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**Kewitsch et al.**

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(54) **HIGH-RELIABILITY ROBOTIC  
CROSS-CONNECT SYSTEMS**

(71) Applicant: **Telescent Inc.**, Irvine, CA (US)

(72) Inventors: **Anthony Stephen Kewitsch**, Santa Monica, CA (US); **Don Zambos**, Marina del Rey, CA (US)

(73) Assignee: **Telescent Inc.**, Irvine, CA (US)

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(60) Division of application No. 17/717,950, filed on Apr. 11, 2022, now Pat. No. 11,953,731, which is a (Continued)

(51) **Int. Cl.**  
**G02B 6/35** (2006.01)  
**B25J 9/00** (2006.01)

(Continued)

(52) **U.S. Cl.**  
CPC ..... **G02B 6/3508** (2013.01); **B25J 9/0018** (2013.01); **B25J 9/023** (2013.01); **B25J 9/104** (2013.01);

(Continued)

(58) **Field of Classification Search**  
CPC .... G02B 6/3508; G02B 6/3502; G02B 6/356; G02B 6/3866; G02B 6/3556;

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*Primary Examiner* — Michelle R Connelly

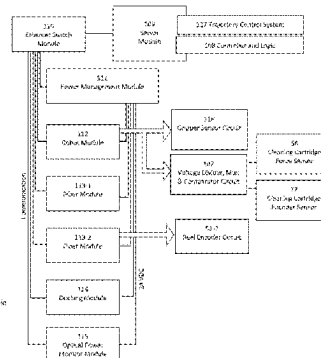
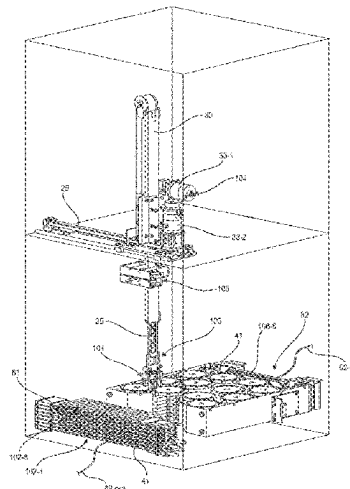
(74) *Attorney, Agent, or Firm* — Sirtitzky Law, PLLC

(57)

**ABSTRACT**

A high-capacity optical fiber switching system enables selective interconnection of individual input fibers to output fibers. A three-dimensional array of paired linear elements with selectable flexibility and length is arranged in horizontal rows and vertical columns to form a transverse interchange plane. Each pair consists of a stationary lower element and a movable upper element, the latter holding a terminus of a distinct optical fiber. Couplers placed within this array facilitate signal conductor connections. A transport device with an axially movable gripper moves in horizontal spaces between columns to reposition the movable fiber terminals. Signal-controlled, orthogonal linear drives provide vertical and horizontal movements of the transport device, enabling placement within the fiber array.

**20 Claims, 29 Drawing Sheets**



**Related U.S. Application Data**

division of application No. 16/858,994, filed on Apr. 27, 2020, now Pat. No. 11,340,402, which is a continuation of application No. 16/504,194, filed on Jul. 5, 2019, now Pat. No. 10,649,149, which is a continuation of application No. 14/949,861, filed on Nov. 23, 2015, now Pat. No. 10,345,526.

- (60) Provisional application No. 62/091,541, filed on Dec. 14, 2014.

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**B25J 9/10** (2006.01)  
**B25J 15/02** (2006.01)  
**B25J 18/02** (2006.01)  
**G02B 6/38** (2006.01)  
**G02B 6/44** (2006.01)

**(52) U.S. Cl.**

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**(58) Field of Classification Search**

CPC .. **G02B 6/3564**; **G02B 6/3568**; **G02B 6/3572**; **G02B 6/358**; **G02B 6/359**; **G02B 6/385**; **G02B 6/4452**; **B25J 9/0018**; **B25J 9/023**; **B25J 9/104**; **B25J 15/02**; **B25J 18/025**

See application file for complete search history.

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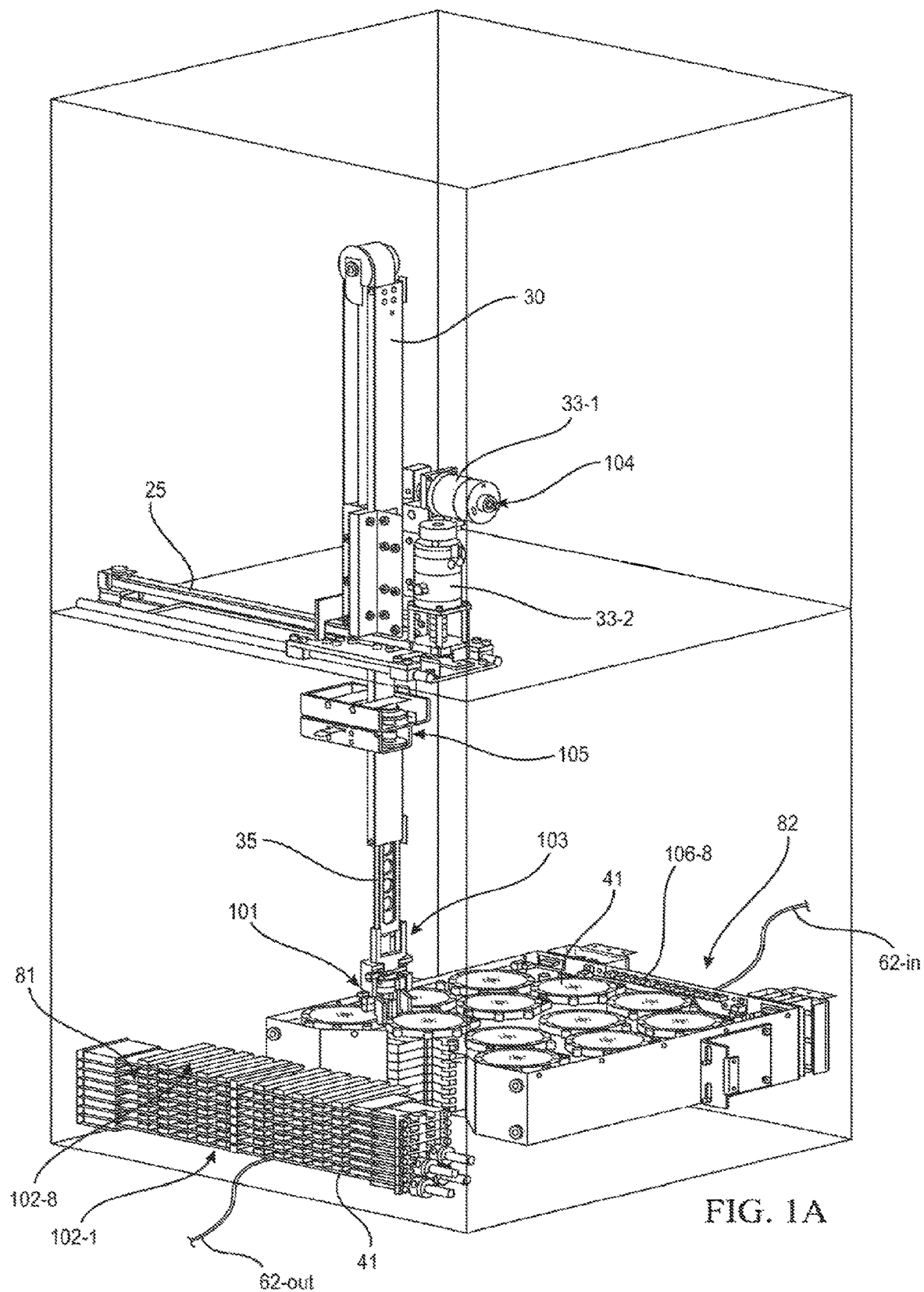
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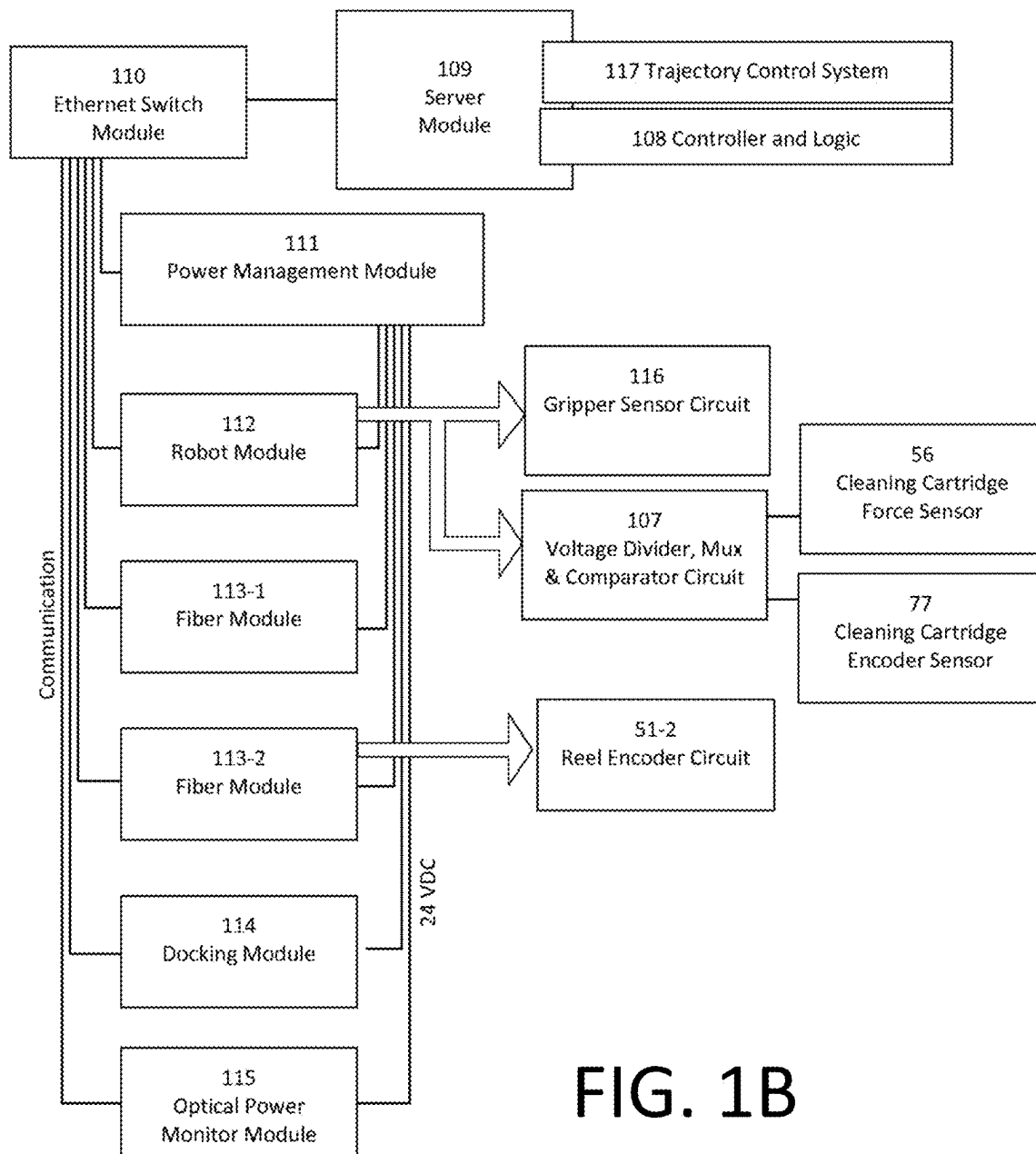


FIG. 1B

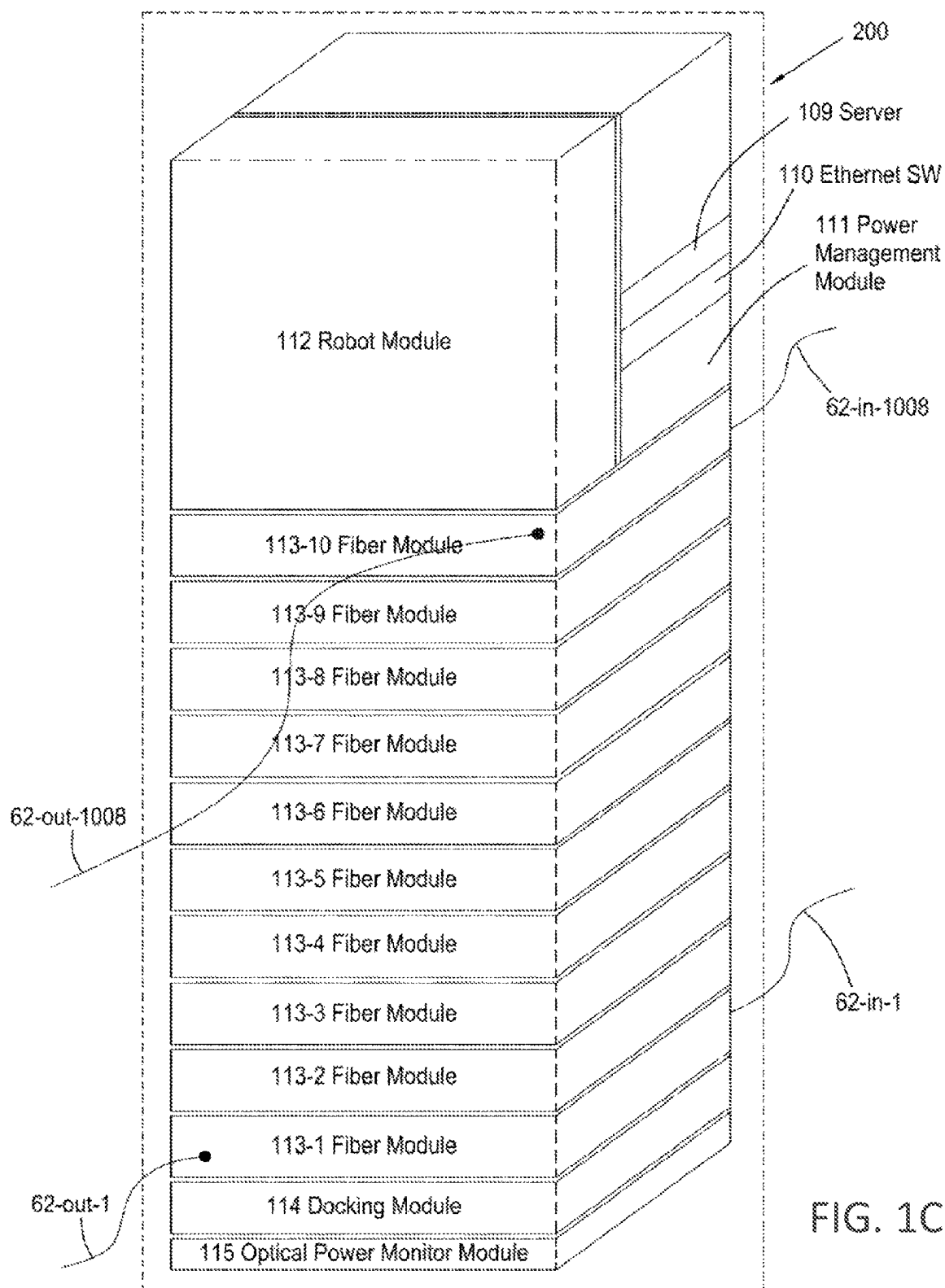


FIG. 1C

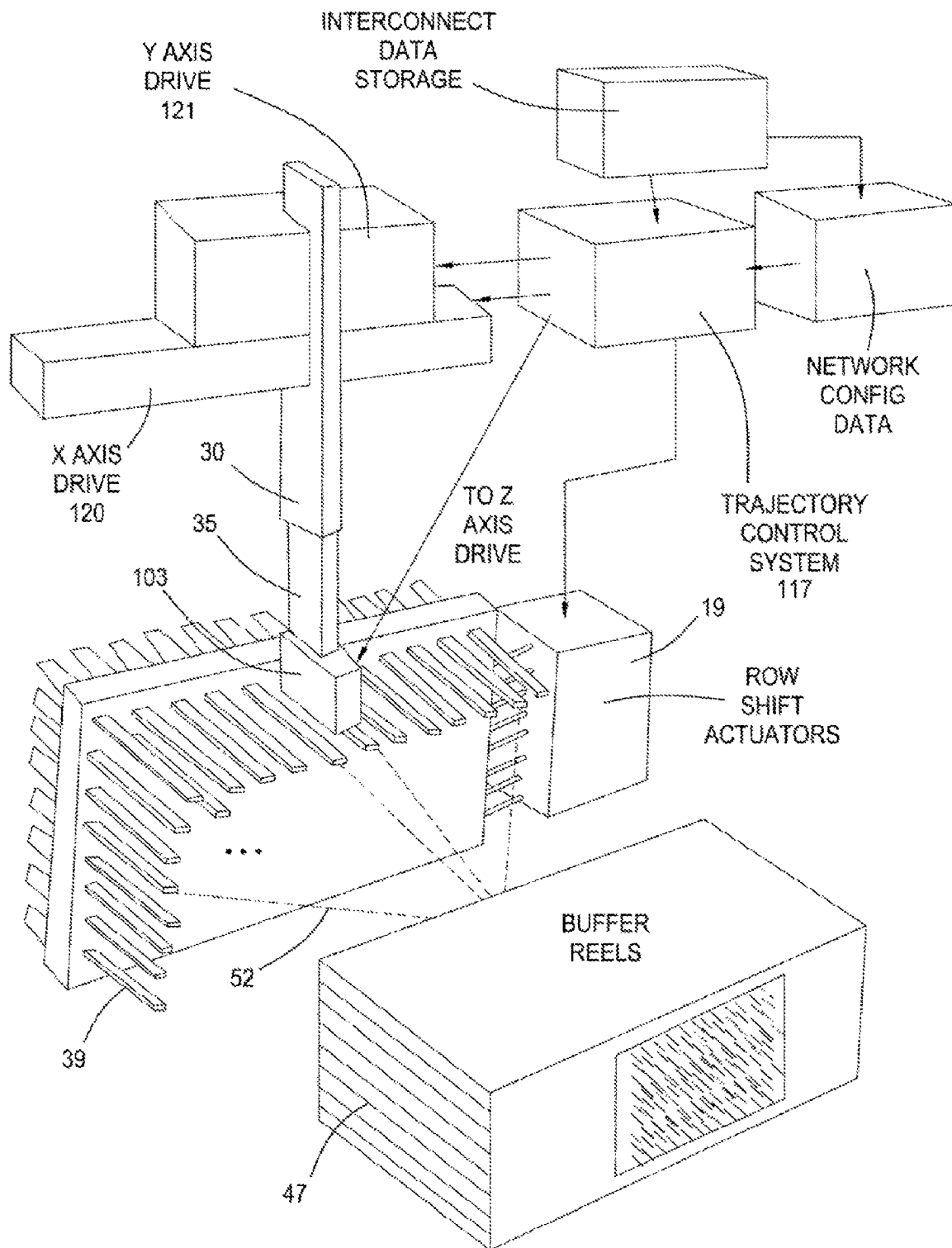


Fig. 1D

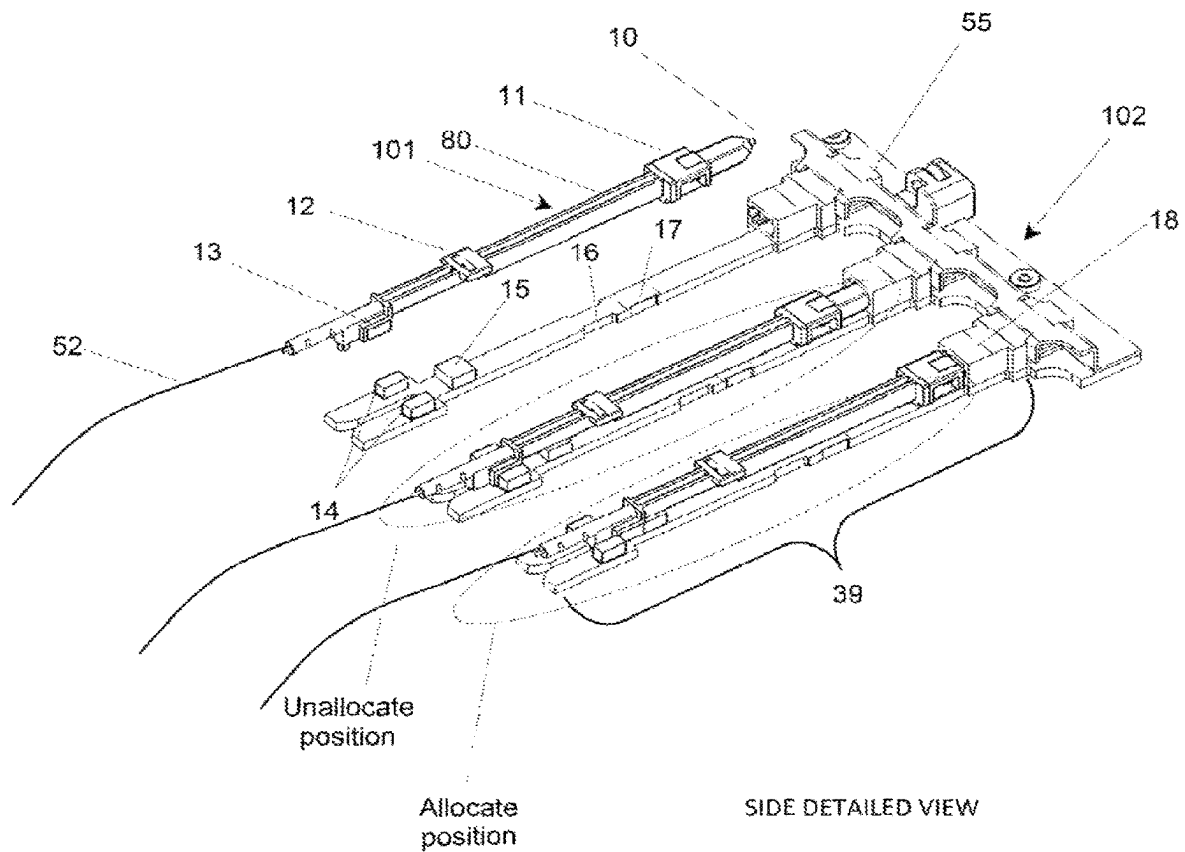
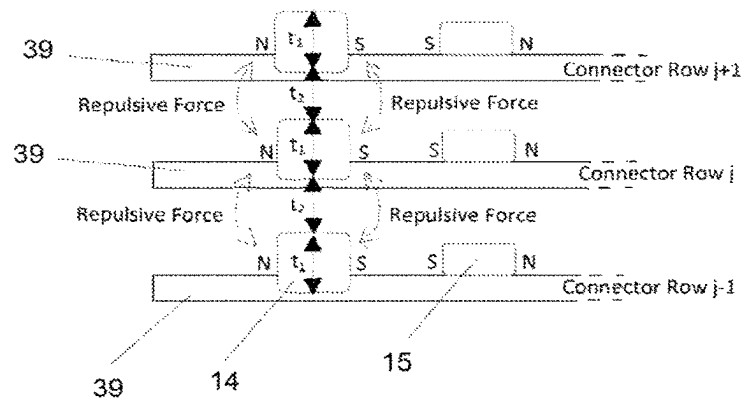
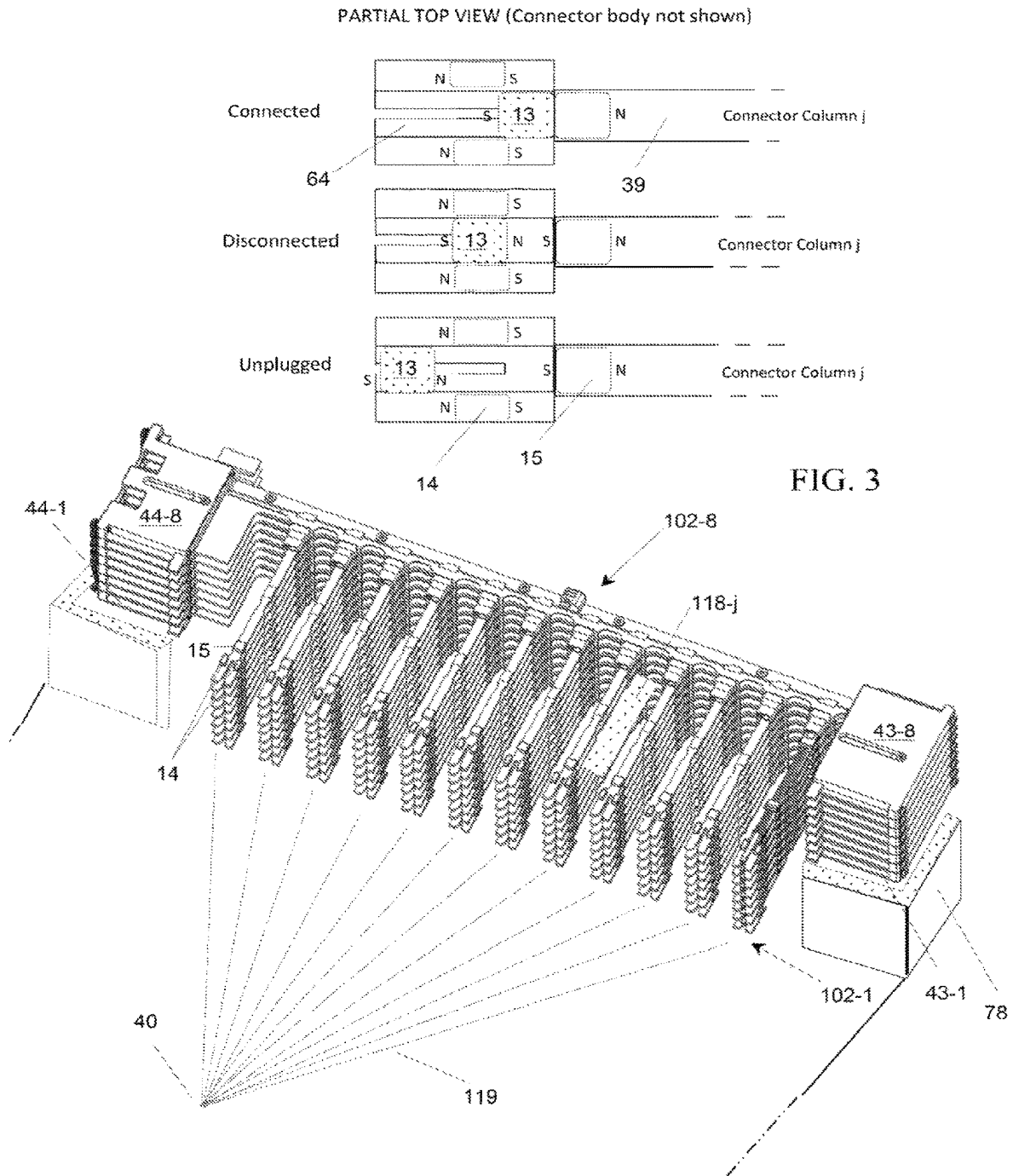


FIG. 2







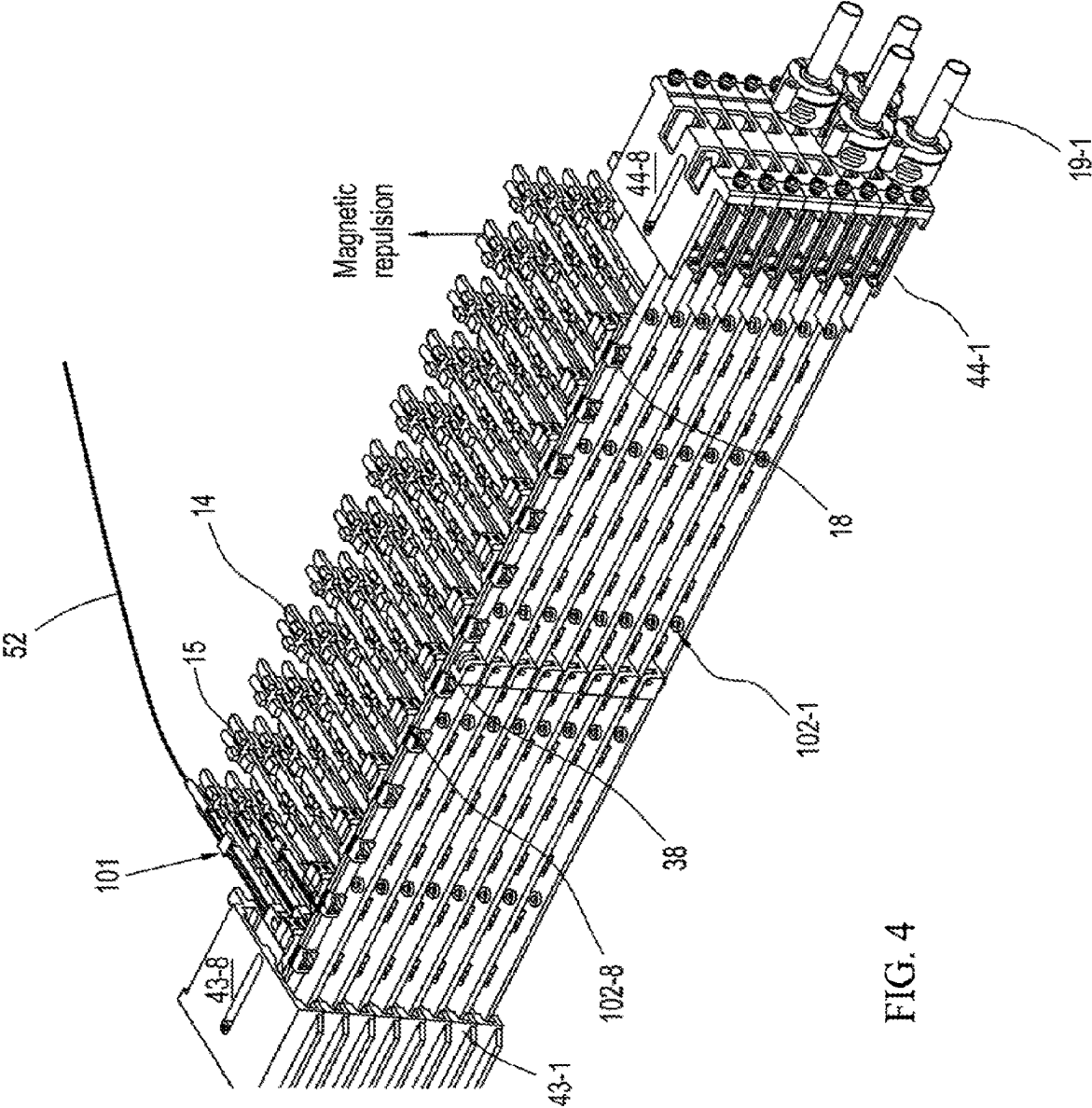


FIG. 4

POSITION 1/3:  
CONNECTOR ALLOCATED

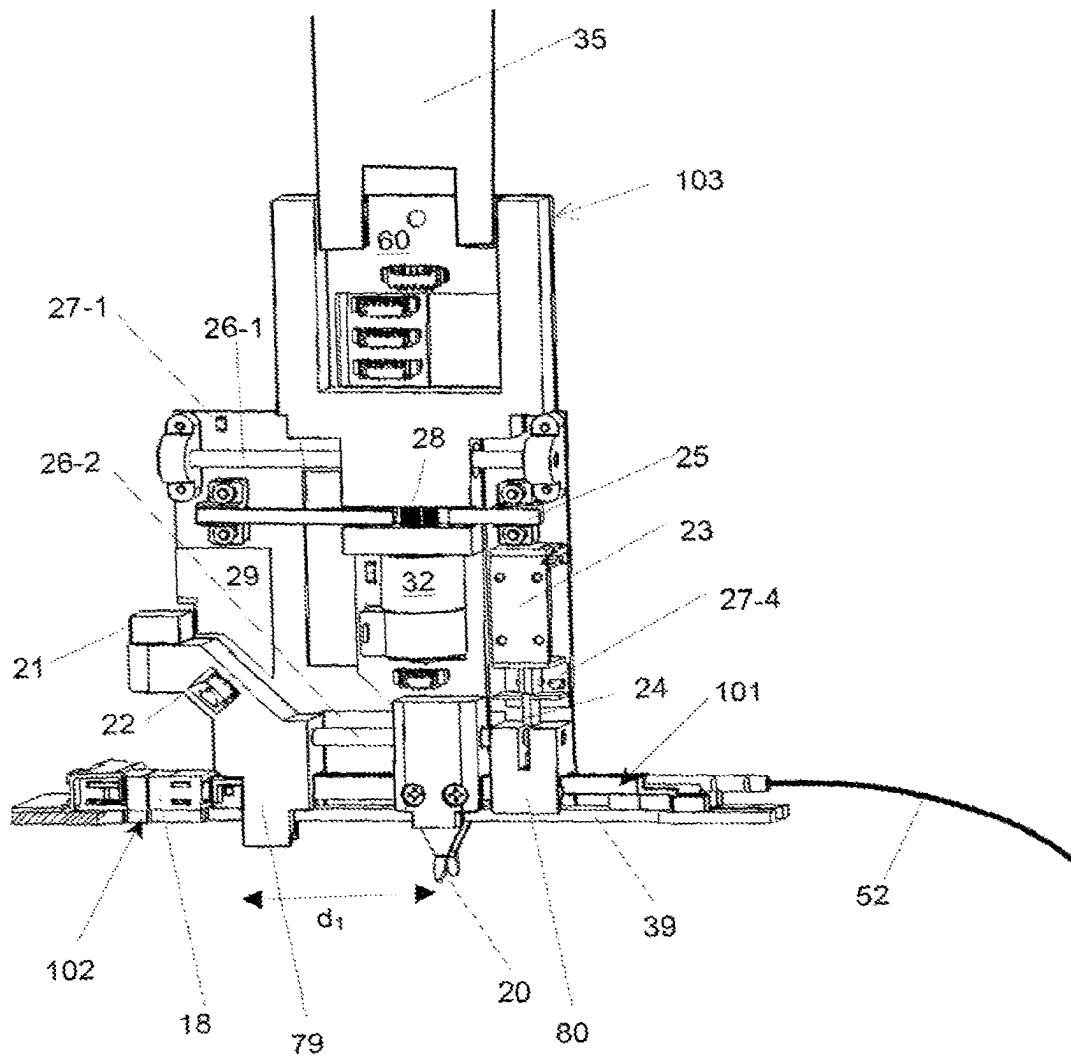


FIG. 5

POSITION 2/3:  
CONNECTOR UNALLOCATED

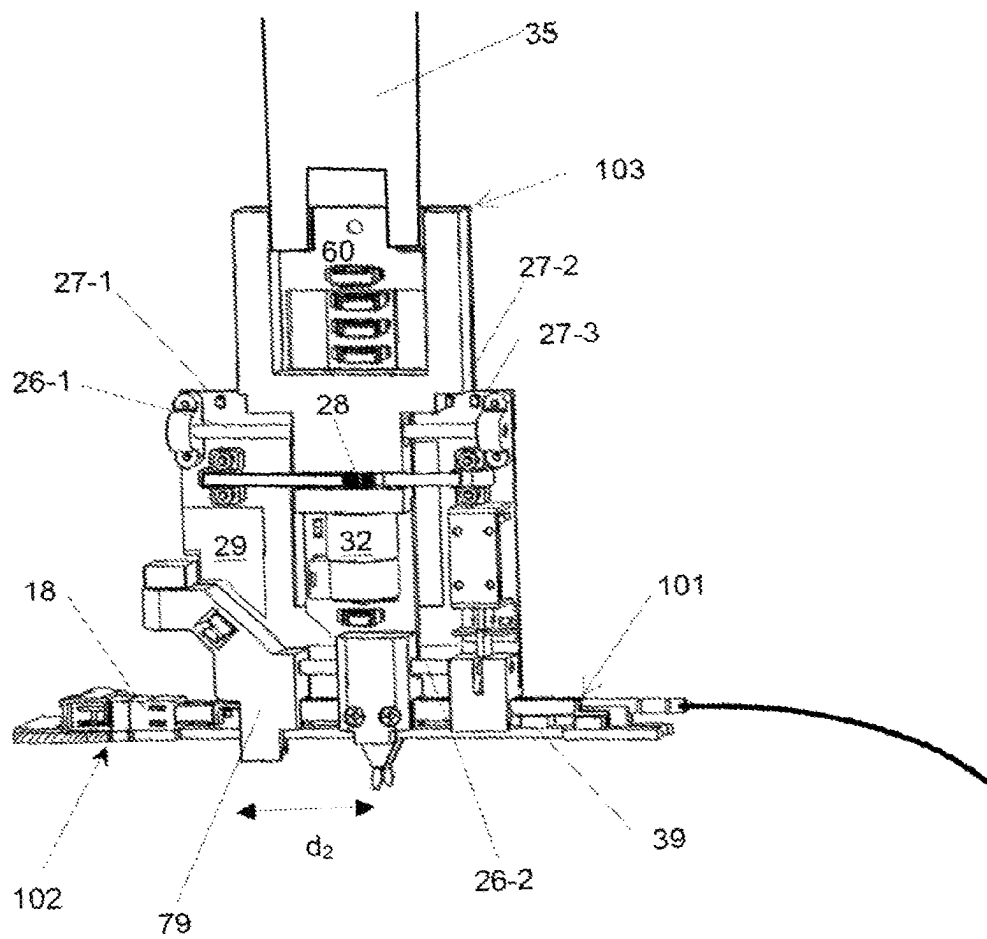


FIG. 6

POSITION 3/3:  
CONNECTOR UNPLUGGED

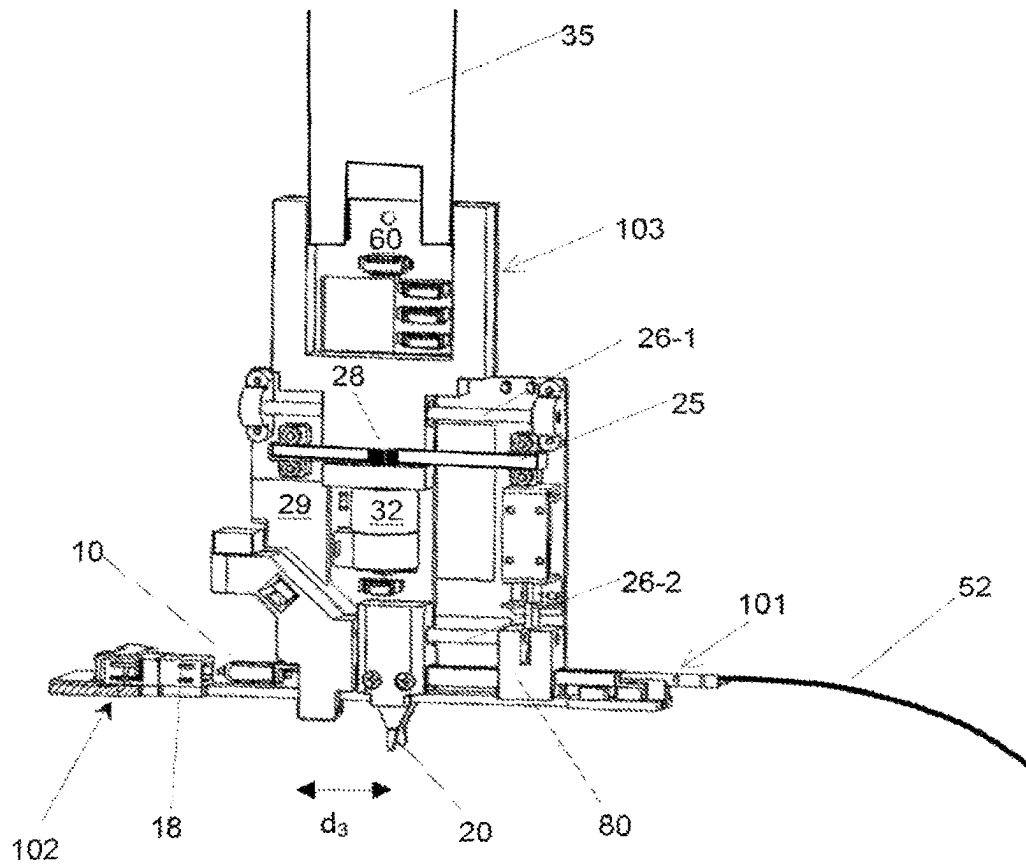
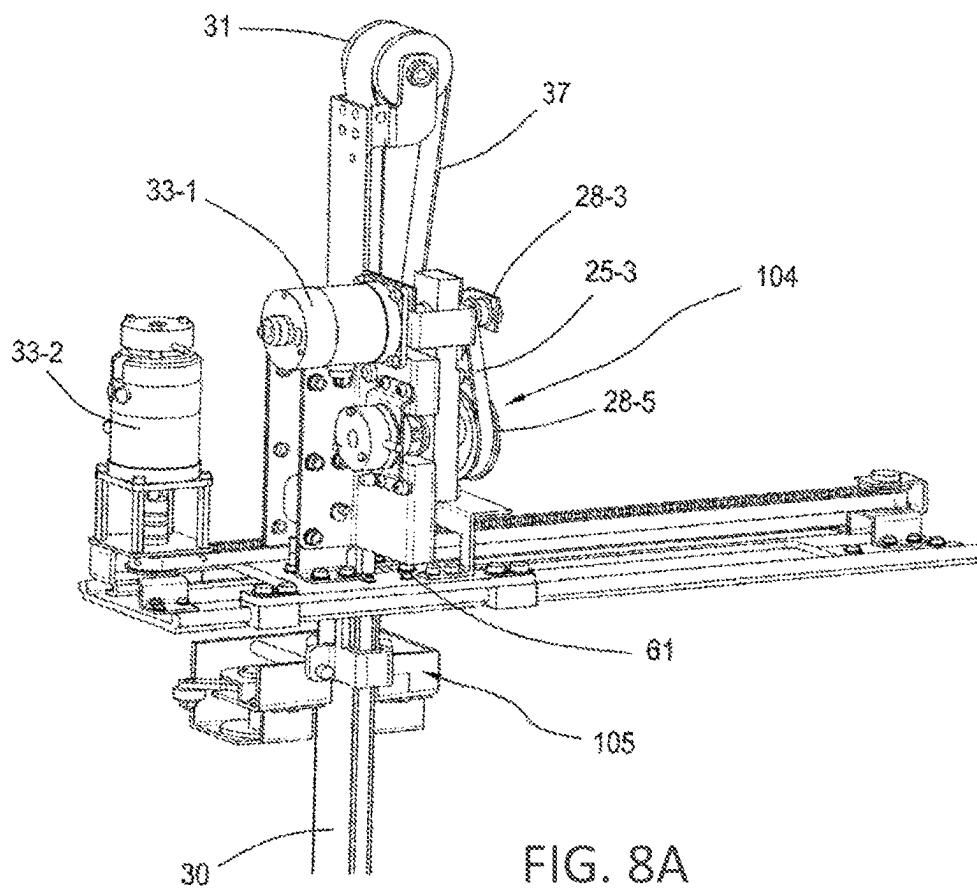


FIG. 7



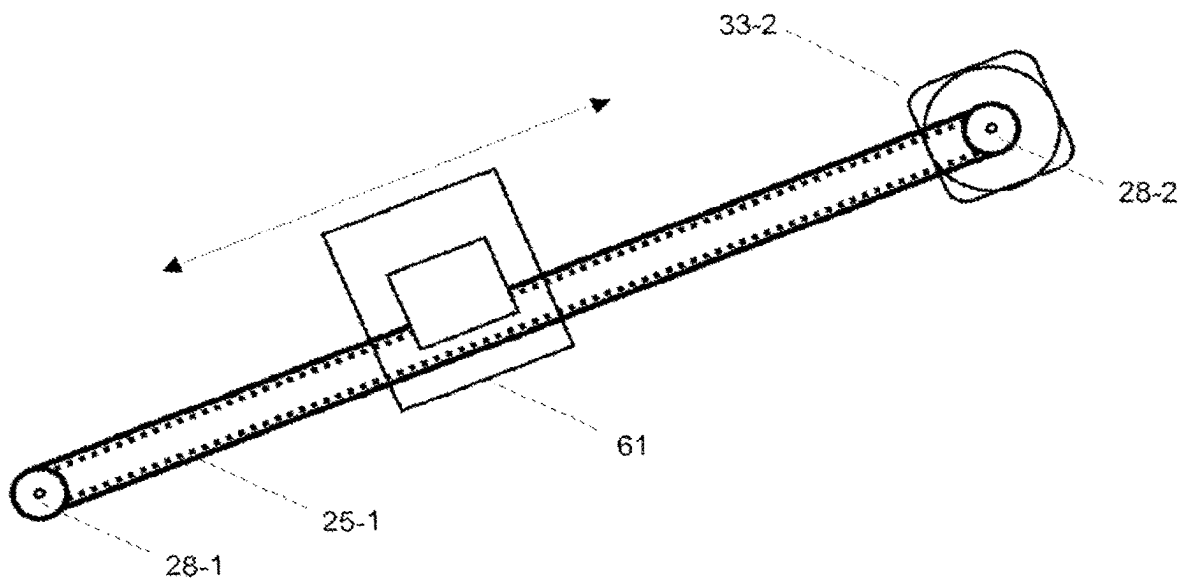


FIG. 8B

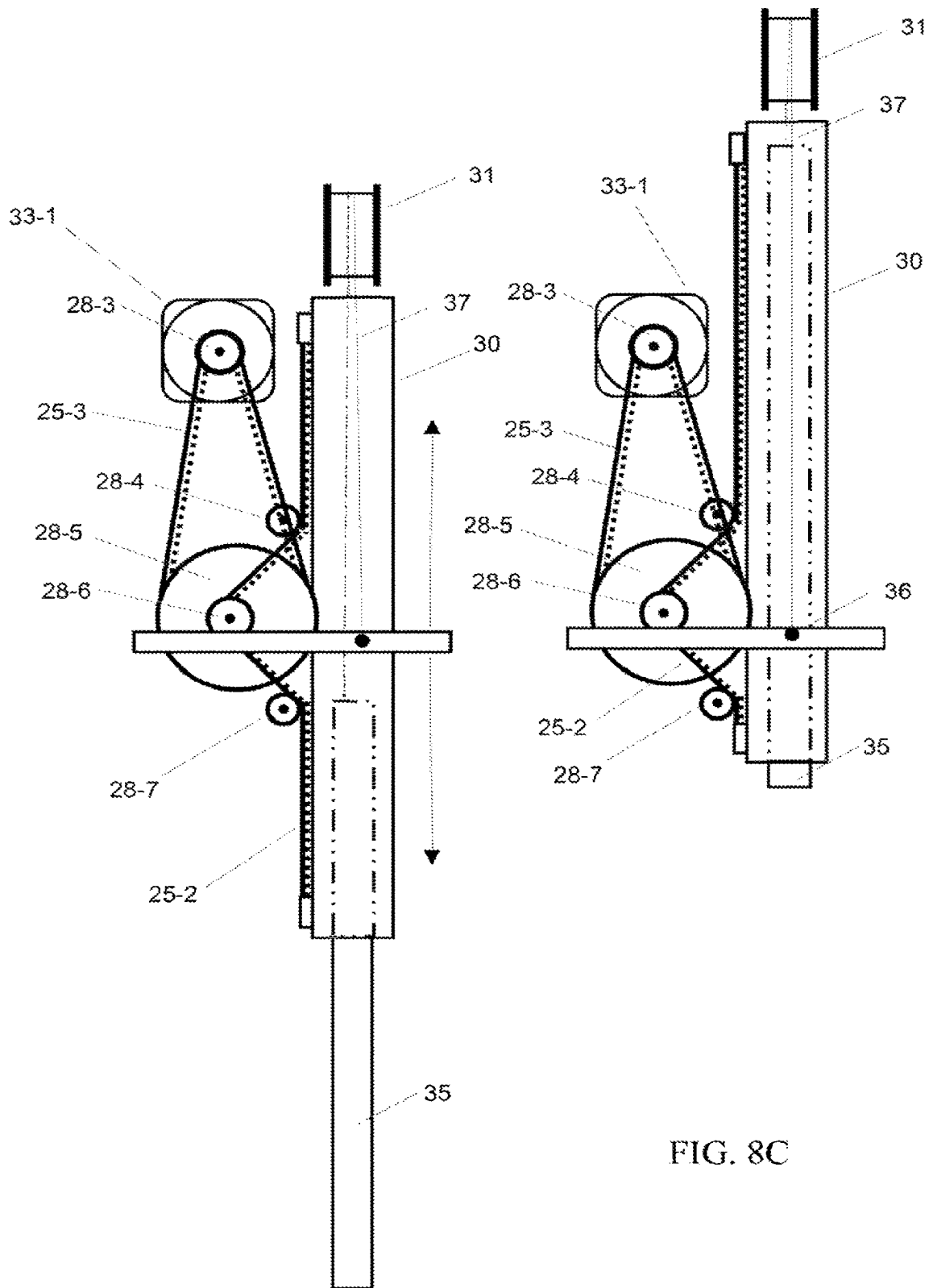


FIG. 8C

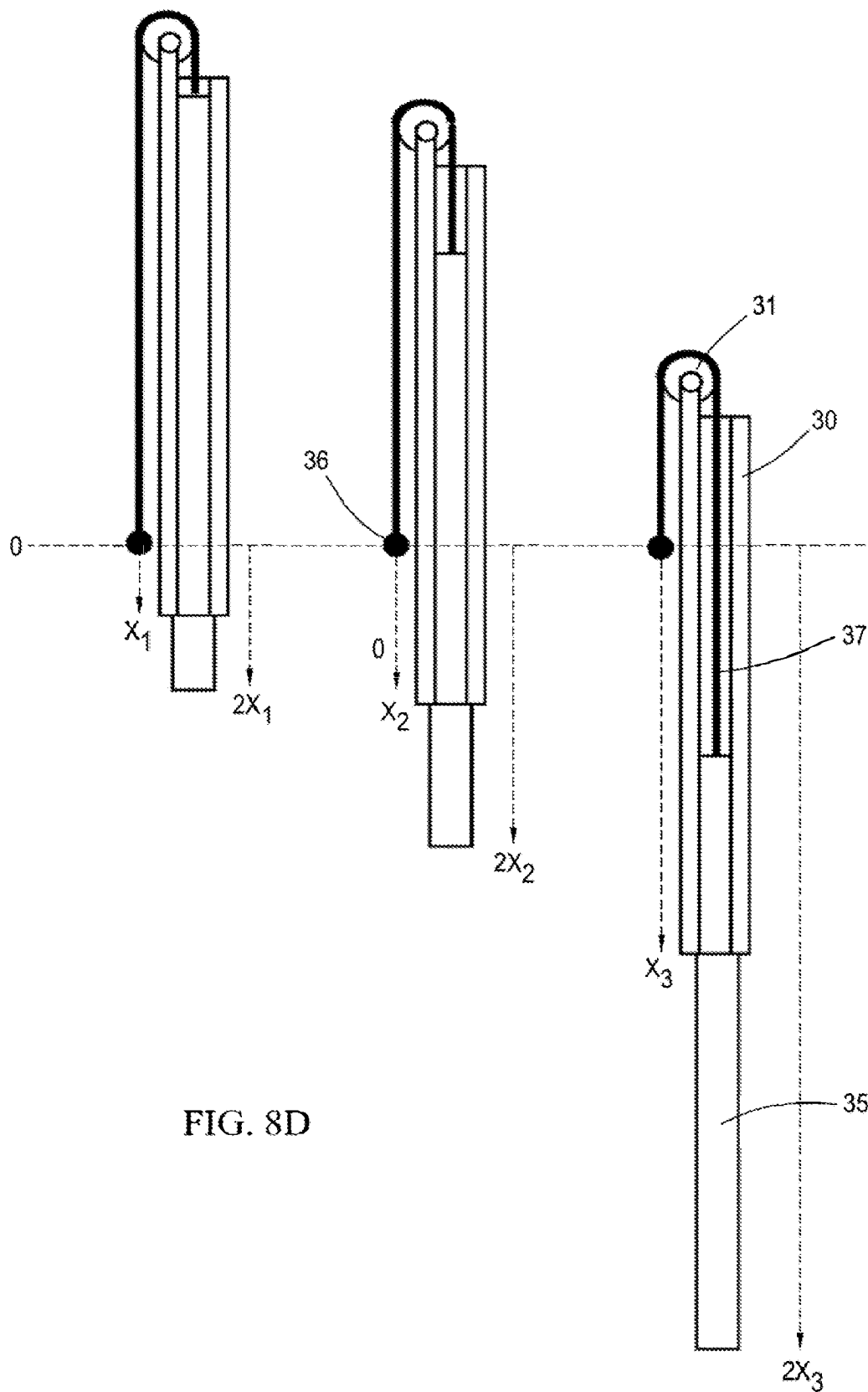


FIG. 8D



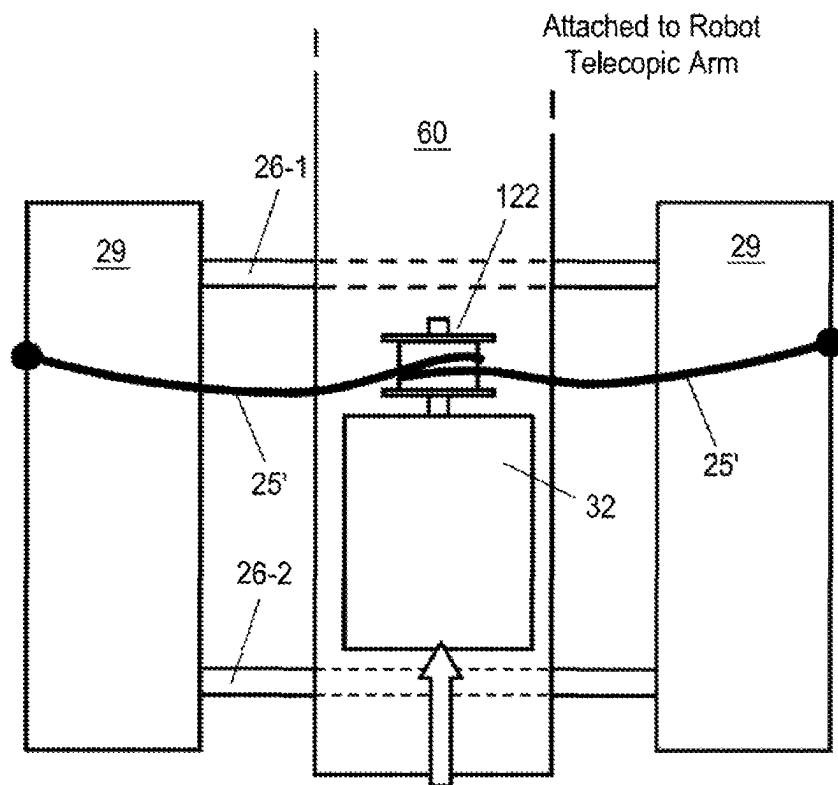


FIG. 8E

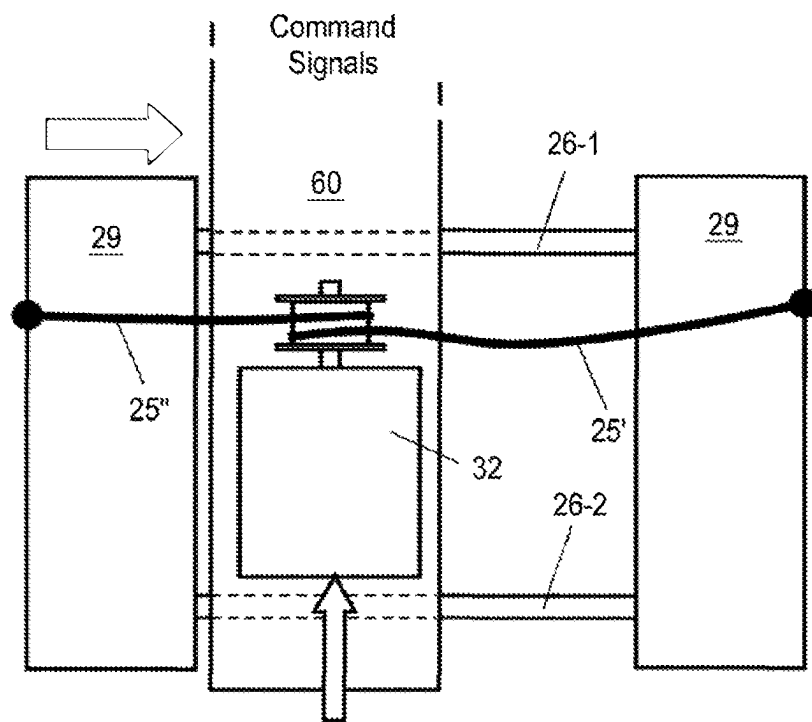


FIG. 8F

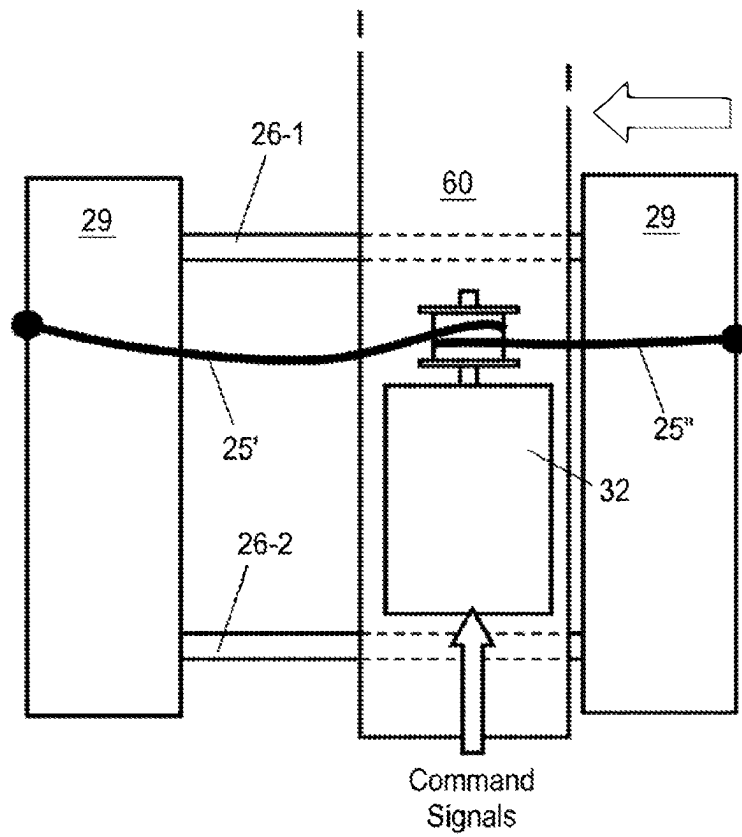


FIG. 8G

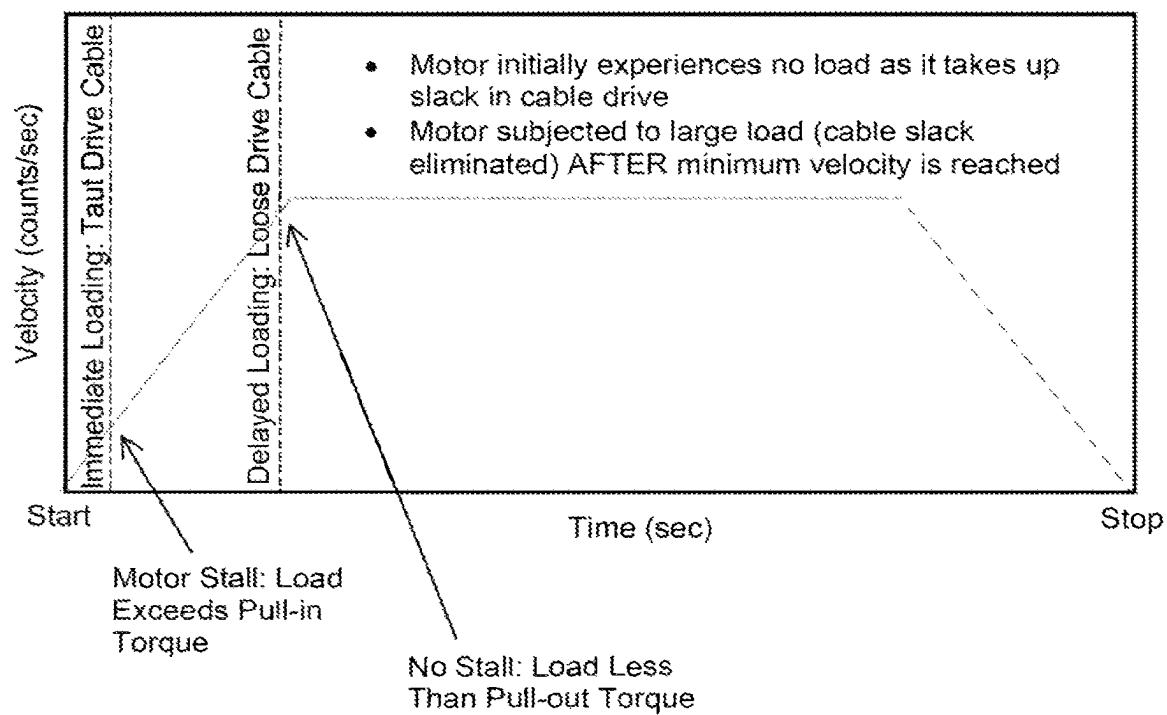
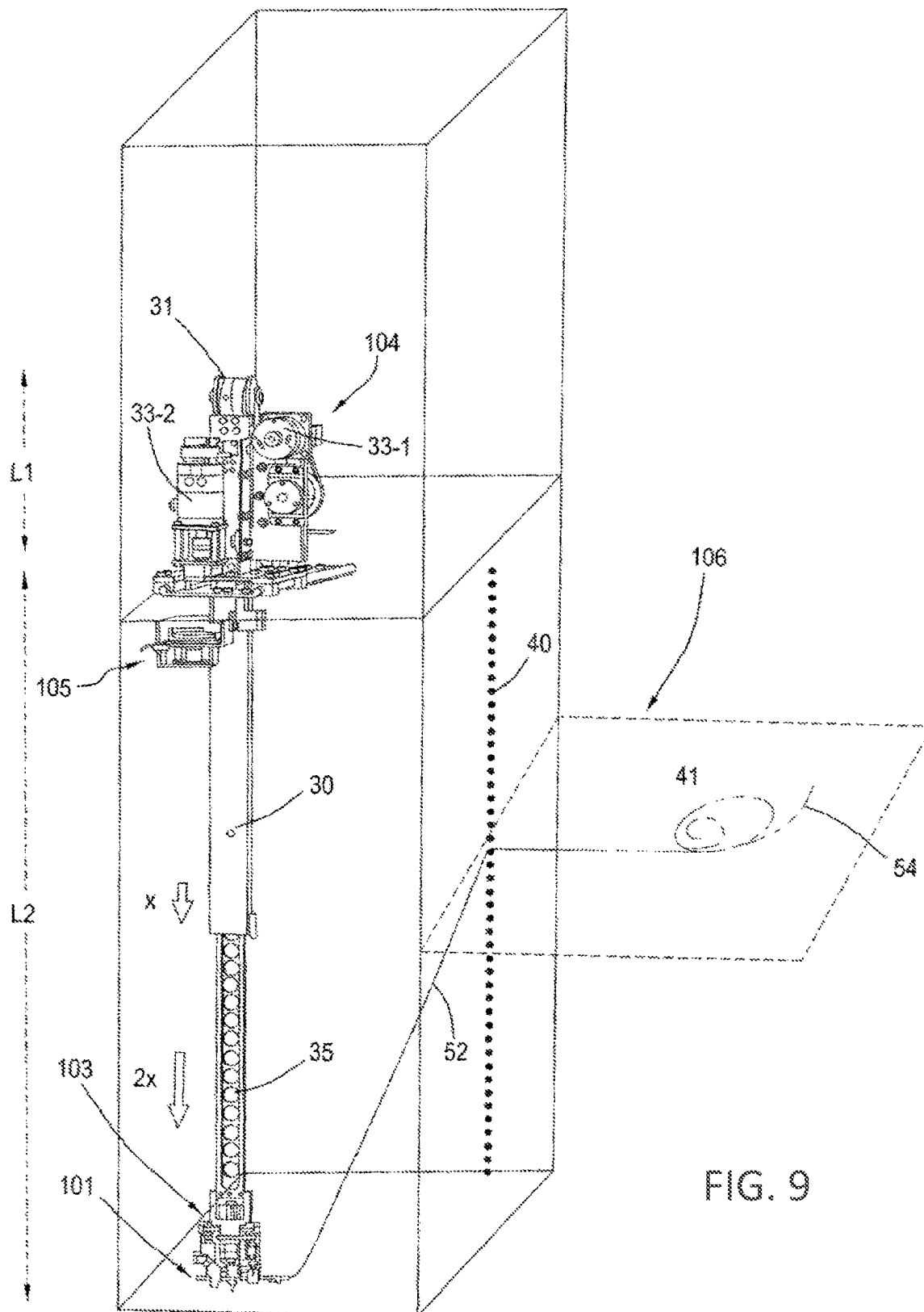


FIG. 8H



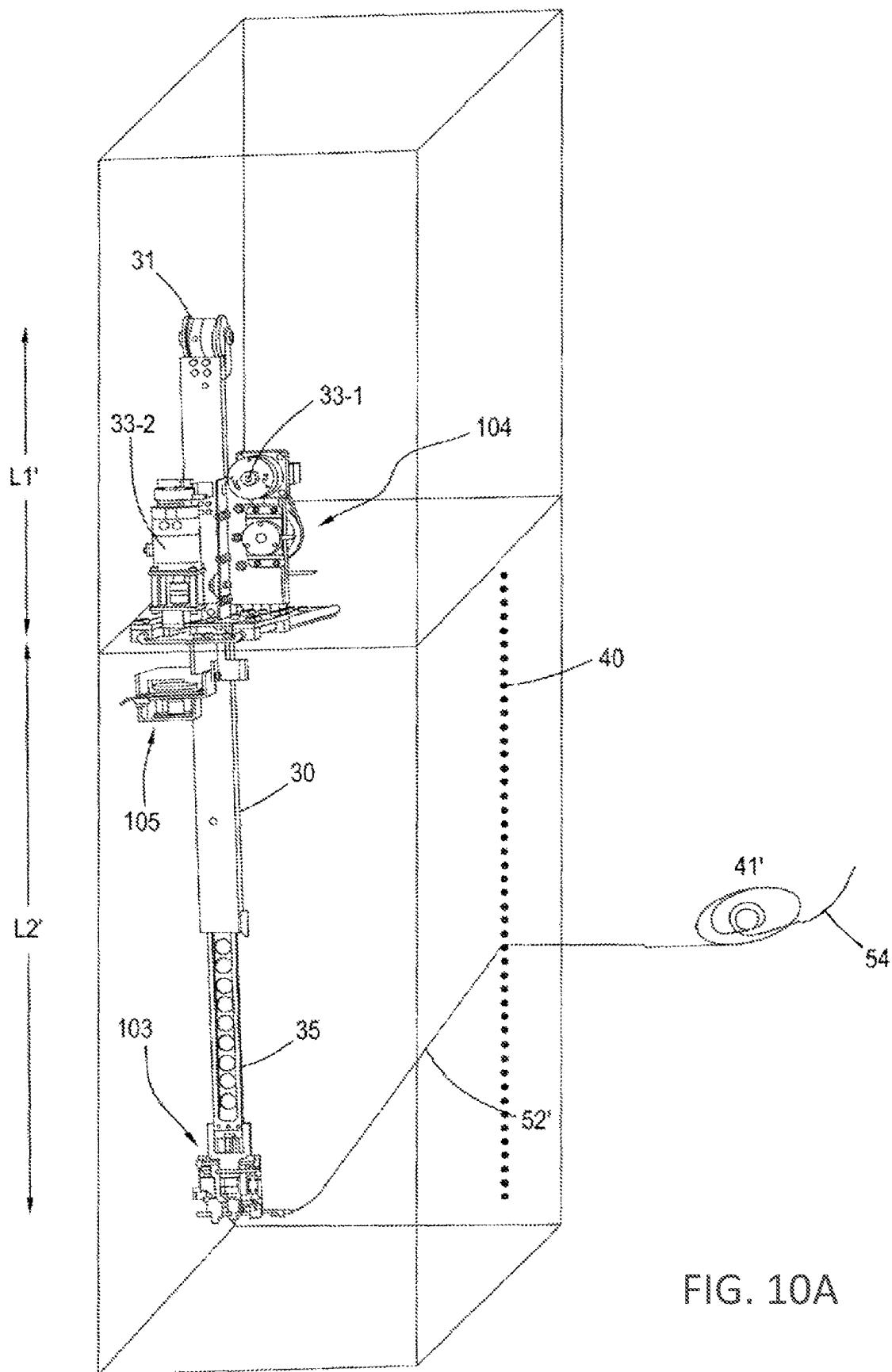


FIG. 10A

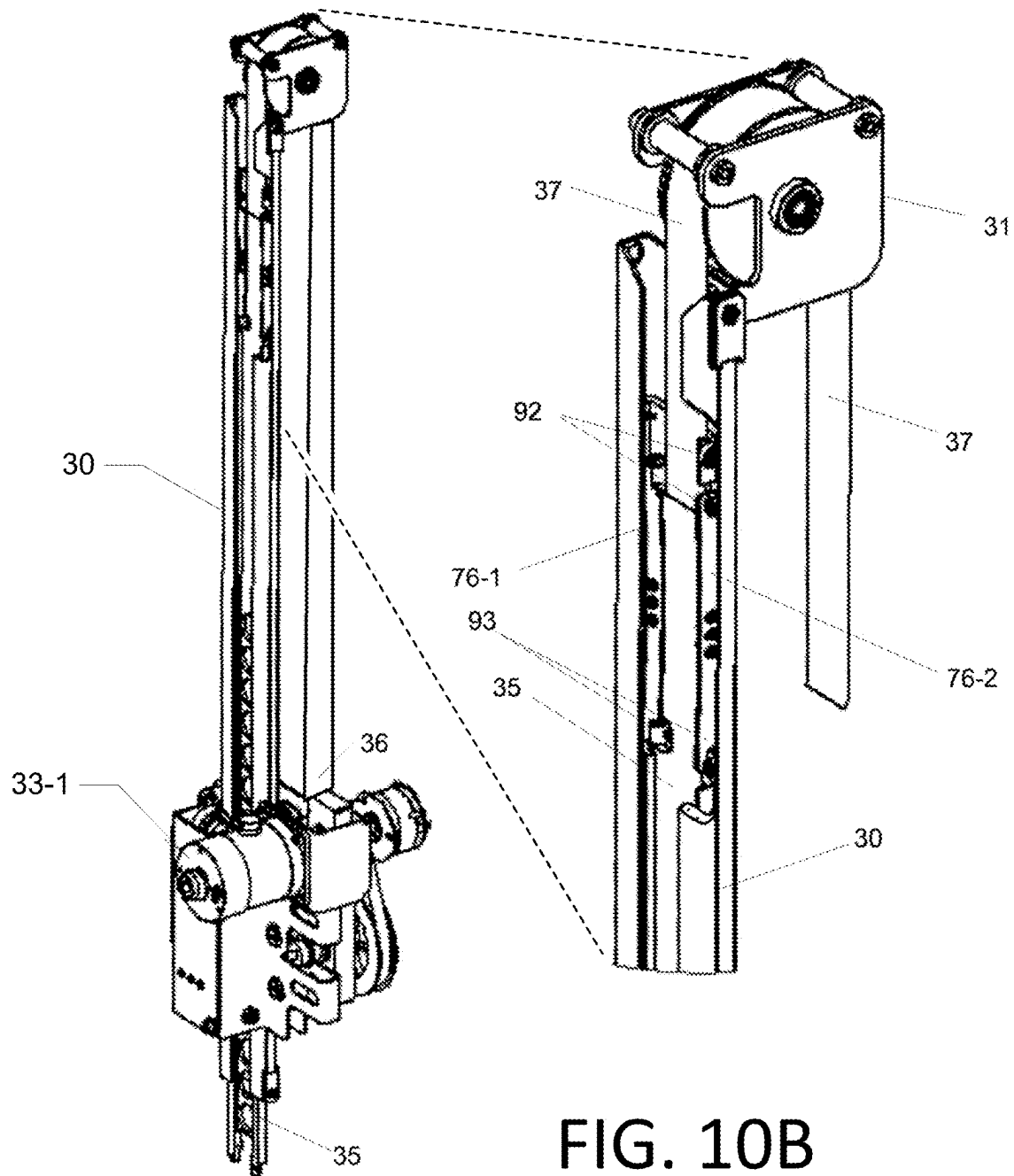


FIG. 10B

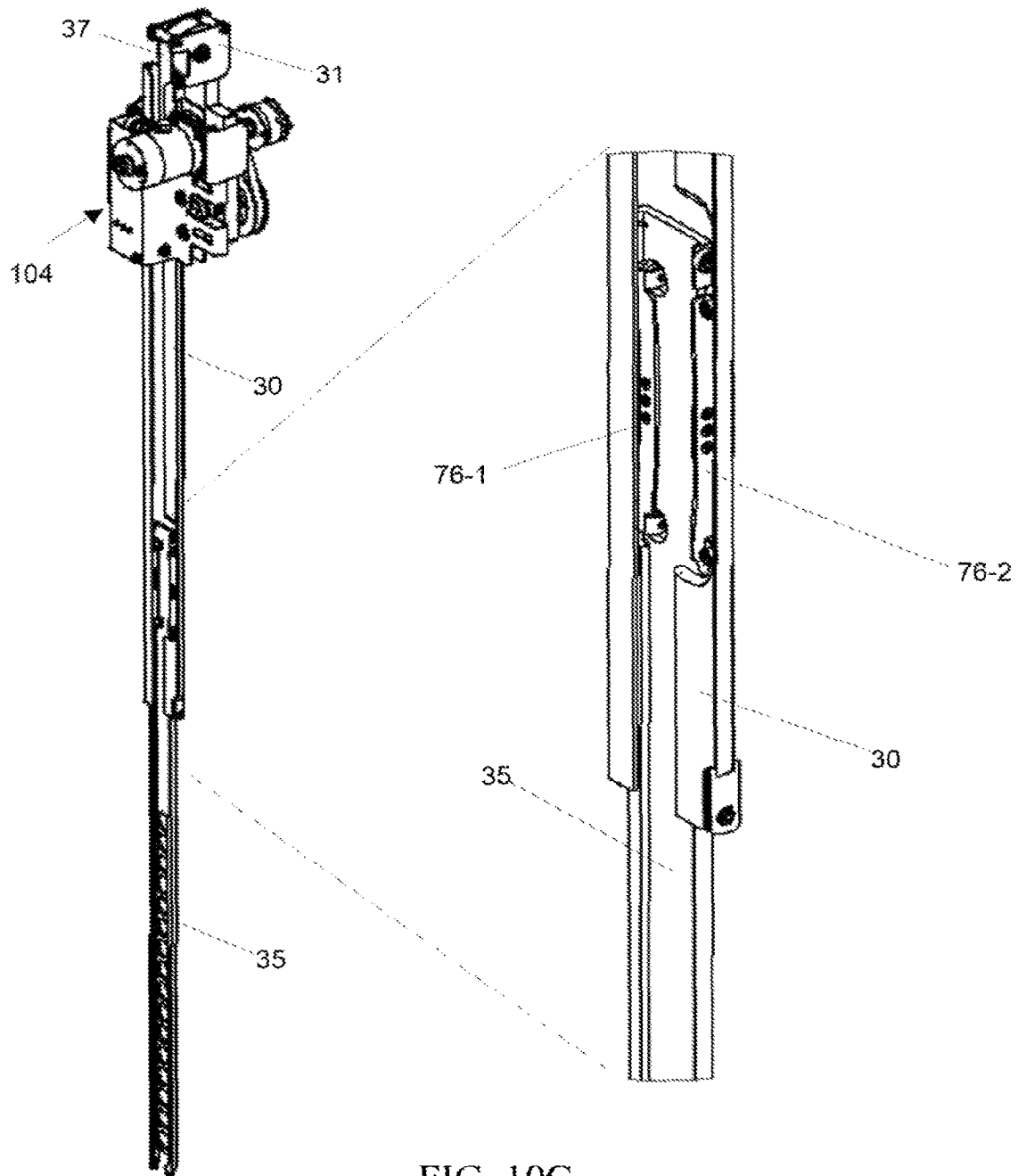


FIG. 10C

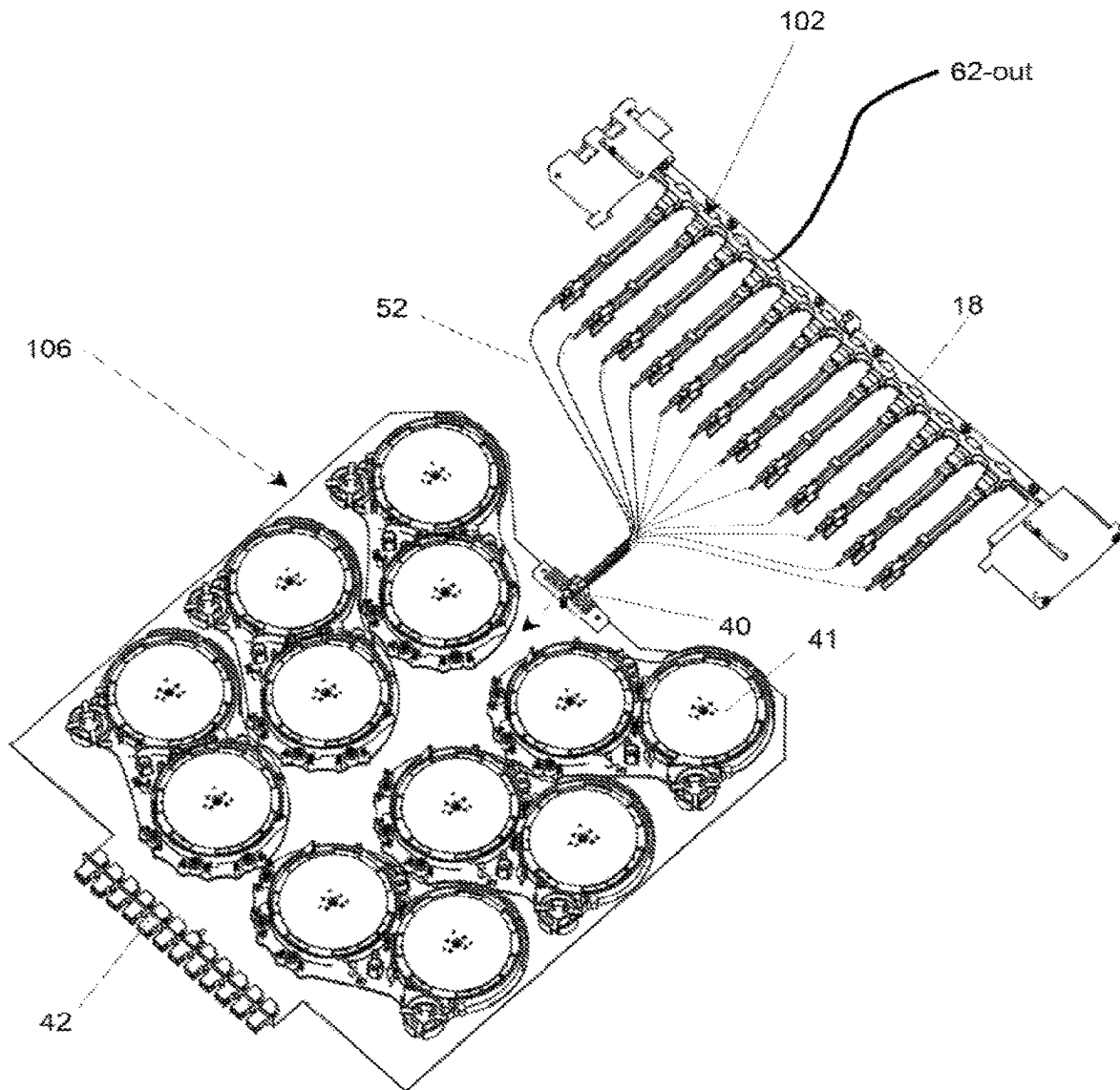


FIG. 11A



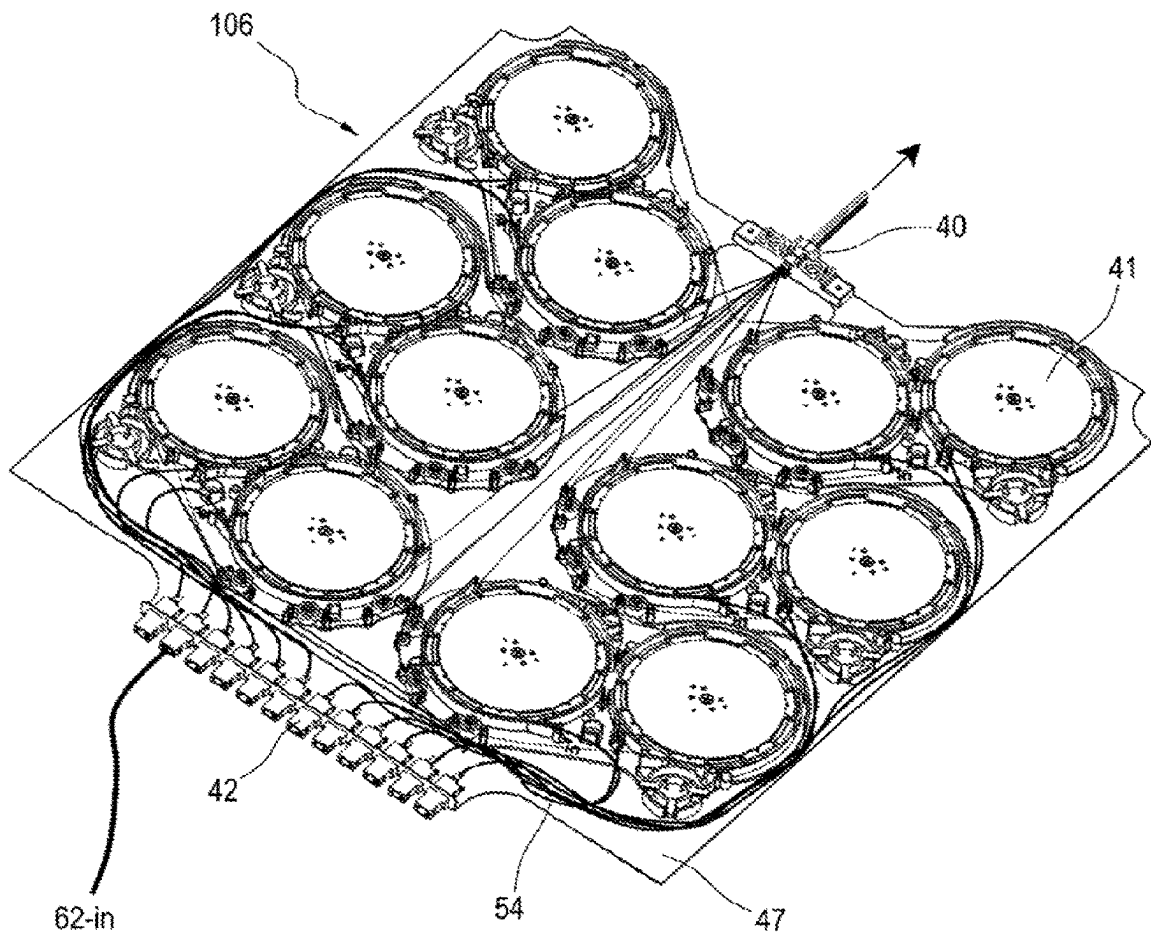


FIG. 11B

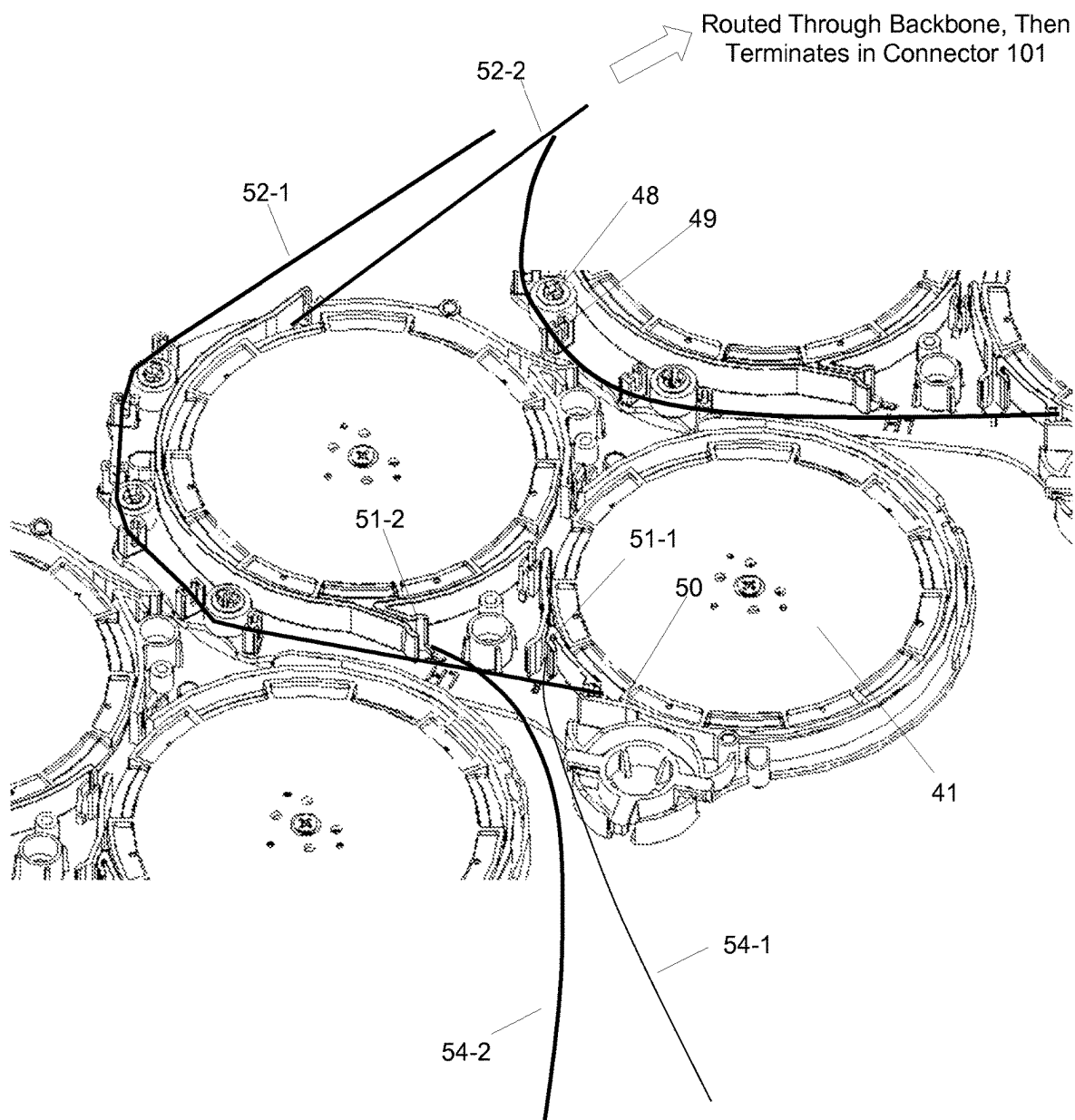


FIG. 12

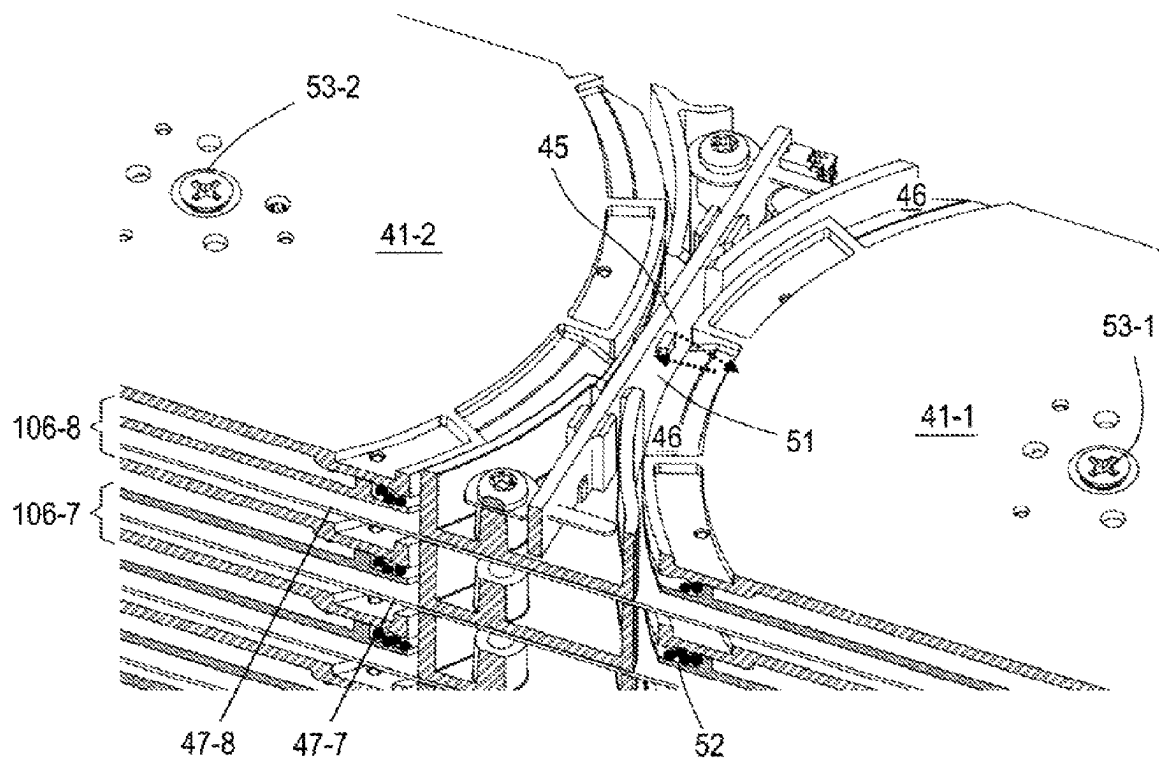


FIG. 13A

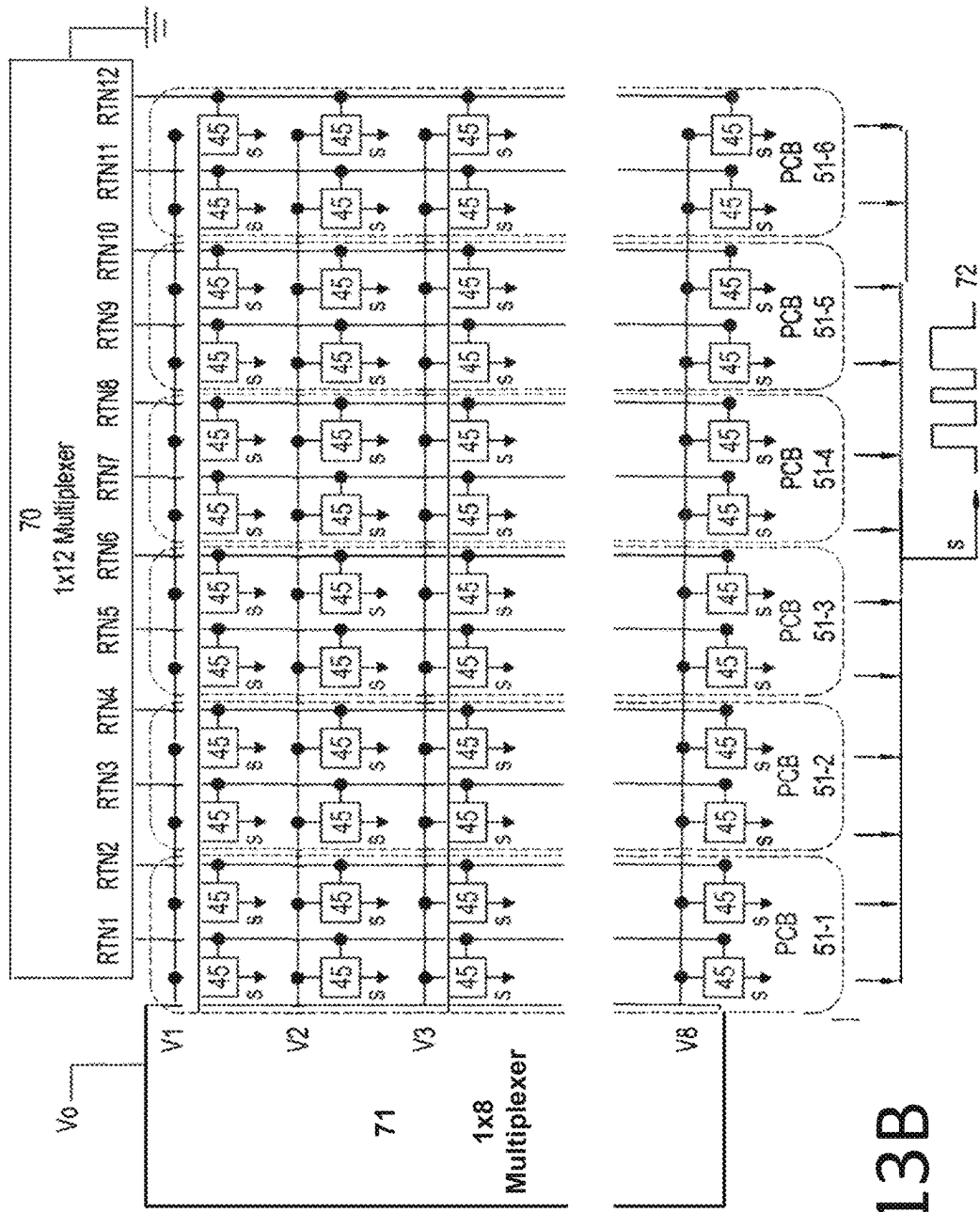
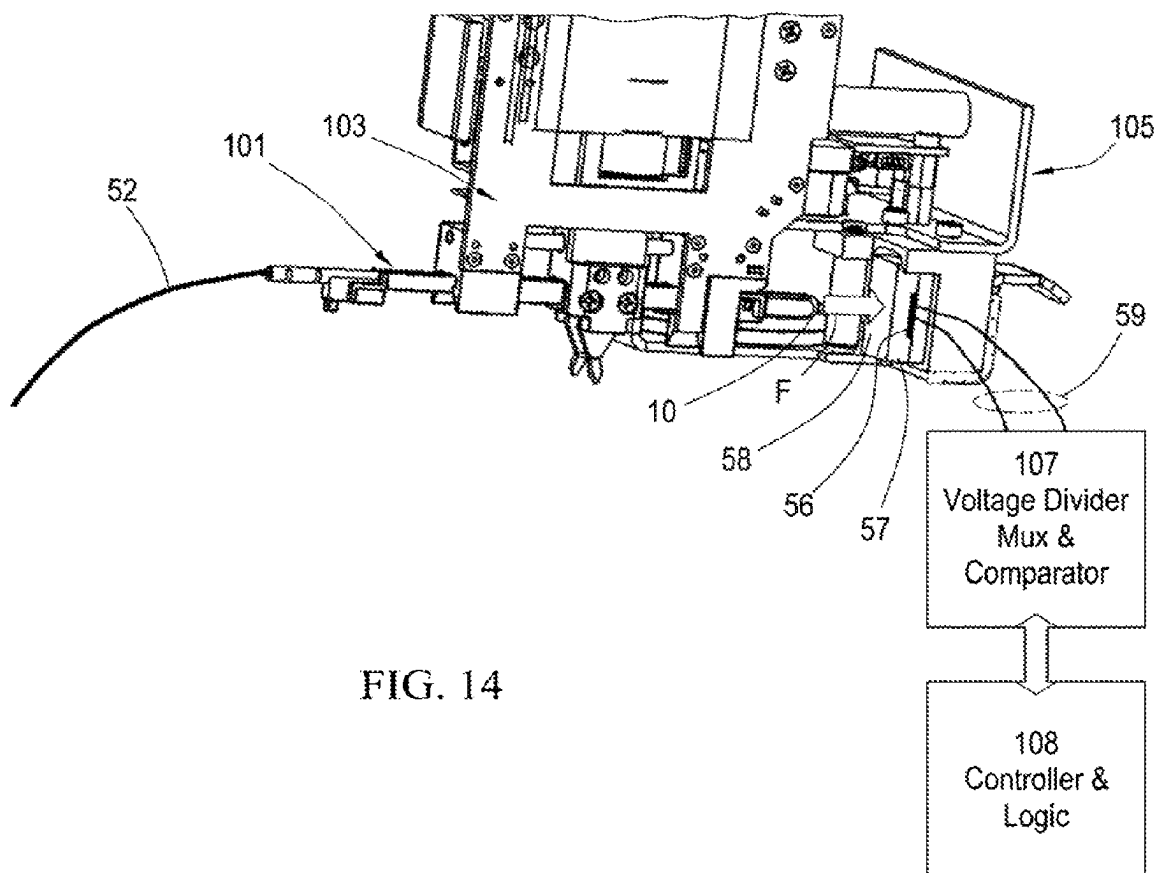


FIG. 13B



LEFT CUTAWAY VIEW

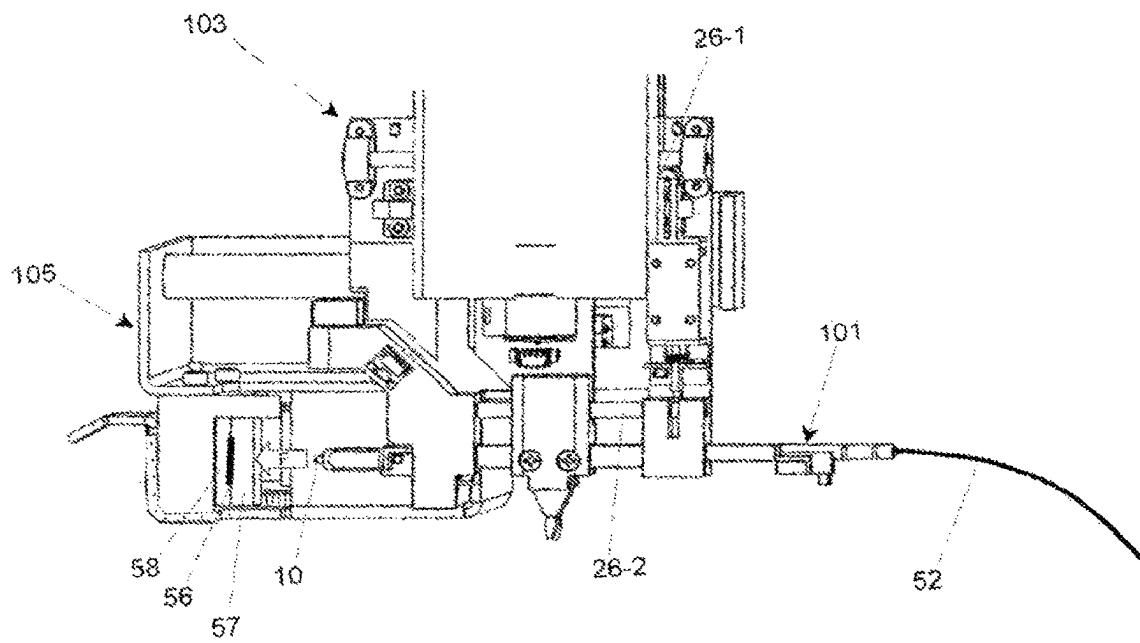


FIG. 15

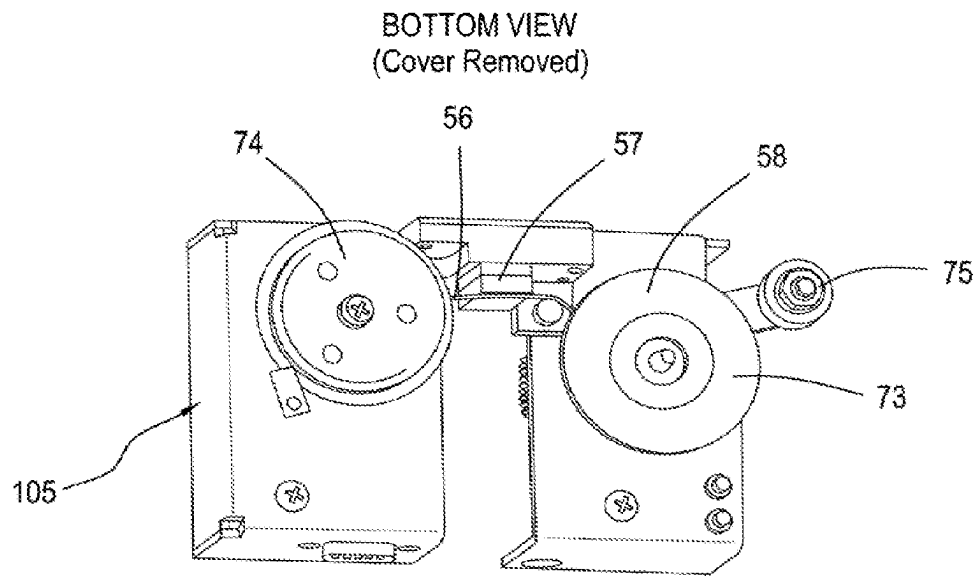


FIG. 16A

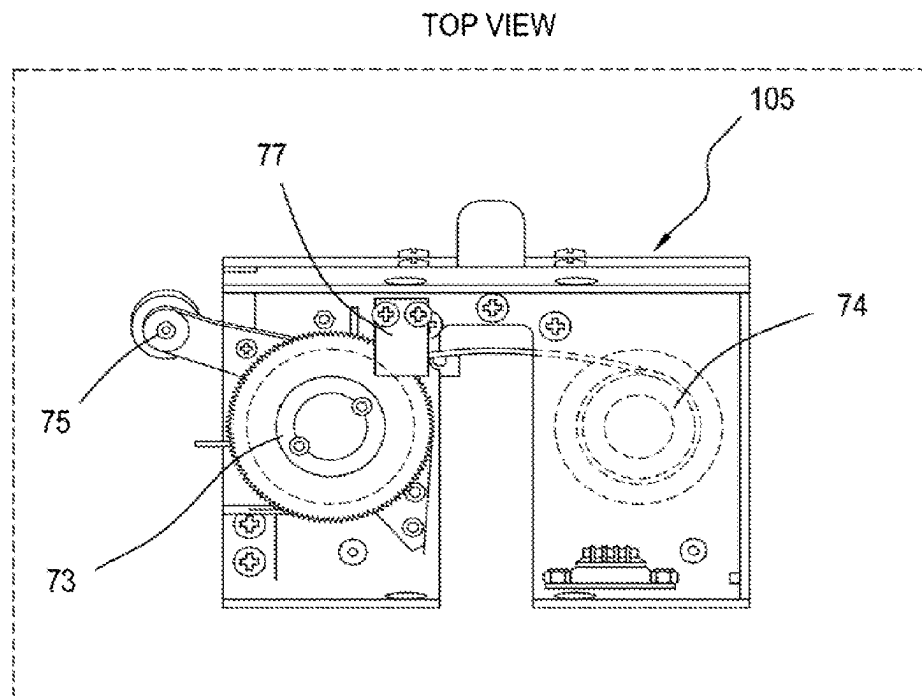


FIG. 16B

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# HIGH-RELIABILITY ROBOTIC CROSS-CONNECT SYSTEMS

## RELATED APPLICATIONS

This application is a continuation of U.S. patent application Ser. No. 17/717,950, filed Apr. 11, 2022, issued as U.S. Pat. No. 11,953,731 on Apr. 9, 2024, which is a divisional (continuation) of U.S. patent application Ser. No. 16/858,994, filed Apr. 27, 2020, issued as U.S. Pat. No. 11,340,402 on May 24, 2022, which is a continuation of U.S. patent application Ser. No. 16/504,194, filed Jul. 5, 2019, issued as U.S. Pat. No. 10,649,149, on May 12, 2020, which is a continuation of U.S. patent application Ser. No. 14/949,861, filed Nov. 23, 2015, issued as U.S. Pat. No. 10,345,526 on Jul. 9, 2019, and which claims priority from U.S. Provisional patent application No. 62/091,541, filed Dec. 14, 2014, the entire contents of all of which are hereby fully incorporated herein by reference for all purposes.

## BACKGROUND

### 1. Field of the Invention

The present invention is directed in general to large-scale robotic cross-connect systems providing low loss, software-defined fiber optic connections between a large number of pairs of ports. Mechanisms in the systems incorporate numerous features that ensure reliable operation.

### 2. Description of the Background Art

Large-scale automated fiber optic cross-connect switches and software-defined patch-panels enable data centers and data networks to be fully automated, wherein the physical network topologies are software-defined or programmable, for improved efficiencies and cost savings. Current fiber optic switch technologies such as crossbar switches scale as  $N^2$  ( $N$  is the number of ports), making them ill-suited for large-scale production networks. Prior art disclosures of crossbar switches include U.S. Pat. No. 4,955,686 to Buhner et al., U.S. Pat. No. 5,050,955 to Sjolinder, U.S. Pat. No. 6,859,575 to Aral et al., and U.S. Patent Publication No. 2011/0116739A1 to Safrani et al.

More recent automated patch-panel approaches that scale linearly with the number of ports utilize braided fiber optic strands. Advances in the mathematics of topology and Knot and Braid Theory (U.S. Pat. Nos. 8,068,715, 8,463,091, 8,488,938, and 8,805,155 to Kewitsch) have solved the fiber entanglement challenge for dense collections of interconnect strands undergoing arbitrary and unlimited reconfigurations. Since this Knots, Braids, and Strands (KBS) technology scales linearly in the number of interconnect strands, significant benefits over crossbar switches such as density and hardware simplicity are realized. Existing systems featuring autonomous patch panel systems and implementing KBS algorithms in accordance with the Kewitsch patents referenced above typically utilize a pick and place robotic actuation system with a gripper at the end of the robotic arm to grab and transport a fiber optic connector and the fiber optic strand extending therefrom to a central backbone in the system. The robotic arm is of a narrow width and extended depth to allow it to descend into the dense fiber optic interconnect volume with no mechanical interference and no contact with surrounding fibers, yet still having sufficient rigidity to experience minimal deflection under transverse forces, including magnetic repulsion and tension originating

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from the fiber being carried in the gripper therein. However, further improvements in this new class of physical fiber-optic switching or connection management system are always desirable, including those relating to improvements in compactness, hardware simplicity, and operative reliability, singly or in combination.

## SUMMARY

The present invention relates to apparatus to improve the performance of this new type of cross-connect utilizing braided fiber optic strands and the application of the mathematics of topology to this scaling challenge. In this invention, a highly reliable automated cross-connect system is employed with multiple unique hardware and operative features to provide superior compactness, performance, and reliability. For example, a dense three-dimensional matrix of parallel and precisely separated connector elements is distributed through two orthogonal dimensions, with a plurality of multi-functional elements being disposed along each connection path in the third dimension. The connector paths each comprise individual ones of a plurality of linear base elements, which are each separately movable to align with a chosen base element in the cross-connect system. The invention includes unique magnetically latched fiber optic connector devices, which enable the system to provide multiple different user-defined states of insertion loss. The devices include reliable, self-guiding, attraction mode magnetic latching to facilitate repeatable robotic engagement and reconfiguration. Robotic miniature gripper devices that retain the magnetically latched fiber optic connectors are further disclosed, wherein the miniature gripper includes integral sensing and actuation means to ensure proper engagement with a selected connector. Furthermore, the system is configured with movable rows of multiple, spaced-apart horizontal connector receptacles stacked vertically therein. Each row is comprised of multiple parallel connector tracks, and each connector track includes a mating connector receptacle, a fiber optic interface port, and combined mechanical and magnetic reference features which are configured to achieve reliable latching and locating of both the fiber optic connector device and the gripper device. The movable rows of connector receptacles incorporate precision injection molded translation assemblies, and actuation means to accurately and precisely translate rows between one of three horizontal locations. These locations generate the vertical row shuffling response as dictated by the KBS algorithm and aid in improving the volumetric efficiency of the system.

The gripper consists of a two-part body, a central body which mechanically engages or interlocks with a particular target connector extended member in between the multiplicity of surrounding extended members, and a driven, translatable outer body or frame incorporating means to engage and sense the reconfigurable internal fiber optic connector assembly. The narrow width gripper, attached to the lower end of the controlled telescopic arm, descends down onto a selected centered connector row until a gripper interlock sensor detects proper engagement with the extended member. The gripper's outer body translates parallel to the extended member to plug-in, unplug or partially disconnect the internal connector assembly. The translation mechanism uniquely incorporates a drive line, wrapped around a motor drive shaft with a small but precise excess length to control bidirectional lateral translation of the gripper. This obviates the stalling of the drive motor upon a startup acceleration from a state of rest.



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The cross-connect system is also based on a three-dimensional array of parallel but precisely laterally separated elongated reference members disposed in an augmentable vertical stack of horizontal rows. The reference members are narrow and of selected uniform length, having chosen flexure properties, and include sets of small permanent magnets deployed so as to utilize both magnetic attraction and repulsion forces during different and separate operative states of engagement. Each narrow reference member is positioned to be closely adjacent to a different receiving aperture into which the end of a different optical fiber connector can be inserted. The end apertures lie in transversely disposed horizontal rows in a vertical connection plane, and each is positioned to potentially receive the end of the optical fiber connector repositioned by the system. The small permanent magnets along their lengths are positioned selectively and with such polarities as to provide at least two stable insertion positions and also a transversely repulsive force, to maintain adjacent elements separate in a dense three-dimensional array of elements.

This application further discloses a uniquely compact configuration for accessing and repositioning optical fibers on command. Telescopic robotic arm devices of minimal transverse compliance and high length efficiency (ratio of the range  $L_2$  to retracted height  $L_1$ ), independent of extended length (zero to  $L_2$ ), are achieved by deployment of a unique vertical telescoping structure that is horizontally movable from one connector track, through surrounding fibers and to another connector track under the direction of the KBS algorithm. The two-stage telescopic arm arrangement is based on chosen linear lengths of a vertical rectangular tube or "C" shaped outer body, with an internal slider body maintained in alignment by a unique sliding bearing carriage and spring preloading arrangement within the telescopic arm. The arrangement enables a constant length, flat, flexible electrical interface cable to be routed dynamically from the gripper mechanism to an external control system, which serves the dual purpose of pulling the internal sliding body, so it moves in synchronism with the outer body. The robotic arm and gripper configuration are of very narrow width, enabling it to move unencumbered throughout the limited spaces in the fiber interconnect volume.

An automated cleaning device is further described, with the additional feature of integral sensing of the force on the cleaning fabric and polished fiber optic connector ferrule during cleaning. The electrical signal produced therein is utilized to provide feedback to accurately control the robot position and maintain less than a maximum value of compressive force at the fiber end face. This precise control ensures repeatable, high-quality cleaning of the fiber end face, preventing the accumulation of particulates to thereby achieve consistently low insertion loss, high return loss optical connectivity, for superior quality and consistency compared to present manual processes. In the fiber cleaning subsystem, the cleaning fabric is fed from a supply spool through the cleaning cassette pad and onto a dispense spool. The arrangement enables multiple fibers to be cleaned from a single supply spool.

Stacked planar arrays of optical fiber take-up spools with fibers dynamically routed through a combination of eyelets, guides and rollers distributed in a precisely spaced geometry provide a source of low loss optical fiber connections between a fixed input array and a physically changeable output array. Each spool is independently tensioned to the degree necessary to retract any excess length of fiber between the internal one-dimensional backbone and two-dimensional output connector array, without subjecting the

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fiber to excessively sharp bends resulting from the controlled tension, such that the reliability and optical transmission characteristics of the fiber are not compromised.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A depicts the arrangement of a number of significant functional elements comprising a robotic fiber optic cross-connect system in accordance with the present invention, populated with one set of eight rows and with capacity for adding more rows both below and above those eight rows as depicted; FIG. 1B is a block diagram of other inventive combinations in accordance with the invention; FIG. 1C is a simplified perspective view illustrating the arrangement of interrelated modules, and FIG. 1D is a block diagram of some interrelated system elements in accordance with this invention;

FIG. 2 depicts a fragmentary view of the magnetically latching internal fiber optic connector in accordance with the invention, including its features for interfacing and mating within the robotic gripper, its relationship to a connector row for receiving and holding the connector, and a side detailed view of the resulting magnetic repulsion forces between connector rows;

FIG. 3 is an interior view of a stacked arrangement of eight connector rows, forming a stackable module of 96 fiber optic ports with means to magnetically engage fiber optic connectors transported thereto by the gripper, further illustrating the relationship between the connector magnet and the connector row magnets with a tri-state configuration;

FIG. 4 illustrates an exterior view of the same stacked arrangement of eight connector rows, producing the two-dimensional array of fiber optic ports to which external cables requiring cross-connections are plugged in;

FIG. 5 is a side view of a gripper device in accordance with the invention, with fiber optic connector in the allocated configuration detailing the numerous positional sensing and actuation means;

FIG. 6 is a side view of the gripper device in the unallocated configuration;

FIG. 7 is a side view of the gripper device in the unplug configuration;

FIG. 8A is a partial, perspective view of a two-axis robotic actuation system in accordance with the invention, which moves a gripper mechanism within the internal fiber cross-connect volume; FIG. 8B is a schematic view of an x axis drive mechanism; FIG. 8C is a schematic view of a y axis drive mechanism; FIG. 8D is a schematic view of the y axis drive in various extended states; FIG. 8E illustrates the gripper z axis drive mechanism in central position, FIG. 8F in left position, FIG. 8G in right position, and FIG. 8H illustrates the velocity trajectory of the gripper stepper motor actuating the z axis drive;

FIG. 9 is a further perspective and diagrammatic view of actuation system of FIGS. 8A-8C, depicting the gripper at the end of a two-stage telescopic arm in the fully extended state;

FIG. 10A is a partial view of the two-stage telescopic arm in the partially extended state, FIG. 10B is a partial break-away view of the vertical portion of a telescopic arm in the substantially retracted range of travel, and FIG. 10C is a perspective view, also partially broken away, of different segments of the telescopic arm in the substantially extended range of travel;

FIGS. 11A and 11B are top perspective views of an improved fiber take-up tray for fiber tensioning and dynamic slack fiber management, each including twelve individual

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reels and fiber guides facilitating low loss, dynamic optical fiber routing therebetween to the central backbone, depicting the portion of fibers in front of the backbone in FIG. 11A and the portion of the fibers in back of the backbone in FIG. 11B;

FIG. 12 is a perspective view of a portion of the stacked arrangement of multiple fiber take-up trays, detailing the routing of optical fibers from individual reels to the central backbone through low friction O-ring shaped eyelets and soft rubber-clad rollers;

FIG. 13A is a partial cutaway perspective view of a portion of the optical fiber reel system including sensing electronics to detect the rotation of the reel during dynamic reconfiguration such that proper fiber slack management can be validated, FIG. 13B is a block diagram of a subsystem for processing the electronic signals from the sensing electronics to establish proper system response to reel position commands;

FIG. 14 is a first partial cutaway perspective view detailing a part of a gripper device and the cleaning cartridge, and in accordance with the invention, showing a force sensor integral to a fiber end face cleaning device in operative position;

FIG. 15 is a second partial cutaway view of the operative side of the fiber end face cleaning device of FIG. 14 in operative position relative to the gripper device; and

FIGS. 16A and 16B are partial cutaway bottom and top views respectively, of the fiber end face cleaning device, as depicted generally in perspective views of the system such as FIGS. 1, 9 and 10A, and showing a number of advantageous operative features therein.

## DETAILED DESCRIPTION

### I. Robotic Cross-Connect System

This application discloses robotic cross-connect systems providing low loss, software-defined fiber optic connections between a large number of pairs of ports. The number of ports typically ranges from 48×48 up to 1008×1008 and beyond. FIGS. 1A-1D illustrate a number of principal aspects of this system, comprised of a robot module 112 including a telescopic two axis robot arm assembly 104, a fiber optic connector end face cleaning cartridge module 105, a miniature actuated gripper or gripper assembly 103, a stacked arrangement of connector rows 102-1 . . . 102-N, and a stacked arrangement of fiber take-up reel trays 106-1 . . . 106-N. Groups of connector rows 102-1 . . . 102-8 further comprise the front actuated patch-panel of fiber module 113. The gripper 103 is able to unplug any fiber connector 101-n from among the array of fiber connectors inserted along the connector rows 102, then transport it in a deterministic, optimal weaving pattern between the surrounding fiber connectors of the array upon manipulation by the robot arm assembly 104. The process of transport thus includes a coordinated, sequential, multi-step movement of the robot and programmatic shuffling of each connector row 102 in accordance with the KBS algorithm as described in U.S. Pat. No. 8,463,091 referenced above. Before plugging in the fiber connector 101-n to its chosen final port 55, the polished fiber end face of fiber connector 101-n may be cleaned by the fiber end face cleaning cartridge module 105 as shown generally in FIGS. 1 and 9 and described in detail below with respect to FIGS. 14 to 16B. The fiber connector 101-n terminates the internal optical fiber 52, wherein this optical fiber originates from an automatic, spring loaded take-up reel residing within the multiple take-up reel tray 106. The take-up reels ensure that all internal optical fibers are maintained under slight tension in the fiber interconnect

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volume between the connectors 101 and the take-up reels so that they follow substantially straight-line paths for all possible arrangements of connectors 101 within ports 55. Straight-line paths are efficiently represented mathematically and facilitate the routing by the KBS algorithm as described in the above referenced patents.

In reference to the block diagram in FIG. 1B and the perspective views in FIGS. 1C-1D, the KBS algorithm is implemented in software instructions residing on server module 109 and communicating in parallel with each Fiber Module 113-1 . . . 113-10, Docking Module 114, Optical Power Monitor Module 115, Robot Module 112, and Power Management Module 111 through the Ethernet Switch 110 and by use of the Ethernet protocol TCP/IP. In a further example, each module is powered by 24 VDC, which is supplied by a power distribution bus in the Power Management Module 111. The Robot Module 112 is in communication with a Gripper Sensor Circuit 116 to detect the operative state of the fiber connector in transport, as well as a comparator circuit for a force sensor 56 (e.g. a thin film resistive sensor) integral to the cleaning cartridge. The fiber modules 113 each are in communication with a multiplexed array of reel encoder sensors responsive to the rotation of any particular take up spool/reel 41, the rotation resulting from internal fiber length changes due to movement of the internal fiber connector.

FIGS. 1A, 1B, 1C further depict details of the integrated and cooperative relationship between several novel operative parts of this system, which further extend the art of automatic switching of selected ones of a plurality of optical fiber lines as described in the above-referenced Telescent patents. Inputs to the system comprise a plurality of lines 62-in (FIGS. 1A and 1C) distributed in ordered spaced apart columns and rows in a coupling plane, and spaced apart by a predetermined gap, fed into one side of each individual one of an array of two-sided optical couplers 18. They are then connected in the coupling plane with low loss internal fiber connectors to an opposing array 42 of input optical couplers, and connected to a plurality of lines 62-out at the opposite side of the patch panel system 200. The individual rows stacked orthogonally in a first direction and are separately incrementally shiftable laterally by one of a stack of row shift actuators in accordance with the fundamental Knots and Braids methodology (referenced above). Changeable lines/optical fibers 52 (FIG. 4) are coupled into the second side of the optical couplers 18 and these lines converge into a one-dimensional alignment at backbone 40 and are then distributed into ordered levels of multiple spools serving as buffer reels 41, as described below in more detail in relation to FIGS. 11 to 13. These reels 41 compensate for path length variations as internal fiber 52 positions and their corresponding suspended lengths are changed, without introducing curvatures in the optical fibers that are so sharp and non-adiabatic that they would introduce light loss at bends. From the assembly of buffer or take-up reels 41 the fiber pattern is reconfigured, typically into an array of the linearly disposed receptacles or optical couplers 18, which can then be retransmitted or otherwise reconfigured as desired.

Given this context, some principal aspects of the present invention that are also shown in generalized form in FIG. 1A (although shown and discussed in more detail below) further establish the internal cooperative relationships in form and function. For example, the arrangement of rows and columns of two-sided couplers in the connector row assemblies 102 provide signal interchange between lines from opposite sides. On the internal, changeable side, the structures comprise individual linear fixed elements of predetermined

length, cross-sectional configuration and flexibility. Each of these fixed elements also supports a pattern of small permanent magnets within its boundaries and adjacent its internal end as described in detail below with reference to FIGS. 2 to 4. In combination with this, each changeable optical fiber 52 in the system terminates in a connector row assembly 102 of approximately matching length for coupling to any individual fixed element 63 with which it is to be paired. When a terminal protruding end of ferrule 10 of the optical fiber 52 is inserted in the individual optical coupler 18 of the connector row assembly 102, an individual changeable optical circuit is completed. Together with a number of features described in detail hereafter, that pertain either or both to design and operative relationships, this concept and its implementation are unique.

Interrelated functions are provided in the system that pertain to the engagement and disengagement actuation operation as well as to the interchange of fibers to and from the couplers. Two different states of linear engagement and a related state of disengaged physical proximity are utilized, as is described in more detail below. These states are affected during a linear alignment phase independently of the repositioning of fibers by interweaving through the columns and rows as described in detail in the previously referenced patents.

These as well as other functions are affected by commands from a trajectory control system 117 (FIG. 1B) which receives cross-connect configuration information from a server module 109, and a source of updated data, based on stored interconnection data from a memory system in server module 109 holding updated data. Again, reference may be made to the patents mentioned above for a full understanding of the elements and relationships that are germane to positioning of the gripper assembly 103. These movements are substantial in orthogonal X and Y directions and also incremental in the Z dimension under commands to the activated gripper assembly 103 at the activator from the trajectory control system 117. For these functions the system 200 deploys a vertical multi-stage head positioner controlling movement in the Y axis, comprising a narrow rectangular hollow robot arm upper stage/outer stage 30 inside of which a linear and narrower lower section or inner stage 35 slides by spring-loaded rollers in a proportional ratio. Both receive command signals from the trajectory control system 117, and are driven by a Y axis drive 33-1, typically a brushless de servomotor or stepper motor, responsive to command signals from the server module 109. The Y axis robot arm outer and inner stages 30, 35 are moved horizontally as command signals are delivered from the trajectory control system 117 which activates the X axis drive motor 33-2. Most of this mechanism is positioned above the fiber interchange matrix, while the narrow fiber interchange head acting as a gripper 103 as discussed in detail below (FIGS. 5-7) is movable vertically in the spaces between the vertical column j of fibers 52 and indicated by 118-j in FIG. 3. The horizontal connector rows 102 of the interchange matrix are selectively moved incrementally in a first horizontal direction or oppositely during threading through the matrix. When the activated head of the gripper assembly 103 reaches a target location in a connector row 102, it can be moved incrementally along the Z axis to couple or decouple a target fiber connector 101 to the selected one of the optical couplers 18. Also, along the Z axis, it can shift the target connector incrementally between "allocate," (FIG. 5) "unallocate," (FIG. 6) and "unplugged" (FIG. 7) positions. The

corresponding magnet interactions between the connector 101 magnet 13 and the row magnets 14, 15 are noted in FIG. 3.

## II. Two-Dimensional Array of Switchable, Magnetically Latched, Multi-State Fiber Optic Connectors

This application further discloses a multi-dimensional array of fiber connector devices/assemblies 101 arranged in incrementally shiftable vertically spaced connector rows 102 (FIGS. 2-4) disposed in generally horizontally aligned columns as best seen in FIGS. 3 and 4. The horizontal rows, as best seen in FIG. 2, comprise a plurality of spaced apart parallel base elements each fixed at one end to a different optical coupler 18 which is to receive the terminal ferrule 10 of a different and changeable fiber optic line 52. Thus, the array in part comprises, as seen in the perspective views of FIGS. 1A, 3 and 4, a plurality of horizontally spaced fixed connector tracks or track elements 39 of selected flexibility and substantial length relative to their width and cross-sectional area. They are each fixedly attached at what can be called a receiver end to the transverse connector row assembly body 102, and thus provide parallel interactive elements for receiving the individual fiber optic connectors 101. These fixed connector track elements 39 have a length to width ratio of greater than 10:1, and are of substantially less height than width so they have resilience in a selected range, and no or low magnetic permeability, since magnetic forces are to be used for specific deflection purposes therewith, as described below.

Each optical fiber 52 in the system terminates in an elongated connector 101 leading to a ferrule 10 that engages in the optical coupler 18. When fully inserted, the optical fiber terminus defined by the ferrule 10 is in physical and optical contact with an external fiber terminus pre-existing in the opposite side of the two-sided optical coupler 18 and in parallel adjacency to the fixed element of the connector track 39. As seen in the three different and adjacent insertion positions for the fiber ferrule 10 depicted in the partially exploded and fragmentary perspective view of FIG. 2, a detachable portion of the connector 101 extends from the ferrule 10 at the inserted end through a shaped, slightly larger housing 11 which limits the depth of insertion of ferrule 10 in the optical coupler 18 and provides the means to engage within a matching receptacle in underside of gripper 103. The removable part further includes an intermediate section of elongated U-shaped housing 80 of a predetermined length that provides an external wall that substantially surrounds and protects the optical fiber 52. This housing member 80 encompasses an internal length of optical fiber that couples at one end to the ferrule 10 and merges at the other end with an individual different optical fiber 52 in the system. The movable connector 101 also includes a gripper latch receiving element 12 intermediately positioned along its length and a small magnet 13 of high permanent magnetic field strength at a predetermined substantial spacing from its terminal ferrule 10 which provides cooperative functions described in detail below.

The connector 101 also provides predetermined optical, mechanical and magnetic interaction with the system in general and with each different adjacent elongated fixed connector track element 39 in particular. Since, as seen in FIG. 2, each such fixed connector track element 39 extends from the underside of an optical coupler 18 in parallel adjacency to a movable fiber optic connector 101 therein, it incorporates a number of cooperative features along its length. Starting from the free end, the fixed element comprises a pair of bifurcated end sections serving as supportive bases for two small permanent magnets 14, of the same

selected polarity, at like distances from the optical coupler **18** end. These may be termed the “unallocate” magnets, to designate their operative function, while a third magnet **15** is centered on the elongated body at a predetermined small lengthwise spacing from the magnet pair **14**, and may be termed the “allocate” magnet. The third “unplugged” state shown in FIG. **3** is one that exhibits little magnetic attraction between the inserted magnet **13** and any of the magnets **14** and **15** in the fixed element. The fixed member/connector track element **39** also includes a short, slightly narrowed docking section **16** intermediate its length, and an adjacent reflector surface **17** that can be used in positioning.

The three different positions of relative engagement of the connector **101** are depicted in FIGS. **2** and **3**. The “allocate” state, as used herein refers to a relationship in which the ferrule **10** of the fiber connector **101** is fully engaged within the mating sleeve of the optical coupler **18**. The term “unallocate” refers to the state wherein the fiber connector is partially engaged within the mating optical coupler **18**. The “allocate” state produces near zero insertion loss and the “unallocate” state produces about 20 dB or more loss by virtue of the air gap between the fiber connectors. “Unplug” refers to the state in which the fiber connector is fully withdrawn from the mating sleeve, wherein the gripper is able to withdraw a connector **101** from its corresponding connector port **55** for movement to a different destination port **55**.

In a preferred exemplification, the four magnets **13**, **14**, **15** are about 6 mm×6 mm×3 mm in size, and their material is Neodymium 42SH. This magnet grade provides high magnetic attraction force of at least 500 gram-force in “allocate” state, and also maintains magnetic properties even when exposed to high temperatures (above 150 degrees C.). The N-S magnetization axis is typically parallel to the 6 mm side. Ideally, the magnets are nickel-plated so they can be soldered to metalized pads of the printed circuit board connector row using a standard solder reflow process.

### III. Parallel Rows of Fiber Optic Connectors that Independently Translate Laterally Under Software Control

A portion of the automated cross-connect structure **200** in the present invention thus comprises a stacked arrangement of independently translatable connector rows which form a two-dimensional array of ports. A particular example with eight vertically stacked connector rows **102** with a vertical spacing of about 12.5 mm is depicted in FIGS. **3** and **4**. In this particular example, each row **102** is comprised of twelve parallel connector tracks each spaced transversely by about 32 mm. Each connector track is elongated and narrow and has selected flexure properties. The N-S polarity and arrangement of magnets **14**, **15** at the distal end of each connector track are identical for each track and row. As a consequence, when the rows are in horizontal (x) alignment as shown in FIG. **4**, the magnets **14**, **15** on each row cause the distal ends of each connector track **39** to repel one another in the x and y directions. These repulsive forces are effectively positioned to partially magnetically levitate the narrow semi-flexible connector row assembly **102** and reduce the potential for interference of adjacent rows of extended connector tracks **39**.

In the absence of magnetic levitation of fixed connector tracks **39** detailed in FIG. **2**, deflection of the extended connector track could otherwise occur due to the tension vector of the fiber optic connector **101** engaged therein. The minimization of deflection is effective to eliminate potential jamming of vertically adjacent rows and the fiber connectors seated therein during the independent row shuffle process.

In further accordance with this invention, each connector row is supported at opposite ends by sets of three miniature rotary bearings mounted in bearing blocks **43**, **44** that provide guidance in the two axes (x, z) parallel to the surface of the connector row, and support it above the lower row. Each bearing rides within its own track within an injection molded plastic block on the left and right ends respectively, as viewed in FIG. **4**. A central support roller **38** further provides a mechanical reference point at the center of the row to preclude a potential slight bowing along its length of the mechanical row assembly **102**. This reference surface provides adequate support to prevent large deflection of the connector row during gripper engagement when the gripper mechanically latches onto a particular connector track **39** (FIG. **2**) of the connector row.

Preferably, the connector row **102** is comprised of a printed circuit board substrate made of common circuit board materials such as FR-4 with a thickness of 2.4 mm for high stiffness. This material is flat, stiff, inexpensive, and facilitates the reliable placement and soldering of magnets onto the circuit board. The ability to add circuitry also enables the implementation of RFID tracing of connectors as well as optical power monitoring and detection.

Each connector row **102** is independently shiftable by a motor **20-1**, only some representative examples of which are seen in FIG. **4** and which are shown as a unit of four motors in FIG. **4**. This motor **20-1** is typically a linear permanent magnet dc stepper motor that provides precise, programmable linear translation of the row over about 37 mm range of travel. The low friction of the bearing track blocks or assemblies **43** and **44** ensures that only a minimal force (<100 gram-force) and low current are required to actuate each row.

As seen in the perspective views of FIGS. **3** and **4** of the connector row subassemblies **102**, the narrow elongated connector elements or tracks **39** in each row are positioned to define like vertical columns or stacks of connector elements or tracks **39**. These elements are horizontally separated from each other by a standard distance which in this example is about 37 mm. For clarity only one fiber connector assembly **101** is depicted in the upper view of FIG. **4**, and shown as coupled to an internal fiber **52** leading to an external buffer port (not shown) in the system. It will be understood from the referenced previously issued patents that interweaving through the three-dimensional mass of fibers **52** is affected by laterally shifting the rows of elongated fixed elements in timed relationship to the instant vertical position of the fiber transport. The fiber is thus repositioned by being interwoven through the existing pattern of fibers, without entanglement, until it reaches its destination, where it is engaged in the terminal thereat, as described in the earlier issued patents.

Those skilled in the art will appreciate the problems that can potentially be encountered when navigating a thin element such as an optical fiber through a dense population of other optical fibers. In this respect, the employment of static small magnetic elements on narrow elongated elements to provide strategic magnetic attraction and repulsion forces, offers material benefits in the form of the presently disclosed system, both as to changing positions of elements and in maintaining stable operating states.

### IV. Narrow Form Face Gripper to Selectively Transport, Install and Reposition Fiber Optic Connectors in a Dense Matrix

FIGS. **5**, **6** and **7** illustrate an electronically actuable gripper device **103** changeably interlocked or docking with a typical connector row **102** to produce adequate local

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actuation force at the connector **101** to vary the engagement position of a fiber connector **101** in the two-dimensional array of output ports **81** as best seen together in context in FIGS. 1-4. The gripper is shown in three primary states of axial engagement corresponding respectively to the fiber connector **101** being "allocated" (FIG. 5) (or operatively engaged), "unallocated" (or partially inserted) (FIG. 6), or "unplugged" or fully disengaged (FIG. 7) from the connector and free to be moved elsewhere (or inserted). The gripper **103** descends onto the connector row and stops upon optically detecting engagement with a particular individual optical coupler **18** of the connector row **102** using a reflective optical photo-interrupter sensor **27-6**. The light from the sensor is reflected from the edge of the connector track by a reflective plating/reflector surface **17** (FIG. 2), which is typically gold, and instructs the trajectory control system **117** (FIG. 18) that the gripper is properly docked onto the optical coupler **18**. The interlocking is accomplished by mechanical engagement of the gripper guides **20** with the reduced-width docking section **16** (as best seen in FIG. 2) present on each optical coupler **18**. The gripper subsystem comprises two closely adjacent printed circuit boards **60** and **29** lying in the narrow vertical plane which extends down to any selected row, the gripper subsystem also including multiple sensors and actuators. The upper circuit board **60** is attached to the lower end or inner stage **35** of the telescopic robot actuator (see FIG. 5). The adjacent lower sliding circuit board **29** is mounted on a linear bearing assembly, including parallel horizontal upper and lower shafts/rods **26-1** and **26-2** respectively, so that this portion of the gripper, which is not fixed to the closely adjacent printed circuit gripper board **60**, can translate horizontally in either direction between closely spaced limits within the same narrow columnar region as the fiber connector **101**. Sensors **27-1**, **27-2**, and **27-3** detect the translation of the overlapping but lower circuit board **29** in the allocate, unallocated and unplug locations, respectively, as the distance  $d$  decreases from  $d_1$ ,  $d_2$  to  $d_3$ , respectively. The lower sliding circuit board **29** includes mechanical elements **79**, **80** spaced along its length that can retain (**79**) and lock (**80**) onto the length of the fiber connector **101**. Optical sensors are typically reflective and/or transmissive photo-interrupters. A solenoid **23** responsive to control system **117** triggers a spring-loaded mechanical latch **24** within the locking element housing **80**, wherein the state of the latch is detected by reflective photo-interrupter sensor(s) **27-4** and **27-5** integrated on electronic circuit board **29**. In a particular example, translation of the gripper device **103** is powered by a motor **32** and timing belt drive consisting of a timing belt pulley **28** and timing belt **25**, or a high efficiency drum/wire drive system.

In a further example, to identify fibers based on their barcode and to provide machine vision alignment, the gripper **103** may further include a camera **21** and LED illuminator **22** to capture images of the connector **101** and its unique barcode identifier. Alternatively, the reel encoder circuit **51** enables any fiber to be uniquely identified by monitoring the reel encoder sensor signal **72** as the fiber is transported by the gripper.

In a particular example, the gripper **103** provides about 19 mm of linear travel, sufficient to allocate (FIG. 5,  $d_1$ ), unallocate (FIG. 6,  $d_2$ ), or unplug (FIG. 7,  $d_3$ ) the connector **101** as commanded where the incremental distances  $d_1$ ,  $d_2$  and  $d_3$  are approximate as depicted. When unplugged, the connector **101** can be transported vertically without interference through the lateral volumetric space **118-j** extending from the top to bottom of any particular column  $j$ , between

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and independent of all other fibers in the matrix. When a connector assembly **101** is delivered to its destination connector track **39** on the connector row, its forward or ferrule tip **10** is adjacent but spaced apart from the chosen fixed connector in the assembly of connectors **102**, as seen in FIG. 7. The gripper assembly **103** is thus held in the "unplugged" position, as seen in FIG. 7 prior to allocation. In this mode the lower planar circuit board **29** of the gripper assembly **103** is spaced apart from the connector **102**. The gripper guide **20** remains fixed as the lateral position of fiber connector assembly **101** changes. Full engagement is seen in the view of FIG. 5, in which the lower printed circuit board **29** has been shifted to the left by the actuated gripper assembly **103** in response to energizing the motor **32** of gripper actuator. This is the "allocate" position, in contrast to FIG. 6, which shows the "unallocate" or partially engaged position, and FIG. 7, in which there is no connector engagement.

#### V. Telescopic Robotic Vertical Actuator

The gripper device **103** is mounted on the lower end of, and is transported by, a two-axis robot mechanism **104** as illustrated in FIGS. 1A, 8A, 9, 10A, 10B and 10C. The robot device **104** is telescopic in the vertical direction to enable the gripper device **103** to reach a large number of cross-connects within a height constrained installation. It comprises a rectangular outer arm or outer stage **30** and an inner arm or inner stage **35**, and is movable in the horizontal direction by a drive belt **25** or wire/string extending between fixed end points. The vertical telescoping and horizontal movement capability ensure that the arm can reach all connectors within the two-dimensional array of rows of connector ports **55** (FIG. 2) without adding excessive height to the overall robotic cross-connect system above the 2.15 meter height standard preferred by the industry.

Telescopic robot arms in the prior art do not have the required stiffness nor the aspect ratio/miniaturization needed to descend and operate in between the internal fiber connectors with requisite positioning accuracy ( $\sim \pm 3$  mm) of the internal connector with tensioned fiber attached. In the present system, however, a vertical linear outer stage **30** of a slender hollow rectangular or partial rectangular cross section receives a sliding interior member or inner stage **35** of smaller cross section. As seen in FIG. 10B the top end of the arm or inner stage **35** of the robot arm includes an internal carriage that spring-loads roller bearings **92**, **93**, which contact the inner side walls of the rectangular or "C" shaped hollow cross section outer arm or outer stage **30**. In the preferred embodiment, the outer stage **30** and inner stage **35** are stainless steel or plain steel; however, aluminum, plastic, fiberglass, and carbon fiber are all suitable alternatives.

The gripper mechanism **103** is attached to the lower end of the inner stage **35** of the robotic arm system, which telescopes within the tubular outer stage **30** and variably extends in length, as seen in FIGS. 9 and 10A. The electrical cable **37** carrying electrical signals for the sensors and actuators embedded within the gripper **103** travels up the inner stage **35**, then through the outer stage **30**, exits the top of the outer stage **30**, wraps around an upper pulley **31** and then extends down to a fixed attachment at point **36**. As seen in FIGS. 8A and 9, a Y axis motor **33-1**, for example, a dc servomotor or stepper motor, drives the tubular outer stage **30** up and down through a timing belt drive mechanism attached to the top and bottom of the outer stage **30**. The multi-conductor electrical ribbon cable **37** is rigidly affixed to the top of the inner stage **35** and its midpoint is fixed at a cable attachment point **36**. As the outer stage **30** moves up and down (FIG. 8D), the inner stage **35** moves at twice the

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outer stage distance because of the action of the cable 37 looping over the pulley which is attached to and moves with the outer stage.

The telescopic arm exhibits relatively low transverse compliance or equivalently high rigidity. In a particular example, less than 2 mm of deflection results for about 50 gm of transverse force applied perpendicular to the telescopic direction (i.e. in x and z directions defined in FIG. 1) and high length efficiency (ratio of the telescopic arm range  $L_2=1.5$  meters to arm retracted height  $L_1=1$  m, FIGS. 9, 10A, 10B). This rigidity is important to prevent the tension from the fiber 52 attached to connector 101 from dragging or deflecting the telescopic arm out of true vertical alignment. In contrast to prior art telescopic arms (e.g. drawer slides, telescopic booms, etc.), the transverse compliance is independent of extended length  $L_2'$  (0 to 1.5 meters) of the telescopic structure. This is a significant advantage of the present invention, because reliable engagement of any connector 101 across the extended front connector array, by gripper 103, also requires some non-zero level of deflection and consistent deflection and compliance characteristics to enable automatic, passive alignment via the mechanical capture method. On the other hand, low vibration at all locations of the connector array at the end of the telescopic arm should also be maintained.

In accordance with the invention, tightly controlled compliance characteristics are achieved by (1) providing a roller bearing system for the outer, first stage that is very stiff and (2) providing a roller bearing carriage for the inner, second stage, wherein a set of bearings are located at the upper 150 mm of the inner, second stage, suitably preloaded by mounting the inner carriage on spring loaded roller bearing flexures 76-1, 76-2 so that the carriage is guided within the tube (outer stage) 30 with high angular consistency. The bearing system is illustrated in part in FIGS. 10B and 10C and is comprised of internal x axis support bearings 92, and internal z axis support bearings 93. To preload the system there are further preloaded internal x support bearings 92' at opposite, suspended ends of flexure 64 and preloaded internal z support bearings 93' at opposite, suspended ends of flexure 76.

The bearing flexures 76-1, 76-2 are, for example, semi-hard stainless-steel sheet metal structures deflecting under load like a leaf spring, with radial ball bearings 93 attached at both ends of the flexure arm. Mechanical stress arising from deflection is by design smaller than the yield stress of the material, thereby preventing the flexure from permanently deforming. These flexure arms 76-1, 76-2 are affixed to the rigid, steel inner second stage at the top of the inner stage 35 so that the opposite bearings are preloaded and in contact with the outer tube as they ride up and down the inner cavity of this outer first stage 30. The friction of the bearing assembly is sufficiently low that the inner stage descends controllably within the outer tube due to gravity alone and is supported by the electrical ribbon cable 37. This cable serves two purposes: it resists gravity preventing the arm from dropping and transmits signals from the gripper 103 to the trajectory control system 117. This cable 37 is routed around the pulley 31 attached to the top of the outer stage 30 and affixed to the main robot x axis carriage 61.

FIG. 8B is a schematic top-view of the horizontal or x-axis carriage drive system, consisting of a timing belt 25-1 with drive pulley 28-2 coupled to the X axis servomotor 33-2 with gearbox at one end, and an idler pulley 28-1 at the opposite end. The x-axis carriage of platform 61 is attached to timing belt 25-1, which translates the platform from one end of the x rail to the other end.

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FIG. 8C is a schematic side-view of the y-axis actuation system, detailing the timing belt pulley drive system. A first timing belt 25-2 is affixed at opposite ends to the outer y axis tube or outer stage 30 and is used to drive the tube robot arm/outer stage 30 up and down. Timing belt 25-2 is redirected and wrapped around timing belt drive pulley 28-6 by a pair of idler rollers 28-7 and 28-4. Drive pulley 28-6 and reduction pulley 28-5 are rigidly attached to a common central shaft. The drive motor 33-1 turns a small drive pulley 28-3. A timing belt 25-3 wraps tightly around both the small diameter pulley 28-3 and a spaced apart large diameter pulley 28-5. The ratio of large to small pulley diameters is typically 5 to 10 to produce a torque multiplier.

As depicted in FIG. 8D, driving the outer arm or outer stage 30 with the timing belt raises or lowers the pulley 31 by a corresponding distance X, since the pulley 31 is mounted to arm or outer stage 30. The pulley 31 is free to spin. A fixed length elongated band, cord, wire, or cable 37 is attached at one end to a fixed point 36 of the y-drive platform, and the opposite end is attached to topmost portion of inner stage 35. This configuration results in the robot arm inner stage 35 moving at 2X, twice the distance of the robot arm upper or outer stage 30. FIG. 8D illustrates the configuration of the arm at various degrees of telescopic extension. The wire or cable 37 is wrapped around moving pulley 31. For a particular distance  $X_1$  the outer stage arm 30 moves, the pulley also moves in the same direction the same distance  $X_1$ . Since the cable is a fixed length and suspends the inner stage 35, as the pulley moves a distance  $X_1$  the translating end of the cable moves by a distance  $2X_1$ . As a result, the inner stage 35 moves a distance  $2X_1$ .

A particular exemplification of the gripper shown in FIGS. 8E, 8F and 8G, to which reference is now made, details a drive mechanism for reliably incrementing a selected optical fiber mounted on the fixed printed circuit board 60. The gripper includes a gripper activator in the form of a stepper motor 32 which rotates a gripper drive drum 122 on which a cable/wire or timing belt 25' is wrapped with a controlled looseness or "play." The winding of wire 25' on drum 122 pulls the outer printed circuit board structure 29, riding on parallel rods 26-1, 26-2 to the right (as shown by the arrow in FIG. 8F) by tightening the portion of wire 25', seen here on the left side of FIG. 8F, or left (FIG. 8G) by tightening the portion of wire 25' as seen on the right side of FIG. 8G. The provision of a chosen degree of slack within the wire provides a significant improvement in the amount of torque and corresponding linear actuation force available from a given stepper motor. Under typical operating conditions, the motor 33 must drive the gripper from an initial position of maximum resistance, thereby requiring the maximum torque at the start of motion. If the wire has no slack, the motor would need to overcome a large initial force as it accelerates. This is the force to plug-in or un-plug an internal LC connector 101. It is known in the art that stepper motors stall under conditions of high torque during an initial start-up acceleration. By providing a length of slack wire 25' on each side of the drum 122, the motor initially experiences only minimal load as it takes up slack by winding excess wire on drum 122. As a result, the motor is not subjected to the large load until after (1) it reaches a minimum velocity/is no longer in acceleration phase and (2) the wire no longer exhibits slack in taut section of wire 25' on one side or the other (e.g. FIGS. 8F, 8G).

The stepper motor pull-in torque is the measure of the torque at which the stepper motor will stall when it is starting from rest. The pull-in curve defines an area called the start/stop region. When operating with proper selection

of parameters such as velocity, acceleration and load torque, the motor can be started instantaneously with a load applied and without loss of synchronism. The slack wire in the cable drive ensures that this load torque is initially low (FIG. 8H). In contrast, stepper motor pull-out torque is the torque that can be produced at a given velocity until the motor stalls. The pull-out torque is typically at least a factor of 2 higher than the pull-in torque. It is therefore advantageous for the gripper stepper motor to operate in the pull-out torque regime when experiencing the largest loads associated with plugging-in/unplugging internal optical connectors **101**, to ensure the maximum torque output for a given z drive system.

#### VI. Slack-Fiber Take-Up Reels and Rotation Sensing

The fiber connectors in the connector assembly **101** terminate as output fibers **52** (FIG. 11A) from low profile spring-loaded reels **41** (FIG. 11B) that are arrayed on a planar, low profile tray **47**, as shown in FIGS. 11A to 13A. This example of a fiber tray assembly **106** (FIGS. 11A and 11B) includes twelve fibers that are rendered individually and independently self-tensioning, by reels **41** to which the fibers **52** are guided after passing through a center backbone **40** of linearly arrayed flexible guides. Flexible guides are typically a low friction tubing material such as PTFE, FPA, FEP, etc. In the particular example shown here, the opposite ends of each of the twelve fibers exiting the backbone have originated in connectors that are plugged individually into different ones of a linear array of mating sleeves or optical couplers **18**. The internal paths of the fibers **52** between the interior reels **41** and the output connector array **42** are depicted in FIG. 11B.

The fragmentary perspective view of FIG. 12 details the paths of the fibers to individual reels including front, dynamically moving fibers **52** exiting from the reel fiber exit location **50** and terminated in connectors to form the dynamic output connector array **81** (FIG. 1A), and rear, fixed-length fibers **54** (FIG. 11B), also exiting from reel fiber exit location **50** and ultimately terminated in connectors to form the static input connector array **82**. As seen in FIG. 12, the fibers are routed through O-ring eyelets **49** and around fiber rollers **48** to redirect the dynamically moving fibers with low friction and low stress as they experience an angular change of about 90 degrees while passing around an intervening reel **41**. As the fibers **52** are withdrawn or retracted back into a reel, the reel **41** rotates, causing the reel's internal fiber to spiral on its underside (as disclosed in U.S. Pat. No. 8,068,715) so as to coil or uncoil, respectively. As seen in FIG. 13A, the outer wall of the reel is segmented and/or colored with alternating reflective/non-reflective circumferential segments **46** such that a reflective photo-interrupter **45**, in combination with an electronic multiplexing and counter circuit **51** detects the number of turns the reel undergoes. This provides validation during operation that the proper length of output fiber **52** is present on the reel as a function of the movement of fiber connector assembly **101** during robot control.

Different novel aspects of an improved multi-reel module are also depicted in FIGS. 11 to 13. FIGS. 11A and 11B, for example, illustrate an advantageous geometric layout of twelve take-up reels **41** for providing individually adjustable lengths of optical fiber. Here, each fiber tray assembly **106** distributes individual optical fibers from the backbone **40** to reels **41** which are linearly aligned in spaced apart sets of four extending from front to back on the reel tray **47**. Furthermore, these reel sets are each adjacently positioned so that the pairs of adjacent reels each define an acute angle relative to the front to back axis on the tray **47**. There are

thus six reels on one side of the tray **47**, and six reels on the opposite side positioned in oppositely angled pairs with an open central area of the tray **47** providing a pathway to input fibers from the backbone **40** input.

The fiber **52** inputs to the different reels **41** feed into the central area and are directed clockwise about the individual reels in the left (as seen in FIG. 11B) side set of six reels, and counterclockwise about each of the six reels on the right-side set. Since the reels of each pair are closely adjacent but spaced apart, the paths of fibers incoming from the central backbone **40** are different, dependent on whether a reel is the innermost one of the angled pair, or the outermost one of the pair. The problem is resolved, while still maintaining compactness and control, by the fiber guide geometry shown in FIG. 12, to which reference is now made. The inner (closest to the center) reel **41** of an angled pair receives a variable length of fiber **52** to take up or supply fiber as needed during reconfiguration. The variable length reconfigurable, auto-tensioned fiber **52** is controllably guided with curvature of greater than a minimum acceptable bend radius (typically >5 mm). The reels of each pair are closely adjacent but operationally distinct, which result is made possible by the angled and spaced geometry of the reels **41** of any module. At the opposite end of the fiber, a fixed rear length of fiber **54** is fed to the individually coupled lines in the array **42** (FIG. 11B).

A useful novel expedient for monitoring the dynamic operation of the multiple reels **41** is provided by the sensor arrangement depicted in FIG. 13A and an example of the associated multiplexing circuitry as depicted in FIG. 13B. Referring to those FIGS. it can be seen that a small reflective photo sensor **45** is mounted in a thin wall adjacent the periphery of a take-up reel **41**. The sensor **45** is positioned outside the take-up reel and generates a signal which varies with the then adjacent circumferential segment **46** of the take-up reel **41**. There are, as seen in FIG. 12, seven such indented (small radius) segments, evenly distributed around the periphery of each fiber take-up reel **41**. Thus, as the reel rotates to feed out or take up fiber, a responsive signal from the associated sensor **45** is sent to reel encoder circuits **51**. These circuits **51**, one for each individual reel **41**, provide signals responsive to the changing rotational position of the reel. To read out any particular sensor, the electronic multiplexers **70**, **71** in the internal monitoring system (FIG. 13B) must be set to its particular address. As shown in FIG. 13B, multiple individual power and ground lines from different sensors **45** can be shared by feeding into separate multiplexer circuits **70**, **71** to selectively activate a particular reel and generate signals **72** corresponding to its particular reel **41**, for processing by command circuits which monitor the operation of the multiple reels.

#### VII. Automatic Fiber Endface Dry Cleaning Cartridge with Integral Sensing for Process Control

Reference is now made to FIGS. 14, 15, 16A and 16B, which illustrate partial cutaway and perspective views of an advantageous cleaner device **105** detailing how force sensing is effected by means comprising a compliant pad **57** behind a cleaning fabric **58**, further including a force sensor **56** within the compliant pad **57** which detects the existing ferrule tip compressive force **F**, the direction of which is indicated by the block arrow in FIGS. 14 and 15. A fiber connector **101** within the gripper **103** is raised to above the fiber interconnect volume and the top most fiber module **113-10** along the y axis so that the connector is at the elevation of the cleaning cartridge **105**. The cleaning cartridge is mounted rigidly to the bottom of the translating x axis carriage **61** and moves with the carriage as it translates in x. The cleaning fabric is advanced by moving the robot to

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the far right, to depress the cleaning cartridge advance lever **75** which advances the cleaning fabric to a clean, unused portion of the fabric. In a particular example, the force sensor **56** is a substantially planar element on a flexible substrate with internal electrode features that include two wire terminals **59**, and produces a resistance change proportional to the average local force within the sensing region. The sensing region is typically 5 to 10 mm in diameter and the thickness of the sensor is typically 0.25 to 0.5 mm. The sensor wires **59** are interfaced to external electronic circuits **107** including a voltage divider, wherein the target force sensing threshold is 100 gm-F and the reference resistor value of the voltage divider is selected to produce a voltage of about 2.5V for a supply voltage of 5V. A typical resistance crossing value for the force sensor is 100 K $\Omega$ . and the reference resistor is typically chosen to be 1 M $\Omega$ . A comparator in the circuit **107** converts the analog voltage on the voltage divider into a digital signal. This digital signal is input to a controller **108** and monitored by embedded control software to accurately terminate the gripper **103** and fiber connector **101** advancement at the prescribed cleaning fabric compression force. The robot gripper **103** (FIG. **14**) moves the fiber end face/ferrule **10** of the connector **101** until the fiber end face touches the fabric and compresses the compliant pad **57** behind the fabric. The force sensor is integral to the compliant pad **57** and senses the compression therein. The desired force for automated cleaning is in the range of 25 gm-F to 250 gm-F. Control of force within a range is important because excessive force can create tears in the fabric and contaminate fiber; inadequate force can result in incomplete cleaning.

Furthermore, in accordance with the invention, the cleaning cartridge **105** which is disclosed provides integral sensing of the cleaning fabric consumption. Referring to FIGS. **16A** and **16B**, the cleaning cartridge includes sensing means, such as a reflective photo-interrupter **77**, to detect the advance of the cleaning fabric **58** from its spool, feeding its signals to the electronic circuits **107** and **108** (FIG. **14**). The cleaning cassette fabric **58** is fed from the supply spool **73** past the cleaning cassette pad **57** and the sensor **56** to the dispense spool **74**. The cleaner advance lever **75** is actuated to feed the fabric **58** in increments as needed by horizontal movement along the x axis to depress the lever when it strikes the hard stop in the vicinity of the rightmost limit of travel. As is evident from the perspective view in FIGS. **14** and **15** of the relationship of the gripper assembly **103** when it is in operative relationship to the cleaning cartridge **105**, the supply spool **73** and dispense spool **74** straddle the cleaning cassette pad **57**. The spacing between the two spools thus facilitates accessing any chosen optical fiber ferrule **10** in operative position for cleaning and return to operative position in the precisely ordered bank of changeable optical fibers. At the same time, the source of cleaning material is large enough for many different cleaning sequences, but readily replaced when adequately used or when an inspection is needed.

In conclusion, new mechanisms and designs to achieve reliable operation of compact, robotically reconfigured, software-defined fiber optic patch-panels are disclosed herein. Those skilled in the art will readily observe that numerous modifications and alterations of the devices may be made while retaining the teachings of the invention.

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## APPENDIX—DRAWING LEGEND

- 10** Polished fiber ferrule
- 11** Plastic connector housing
- 12** Gripper mechanical locking feature
- 13** Connector magnet
- 14** Connector row unallocated magnets
- 15** Connector row allocate magnet
- 16** Reduced width mechanical feature for docking
- 17** Edge plated reflector
- 18** Fiber optic union adapter
- 19** Connector row actuator
- 20** Gripper guides
- 21** Camera
- 22** LED illuminator
- 23** Solenoid
- 24** Latch of solenoid
- 25** Cable or timing belt
- 25'** Loose cable drive
- 25"** Taut cable drive
- 26** Gripper translation shaft
- 27** Reflective photo-interrupter
- 28** Timing belt pulley
- 29** Gripper sliding printed circuit board
- 30** Robot arm outer stage
- 31** Telescopic arm cable pulley
- 32** Gripper actuator
- 33** Motor
- 35** Robot arm inner stage
- 36** Fixed cable attachment point
- 37** Electrical cable
- 38** Central support roller for row
- 39** Connector track
- 40** Backbone with flexible guides
- 41** Fiber take-up reels
- 42** Rear fiber optic union adapters
- 43** Left bearing block
- 44** Right bearing block
- 45** Reflective photo sensor
- 46** Reflective reel segments
- 47** Tray for reels
- 48** Fiber rollers
- 49** Ring eyelets
- 50** Reel fiber exit location
- 51** Reel encoder PCB
- 52** Internal, reconfigurable, auto-tensioned fibers
- 53** Reel axis of rotation
- 54** Rear, fixed fibers
- 55** Reconfigurable fiber optic connector ports
- 56** Cleaning cassette sensor
- 57** Cleaning cassette pad
- 58** Cleaning cassette fabric
- 59** Pair of electrical wires from force sensor
- 60** Gripper center printed circuit board
- 61** Robot x carriage
- 62** External fibers
- 63** Output fiber connector mount
- 64** Magnetic steel insert
- 70** Column electronic multiplexer for sensor
- 71** Row electronic multiplexer for sensor
- 72** Reel encoder sensor signal
- 73** Cleaning fabric supply spool
- 74** Cleaning fabric dispense spool
- 75** Cleaner advance lever
- 76** Spring loaded rollers
- 77** Cleaning fabric usage sensor
- 78** Output connector array support structure



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79 Gripper connector retaining feature  
 80 Gripper connector locking feature  
 81 Dynamic two-dimensional array of output ports  
 82 Static two-dimensional array of input ports  
 101 Fiber connector assembly  
 102 Connector row assembly  
 103 Actuated gripper assembly  
 104 Two axis robot  
 105 Cleaning cartridge  
 106 Fiber tray assembly  
 107 Voltage divider, mux & comparator circuit  
 108 Controller & logic  
 109 Server module  
 110 Ethernet switch module  
 111 Power management module  
 112 Robot module  
 113 Fiber module  
 114 Docking module  
 115 Optical power monitor module  
 116 Gripper sensor circuit  
 117 Trajectory control system  
 118 Gripper travel location within column gaps  
 119 Projection of fiber trajectories onto xz plane  
 120 X axis drive  
 121 Y axis drive  
 122 Gripper drum  
 200 Automated patch panel system  
 We claim:

1. A high-capacity optical fiber switching system for selectively interconnecting individual input fibers to individual output fibers, comprising:

a three-dimensional distribution of paired linear elements of selected flexibility and length with a first element of each pair disposed in spaced-apart horizontal rows and vertical columns defining a transverse interchange plane and each having a lower length extending for a selected distance perpendicularly in a first direction from the transverse interchange plane, including individual couplers distributed throughout the rows and columns to couple different signal conductors received oppositely therein, the paired linear elements each including a second movable element including a terminus of a different chosen optical fiber in the switching system and engageable in any selected coupler in a position above and parallel to the lower element of the pair;

an optical fiber engagement/disengagement transport device having a narrow horizontal dimension to be movable in horizontal space between any two adjacent columns, and including an axially movable gripper for selectively engaging the second movable element of a chosen optical fiber to transport the chosen optical fiber to a different position; and

a two-dimensional positioning system, coupled from above the transport device to the position of the transport device within the three-dimensional distribution in the spaces between columns, to selected row levels, the positioning system comprising coupled signal-controlled and orthogonally related vertical and horizontal linear drives selectively and oppositely moving the transport device parallel to the columns and rows, the vertical linear drive comprising an upper hollow linear body fitting movably within the spaces between adjacent columns of fibers, a lower inner linear body slidably movable within the upper hollow linear body, and a motor-driven cable drive coupled to move both linear bodies in a selected proportionality.

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2. The system of claim 1, wherein the vertical linear drive further comprises an internal low friction guidance mechanism appended to an upper end of the lower linear body and contacting an inner wall of the upper hollow linear body, and the cable drive comprises a drive motor on the exterior of the two-dimensional positioning system.

3. The system of claim 1, wherein the optical fiber engagement/disengagement transport device further comprises a transport body that is narrow relative to a longitudinal axis of an optical fiber engaged thereby, and wherein the transport body includes a signal-actuated drive providing two different states of engagement and one state of disengagement of an optical fiber in said optical fiber engagement/disengagement transport device.

4. The system of claim 3, wherein the states of engagement and the state of disengagement are affected during a linear alignment phase independently of repositioning of fibers in corresponding linear elements.

5. The system of claim 3, wherein an optical fiber in the system terminates in an elongated connector, leading to a ferrule that engages in a coupler.

6. The system of claim 5, wherein the states of engagement and the state of disengagement are achieved using three different positions of relative engagement of an elongated connector with a corresponding linear element.

7. The system of claim 6, wherein the states of engagement comprise:

a first state of engagement in which the ferrule of the connector is fully engaged within a mating sleeve of the coupler; and

a second state of engagement in which the connector is partially engaged within the mating sleeve of the coupler, wherein

the state of disengagement corresponds to a state in which the connector is fully withdrawn from the mating sleeve, wherein the gripper is able to withdraw the connector from a connector port for movement to a different destination port.

8. The system of claim 7, wherein the first state of engagement produces near zero insertion loss and the second state of engagement produces about 20 dB or more loss by virtue of an air gap between the connectors.

9. The system of claim 6, wherein the states of engagement and the state of disengagement are achieved using magnets on the elongated connector and on the corresponding linear element.

10. The system of claim 9, wherein polarity of at least some of the magnets provides (i) magnetic attraction forces between extremities of adjacent connectors and connector assembly pairs, and (ii) magnetic repulsion forces as to adjacent pairs of narrow, elongated connector elements.

11. The system of claim 1, further comprising:

a removable and replaceable cleaning cartridge positioned on the engagement/disengagement transport device, said cleaning cartridge to clean end faces of optical fibers in the system.

12. The system of claim 1, wherein the first element of each pair of paired linear elements has a length-to-width ratio of greater than 10 to 1.

13. The system of claim 1, wherein a predetermined gap between the couplers is at least twice a width of the first element of each pair of paired linear elements.

14. A high-capacity optical fiber switching system for selectively interconnecting individual input fibers to individual output fibers, comprising:

a three-dimensional distribution of paired linear elements of selected flexibility and length with a first element of

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each pair disposed in spaced-apart horizontal rows and vertical columns defining a transverse interchange plane and each having a lower length extending for a selected distance perpendicularly in a first direction from the transverse interchange plane, including individual couplers distributed throughout the rows and columns to couple different signal conductors received oppositely therein, the paired linear elements each including a second movable element including a terminus of a different chosen optical fiber in the switching system and engageable in any selected coupler in a position above and parallel to the lower element of the pair;

an optical fiber engagement/disengagement transport device having a narrow horizontal dimension to be movable in horizontal space between any two adjacent columns, and including an axially movable gripper for selectively engaging the second movable element of a chosen optical fiber to transport the chosen optical fiber to a different position; and

a two-dimensional positioning system, coupled from above the transport device to the position of the transport device within the three-dimensional distribution in the spaces between columns, to selected row levels, the positioning system comprising coupled signal-controlled and orthogonally related vertical and horizontal linear drives selectively and oppositely moving the transport device parallel to the columns and rows, the vertical linear drive comprising an upper hollow linear body fitting movably within the spaces between adjacent columns of fibers, a lower inner linear body slidably movable within the upper hollow linear body, and a motor-driven cable drive coupled to move both linear bodies in a selected proportionality,

wherein the vertical linear drive further comprises an internal low friction guidance mechanism appended to an upper end of the lower linear body and contacting an inner wall of the upper hollow linear body, and the cable drive comprises a drive motor on the exterior of the two-dimensional positioning system, and

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wherein the optical fiber engagement/disengagement transport device further comprises a transport body that is narrow relative to a longitudinal axis of an optical fiber engaged thereby, and wherein the transport body includes a signal-actuated drive providing two different states of engagement and one state of disengagement of an optical fiber in said optical fiber engagement/disengagement transport device.

15. The system of claim 14, wherein the states of engagement and the state of disengagement are affected during a linear alignment phase independently of repositioning of fibers in corresponding linear elements.

16. The system of claim 14, wherein each optical fiber in the system terminates in an elongated connector, leading to a ferrule that engages in a coupler.

17. The system of claim 16, wherein the states of engagement and the state of disengagement are achieved using three different positions of relative engagement of an elongated connector with a corresponding linear element.

18. The system of claim 17, wherein the states of engagement comprise:

a first state of engagement in which the ferrule of the connector is fully engaged within a mating sleeve of the coupler; and

a second state of engagement in which the connector is partially engaged within the mating sleeve of the coupler, wherein

the state of disengagement corresponds to a state in which the connector is fully withdrawn from the mating sleeve, wherein the gripper is able to withdraw the connector from a connector port for movement to a different destination port.

19. The system of claim 18, wherein the first state of engagement produces near zero insertion loss and the second state of engagement produces about 20 dB or more loss by virtue of an air gap between the connectors.

20. The system of claim 17, wherein the states of engagement and the state of disengagement are achieved using magnets on the elongated connector and on the corresponding linear element.

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