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IN-74 69478

NASA CASE NO.: MSC-21806-1

PRINT FIG: 5

p-26

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Serial Number: 07/780,513

Date Filed: October 22, 1991

JSC

(NASA-Case-MSC-21806-1) CLOSED-LOOP MOTOR CONTROL USING HIGH-SPEED FIBER OPTICS Patent Application (NASA) 26 p CSCL 20F

N92-17863

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MSC-21806-1
Serial No. 07/780,513
Filed: 10/22/91

AWARDS ABSTRACT

MSC-21806-1

CLOSED-LOOP MOTOR CONTROL USING HIGH-SPEED FIBER OPTICS

This invention relates to electrical control systems for controlling electrical devices from a remote station and, more particularly, to a closed-loop system wherein a servo controller sends control signals to an electrically controllable device via a high-speed fiber optic link which is immune to electromagnetic interference and received feedback signals from a sensor associated with the controlled device.

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Employer: Lockheed

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CLOSED-LOOP MOTOR CONTROL USING HIGH-SPEED FIBER OPTICS

Origin of the Invention

The invention described herein was made in the performance of work under a NASA contract and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958, Public Law 85-568 (72 Stat. 435; 42 U.S.C. 2457).

Field of the Invention

This invention relates to electrical control systems for controlling electrical devices from a remote station and, more particularly, to a closed-loop control system wherein a servo controller sends control signals to an electrically controllable device via a high-speed fiber optic link which is immune to electromagnetic interference and receives feedback signals from a sensor associated with the controlled device over the same fiber optic link.

Background of the Invention

Electrical controller systems of both analog and digital types can be characterized as having either a centralized control architecture or a distributed control architecture. In a centralized control architecture, the controllers and computers of the system are connected to a high-performance bus with a wide communications bandwidth which allows cooperative interactions among the controllers as may be necessary for coordinated control of multi-axis systems, such as robotic arms and hands. The centralized control architecture requires at least four signal wires, usually of long lengths and low signal power, for connecting the controller and the power electronics for the controlled devices. For many applications these signal lines may have to be routed through an environment polluted with interfering electromagnetic radiation, frequently referred to as EMI, which leads to problems associated with signal "noise". In some instances, where the signal lines carry high-frequency pulse-width-modulation current, they often become a source of EMI themselves. Furthermore, the number of wires required and their relatively long lengths may pose a difficult packaging problem.

In a distributed control architecture, the controllers for the system and the power electronics for the actuating motors for the controlled devices are located close to the motors such that the connecting wires are kept to a minimum and are of relatively short lengths. Since parallel, high-performance busses cannot be used in this approach because they would require too many lengthy wires, a low bandwidth bus, typically a serial bus for a formatted data stream, is used for communications between the controllers. However, because of its electrical nature the low bandwidth bus is highly susceptible to electronic "noise" or EMI which affects the control system with undesirable performance characteristics such as imprecise and sluggish responses, "shaky" movements and "overshoot".

It has also been known to use fiber optics as a communications link in electrical control systems such as shown in U.S. Patents 4,596,049; 4,819,273; and 4,916,689. None employ a fiber optic link which closes the control loop of a closed-loop motor controller.

Summary of the Invention

The invention is a closed-loop control system for controlling the operation of one or more servo motors or other controllable devices. A servo controller at a remote station sends control signals to the motors or other controllable devices at a local station over a fiber optics link which is immune to electromagnetic interference and receives information feedback signals over the same link. At the remote station the electrical control signals are converted to a formatted serial bit stream, time-multiplexed and converted to light signal for transmission over a single fiber of the fiber optics link. At the local station, the optical signals are received and reconstructed as electrical control signals which are coupled to the power electronics for driving the motors or other devices. At the local station an encoder sensor linked to the motor or driven device generates encoded feedback signals which provide information as to a condition of the controlled device. The encoded signals are placed in a formatted serial bit stream, multiplexed, and transmitted as optical signals over a second fiber of the fiber optic link which closes the control loop of the motor controller. The encoded optical signals which are received at the remote station are demultiplexed, reconstructed and coupled to the controller(s) as electrical feedback signals.

Brief Description of the Drawings

FIG. 1 is a functional schematic diagram of a motor control system with a centralized digital controller as is typical of prior art control systems;

FIG. 2 is a functional schematic diagram of another prior art motor control system with centralized digital controller but wherein the power electronics are located near the controller;

FIG. 3 is a schematic diagram of a preferred embodiment of a closed-loop motor control system in accordance with the invention;

FIG. 4 is a schematic diagram of an embodiment of the invention applied in a multi-motor system;

FIG. 5 is a schematic diagram of a further embodiment of the invention applied in a control system which includes a combination of motor and sensor subsystems and sensor systems with digital interfaces;

FIG. 6 is a schematic illustration of an electrical control system for a robot and showing the location of motors and electrical subsystems which are potential sources for electromagnetic interference;

FIG. 7 is a schematic diagram of a motor control system with a centralized control architecture which is typical of the prior art wherein the computational elements are at a centralized location, relative to a plurality of remotely distributed motor subsystems;

FIG. 8 is a schematic diagram of a motor control system with a distributed control architecture also representative of prior art systems wherein decentralized computational elements are located proximate the controlled electrical devices;

FIG. 9 is an electrical schematic of the invention showing the association of major components of the invention in an application for controlling a robotic mechanical arm;

FIG. 10 is a system block diagram of a motion-control processor for use with a DC servo motor and designed in accordance with the invention;

FIG. 11 is an illustration of a typical information packet formatted in a serial bit stream by a transmitter chip in a fiber optic link component of the invention for transmission to a receiver included in the fiber optic link;

FIG. 12 is an electronic schematic of a transmitter of the high-speed fiber optic link of the invention; and

FIG. 13 is an electronic schematic of a receiver of the high-speed fiber optic link of the invention.

Detailed Description of the Invention

Schematic illustrations of motor-control systems which are representative of the prior art are shown in FIGS. 1 and 2. In the design approaches depicted therein, the systems 10 and 11, respectively, each incorporates a centralized architecture with the digital motor controller 12 located at a centralized remote location. In the design of FIG. 1, the controller 11 is coupled to the power electronics 15 which drive the servo motor 17 by means of four signal lines - one of which carries pulse-width-modulation signals, another which carries signal direction information, and the remaining two of which, designated as channels A and B, carry encoded feedback information signals from an encoder sensor 18. The power and buffer electronics 15 are located at a proximity location near the servo motor 17 to which they may be connected by relatively short wires. However, the signal transmission lines which connect the digital controller 12 at the remote location to the power electronics may be of relatively great lengths and therefore are most susceptible to EMI noise and its debilitating effect.

A specific application for which a prior art motor-control system as shown in FIG. 1 presents serious performance limitations is in a robotic system such as the human-like robot 20 of FIG. 6. In the robot 20, the computer controllers 21 are located in the central torso area and direct the control of the shoulder motors 22, the elbow motors 23 and hand motors 24. For each motor, communication with the computer controllers 21 requires four wires which, because they are long and carry low-power signals, are highly susceptible to EMI as may be generated by the wires themselves or other electrical subsystems 25 typically located in the torso between the shoulders of the robot. In addition, the bulkiness of the wires may impede the flexural mobility of the robot joints.

In FIG. 7, the centralized control architecture of FIG. 1 is shown in a motor control system 30 for controlling a plurality of motor subsystems. In the control system 30, a plurality of digital controllers 112, one for each motor subsystem, reside on a high performance bus 32 and communicate with each other across the bus. Each controller 112 on the bus 32 serves as a digital filter that compensates for any instabilities in its own motor subsystem. The digital filter may take the form of a proportional-integral-derivative (PID) loop with programmable gains or a Z- transform function with programmable coefficients. The controller 112 need not be a specialized integrated circuit processor but may be a general purpose digital computer adapted to execute the control loop in software.

A second design approach which also uses centralized control architecture in a motor control system is represented by the system 11 illustrated schematically in FIG. 2. The system 11 is similar to the system 10 of FIG. 1 but the power and buffer electronics are located near the digital controller 12 at the remote station. As in system 10, there are four wires which connect the power electronics to a servo motor. Two of these wires carry high-frequency PWM motor current such that they may become an EMI source themselves and therefore radiate and induce electrical noise in other systems.

A third design approach in the prior art relies on a distributed control architecture wherein the controller and the power electronics are placed close to the motor. Accordingly, the wires between the controller and the power electronics and the wires between the power electronics and the motor can be made very short. A control system 35 which incorporates a distributed control system architecture and decentralized computational elements, such as digital controllers 112A, each connected locally to an associated motor subsystem, is shown schematically in FIG. 8. A low bandwidth bus 37, such as a twisted pair RS-232 link is used for communications between the controllers since a high performance bus would require too many lengthy wires. A central computer 38 at a remote station is also connected for two way communication with the bus 37. Because a serial communications link is used, the communication bandwidth between the controllers is drastically reduced.

In the control system 35, comparatively more electronics must be packaged locally near the motors. Furthermore, because of its electrical nature, the low bandwidth bus is susceptible to the undesirable effects of EMI. If communications between the controllers 112A is sparse, the system 35 may provide adequate performance. However, it does not generally deliver the required performance for coordinated control of a multi-motor system.

A motor control system designed to overcome many of the problems associated with the prior art control systems is shown in the schematic block diagram of FIG. 3, which illustrates an embodiment of the invention. As shown in FIG. 3, a closed-loop control system 40 comprising a digital motor controller 41 at a remote location controls by low power digital electrical signals the operation of a DC servo motor 42 which is located at a station in close proximity to the device to be controlled. In the closed-loop control system 40, the digital controller 41 generates control signals which are converted to serial bit streams of time-multiplexed signals and sent to the motor 42 through a high-speed fiber optic link 44. The controller 41 receives position feedback signals over the same fiber optic link from an encoder sensor 45 which senses and indicates the condition of the controlled device such as the motor 42. The link 44 is a duplex fiber optic link connecting a precision digital motor controller 41 to a motor driver semiconductor which is part of the power and buffer electronics 46 installed at the proximity location to regulate the current through the motor.

As shown in FIG. 3, there are four signal lines which communicate between the digital motor controller 41 and the power and buffer electronics 46 by means of the bi-directional fiber optic link 44. The lines 51 and 52 between the controller 41 and the bi-directional optic link 44 and corresponding lines 51A,52A between the link 44 and power electronics 46 communicate a direction information signal, + or -, and a pulse-width-modulation signal over one fiber of the fiber optic link 44. Two other signal lines, 53A,54A, designated respectively as channels A and B, carry encoded information from the encoder 45 to a second fiber of the fiber optic link 44 and by lines 53 to 54 convey this information from the link 44 to the controller 41.

A modified form of the control system of the invention represented by the closed-loop control system 48, shown in FIG. 4, is a modified form of the control system 40 of FIG. 3 and is adapted to provide motor control for a plurality of servo motors 42. In the two systems 40 and 48, like components are similarly numbered. It is to be appreciated, however, that each motor 42 to be controlled by the system 48 is provided with its own power and buffer electronics and its own set of signal lines, such as lines 51B - 53B. A fiber optic link 44, immune to EMI noise, carries the control signals between the digital controllers and the motor and return feedback signals from the encoder to the digital controllers.

In FIG. 5, there is shown still another embodiment of the invention in a form of closed-loop control system 55 adapted to control sensor subsystems 56 with digital interfaces 57 or a combination of motor and sensor subsystems. Where analog sensors are employed the digital interface can be provided by an analog-to-digital converter. For ease of illustration, components corresponding with like components in the systems of FIGS. 3 and 4 are similarly numbered. It is to be noted in FIG. 5 that each sensor subsystem 56 is provided with its own signal lines for a digital interface with the fiber optic link 44.

A motor controller chip particularly suited for use in the invention is the LM628 integrated circuit of the National Semiconductor Corporation which is a processor designed for use with a variety of DC and brushless DC servo motors, and other servomechanisms which provide a quadrature incremental position feedback signal. A servo system which utilizes the LM628 processor is illustrated schematically in FIG. 10. The system includes an LM628 motion controller processor 60 which executes proportional-integral-derivative (P.D.) algorithms with programmable gains. Among other required components for the servo system is a digital-to-analog converter 61 with an input terminal coupled to an output port of the processor 60. The output of the converter 61 is coupled to a power amplifier 62 which, through a communications link 65 such as the duplex fiber optic link of the present invention, connects with a DC servo motor 66 for actuating the device or apparatus to be controlled. An incremental encoder 67 with sensor for indicating a condition of the motor 66 is connected to the motor 66 by a mechanical link 68 and by signal channels to a communications link 65A with the processor 60. Preferably, links 65 and 65A are two fibers of the same communications link.

The motion-control processor 60 has two interfaces: a host-computer interface and a motor control interface. The host-computer interface 71 is a host control software interface which connects the processor 60 to a host-computer bus and provides the means for host-programming of the controller chip. The interface 71 consists of address/data lines and read/write control lines.

The processor 60 also comprises a command position sequencer 73 and a position feedback processor 75, the outputs of which are coupled to the inputs of a summing comparator 76 which supplies a signal to a PID digital filter 78 with an output 79 as the processor output.

The motor control interface is provided by the signal lines which couple the output signals for sign (or phase) and magnitude (or PWM) of the processor 60 to the power electronics 69 for driving the motor 66. The motor control interface also includes the signal channels A and B which carry feedback information signals from the encoder 67 to the processor 60. The sign and magnitude signals control the direction and amount of current flowing through the motor 66 and the channels A,B carry quadrature encoder feedback signals which are used to determine motor shaft positions.

Since the motion-control processor 60 may be located at a station remote from the servo motor 66, a communications connection using long electrical conductors would be highly susceptible to EMI. In the present invention, such wiring is replaced by a full-duplex fiber optic link as shown schematically in FIGS. 12 and 13. The link consists of two identical circuit boards, one providing the interface with the controller processor, such as the processor 60, and the other providing the interface with the power electronics for the servo motor. The interfaces between the fiber optic link and the devices with which it connects are in functionally parallel relation because the fiber optic link is adapted for a very high through-put rate of 175 MHz. The link is therefore able to replicate bit-patterns of a 32- bit parallel port from one end of the link to the other at a rate of approximately once every 230 nanoseconds.

The heart of the fiber optic link is a two piece chip set called TAXI- chips by the manufacturer, Advanced Micro Devices, Inc. Two such chips, one of which is the transmitter chip and the other the receiver chip are shown in FIGS. 12 and 13 as mounted on respective transmitter and receive circuit boards 81,82. In operation, the transmitter chip converts an 8- bit wide parallel bit- pattern into a serial bit stream and sends it out to the fiber optic cable 85 which constitutes a communications channel between the transmitter and receiver. The receiver then decodes the serial stream and reconstructs the 8- bit pattern at the receiving end.

The transmitter board is provided with a 34 pin connector 86 adapted to receive data input signals such as control signals from the digital controller. A buffer 88 for temporary storage of data is provided by four integrated circuits 89, which in the illustrated embodiments of the invention are 74HC374 chips. The buffered signals are then delivered to a programmable logic sequencer 90 which is used to expand the width of the pattern transmitted from 8 bits to 32 bits and to time-multiplex the signals. The sequencer output is delivered to a parallel-to-serial converter 91 which converts each date input signal to a serial stream in information packets formatted as shown in FIG. 11 wherein 256 bits constitute a packet. The sequencer 90, coupled to and controlled by an oscillator 92, provides for error-checking by appropriately inserting sync-bytes into the serial stream.

The serial output of the parallel-to-serial converter 91 is then delivered to an electrical-to-optical converter 93 which converts the electrical signals to light signals and by means of connection with the fiber optic cable 85 communicates the light signals to a receiver located at a station proximate the servo motor and the motor-controlled device.

The through-put of the fiber optic link is switch selectable from 66.6% to 99.8%, depending on the frequency of sync-bytes transmitted. It can be computed using the formula:

through-put = 32L/[8(sync byte + command byte)]+32

where L is the number of information packets sent before each sync byte and command byte sent in the cycle.

At the receiver, the fiber optic cable is connected to an optical-to-electrical converter 95 which converts the light signals to electrical signals and couples the electrical signals to a serial-to-parallel converter 96. The output of the serial-to-parallel converter 96 is coupled to a sequencer and formatter 97 which de-multiplexes and finishes the reconstruction of the received signals to the form in which they were first delivered to the input terminals of the transmitter. The reconstructed signals from the sequencer and formatter 97 are delivered to a buffer 98, the output terminals of which are coupled to a 34 pin connector 99. The buffer 98 is comprised of four integrated circuits 100 which in the preferred embodiment of the invention, are 74HC374 chips. Also, in the preferred embodiment of the invention the electrical-to-optical converter 95 is a DLR1000 chip, the serial-to-parallel converter 96 is a AM7969 (RX) chip, and the sequencer formatter 97 is a 5C031 chip.

It is to be noted that the transmitter and receiver of the fiber optic link as described above, are at opposite ends of the fiber optic cable 85 and are but one of two such combinations required such that if the transmitter is at a remote location accessible to the digital motor controller, the receiver is located at a local station in proximity to the servo motor and the motor-controlled device. The receiver outputs at the connector 99 are then connectable to the power electronics, which typically includes drivers for the servo motors of the controlled device.

An identical transmitter - receiver combination is also provided for communicating encoded feedback signals over channels A and B as shown in FIG. 3. The feedback signals are transmitted by a transmitter at the proximity location over the fiber optic cable to a receiver at the remote station which delivers its output to the digital controller, such as the processor 60 in the servo system of FIG. 10.

A closed-loop motor control system 100 representing an embodiment of the invention is shown schematically in FIG. 9 which illustrates the major components of the control system. The control system 100, which is shown in an application for controlling an articulated mechanical arm 102, comprises a terminal board 104 for a 32 line connector which is adapted to receive input control signals from a plurality of digital controllers (not shown). The control signals are coupled to a communications bus 106 which conveys the input signals to a transmitter 108, such as the transmitter of FIG. 12, at a remote station where they are formatted in a serial bit stream, converted to optical signals, and transmitted over a fiber optic link 44 to the receiver 110, such as the receiver of FIG. 13, at a local station. At the receiver 110, the optical signals are converted to electrical signals and reconstructed to their original form. The reconstructed signals are coupled to a 32 line output terminal board 112 with connections to the semiconductor drivers or other power electronics 114 which drive the several motors 116, 117, 118 for articulation of the mechanical arm 102 and its fingers 121. For each of the articulation motors, an associated encoder sensor (not shown) generates and encodes feedback information signals which provide information as to motor condition. The encoded signals are coupled through the connector 112 to a transmitter 120 at the local station for transmission as optical signals over the fiber optic link to a receiver 122 at the remote station. The transmitter-receiver pair 120,122 may be identical to the transmitter-receiver pair 108,110. From the receiver 122, the encoded feedback signals are coupled to the digital controllers connecting to the connector 104.

It is to be appreciated that in the present invention, as contrasted with controllers of the prior art, the fiber-optic link is used to close the control loop between the power electronics and the controller, rather than used as a data communication channel between the controllers which does not solve the problem of having to package the controller circuit components locally.

It is also to be noted that the invention described herein may be used to control devices other than motors. For example, the fiber optic link can be used in a system for controlling devices such as ON - OFF switches, pneumatic valves or stepper motors. The invention is also adapted to receive feedback signals from sensors other than digital encoders, such as from potentiometers or differential transformers. Furthermore, if the control signals or the feedback signals are in analog form, they may easily be converted to a digital format using an analog-to-digital converter and also reconverted using a digital-to-analog connector.

Since light is not affected by electromagnetic interference, the use of fiber optics communications links where the signal carrier is light confers significant EMI-immunity to the controller of the invention.

This EMI-immunity property of the invention allows the controller to be remotely located without concern about signal corruption. All the controllers can therefore be centrally located on a high-performance parallel data bus.

Further, since light is the signal carrier and optical fiber is the transmission medium, there is no electrical resistance or capacitance to produce propagation delay. Therefore, the transmission frequency is boosted significantly to provide a wide bandwidth, which means that in a closed-loop control system the invention can be used to achieve a high sampling rate as is necessary for fast system response.

Also, the wide bandwidth capability of the invention allows multiple channels of signals to be multiplexed onto the same fiber optic link. This allows a great reduction of wires, as opposed to the large number of wires required by prior art controllers. The invention has a full duplex (bi-directional) fiber optic link, where only two fibers are required. These two fibers are capable of carrying signals for simultaneous control of several motors. As an example the invention is capable of simultaneously controlling 16 DC servo motors with incremental encoder feedback whereas to achieve the same task with a prior art controller would require 64 electrical wires.

A particularly appropriate application for the invention is in the field of robotics systems because it allows the digital servo control loop to be closed around an EMI-immune fiber optic link whereby the digital controllers/computers can be centralized while the power electronics can be distributed. In conventional robotics systems, aside from their susceptibility to electromagnetic interference, bulky route-through wiring is required which creates flexural resistance to a degree that can make accurate robot limb-positioning and movement to be difficult. The present invention can reduce such problems by a significant factor.

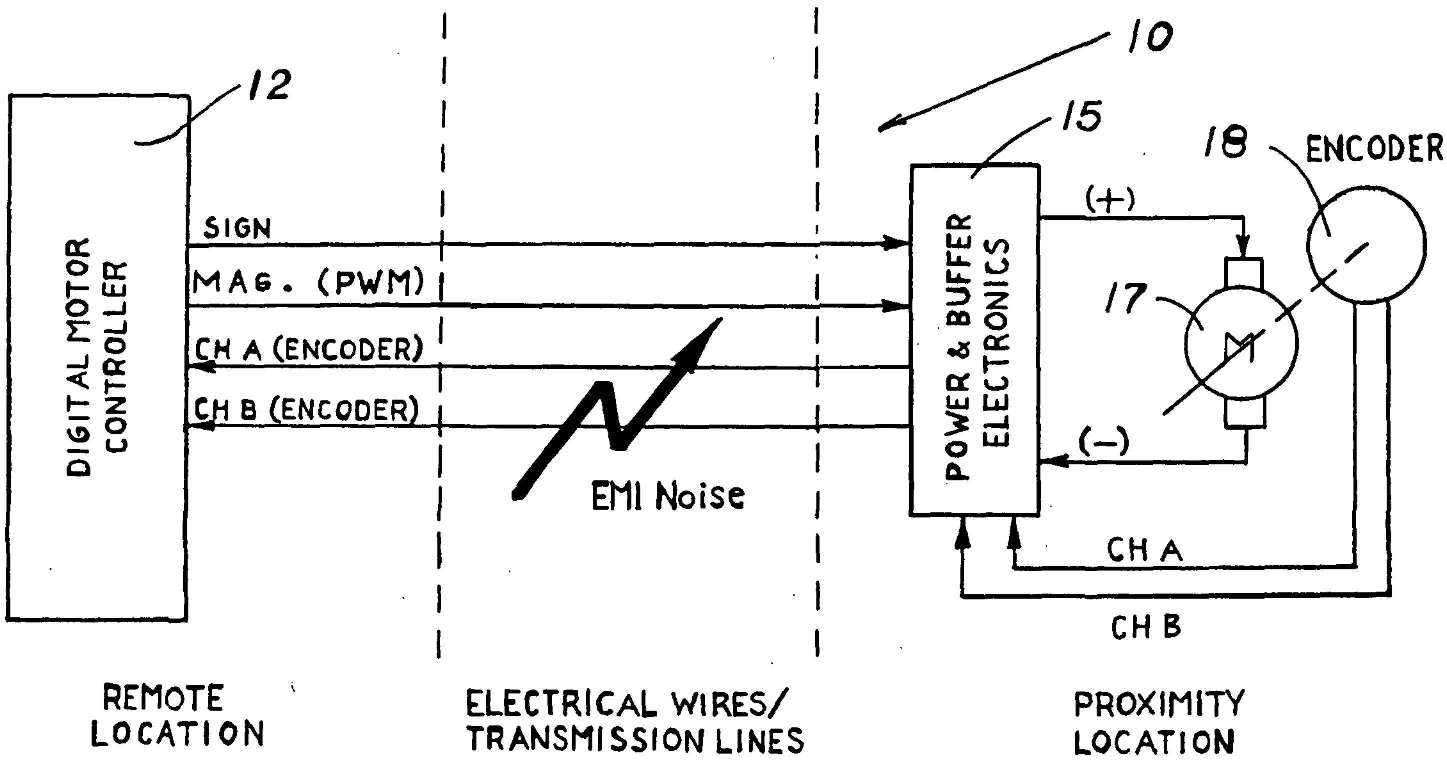
It is also to be noted that the interfaces at the two ends of the fiber optic link are functionally parallel. Although the link itself is serial, because of its high-throughput, the link's parallel interfaces, as seen by the external devices (i.e. controller and power electronics), would appear to be parallel both physically and functionally. No special protocol is required of the controller nor the power electronics to ensure proper transmission of signals. Such interface transparency also allows modularity. Designers of the motor control system can conduct the initial design by breadboarding the system following the conventional method. Then, when the system is functionally verified, the power electronics and the motors can be separated from the controller, and the fiber optic link of the invention can be inserted to connect the controller and the power electronics.

While the foregoing description of the invention has been presented for purposes of illustration and description, it is to be understood that it is not intended to limit the invention to the precise form disclosed.

It is to be appreciated therefore, that various structural changes may be made by those skilled in the art without departing from the spirit of the invention.

ABSTRACT OF THE INVENTION

A closed-loop control system 40,48,100 for controlling the operation of one or more servo motors 42 or other controllable devices. The system employs a fiber optics link 44, immune to electomagnetic interference, for transmission of control signals from a controller or controllers 41 at a remote station to the power electronics 46 located in proximity to the motors 42 or other devices at the local station. At the remote station the electrical control signals are time-multiplexed, converted to a formatted serial bit stream, and converted to light signals for transmission over a single fiber of the fiber optics link. At the local station, the received optical signals are reconstructed as electrical control signals for the controlled motors 42 or other devices. At the local station, an encoder sensor 45 linked to the driven device 42 generates encoded feedback signals which provide information as to a condition of the controlled device. The encoded signals are placed in a formatted serial bit stream, multiplexed, and transmitted as optical signals over a second fiber of the fiber optic link which closes the control loop of the closed-loop motor controller. The encoded optical signals received at the remote station are demultiplexed, reconstructed and coupled to the controller(s) 41 as electrical feedback signals.


10
12
15
18
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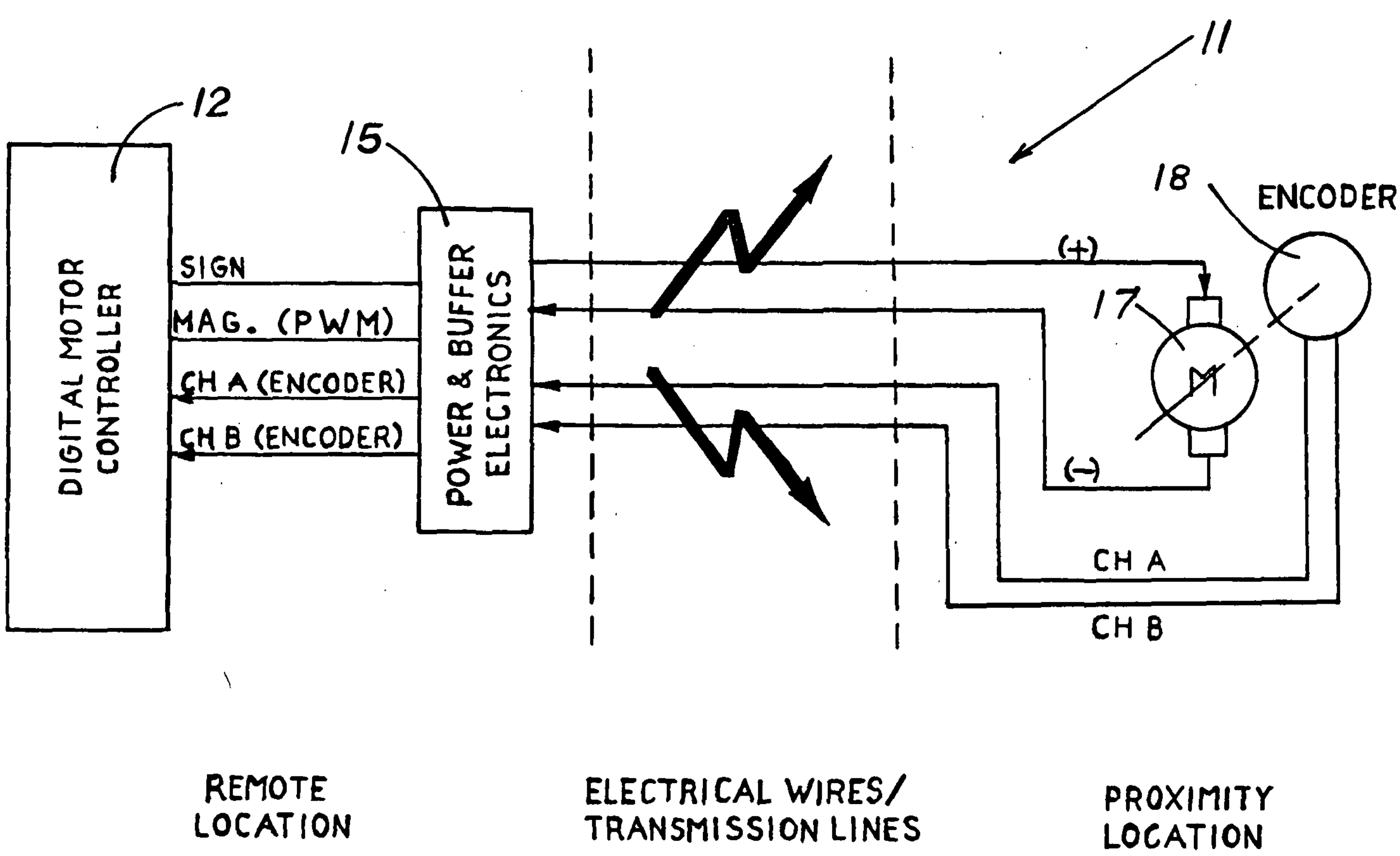
SIGN
MAG. (PWM)
CH A (ENCODER)
CH B (ENCODER)
DIGITAL MOTOR CONTROLLER
POWER & BUFFER ELECTRONICS
(+)
17
(−)
EMI Noise
CH A
CH B
REMOTE LOCATION
ELECTRICAL WIRES/ TRANSMISSION LINES
PROXIMITY LOCATION

FIG. 1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12
15
18
ENCODER
SIGN
MAG. (PWM)
CH A (ENCODER)
CH B (ENCODER)
DIGITAL MOTOR CONTROLLER
POWER & BUFFER ELECTRONICS
(+)
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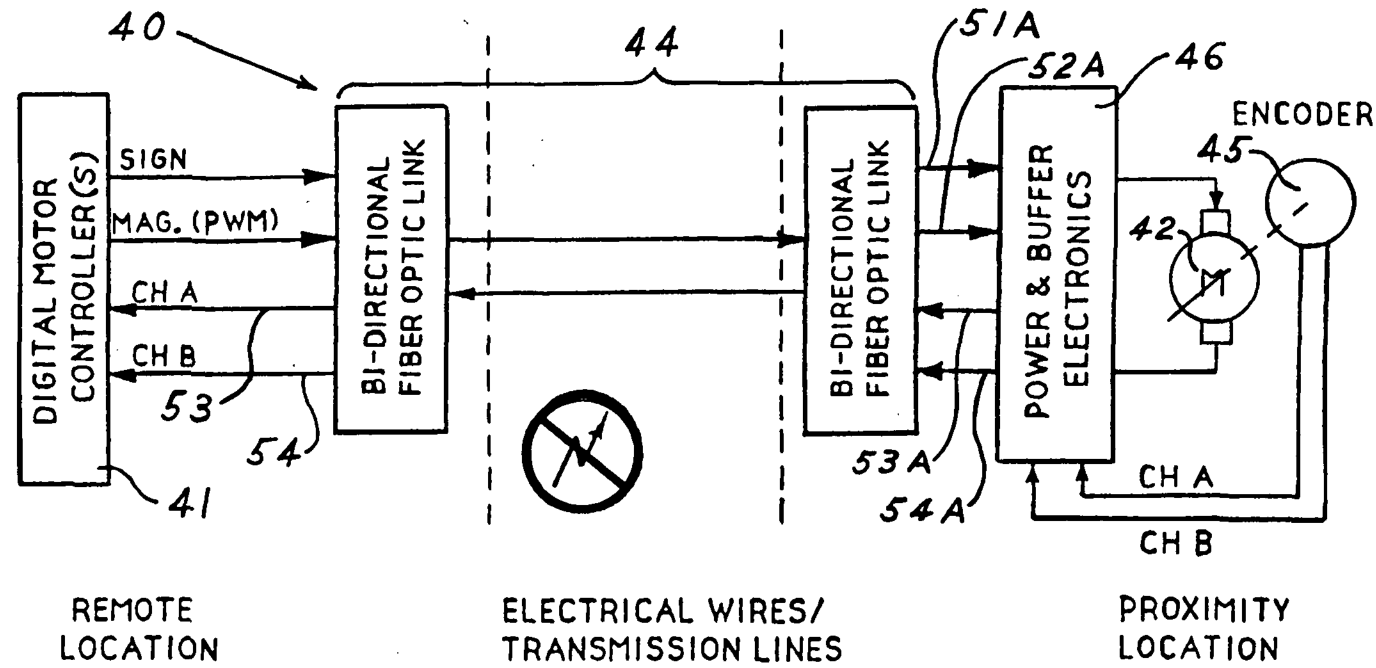
(−)
CH A
CH B
REMOTE LOCATION
ELECTRICAL WIRES/ TRANSMISSION LINES
PROXIMITY LOCATION

FIG. 2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51A
52A
46
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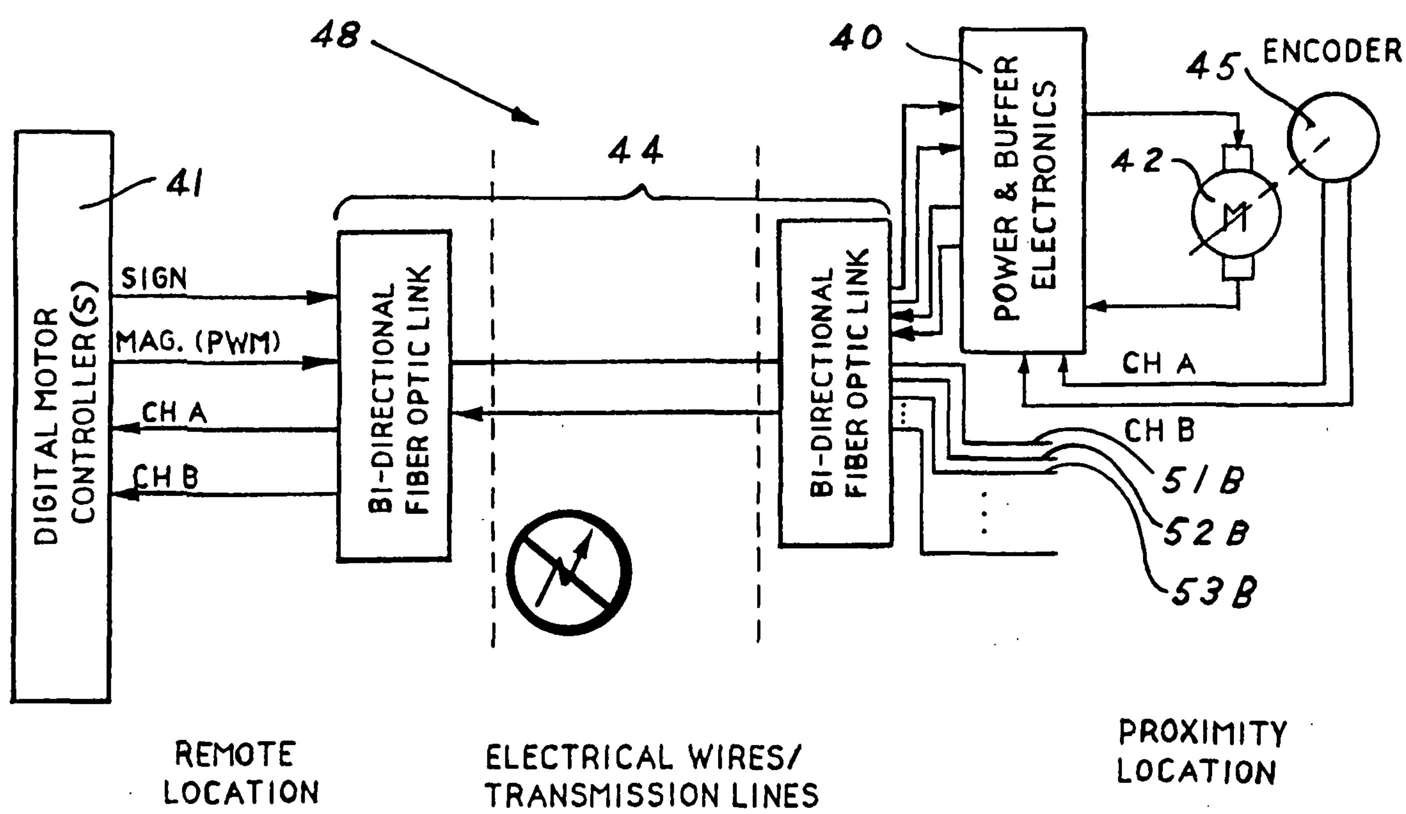
BI-DIRECTIONAL FIBER OPTIC LINK
POWER & BUFFER ELECTRONICS
42
53
54
41
53A
54A
CH A
CH B
REMOTE LOCATION
ELECTRICAL WIRES/ TRANSMISSION LINES
PROXIMITY LOCATION

FIG. 3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BI-DIRECTIONAL FIBER OPTIC LINK
POWER & BUFFER ELECTRONICS
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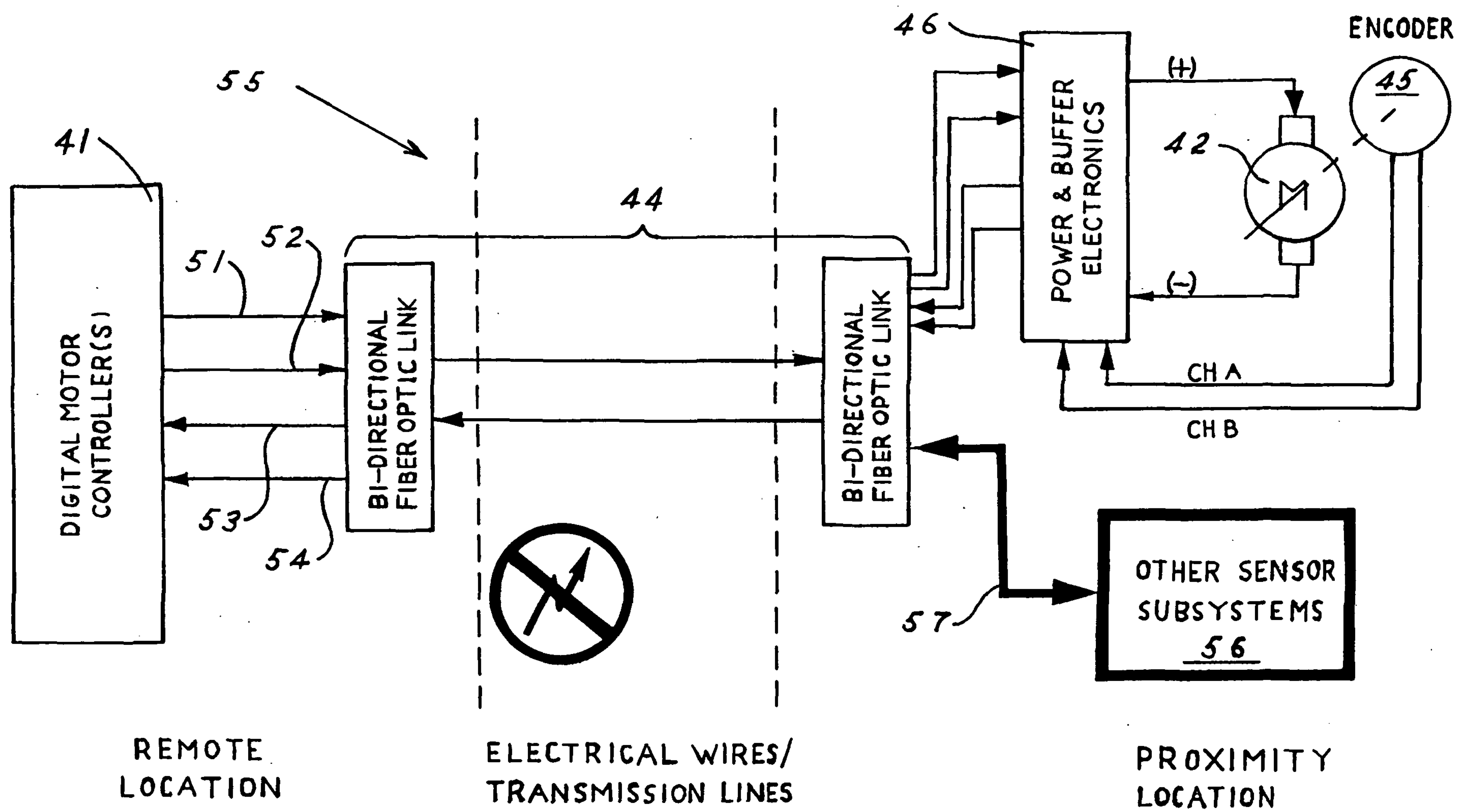
53B
REMOTE LOCATION
ELECTRICAL WIRES/ TRANSMISSION LINES
PROXIMITY LOCATION

FIG. 4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51
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53
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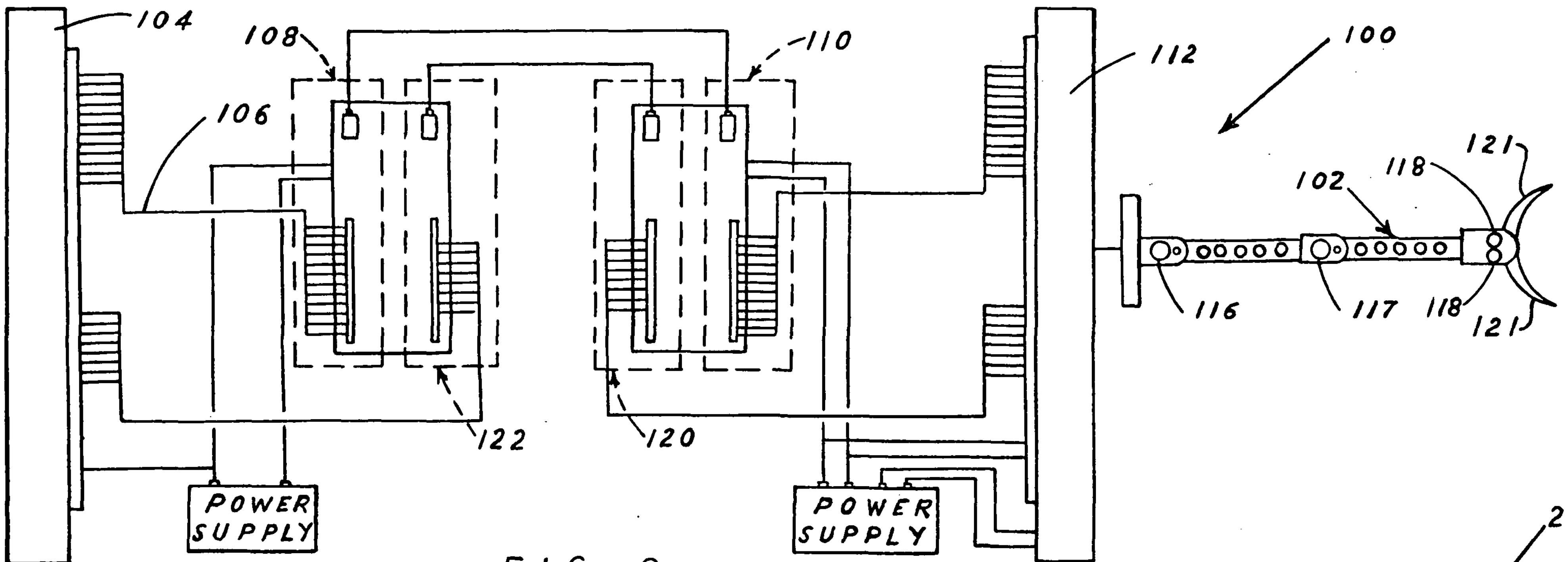
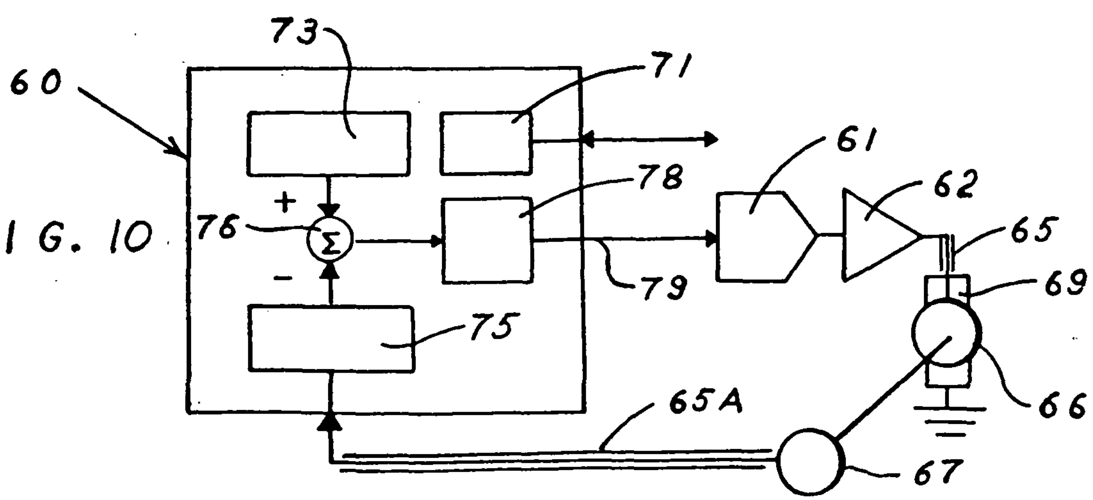
BI-DIRECTIONAL FIBER OPTIC LINK
46
POWER & BUFFER ELECTRONICS
(+)
(-)
42
ENCODER
45
CH A
CH B
57
OTHER SENSOR SUBSYSTEMS
56
REMOTE LOCATION
ELECTRICAL WIRES/ TRANSMISSION LINES
PROXIMITY LOCATION

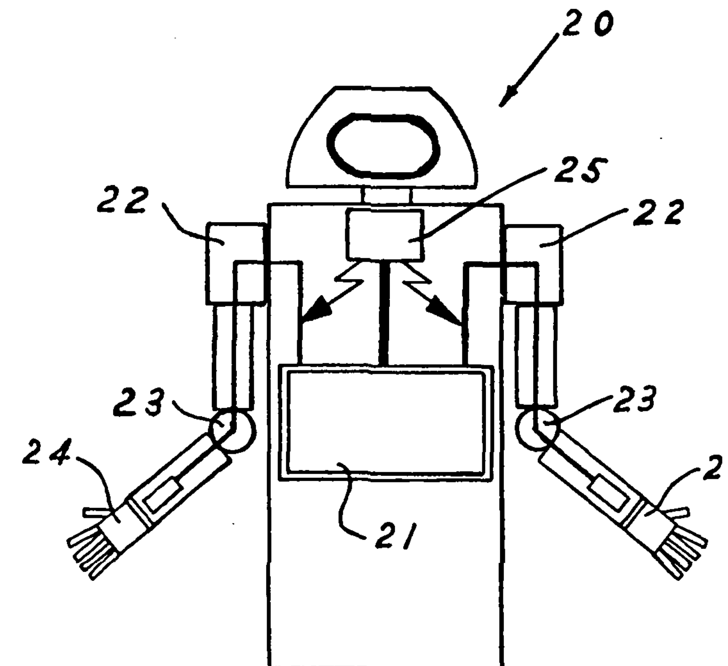
FIG. 5



F I G . 9



F I G. 10



F I G . 6

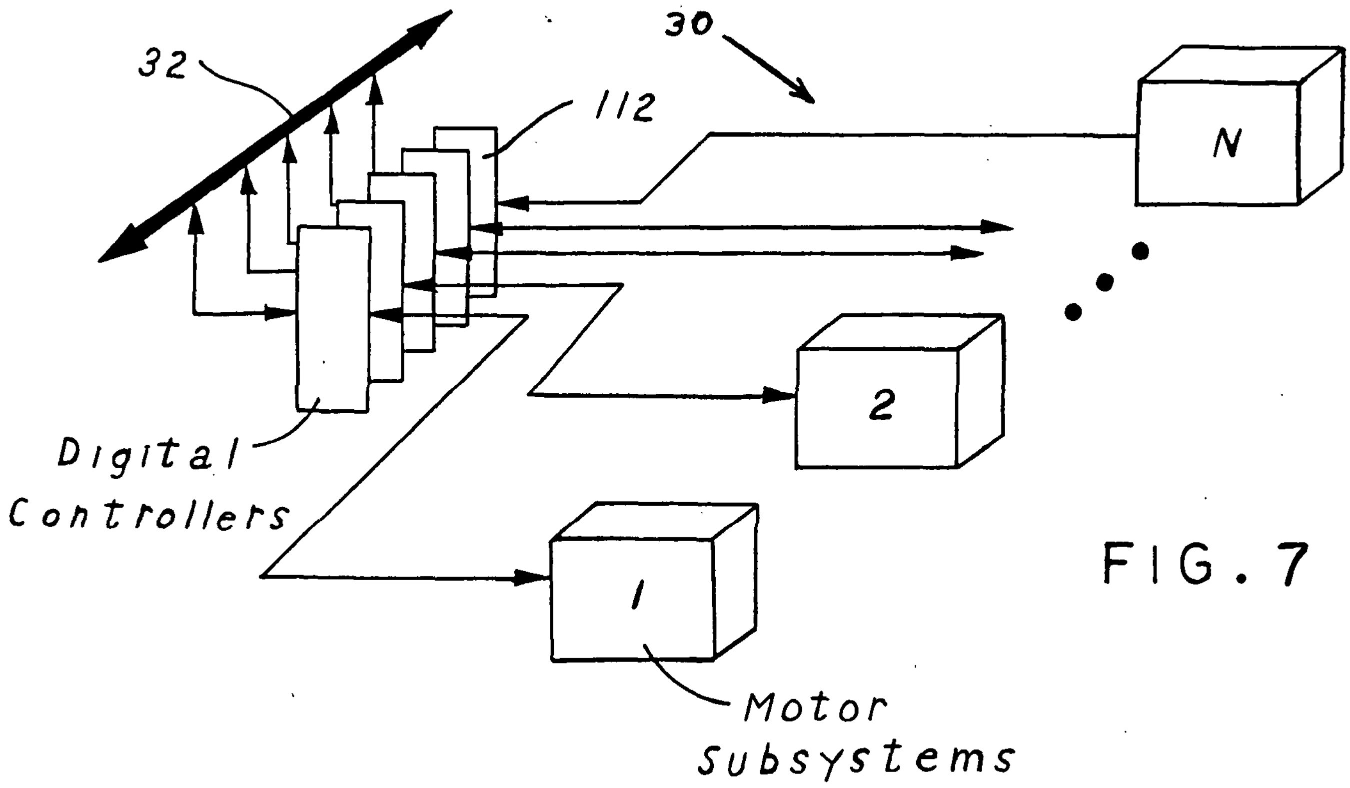


FIG. 7

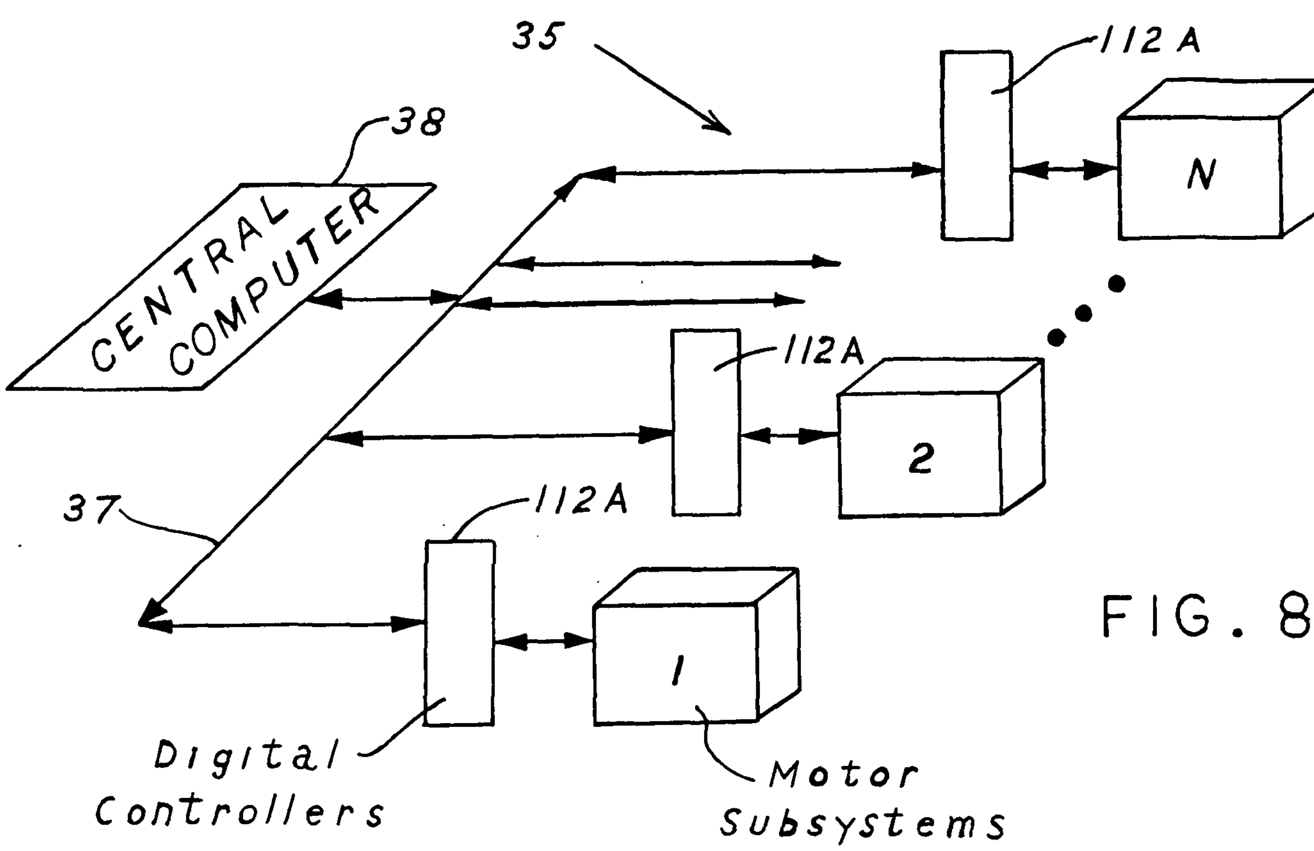
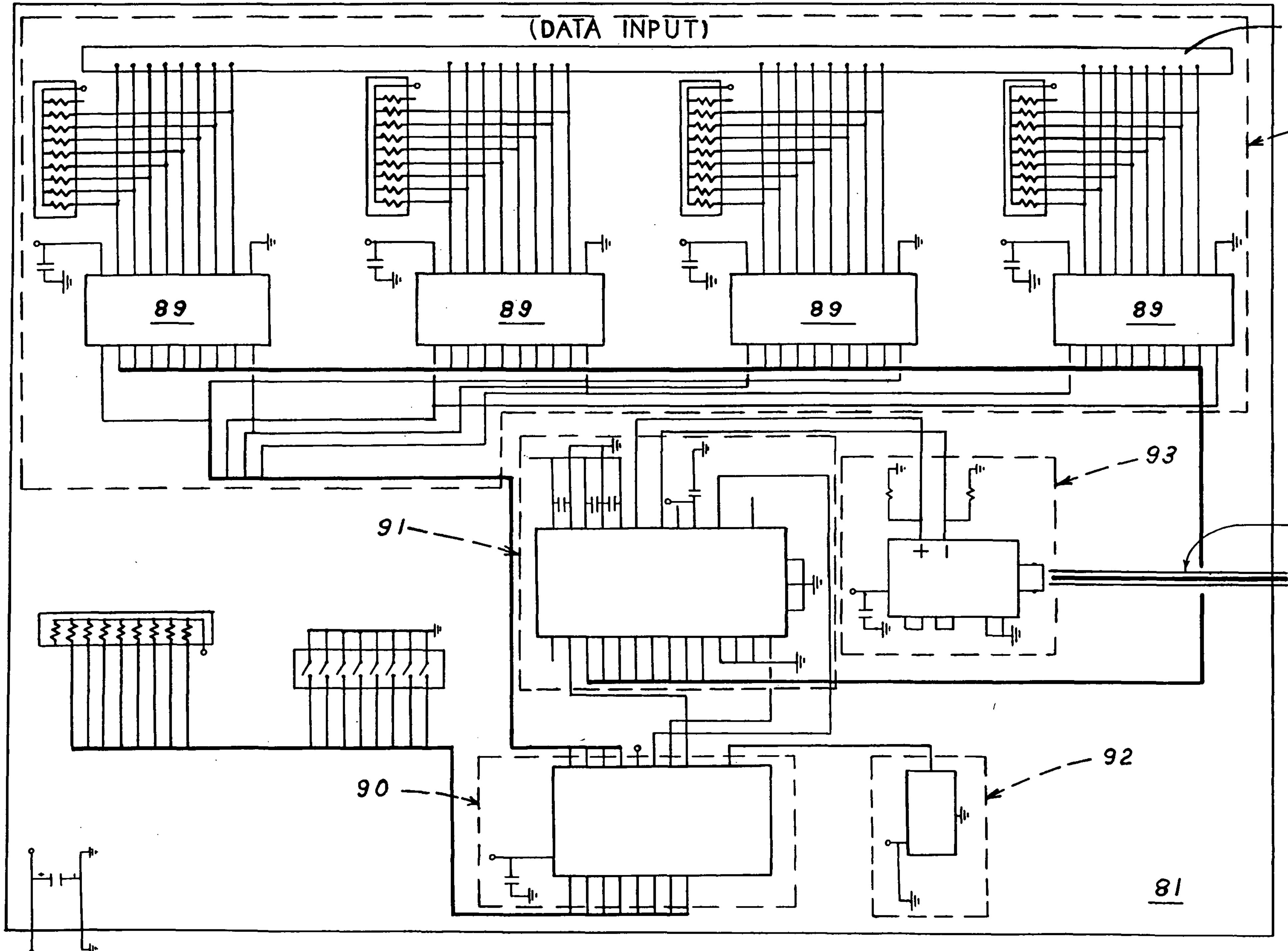


FIG. 8

SYNC-BYTE	COMMAND BYTE	ctrl signal	ctrl signal	ctrl signal	• • • • •

← 1 TO 256 ITERATIONS →

FIG. 11



F I G . 12

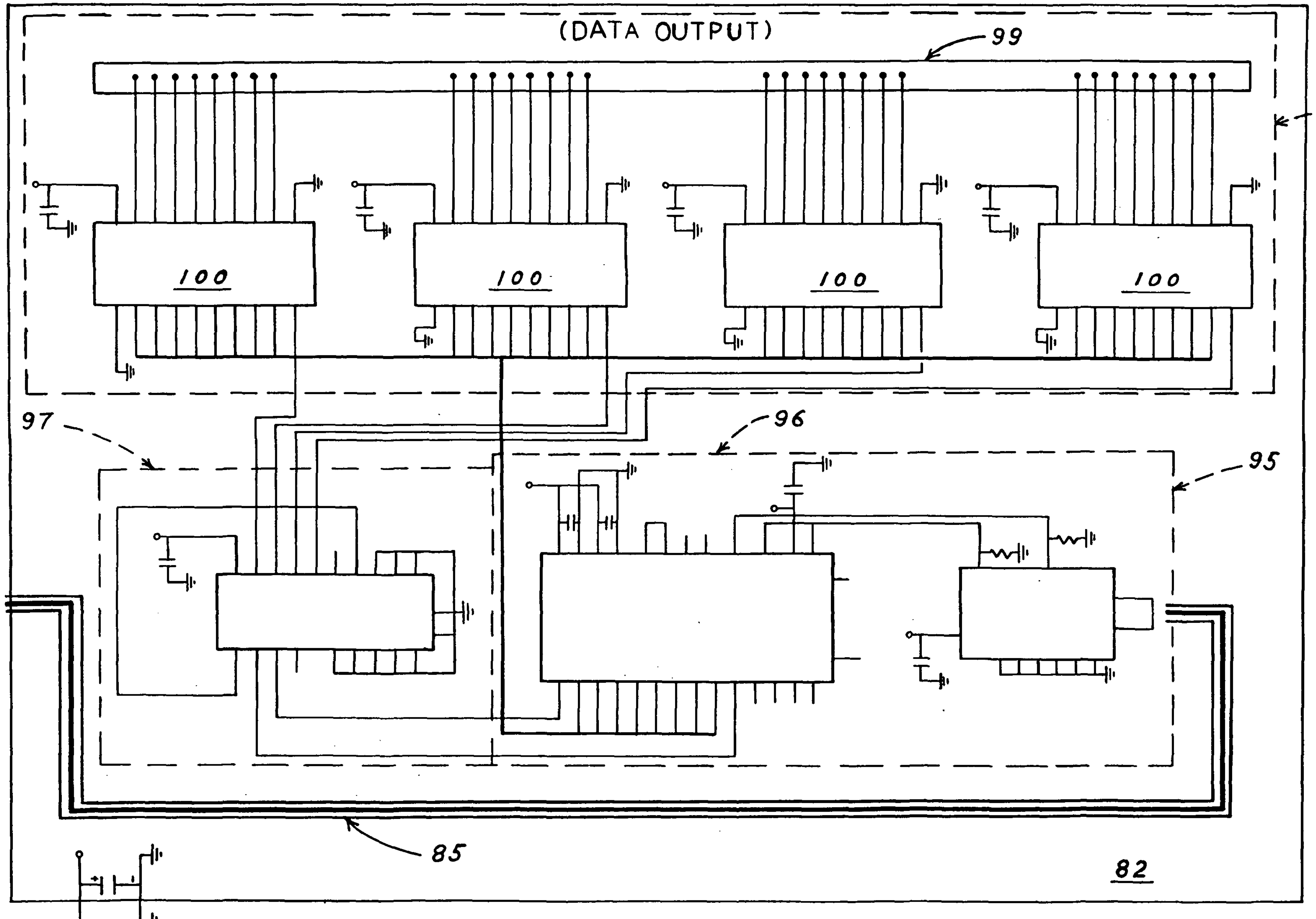


FIG 13

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