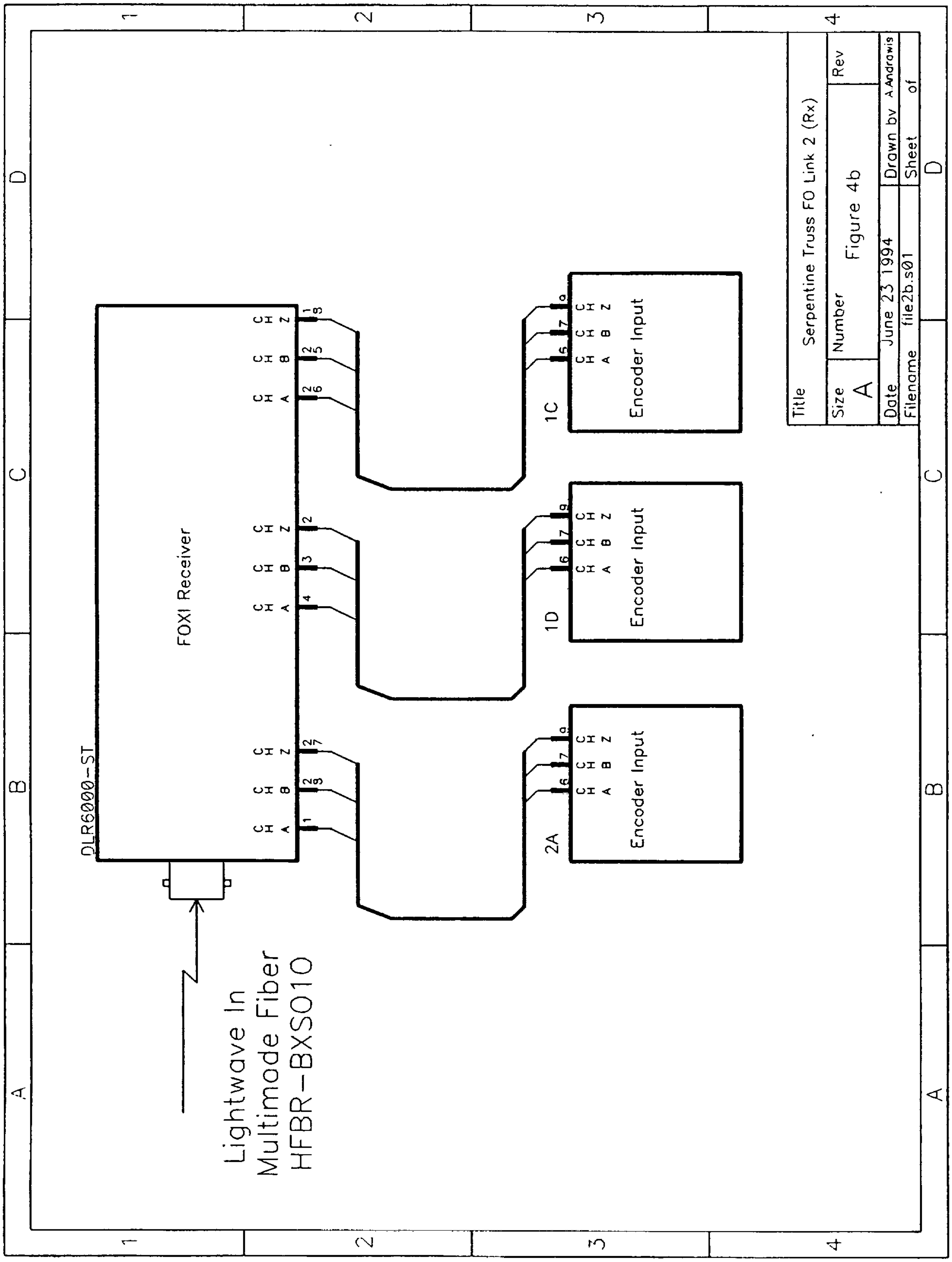
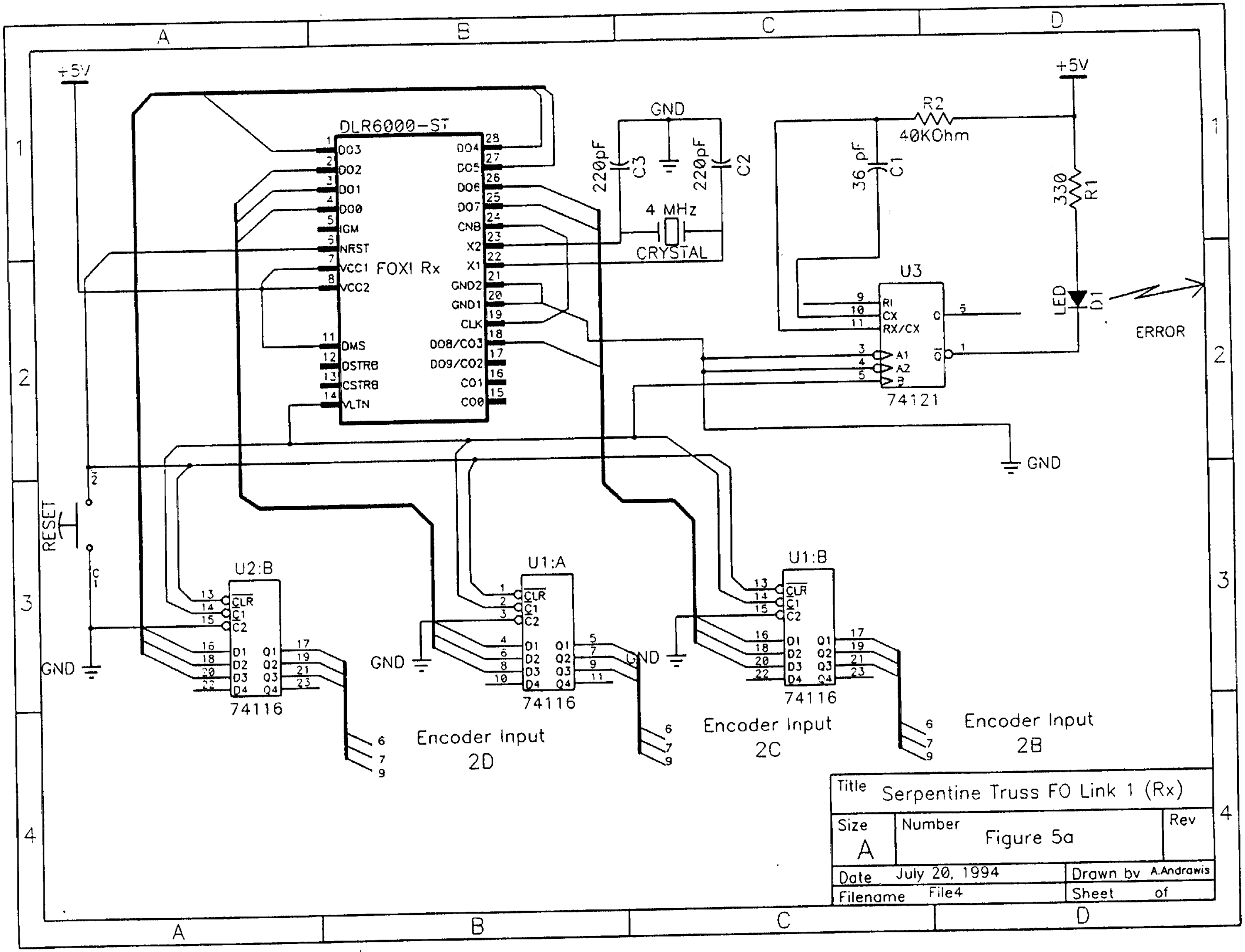


Title
Serpentine Truss FO Link 2 (Rx)
Size
A
Number
Figure 4b
Rev
Date
June 23 1994
Drawn by
A.Andrawis
Filename
file2b.s01
Sheet
of
DLR6000-ST
FOXI Receiver
CH A
CH B
CH Z
Encoder Input
1C
1D
2A
Lightwave In
Multimode Fiber
HFBR-BXS010


A B C D
1 2 3 4
+5V
DLR6000-ST
FOXI Rx
DO3 DO2 DO1 DO0 IGM NRST VCC1 VCC2 DMS DSTRB CSTRB VLTN
DO4 DO5 DO6 DO7 CNB X2 X1 GND2 GND1 CLK DO8/CO3 DO9/CO2 CO1 CO0
GND
220pF C3
220pF C2
4 MHz
CRYSTAL
R2
40KOhm
36 pF C1
330 R1
LED D1
ERROR
U3
RI CX RX/CX A1 A2 B Q
74121
GND
RESET
U2:B
U1:A
U1:B
CLR C1 C2 D1 D2 D3 D4 Q1 Q2 Q3 Q4
74116
74116
74116
Encoder Input
2D
Encoder Input
2C
Encoder Input
2B
Title Serpentine Truss FO Link 1 (Rx)
Size A
Number Figure 5a
Rev
Date July 20, 1994
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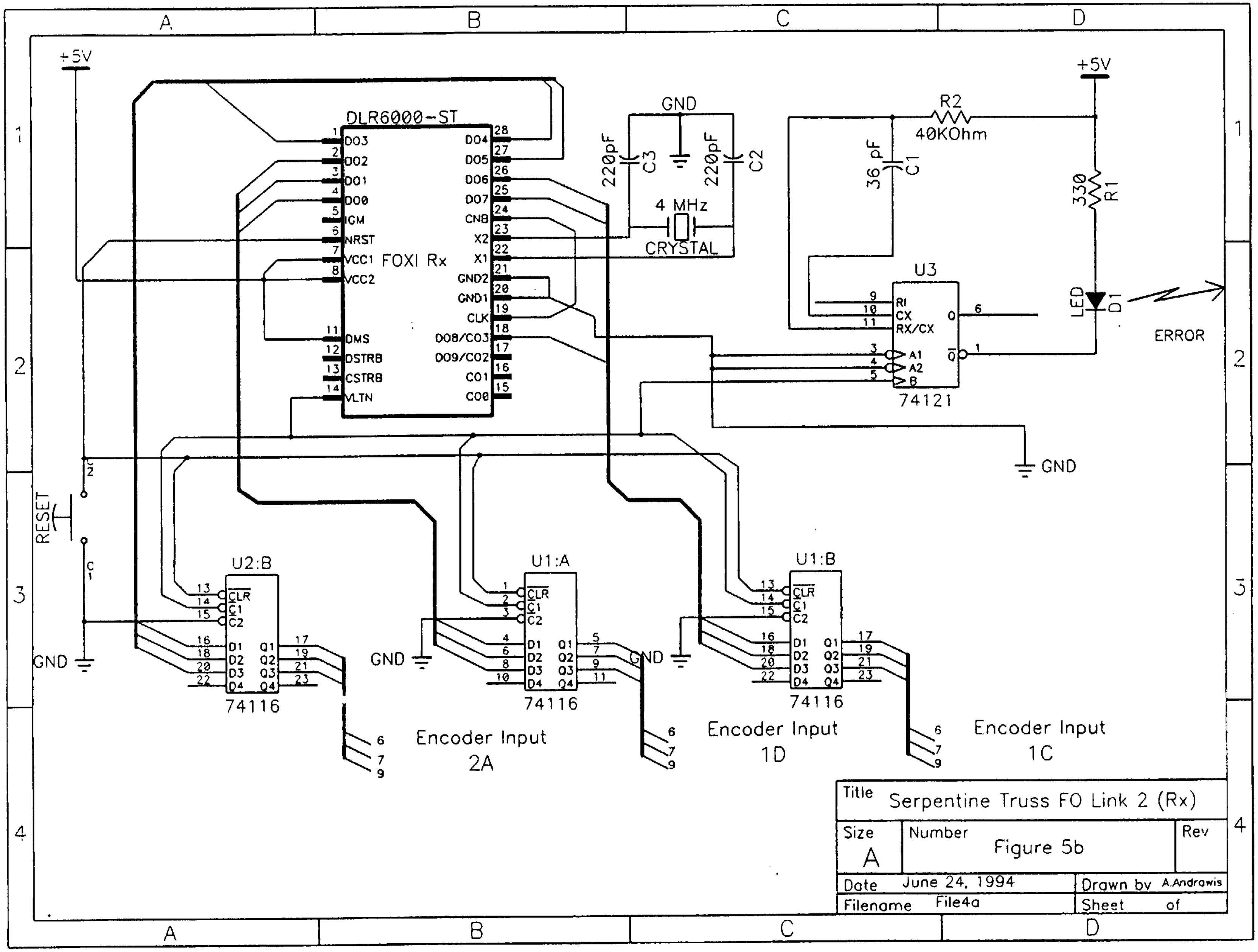
DLR6000-ST
FOXI Rx
DO3
DO2
DO1
DO0
IGM
NRST
VCC1
VCC2
DMS
DSTRB
CSTRB
VLTN
DO4
DO5
DO6
DO7
CNB
X2
X1
GND2
GND1
CLK
DO8/CO3
DO9/CO2
CO1
CO0
+5V
GND
220pF
C3
C2
4 MHz
CRYSTAL
R2
40KOhm
36 pF
C1
330
R1
LED
D1
ERROR
U3
RI
CX
RX/CX
A1
A2
B
74121
RESET
U2:B
U1:A
U1:B
CLR
C1
C2
D1
D2
D3
D4
Q1
Q2
Q3
Q4
74116
Encoder Input
2A
Encoder Input
1D
Encoder Input
1C
Title Serpentine Truss FO Link 2 (Rx)
Size A
Number Figure 5b
Rev
Date June 24, 1994
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Filename File4a
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FOXI parallel interface outputs and *Tech 80* quadrature encoder board inputs are TTL compatible. Both are connected to SN74116 latches as shown in Figure 5a and Figure 5b. Similar to the transmitter, the DMS pin is connected to V_{cc} for the data to be nine bits wide. CLK is a free-running clock output which runs at the byte rate, and is synchronous with the serial data input. When the CLK output is connected to the CNB (Catch Next Byte) input, the receiver operates in the local mode, and each byte is captured, decoded and latched to the output.

b. Phase II:

As mentioned earlier, present Serpentine Truss architecture is a centralized control and processing (industrial-grade 386DX PC with passive backplane). This design requires the transmission of power signals (from the central control and processing unit to actuators) which can not be transmitted through fiber. Phase I of this design report, requires no major design modifications to be implemented. On the contrary, the second phase requires major design modifications for the Serpentine Truss. Considering potential NASA applications at the Kennedy Space Center, the Advanced Systems Section is interested to increase the truss' degrees of freedom (DOF) from 8 to 18. Moreover, the Truss architecture is to be changed to distributed control configuration instead of being a central control configuration. The central processing and control unit in the new upgraded truss acts as a mater computer, while distributed controllers act as slave computers. To achieve the required upgrade, the following has to be implemented;

- Ball Drive Linear Actuators:

  An extra 10 degrees of freedom has to be added to the existing Serpentine Truss Manipulator Arm. Reference to Figure 1, the Serpentine Truss Manipulator Arm consists of five modules, three active modules, and two dummy modules. Each active module consists of two boxes, Box A and Box B. Each box is equipped with two Linear Ball Drive Actuators, one is active while the other is passive. Activating the passive actuators will add six degrees of freedom to the truss. Replacing the two dummy modules with two active boxes adds an additional four degrees of freedom. Only four Ball Drive Linear Actuators are in need to activate the two dummy modules.

- Linear Variable Differential Transformers (LVDTs):
  The Truss is equipped with six *Futaba* linear encoders, an extra 10 units are needed. Since *Futaba's* encoders are bulky and expensive they are to be replaced with Lucus LVDTs. Therefore, a total of sixteen LVDTs is required for the new added DOF and to replace existing *Futaba* encoders and potentiometers.
- DC Servo Amplifiers:
  These amplifiers are to provide DC power to the Ball Drive Linear Actuators.
- Microcontroller Boards (Slave Computers):
  These boards should be able to; convert the analog DC voltage level output from the LVDT to at least 12-bit digital word (12-bit A/D); execute instructions given by the Master Computer; provide PWM signal and direction signal to the servo control.

Table 1 estimates cost of materials and labor needed to upgrade Existing Serpentine Truss from 8 DOF to 18 DOF.

The optical fiber network consists of two directions; from the master computer to the slave computer and visa-versa. Optical fiber links developed for phase 1 will be integrated in network upgrade of phase 2. Exact network configuration depends on the microcontroller chip used for distributed control units. Material and labor cost needed for the development of a fiber optics communication network for controlling the upgraded multidegree-of-freedom Serpentine Truss is included in Table 2. A complete vendor list, along with contact persons, is attached in Appendix A.

TABLE 1

Serpentine Truss
Distributed Control and 18 DOF Upgrade

Materials:

• Ball Screw Actuators	
MOTION Ball Drive Actuator 85261 (2 pcs)	$ 550.00
MOTION Ball Drive Actuator 85199 (2 pcs)	$ 500.00
• LUCAS CONTROL SYSTEMS	
Linear Variable Differential Transformers (LVDTs)	
Coil Assembly and Core	
DC-E-2000 (4 pcs)	$ 1664.00
DC-E-3000 (12 PCS)	$ 5736.00
Rods (242 inches)	$ 363.00
• Cannibalize existing MOTION 85151 actuators to parallel mount, and Reinstall Ball Screws to reduce backlash of all existing MOTION actuators by ~50%	$ 400.00
• Copley 422 PWM Amplifier (16 pcs)	$ 4640.00
• AMDEX Industrial Computer Passiveboard CPU 80-5866	$ 3595.00
Total	$17448.00

Development and Labor:

• Development of the Motor Control Boards, 120 hrs@$40/hr	$ 4800.00
• Expansion of control program, 320 hrs@$40/hr	$12800.00
• Technician Laboratory Work, 400 hrs@$40/hr	$ 16000.00
Total	$33600.00

TABLE 2
Serpentine Truss
Fiber Optic Upgrade

Materials:

• HP DLT6000-ST Transmitter (10 pcs)	$ 2060.00
• HP DLR6000-ST Receiver (10 pcs)	$ 2240.00
• FUTABA PC2455 Female Connectors (6 pcs)	$ 150.00
• Amphenol 953-101-5010 ST multimode connector (20 pcs)	$ 121.00
• Spec-TRAN G1-62.5-A04RB-500 Fiber cable (60 meters)	$ 120.00
Total	$ 4691.00

Development and Labor:

• Technician Laboratory Work, 320 hrs@$40/hr	$12800.00

The following example design [Ref. Advanced Micro Systems publication 17490A] multiplexes 32-bit data words using one DLT6000-ST Transmitter. This design can easily be applicable to systems with wider or narrower data paths with or without command. If we assuming that the microcontroller used has 16 bits wide asynchronous output port, then this example design can serve two distributed control units, i.e. one FOXI Transmitter/Receiver pair is needed for each box. Implementation of the 32-bit multiplexed Transmitter circuit is shown in Figure 6. In addition to the DLT600-ST Transmitter, the following parts are required:

- 74LS00 quadruple 2-input positive NAND gates
- 74LS04 hex inverters
- 74LS20 dual 4-input positive NAND gates
- 74LS174 hex D-type flip-flops
- Am29C821 tri-state registers

The design can be optimized to save board space by fitting it into PAL16R6 device or equivalent.

Figure 7 illustrates the basic concepts involved in demultiplexing data from the FOXI receiver. The particular example design demultiplexes four bytes of data and commands into one 32-bit word

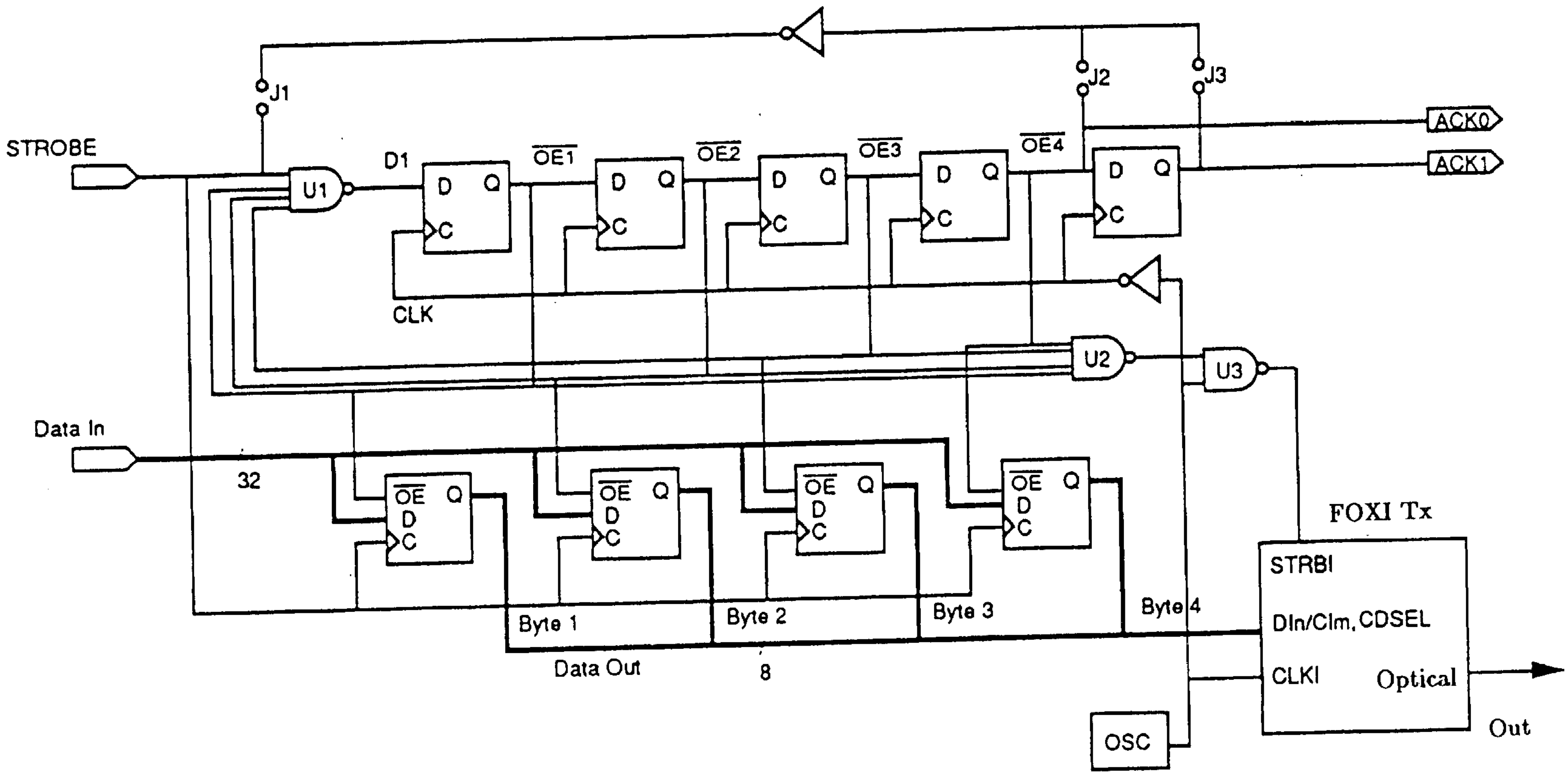

Figure 6: Logic Diagram of 32-Bit Multiplexed Transmitter

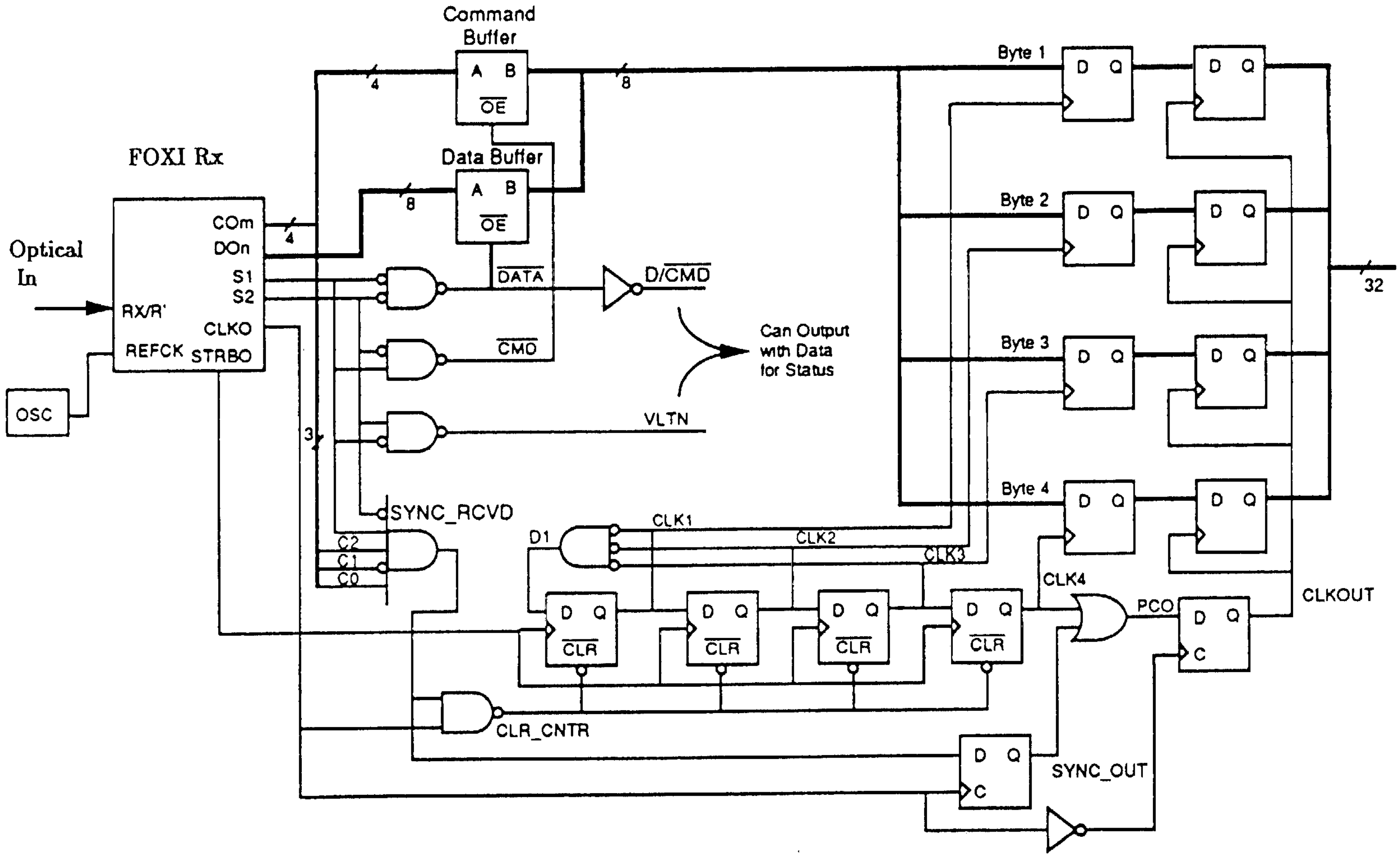

Figure 7: Logic Diagram of 32-Bit Demultiplexed Receiver

APPENDIX A

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