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(54) **MODULAR CONVEYOR SYSTEM HAVING MULTIPLE MOVING ELEMENTS UNDER INDEPENDENT CONTROL**  
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See application file for complete search history.

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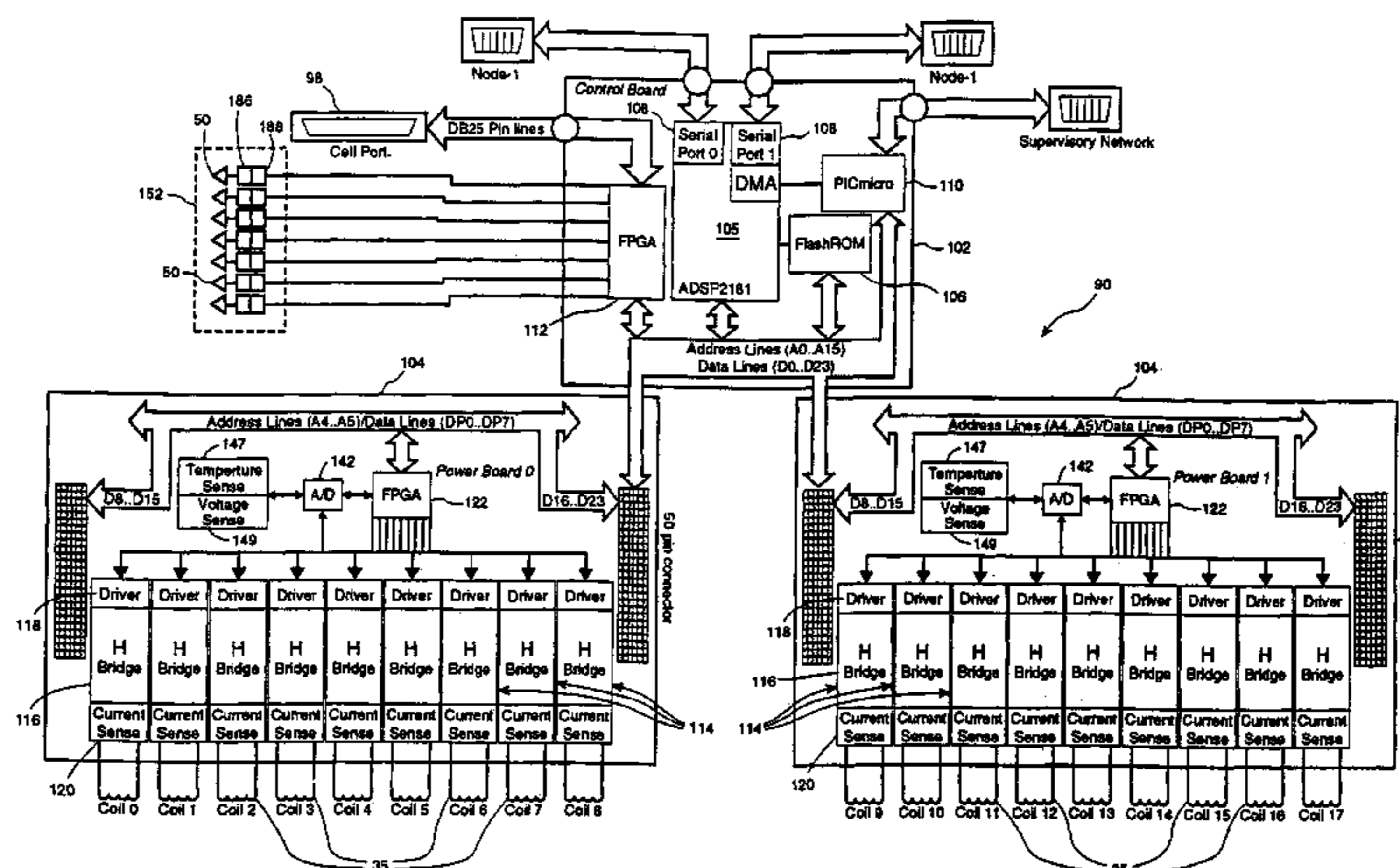
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(57) **ABSTRACT**

The modular conveyor system comprises N interconnected track sections, forming a continuous track, wherein each track section features a plurality of individually controlled coils stretching along the length thereof. Plural pallets, each having thrust producing magnets, travel independently along the track. The track also comprises multiple linear encoder readers spaced at fixed positions therealong, and each pallet includes a linear encoder strip having a length R greater than the spacing E between the readers. Track section controllers associate the encoder strips with only one reader at any time in order to resolve the position of the pallets based on the fixed position of the readers and the relative positions of the strips in relation thereto. The section controllers also regulate and commutate the coils of the corresponding track sections in order to independently control each pallet. Communication links interface adjacent section controllers situated in adjacent track sections. The electromagnetic structure and distributed control architecture of the conveyor system enable it to independently control multiple practical pallets yet be constructed out of modular track sections, with little practical restriction on the length of the conveyor system or the number of pallets controlled thereby.

**40 Claims, 16 Drawing Sheets**



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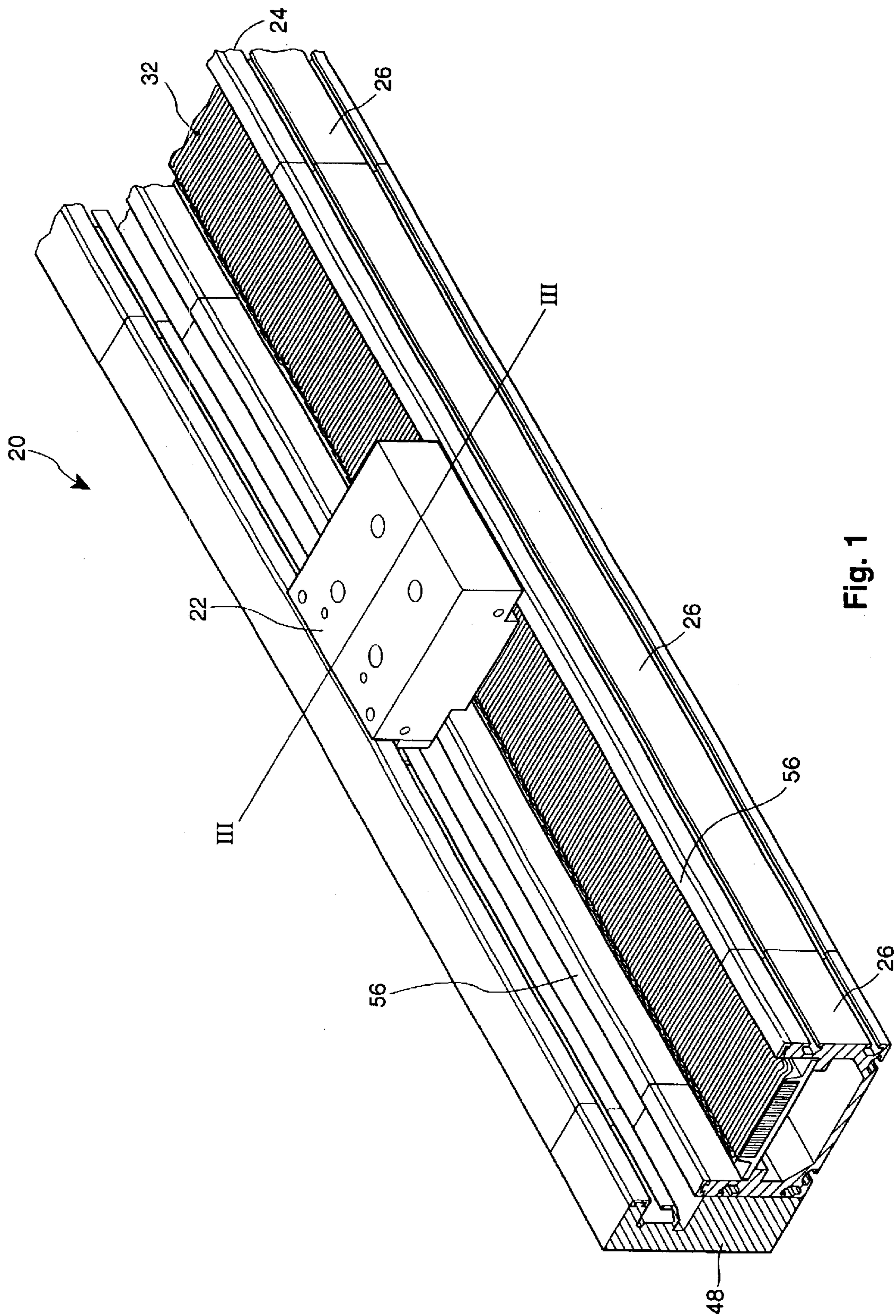
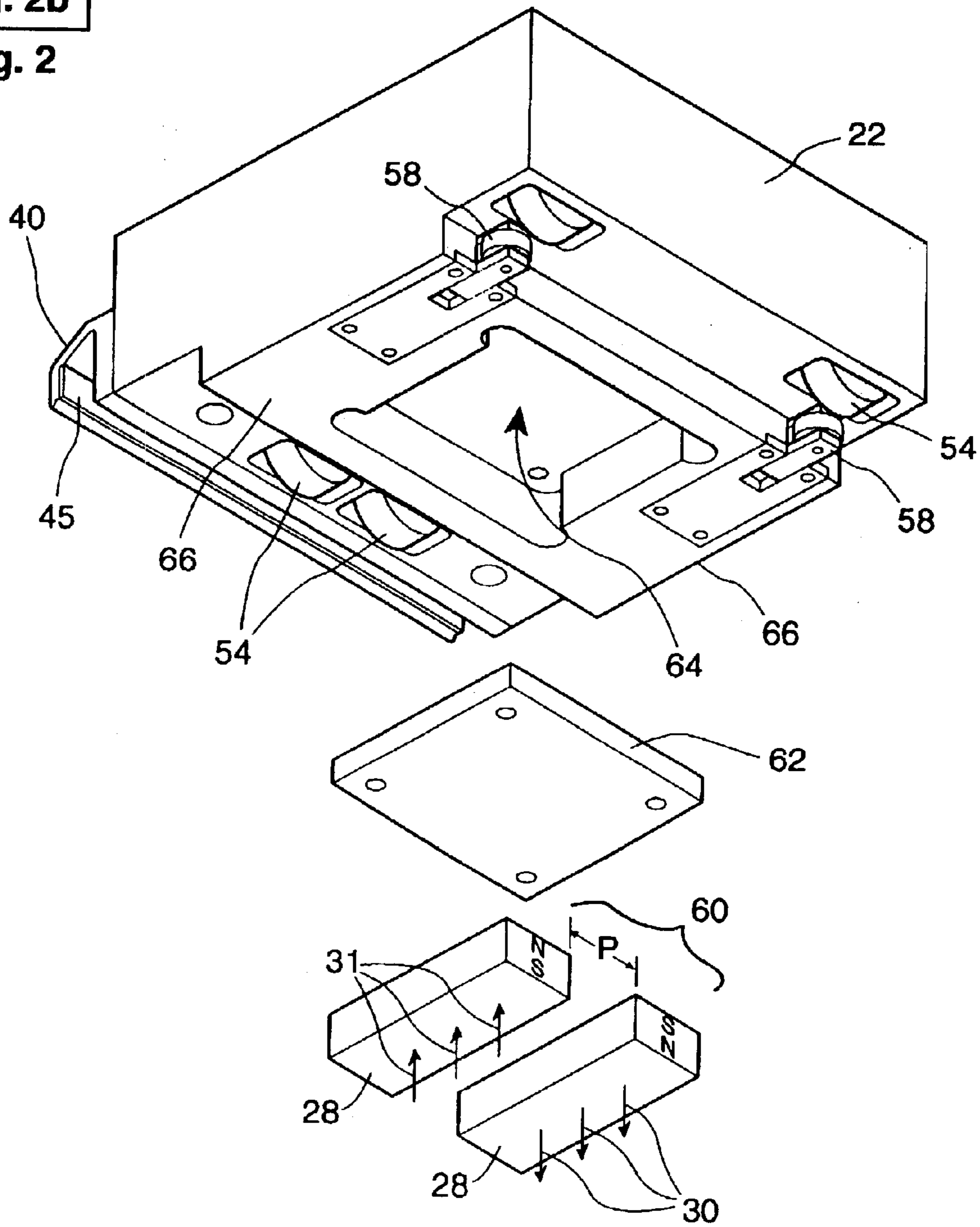


Fig. 1

**Fig. 2a**  
**Fig. 2b**  
**Fig. 2**



**Fig. 2a**

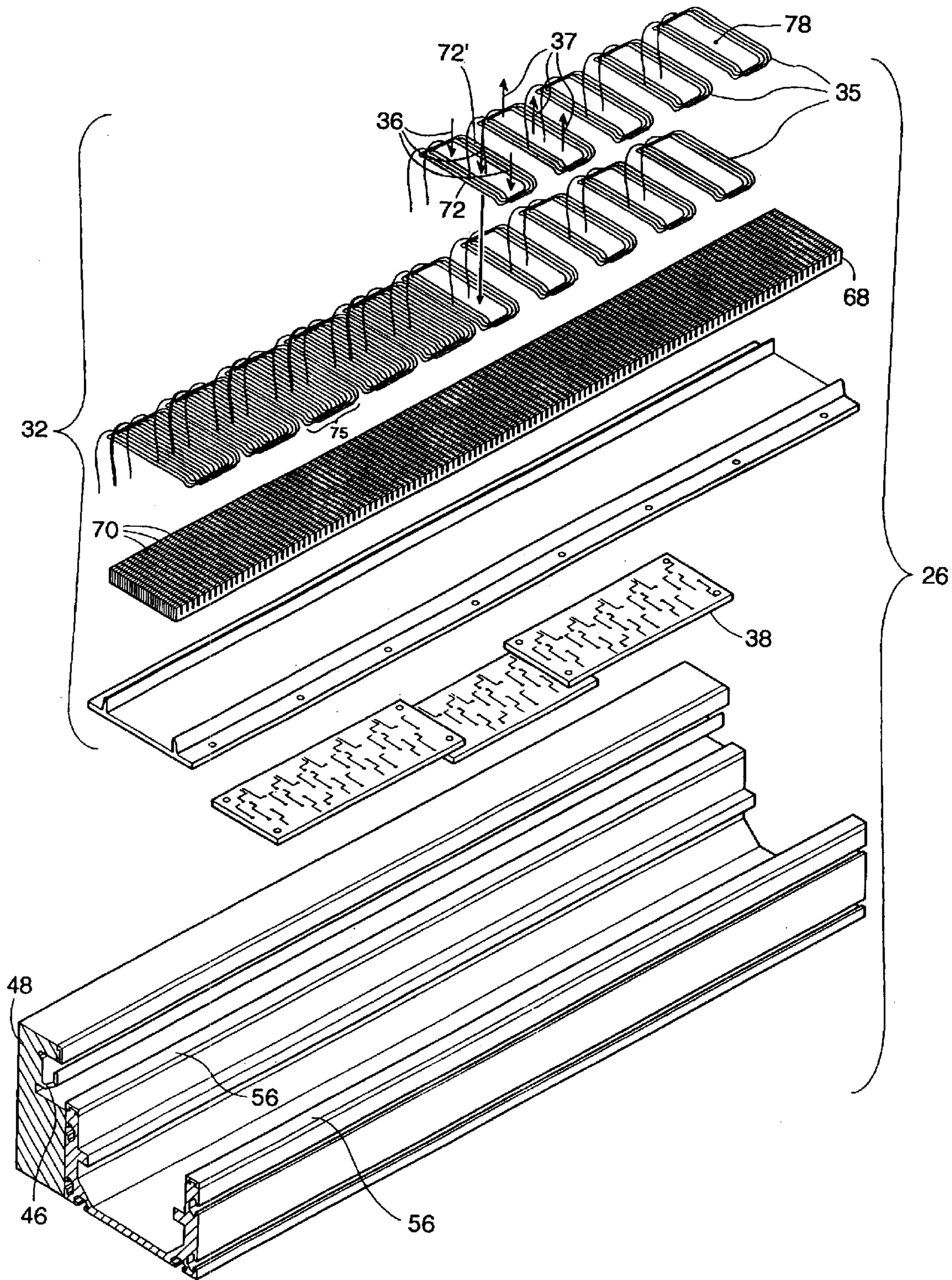


Fig. 2b

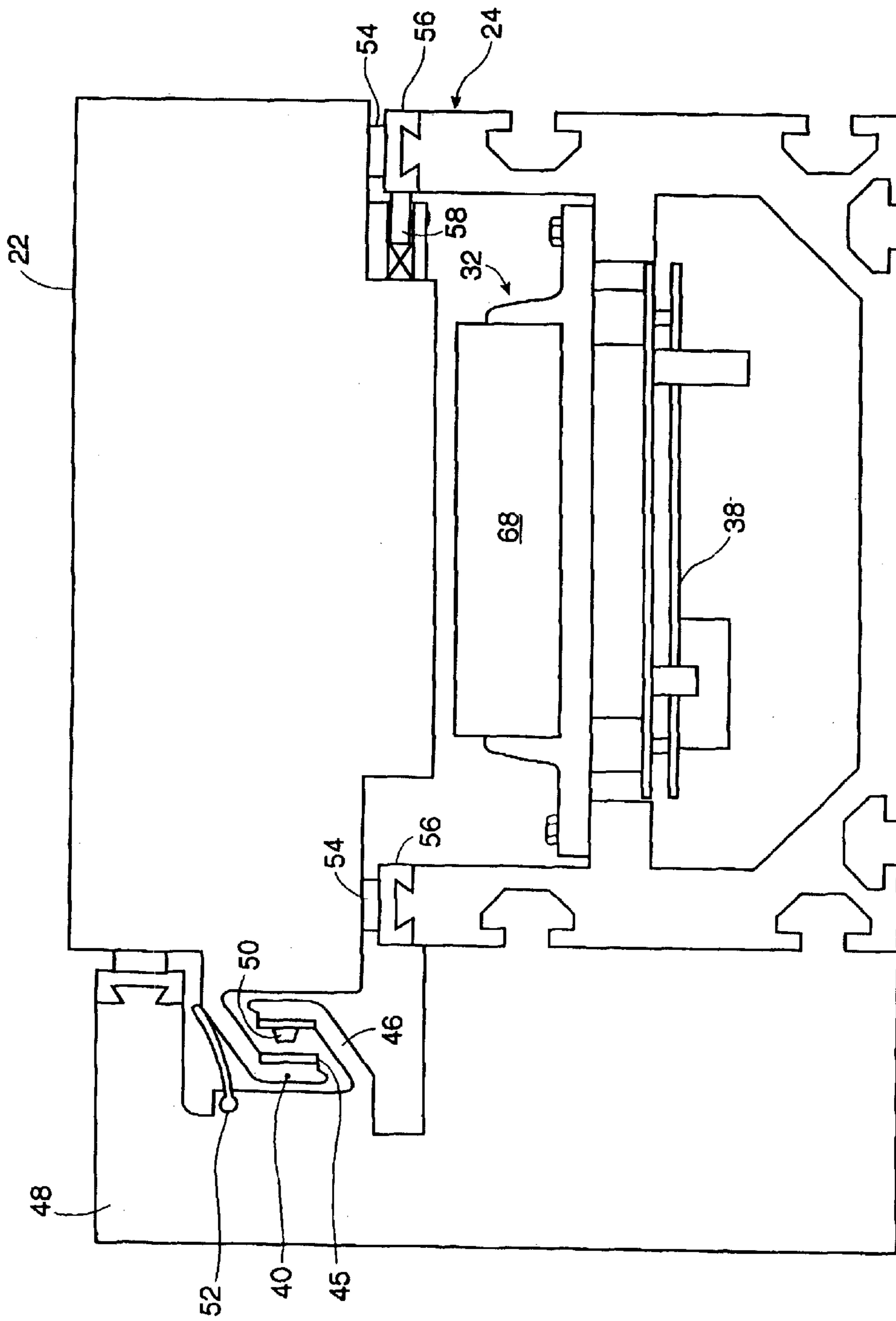


Fig. 3

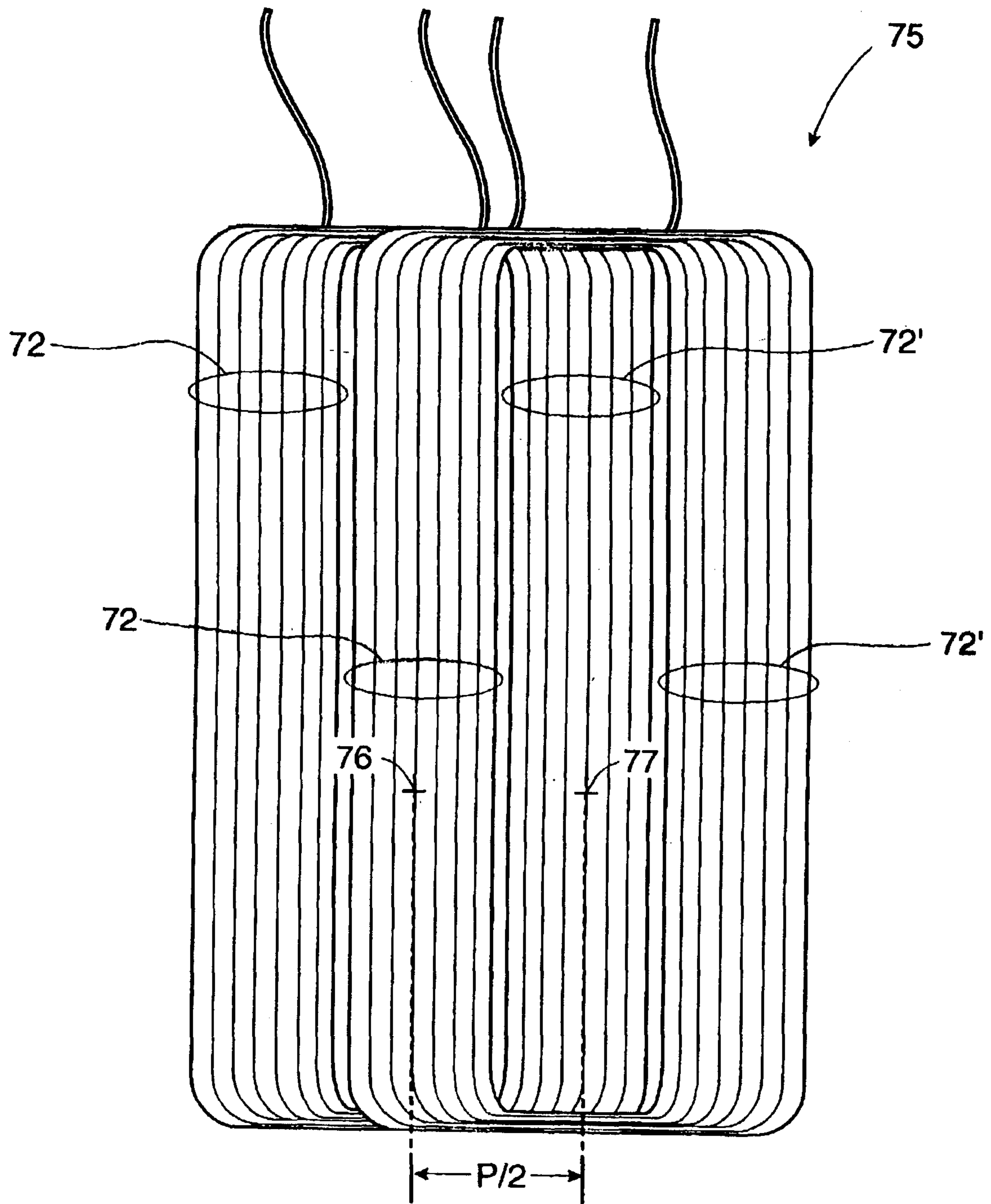


Fig.4

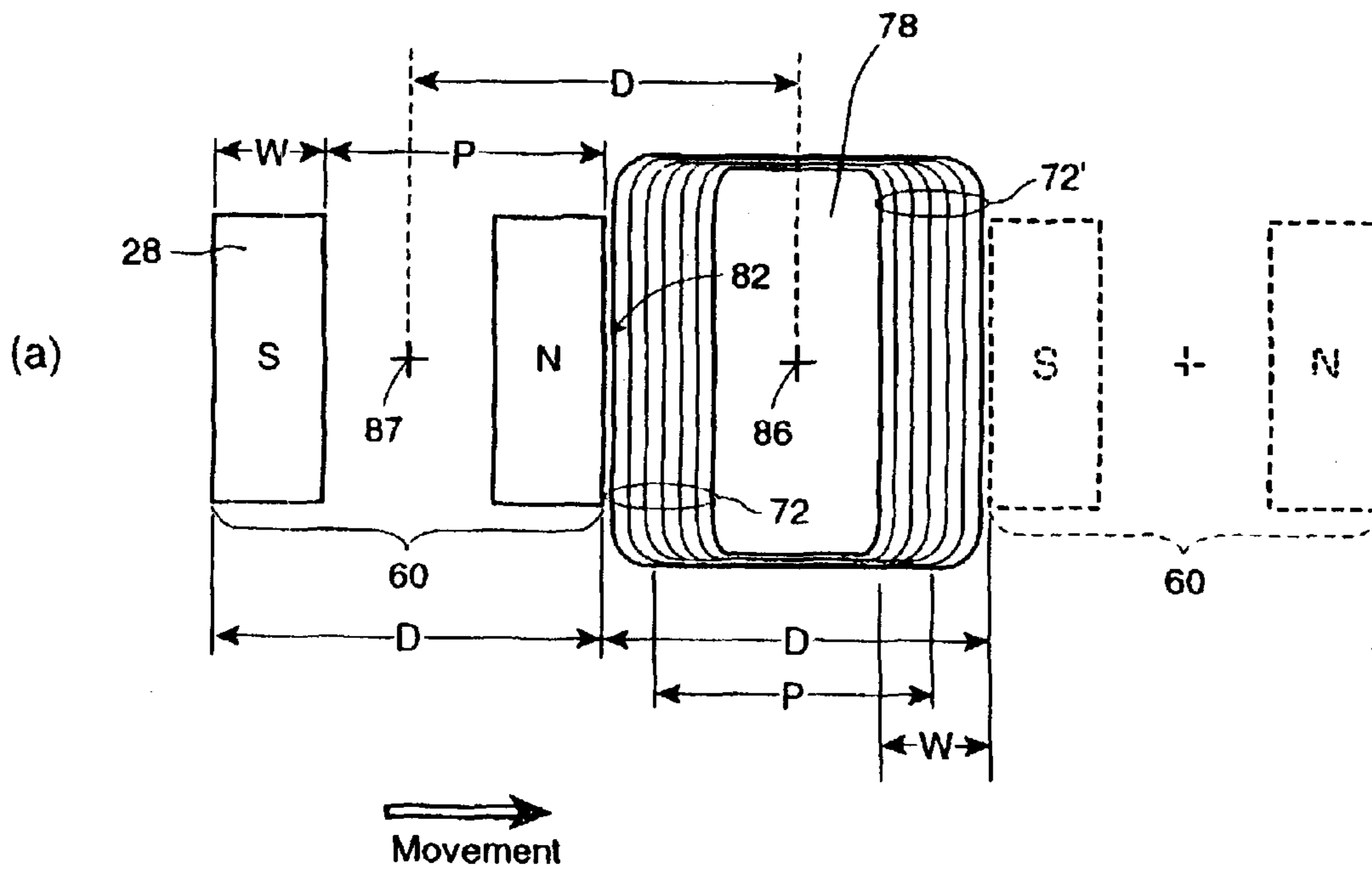
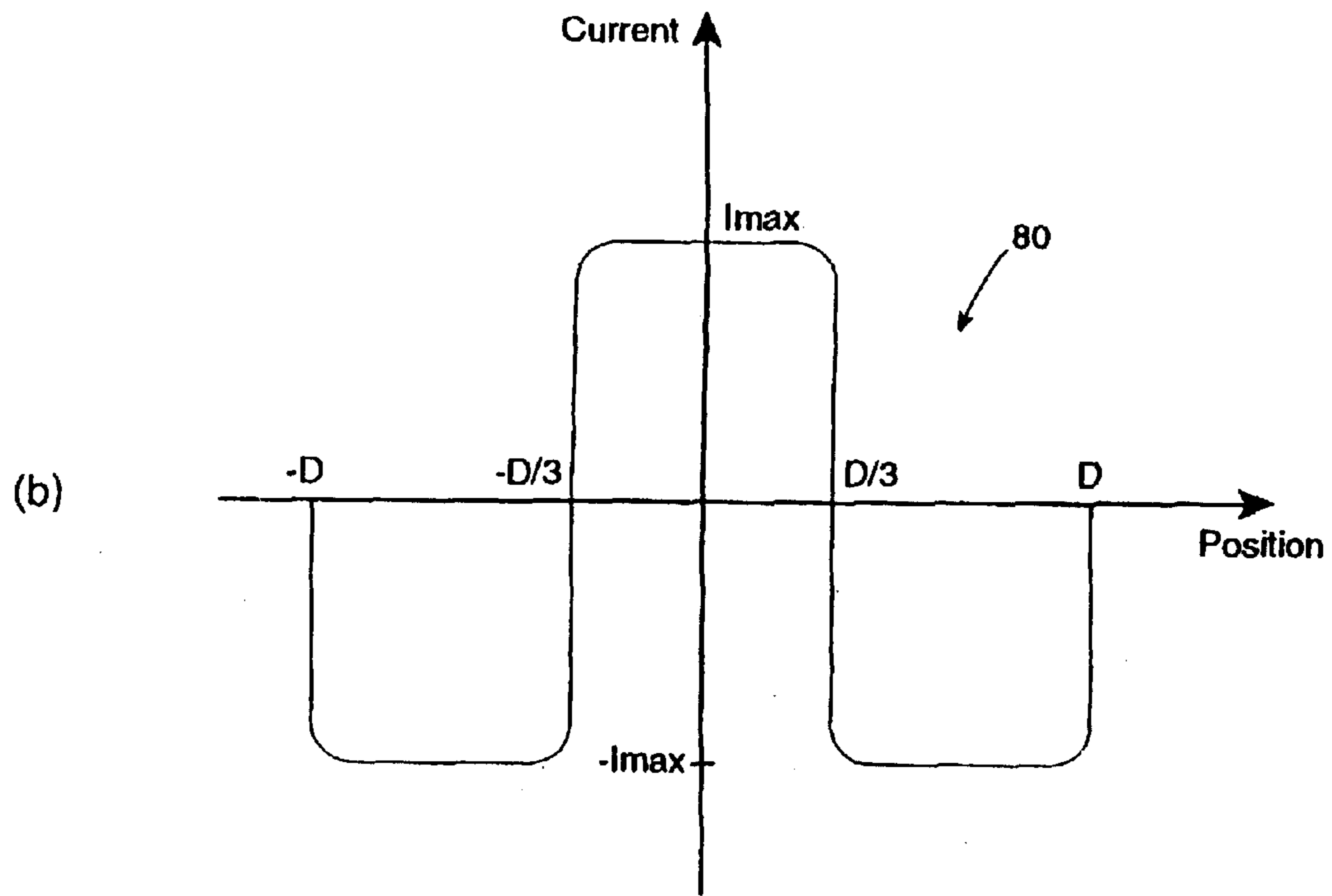


Fig. 5



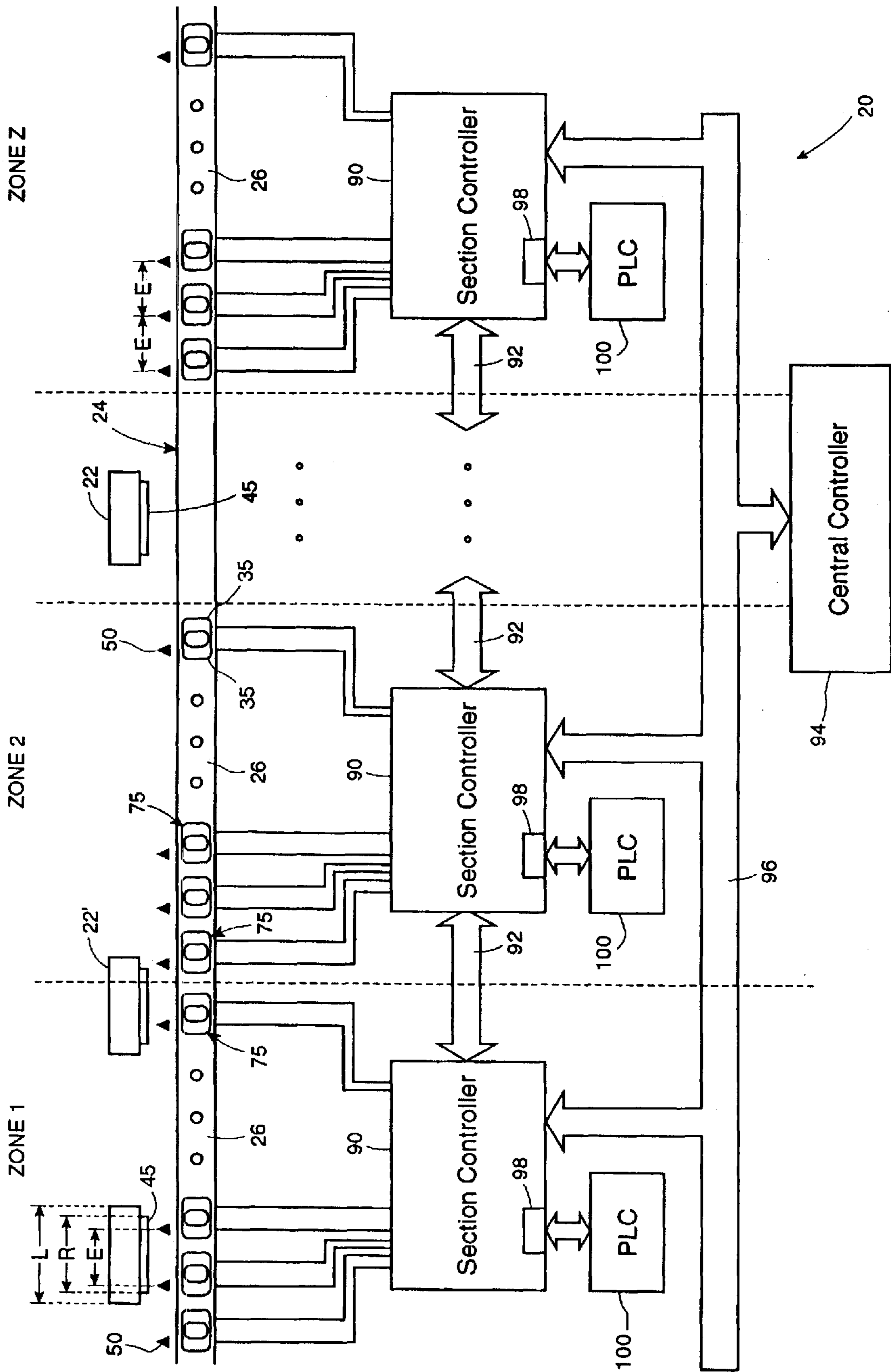


Fig. 6

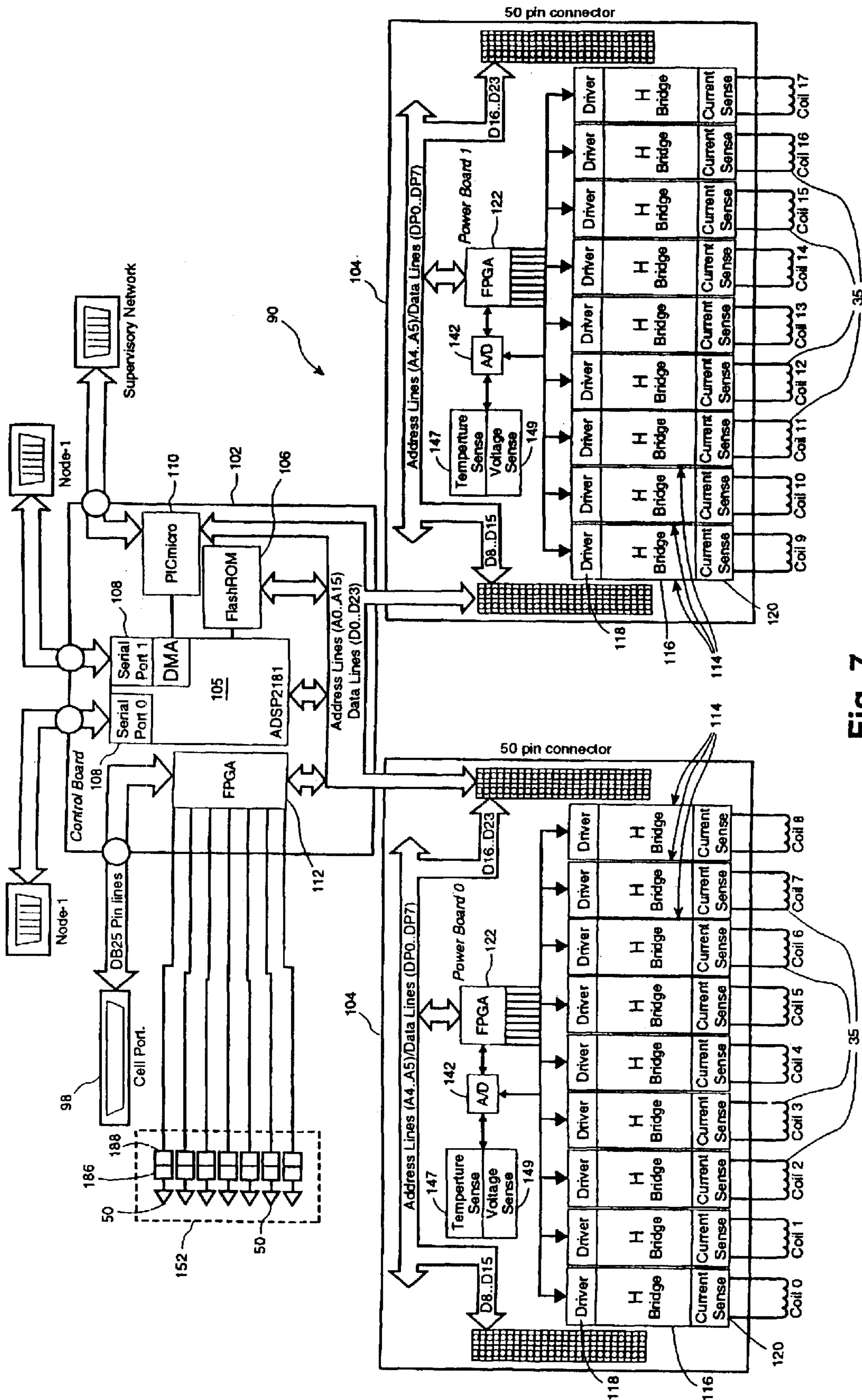


Fig. 7

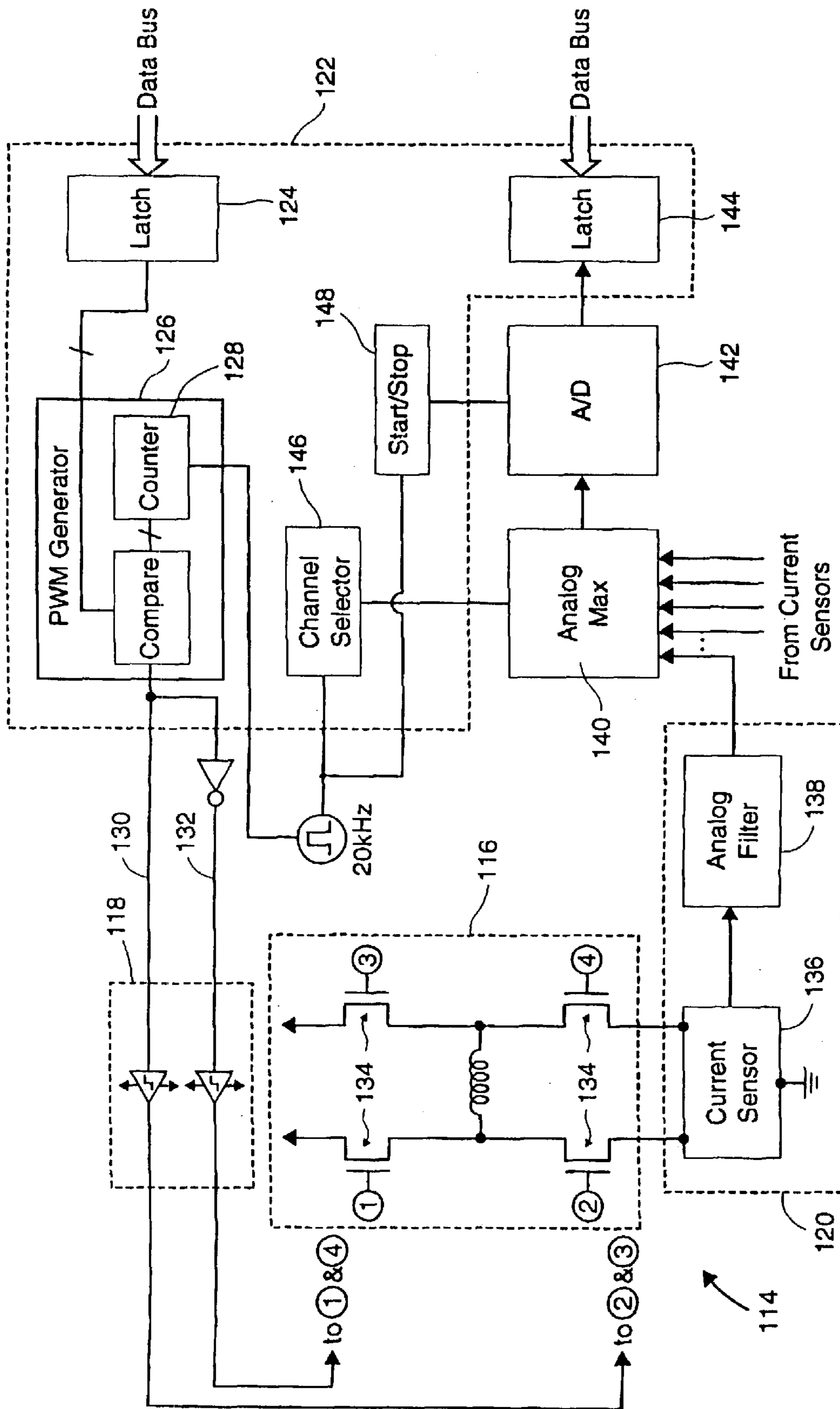


Fig. 8

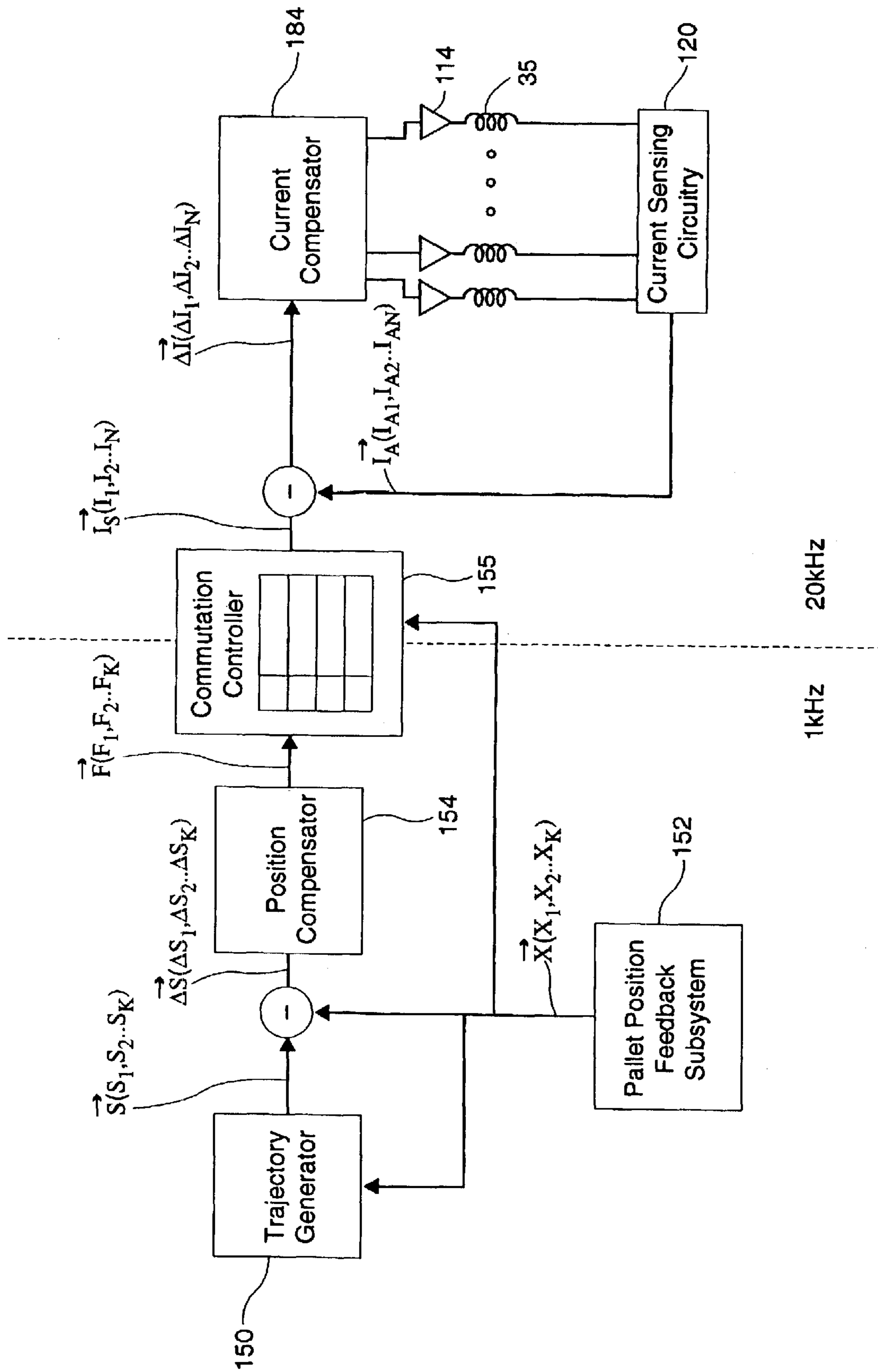
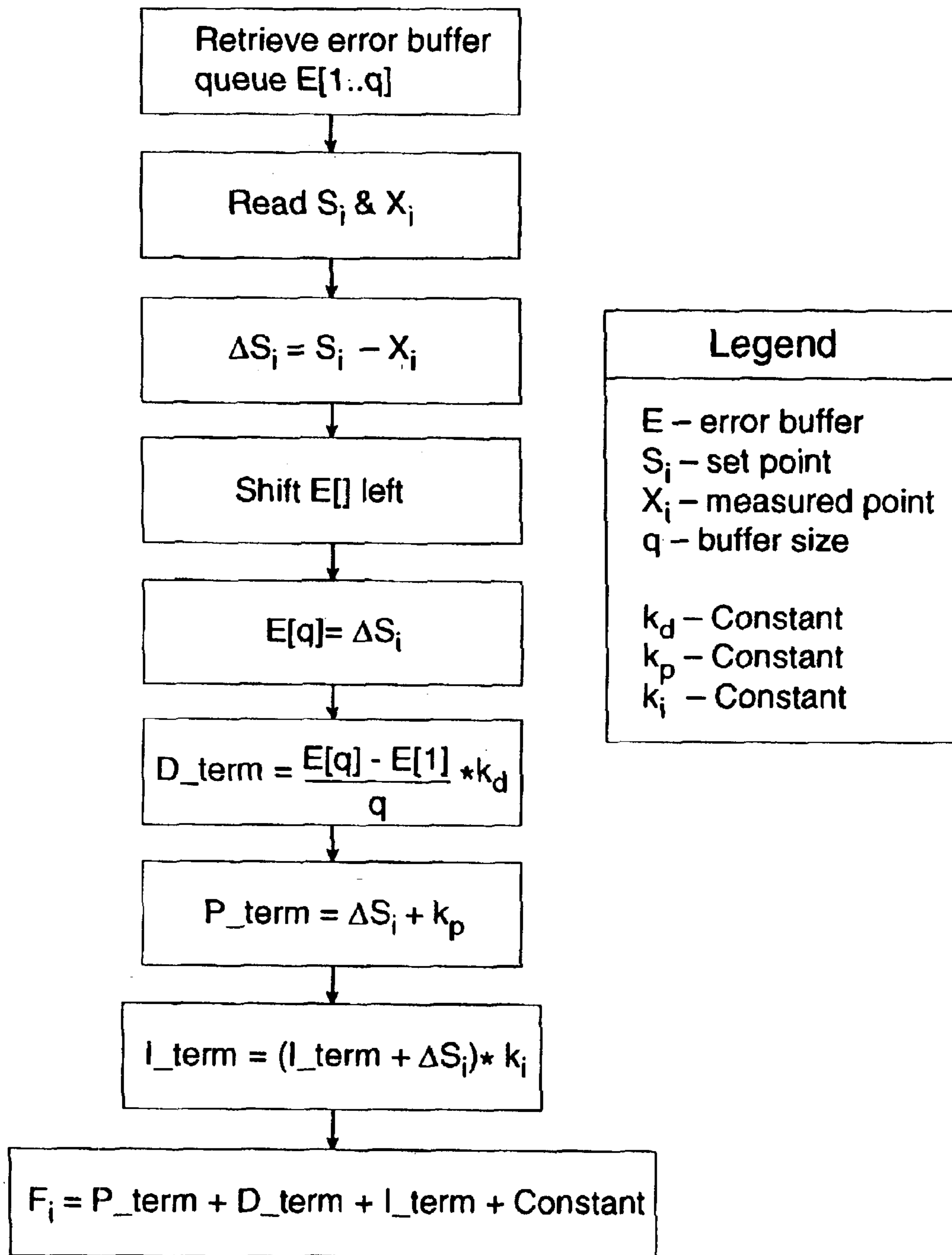


Fig. 9



**Fig. 10**

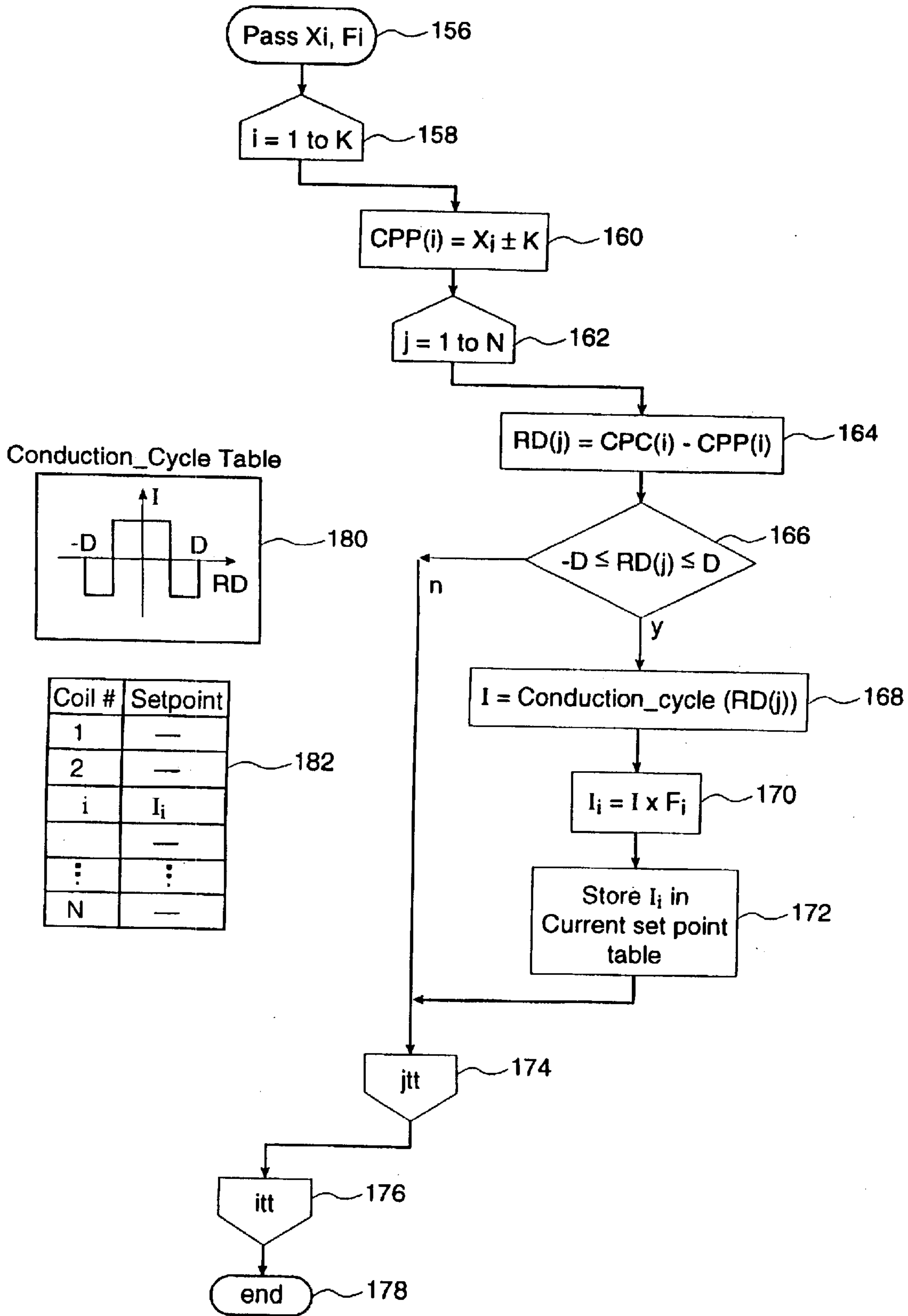


Fig. 11

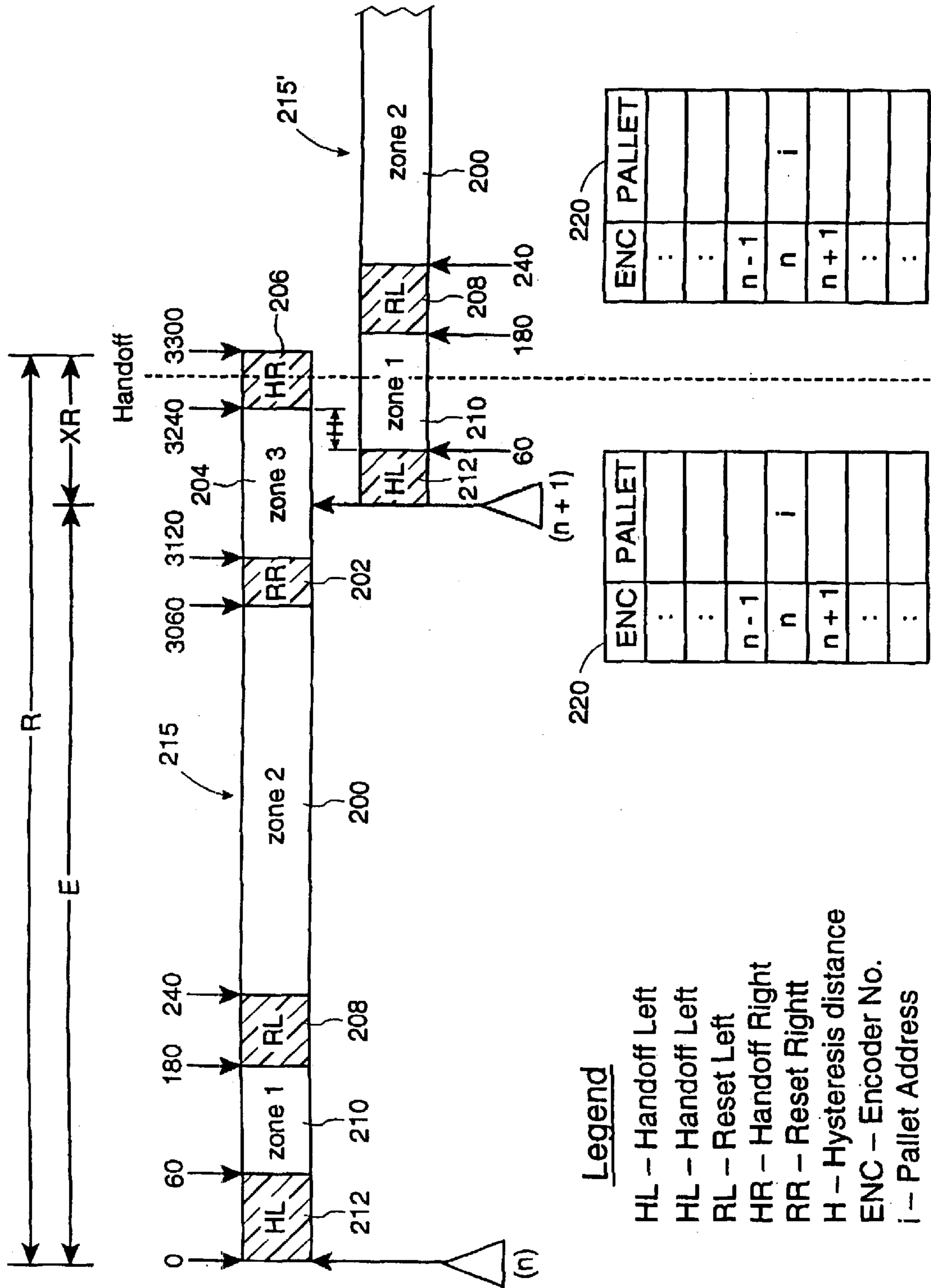
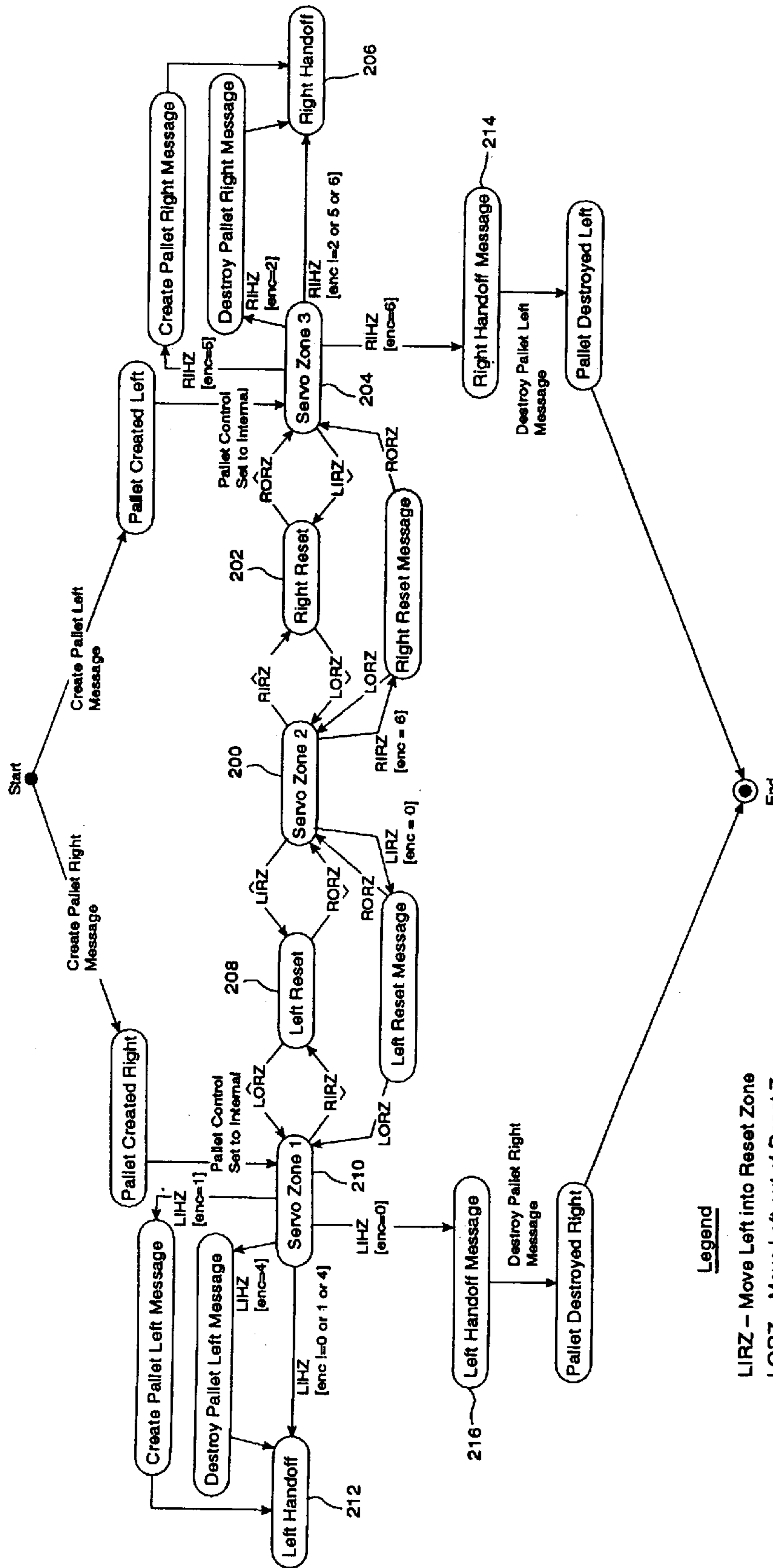


Fig. 12



Legend

- LIRZ – Move Left into Reset Zone
- LORZ – Move Left out of Reset Zone
- RIRZ – Move Right into Reset Zone
- RORZ – Move Right out of Reset Zone
- LIHZ – Move Left into Handoff Zone
- RIHZ – Move Right into Handoff Zone

Fig. 13



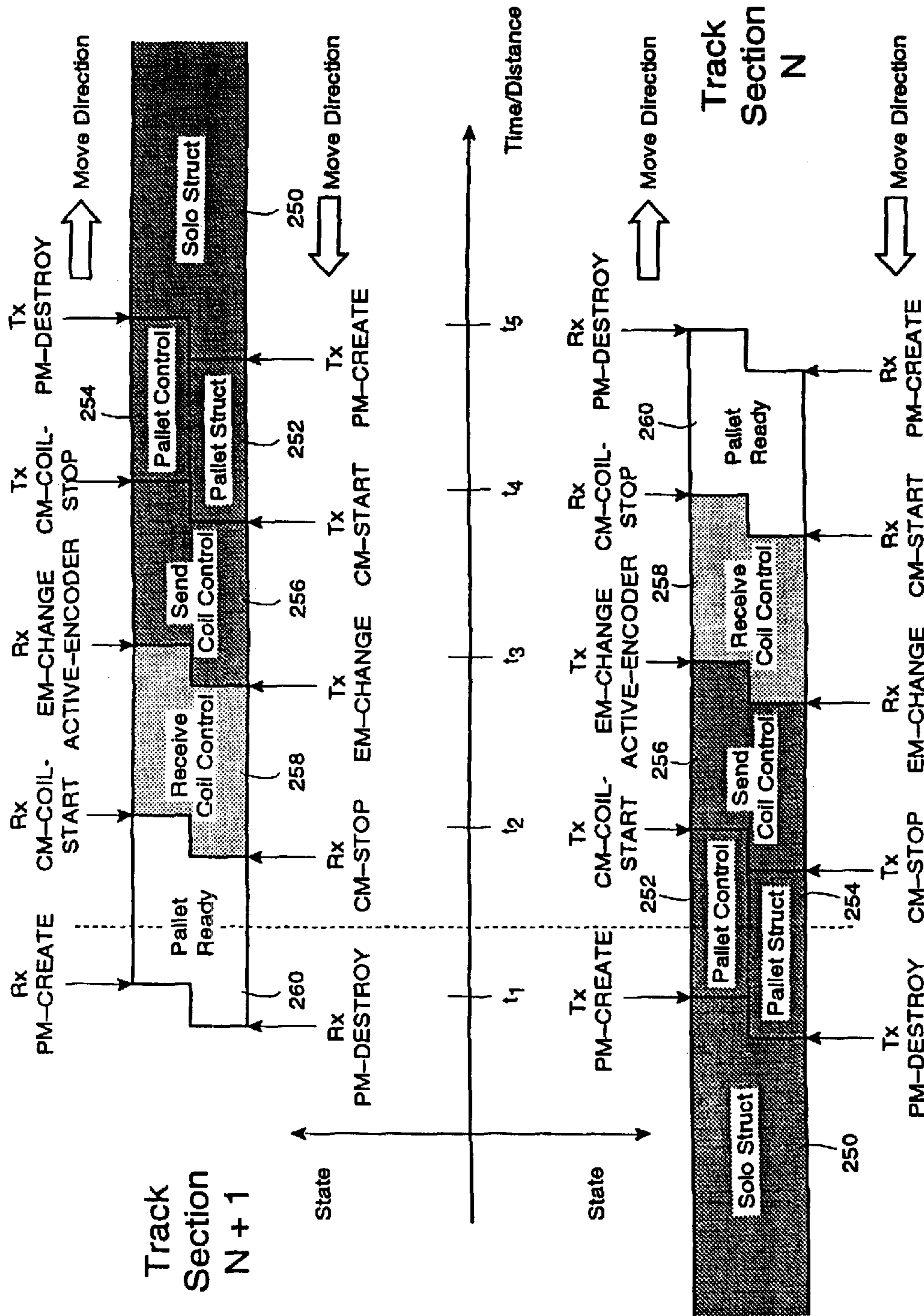


Fig. 14

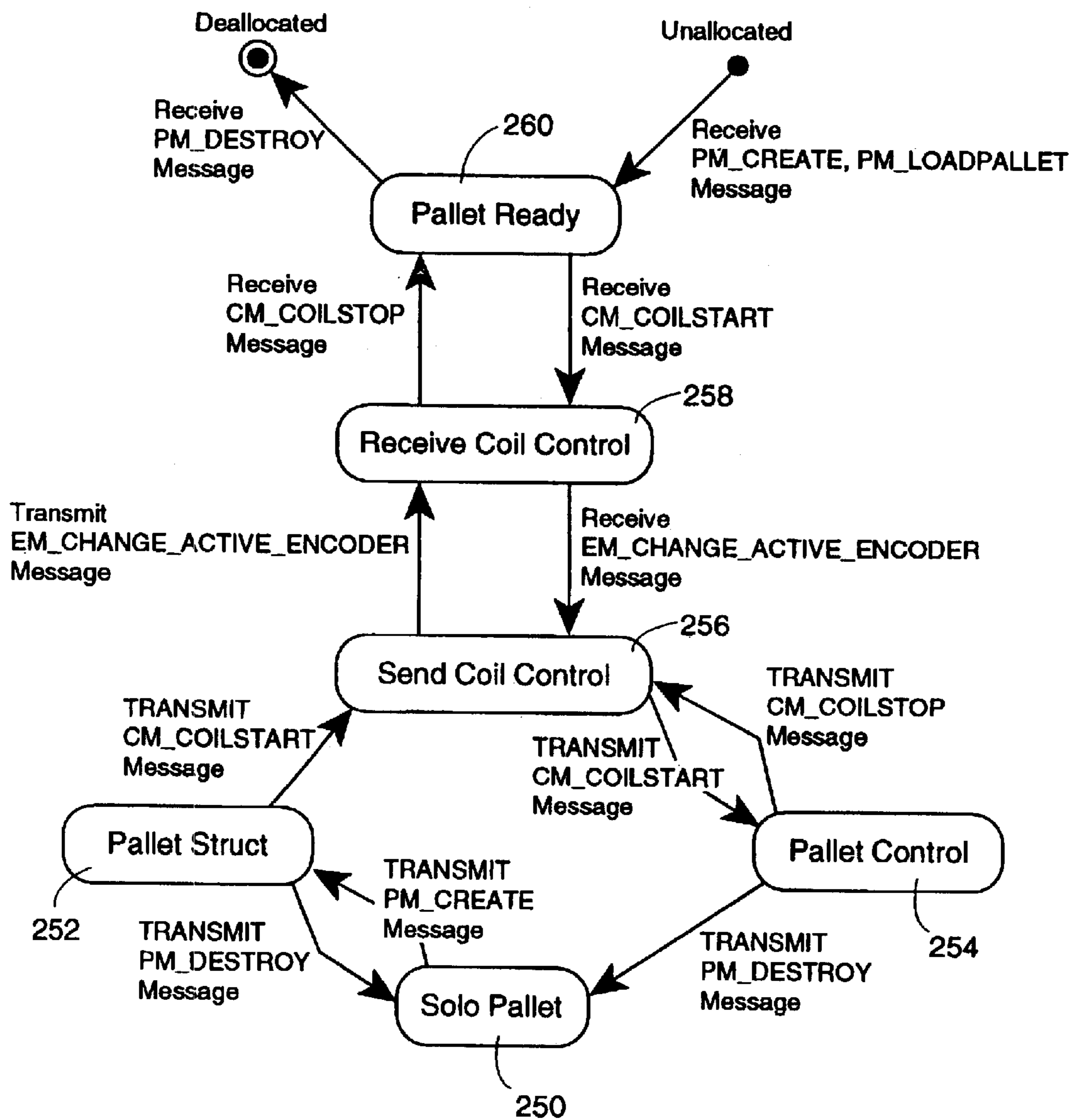


Fig. 15

**MODULAR CONVEYOR SYSTEM HAVING  
MULTIPLE MOVING ELEMENTS UNDER  
INDEPENDENT CONTROL**

**Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.**

FIELD OF INVENTION

The invention generally relates to conveyor systems, and more specifically to conveyor systems in the form of modular linear motors having multiple moving elements under independent control.

BACKGROUND OF INVENTION

There are a number of fundamental limitations with well-known conventional conveyor systems which employ a belt for transporting pallets between processing stations. First, the speed of the belt is typically quite limited. This is largely due to the fact that the pallets are typically stopped, e.g., in order to be processed at a processing station, by mechanical stop mechanisms. Thus, if the belt conveyor is operated at a high speed, the strong impact between a pallet and mechanical stop is likely to jar whatever parts the pallet may be carrying for processing. Second, it is generally not possible to vary the acceleration and velocity profiles for individual pallets. For instance, if a first pallet is empty and a second pallet is loaded with delicate parts, it is generally not possible to aggressively accelerate the first pallet to a high speed while controlling the second pallet using more gentle acceleration and velocity profiles. This limitation affects the latency and possibly the throughput of the manufacturing line. Third, belt conveyor is typically not bidirectional, which may result in a suboptimal design of the manufacturing line. Fourth, the belt conveyor typically provides limited flexibility or programmability, such as being able to very quickly change the positions of processing stations. Finally, the data acquisition capabilities provided by the belt conveyor are typically quite limited. For example, it is typically not possible to know where the pallets and their constituent loads are located along the conveyor at all times. Thus, for instance, it may be difficult to know how many pallets are queued at a particular processing station. For these and other reasons, a conveyor system having multiple moving elements or pallets under substantially independent control may be desirable for various types of applications.

Conveyor systems having multiple pallets under substantially independent control are known in the art, but suffer from a variety of limitations. For example, U.S. Pat. No. 4,841,869 issued Jun. 27, 1989 to Takeuchi et al. discloses a conveyor system utilizing a linear induction motor, comprising a conveyor cart and a guide rail for movably supporting the conveyor cart. The guide rail includes primary coils, and the conveyor cart includes a flexible secondary conductor extending longitudinally of the cart so as to follow the guide rail. The primary coils comprise a station primary coil disposed at each loading and unloading station for stopping and starting the conveyor cart, two primary coils adjacent opposite ends of the station primary coil for decelerating the conveyor cart that is to be stopped at the station by the station primary coil and for accelerating the conveyor cart having started from the station to a target running speed, and a plurality of intermediate accelerating primary coils disposed between two adjacent stations for

accelerating the conveyor cart to maintain the latter at the target running speed.

A major shortcoming with the Takeuchi et al. system is that the carts or pallets thereof cannot be positioned to stop at any point along the conveyor, but only where the linear motors thereof are disposed. This makes changing the location of a station a troublesome endeavour. In addition, the system is not capable of pinpointing the location of a moving pallet at any time. In view of these limitations, the Takeuchi et al. system does not feature truly independent and total control of multiple moving elements.

U.S. Pat. No. 5,023,495 issued Jun. 11, 1991 to Ohsaka et al. discloses a moving-magnet type linear d.c. brushless motor having plural moving elements disposed for motion along a track. The track includes a coreless stator armature having a plurality of contiguously arranged coils thereon. Each moving element includes a thrust-generating field magnet having P contiguous magnetic poles of alternating N and S polarity (i.e. polypolar magnet) having one side facing the stator armature. Each moving element may also include a polypolar position-detecting magnet. The track includes a row of position/commutation sensors, each row of position/commutation sensors being provided for detecting the magnetic poles of only the position-detecting magnet of a corresponding moving element. The position/commutation sensors are used in control circuitry for generating an electric current in the stator armature to move the moving elements in predetermined directions separately and independently.

The Ohsaka et al. system also has a number of shortcomings, particularly with respect to the modularity or scaling properties of the system. First, due to the fact that a separate track of position/commutation sensors is required for each moving element, the system can only accommodate a relatively small number of moving elements. Second, the length of the linear motor is limited by a servocontrol mechanism, described as a single microcomputer, which can only process and accommodate a limited number of the position/commutation sensors and associated electric current generating control circuitry. Third, use of the magnetic position-detecting elements provides a relatively poor resolution for measuring the position of the moving element. Fourth, the winding arrangement of the stator armature is essentially that of a linear stepper motor, which presents an uneven magnetic reluctance along the stator armature resulting in relatively noticeable cogging effects and a jerky thrust production. Finally, the coreless design of the stator armature also results in a relatively low average thrust production which may not be suitable for typical conveyor system applications.

SUMMARY OF INVENTION

The invention seeks to avoid many of the limitations of the prior art in order to provide a conveyor system having multiple moving elements under independent control, and particularly such a conveyor system which can be constructed out of discrete, self-contained, modular track sections, with little practical restriction on the length of the conveyor system or the number of pallets controlled thereby.

One aspect of the invention relates to apparatus for detecting the positions of plural moving elements, such as pallets, relative to a stationary element, such as a track. This apparatus comprises a plurality of linear encoder readers spaced at fixed positions along the stationary element. A device, such as a reflective optical or magnetic strip, readable by the linear encoder readers is mounted on each

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moving element, with each readable device having a length which is greater than the spacing between any given pair of adjacent linear encoder readers. Guide means align the readable devices in order to interact with the linear encoder readers. Plural processing means, such as a digital signal processor connected to each linear encoder reader, associates any given readable device with only one linear encoder reader at any time and resolves the position of the corresponding moving element based on the fixed position of the associated linear encoder reader and a relative position of the given readable device in relation to the associated linear encoder reader.

Another aspect of the invention relates to a moving-magnet type linear motor, comprising a plurality of moving elements traveling along a track, and a stator armature provided substantially along the entire traveling track of moving elements. Each moving element travels separately and independently and comprises  $n$  permanent magnets disposed face to face with the stator armature, the magnets being arranged in alternating North and South sequence and having a pole pitch  $P$ . The stator armature comprises a plurality of individual coils arranged in a substantially contiguous sequence of individual polyphase-like sets, each set comprising  $p$  overlapping coils having centers thereof spaced apart by a distance  $P/p$ , where  $p \geq 2$ . A servocontrol system is provided for regulating and commutating the coils so as to produce a separate moving MMF for each moving element in order to independently control each moving element.

A further aspect of the invention relates to a modular linear motor, comprising:

$n$  interconnected track sections, forming a continuous track, wherein each track section comprises a stator armature having a plurality of individually controllable coils disposed substantially along the entire length of the track section;

a plurality of moving elements traveling separately and independently along the continuous track, each moving element having at least two thrust producing magnets arranged in alternating North and South sequence and disposed face to face with the stator armatures of the track sections;

$n$  track section controllers, one per track section, for regulating and commutating the coils of the corresponding stator armature in order to produce a separate moving MMF for each moving element located in the corresponding track section and independently control each moving element located therein; and

communication means for interfacing the section controllers of adjacent track sections, wherein a given section controller is operative to utilize the communication means in order to transfer a servo responsibility for resolving the position of a given moving element to an adjacent section controller when the given moving element straddles the corresponding track sections, and wherein each of the given and adjacent section controller pair provides at least one coil regulating signal to the other of said pair in the event any portion of the magnets of the given moving element spans any portion of at least one coil situated in the track section corresponding to the other of said pair, provided that the responsibility for resolving the position of the given moving element has not yet been transferred to the other of said pair.

A still further aspect of the invention relates to a modular conveyor system, comprising:

$n$  interconnected track sections, forming a continuous track, wherein each track section comprises a stator armature having a plurality of individually controllable coils disposed

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substantially along the entire length of the track section, and wherein each track section comprises a plurality of linear encoder readers spaced at fixed positions therealong;

a plurality of moving elements traveling separately and independently along the continuous track, each moving element having a plurality of thrust producing magnets arranged in alternating North and South sequence and disposed face to face with the stator armatures of the track sections, each moving element including a linear encoder strip having a length greater than the spacing between any given pair of adjacent linear encoder readers, the length of each moving element being sized to prevent linear encoder strips from adjacent moving elements to interact with the same linear encoder readers;

$n$  track section controllers, one per track section, each section controller providing (a) position-detection processing means for associating any given linear encoder strip of any moving element located in the corresponding track section with only one linear encoder reader located therein at any time and for resolving the position of such moving element based on the fixed position of the associated linear encoder reader and a relative position of the given linear encoder strip in relation to the associated linear encoder reader, and (b) servo means, connected to the position-detection processing means, for regulating and commutating the coils of the corresponding stator armature in order to produce a separate moving MMF for each moving element located in the corresponding track section to thereby independently control each such moving element; and

communication means for interfacing the section controllers of adjacent track sections, wherein a given section controller is operative to utilize the communication means in order to transfer a responsibility of resolving the position of a given moving element to an adjacent section controller when the given moving element straddles the corresponding track sections, and wherein each of the given and adjacent section controller pair provides at least one coil regulating signal to the other of said pair in the event any portion of the magnets of the given moving element spans any portion of at least one coil situated in the track section corresponding to the other of said pair, provided that the responsibility for resolving the position of the given moving element has not yet been transferred to the other of said pair.

In the preferred embodiment of the conveyor system, the magnets of each moving elements have a pole pitch  $P$ ; the electrical pole pitch of each of the coils is  $P$ ; and the coils of each track section stator armature are arranged in a substantially contiguous sequence of individual polyphase-like sets, each set comprising  $p$  overlapping coils having centers thereof spaced apart by a distance  $P/p$ , where  $p \geq 2$ , and where coils associated with one track section do not overlap onto an adjacent track section. This enables the track sections to be self contained and modular in nature.

In the preferred embodiment of the conveyor system, the transfer of the responsibility for resolving the position of a given moving element to an adjacent section controller when the given moving element straddles the corresponding track sections occurs when an aforesaid linear encoder strip is associated with a first linear encoder reader and simultaneously begins to interact with a second, adjacent linear encoder in a second, adjacent track section. The position-detection processing means of each section controller, in combination with the transfer between section controllers of the responsibility for detecting the position of moving elements which cross track sections, enables multiple elements to be tracked along the entirety of the track without

requiring any further infrastructure, thereby not posing any undue limits on the number of moving elements which can be tracked. In addition, it will be appreciated that the moving elements are passive devices which, due to not being tethered in any way, have unrestricted mobility along the track.

In the preferred embodiment of the conveyor system, the section controllers are operative to transfer static data concerning the straddling moving element, such as its destination, to the adjacent section controller prior to the transfer of the responsibility for resolving the position of the straddling moving element. Furthermore, the section controllers are operative to transfer dynamic or memory based servocontrol data concerning the straddling moving element to the adjacent section controller substantially simultaneously with the transfer of the responsibility for resolving the position of the straddling moving element. In this manner, a distributed servocontrol system is presented which enables multiple moving elements to be controlled over a long track.

In the preferred embodiment of the conveyor system, the sections controllers are connected to a central controller which initializes the system and performs a diagnostic monitoring function. In addition, each section controller is directly connected to a station controller, such as a programming logic controller. The station controllers instruct the track section controllers for the purpose of carrying out station-specific tasks and coordinating the movement of the moving elements with other station machinery. The station controllers can also provide the section controllers with the next destinations for the moving elements, thereby alleviating the central controller from this task. The distributed control architecture provided by these additional components further enhance the scaling properties of the system.

#### BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other aspects of the invention are discussed in greater detail below with reference to the drawings, provided for the purpose of description and not limitation, where like objects are referenced by like reference numbers, and wherein:

FIG. 1 is an isometric view of a portion of a modular conveyor system, in accordance with the preferred embodiment, wherein multiple pallets move over a track;

FIGS. 2a and 2b are exploded views of the system shown in FIG. 1;

FIG. 3 is a cross-sectional view of the conveyor system taken along line III—III in FIG. 1;

FIG. 4 is a plan view of an individual poly phase-like coil set employed in the conveyor system in accordance with the preferred embodiment;

FIG. 5 depicts a conduction cycle of an individual coil shown in FIG. 4 in relation to the corresponding movement of a pallet thereover, in accordance with the preferred embodiment;

FIG. 6 is a system block diagram of a preferred distributed control architecture for controlling the conveyor system of FIG. 1 and each section thereof;

FIG. 7 is a hardwire block diagram of preferred electronic circuitry used to control each conveyor system section shown in FIG. 6;

FIG. 8 is an electronic schematic diagram illustrating various portions of the electronic circuitry shown in FIG. 7 in greater detail;

FIG. 9 is a system block diagram illustrating a servocontrol system according to the preferred embodiment for controlling pallets in each conveyor system section;

FIG. 10 is a flow chart of a digital p.i.d. position control loop employed in the servocontrol system of FIG. 9;

FIG. 11 is a flow chart relating to a commutation controller employed in the servocontrol system of FIG. 9;

FIG. 12 is a digram of a preferred scheme employed by the servocontrol system of FIG. 9 for demultiplexing linear encoders spaced along each conveyor system section in order to resolve the position of a given pallet therein;

FIG. 13 is a state transition diagram in relation to the demultiplexing scheme of FIG. 12;

FIG. 14 is a diagram of a preferred scheme for synchronizing the servocontrol systems (each shown in FIG. 9) of adjacent conveyor system sections in order to smoothly control the movement of a pallet thereacross; and

FIG. 15 is a state transition diagram in relation the synchronization scheme of FIG. 14.

#### DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

FIG. 1 illustrates a portion of a modular conveyor system 20, in accordance with the preferred embodiment. The system 20 features multiple pallets or moving elements 22 (only one is illustrated) which are constrained to ride or travel along a continuous, stationary, track 24.

The description of the conveyor system 20 is organized as follows: (1) an introduction to the operating principles thereof; (2) brief description of the physical structure of the system, which comprises a plurality of track sections or units 26; (3) description of the preferred electromagnetic structure of the system; (4) introduction to a preferred distributed control architecture for control of the system; (5) detailed description of a preferred servocontrol system for each track unit 26; (6) detailed description of a preferred servocontrol subsystem for detecting the position of each pallet 22 along each track unit 26; (7) detailed description of a method according to the preferred embodiment for synchronizing the servocontrol system of adjacent track sections 26 when any given pallet 22 crosses therebetween.

#### Principle of Operation

Referring additionally to FIGS. 2 and 3, each pallet 22, as explained in greater detail below, houses a plurality of permanent magnets 28 disposed to provide a magnetic flux depicted by vectors (30 and 31) orientated normal to the track 24. The track 24, as explained in greater detail below, houses a stator armature 32 comprising a plurality of embedded coils 35 which are individually excited so that an electrically-induced magnetic flux (depicted by vectors 36 and 37) produced by the stator armature 32 is located only beneath a given pallet 22 to be controlled, in a direction normal thereto, without affecting adjacent pallets. The motive force for translating each pallet 22 arises from the magnetomotive (MMF) force produced by each pallet and the stator armature, i.e., by the tendency of the corresponding magnetic fluxes provided by the stator and pallet to align. Servocontrol means, as described in greater detail below, enable separate and independent moving MMFs to be produced along the length of the track 24 for each pallet so that each pallet 22 can be individually controlled with a trajectory profile that is independent of any other pallet. The servocontrol means employs a contactless pallet position-detecting subsystem, as described in greater detail below. Structurally, the conveyor 20 may thus be broadly classified as a moving-magnet type linear brushless motor having multiple moving elements.

#### Physical Structure

Mechanically, the track 24 is composed of a plurality of track sections or units 26 which are mechanically self-

contained and quickly and easily separable from one another so as to be modular in nature. In the preferred embodiment, the track units **26** are mounted on a substrate (not shown) so as to merely align and abut one another in order to form the continuous track **24**. This preferred feature requires that stator armature coils **35** from one track unit not overlap or project onto the stator armature of an adjacent track unit, as explained in greater detail below. Also, each track unit **26** houses all of the electronic circuitry **38** required to control the track unit.

As seen best in FIGS. **2** and **3**, each pallet **22** includes an extension **40** onto which is mounted a relatively long, graduated, optically reflective strip **45**. The extension **40** is disposed such that the reflective strip **45** interacts with contactless, optical linear encoder read heads **50** mounted to a corresponding extension **46** depending from a side wall **48** of the track **24**. With the aid of flap **52**, this interengaging structure protects the optical components **45** and **50** from the traffic on the track and assists in precluding ambient light, i.e., light interference or noise, from falsely triggering the optical linear encoder read heads **50**. The optical components **45** and **50** are employed in the pallet position-detecting subsystem explained in greater detail below. At this point, it should be appreciated that by placing the read heads **50** on track **24** and not on pallets **22**, the pallets are not tethered in any way and thus their mobility is not restricted.

Each pallet **22** features load-bearing wheels **54** which ride along rails **56** of track **24**. Each pallet also features spring-loaded bearings **58** for constraining the pallet to stay on the rails **56** and maintain the alignment between optical components **45** and **50**.

#### Electromagnetic Structure

The magnetic structure of each pallet **22** comprises at least two thrust-producing permanent magnets arranged in alternating North-South sequence. The permanent magnet material, which may include Neodymium-Iron-Boron, Alnico and ceramic (ferrite) base magnets, is selected on the basis of air gap flux densities required and the physical dimensions of the pallet magnetic structure. In the preferred embodiment, each pallet **22** carries two Neodymium-Iron-Boron permanent magnets **28** spaced apart by pole pitch  $P$ . This provides each pallet with a permanent magnet pole pair **60** which provides magnetic flux vectors **30** and **31** pointing in opposite directions. For reasons explained shortly below, and referring additionally to FIG. **5**, the pole pitch  $P$  is preferably approximately equal to  $2D/3$ , where  $D$  is the overall width of the permanent magnet poles pair, and the width  $W$ , of each magnet **28** is preferably approximately  $D/3$ . The permanent magnet pole pair **60** abuts a magnetic backplate (FIG. **2**) and these components are preferably mounted in a cavity **64** of pallet **22** such that end portions **66** of the pallet body function as dead poles which magnetically isolate the pallet permanent magnet pole pair **60** from the permanent magnet pole pair of any adjacent pallet.

The magnetic structure of the stator armature **32** comprises a yoke **68**, constructed out of electrical steel, which features a plurality of substantially equidistantly spaced slots **70** disposed in relative close proximity to one another. A representative slot spacing is 3 mm and representative slot dimensions are  $1.5 \times 7 \times 75$  mm. The turns of the stator armature coils **35** are mounted in the yoke slots.

The turns of each coil are formed (FIG. **4**) into two legs **72** and **72'** which are spatially distributed over a specified number of yoke slots **70**. The coil legs **72** and **72'** provide electrically induced, magnetic flux producing pole pairs that produce magnetic flux vectors **36** and **37** pointing in opposite directions. The spatial distribution of coil legs **72** or **72'**

reduces cogging effects caused by uneven reluctance and, in comparison to a non-spatially distributed coil leg or electrically induced pole, enables a smoother thrust production along the stator armature **32**.

The electrical pole pitch (FIG. **5**) of each coil **35** is substantially equal to the mechanical pole pitch,  $P$ , of each pallet permanent magnet pole pair **60**. In the preferred embodiment, the width of each coil leg **72** or **72'** is approximately equal to the width,  $W$ , of each pallet permanent magnet **28**, whereby the overall width of each coil **35** approximately equals the overall width,  $D$ , of pallet permanent magnet pole pair **60**.

The coils **35** are arranged as a sequence of individual polyphase-like windings or coil sets, wherein coils in each set are overlapped such that the coil centres are spaced apart a distance  $P/p$ , where  $p$  is the number of quasi-phases. The preferred embodiment, as seen in FIG. **2** and in FIG. **4** (which is a plan view of a coil set taken in isolation), features a two phase-like arrangement, wherein each polyphase-like winding or coil set (hereinafter "coil pair **75**") comprises two overlapping coils **35** having their centres **76**, **77** spaced apart by a distance  $P/2$ . Since the width,  $W$ , of the leg **72** or **72'** of each coil **35** is  $D/3$ , and the width of the empty inner space of the coil is also  $D/3$ , it will be seen from FIGS. **2** and **4** that one of the legs **72** or **72'** of each coil **35** in coil pair **75** substantially occupies the empty inner space **78** of the counterpart coil such that there are no unfilled yoke slots **70** spanned by the coil pair. In addition, the coil pairs **75** are arranged to be immediately adjacent to one another such that there are no unfilled yoke slots **70** in an inter-coil pair region. This arrangement, in combination with the spatial distribution of the turns of each coil leg, enables the stator armature **32** to present a relatively uniform reluctance in order to minimize cogging effects.

Another advantage provided by the individual polyphase-like windings or coil sets lies in the fact that the track **24** can be modularly constructed in discrete sections as described above such that no coil from one stator section overlaps, projects or otherwise encroaches upon an adjacent stator section. In contrast, a conventional convolute polyphase a.c. stator winding has an essentially endless coil overlapping arrangement such that turns cannot be mechanically separated.

In alternative embodiments, a coil set may comprise a short segment of a conventional polyphase a.c. winding, preferably provided that length of each segment is approximately equal to the length of the magnetic structure of the pallet. Thus, a stator armature according to this embodiment comprises a series of individually controlled polyphase a.c. windings.

The magnetic circuit provided by the pallet and stator armature is as follows (FIG. **2**): the magnetic flux circulates through the pallet backplate **62**, through the permanent magnets **28**, across an air gap to and through the stator armature poles (i.e. coils **35**), through the yoke **68**, back through the stator poles, and back through the permanent magnets **28**, returning to the pallet backplate **62**.

FIG. **5(b)** illustrates a conduction cycle **80** for a single coil **35** of any given coil pair **75**. FIG. **5(a)** indicates that the conduction cycle **80** begins just as a leading edge **82** of pallet permanent magnet pole pair **60** (shown in solid lines) reaches a leading outer turn of the coil **35** and terminates just as a trailing edge **84** of the pallet pole pair **60** (shown in stippled lines) passes over a receding outer winding of the coil. Distances along the position axis of FIG. **5(b)** correspond to the relative distance between a centre point **86** of coil **35** and a centre point **87** of the pallet pole pair **60**. The

conduction cycle **80** corresponds to a 540 degree electrical cycle. It should also be noted that the preferred conduction cycle illustrated in FIG. 5(b), in association with the design of the stator armature **32** as described above, yields a relatively constant MMF, having a ripple of only about 5–10%.

#### Distributed Control Architecture

FIG. 6 is a high level abstraction of a preferred control architecture employed in the conveyor system **20**. Architecturally, the conveyor system **20** is partitioned into a plurality of control zones, each of which corresponds to one track section unit **26**, which is placed under the control of a local section controller **90**. The section controllers **90** are connected to one another in a peer-to-peer communications network such that each section controller **90** is connected to a preceding and following section controller through high speed communications links **92**.

Each section controller **90** is also connected to a central controller **94**, such as a computer workstation, through a supervisory network employing a multi-drop bus **96**. The central controller **94** and supervisory network provides an efficient means for initializing the section controllers. The central controller may also communicate destination data to the section controllers for the pallets (which are preferably uniquely addressed) and receive acknowledgement messages in return when pallets have reached their destinations. As such, the central controller may be used for process (i.e. manufacturing-line) control. The central controller also fulfills a supervisory diagnostic role by monitoring the section controllers (e.g. by engaging in a continuous polling process) in order to determine whether any section controller has failed.

Each section controller **90** may also (but does not necessarily) include a cell port **98** for interfacing section controller **90** to a station controller such as an external programmable logic controller (PLC) **100**. The PLCs provide manufacturing-line station-processing instructions to the track **24**, such as directing the next destination for a pallet along the track, or providing station-specific motion instructions in respect of a given pallet stopped adjacent to or in a processing station (not shown). For instance, a typical two-axis station controller or PLC operates by providing pulse signals in order to synchronize the motion of a pallet along the track with the motion of a station end effector or dispenser moving along a transverse axis, whereby each pulse represents an incremental pallet move command. It will be appreciated that the provision of the station controller or PLC reduces the amount of bandwidth that would otherwise be required to communicate this information to the central controller **94**, thereby substantially eliminating a potential limitation on the length and processing capabilities of the conveyor system.

As illustrated, each section controller **90** is connected to all of the stator armature coils **35** in the corresponding track unit **26** and, as described in greater detail below, is responsible for commutating the coils in the control zone in accordance with an independent trajectory or “move” command for each pallet located therein. However, unlike a conventional convolute two phase stator armature winding, the commutation is complicated by the fact that a given pallet, (such as illustrated pallet **22'**) may straddle two coil pairs **75** whereby both coil pairs have to be simultaneously excited in order to produce a suitable moving MMF along the track **24**.

Each section controller **90** is also connected to all of the optical read heads **50** situated in its control zone. The section controller is responsible for resolving the absolute position

of each pallet **22** located in its control zone, as described in greater detail below.

#### Servocontrol System

FIG. 7 is a hardware block diagram illustrating the major components of a given section controller **90** which, in accordance with the preferred embodiment, physically comprises a control board **102** and two power boards **104**. The control board **102** includes an ADSP2181 digital signal processor (DSP) **105**, commercially available from Advanced Micro Devices of Norwood, Mass. U.S.A., and associated program memory **106**. The DSP **105** includes two on-chip serial ports **108** for providing the communication link interfaces **92** to adjacent preceding and following section controllers. A separate micro-controller **110** provides an interface to the supervisory network **96** which links the section controller **90** to the central controller **94**. A field programmable gate array (FPGA) **112** is used to interface the cell port **98** with the local PLC **100**. The FPGA **112** is also used to interface the optical read heads **50** with the DSP **105**.

The power boards **104** comprises a plurality of current amplifiers **114**, one for each coil **35** controlled by the section controller. (There are eighteen coils in the illustrated embodiment.) Each current amplifier **114** comprises an inverter such as a two phase or H-bridge **116**, drivers **118** for converting logic level signals to analog level signals in order to drive the power switches of the H-bridge, and current sensing circuitry **120** for sensing the coil current. Each power board also includes an FPGA **122** which is used to interface the DSP **105** with the current amplifiers **114**. More particularly, as shown in FIG. 8 which illustrates a given current amplifier and its associated FPGA circuitry, the FPGA **122** provides a latch **124** (for each coil **35** controlled by a given power board), addressable by the DSP **105**, for storing a pulse-width modulated (PWM) duty cycle value used to drive the H-bridge **116**. The latch **124** is connected to a fixed frequency PWM generator **126** which operates by comparing the value stored in the latch **124** with a continuously cycling counter **128** and setting an output signal **130** accordingly. The output signal **130** and a complementary signal **132** are connected to the drivers **118** so as to control the base inputs of power MOSFET devices **134** employed as switching elements in the H-bridge **116**.

The current sensing circuitry **120** comprises a current sensor **136** which is used to measure the current flowing through a given coil **35** for all commutation phases of the H-bridge. A suitable current sensor is disclosed for instance in co-pending U.S. Ser. No. 08/873,158, filed Jun. 11, 1997, by Derek C. Schuurman and assigned to an assignee of the instant application. A variety of alternative current sensing devices may be used, such as current transformers or open and closed loop Hall effect devices. The output of the current sensor **136** is connected to an analog filter **138** which is connected to an analog multiplexer **140** (not shown in FIG. 7). The analog multiplexer **140** multiplexes the current sensing signals from multiple current sensors associated with the other current amplifiers **114** located on the power board **104** and provides these signals to an analog to digital converter (A/D) **142** which is connected to a latch **144** addressable by the DSP **105**. The FPGA **122** provides a channel selection means **146** for continuously sampling the current sensing signals from each current amplifier **114**. The FPGA **122** also provides circuitry **148** for generating the appropriate control signals to the A/D **142**. It will be noted (FIG. 7) that since each section controller **90** comprises two power boards **104** each carrying A/D **142**, the DSP **105** can operate in a pipelined manner so that two coil current readings can occur substantially simultaneously.

Each power board **104** also includes a temperature sensor **147** and a voltage sensor **149** which are connected to the A/D **142** and interfaced to the DSP **105** by the FPGA **122**. The central controller **94** periodically polls each section controller **90** in order to obtain diagnostics data provided by these sensors.

The DSP **105** of each section controller **90** is used to implement a closed-loop digital servocontrol system which is shown in systemic form in FIG. **9**. The servocontrol system comprises a trajectory generator **150**, as known in the art per se, for computing a pallet position set point vector  $\vec{S}$  ( $S_1, S_2, \dots, S_K$ ), where component or signal represents the position set point for a given pallet located in the control zone serviced by the given section controller and  $K$  is the number of pallets in the control zone at any given time. The trajectory generator **150** produces set points for each pallet in accordance with pre-specified acceleration and velocity profiles for the pallets which are downloaded by the central controller **94** to the section controller **90** during system initialization. For example, the trajectory generator **150** may employ a trapezoidal acceleration profile to smoothly accelerate the pallet from an initial rest position to a terminal velocity and then smoothly de-accelerate the pallet to a destination position. In the preferred embodiment, the pallet position set point vector  $\vec{S}$  is computed at a rate of approximately 1 KHz.

The pallet set points are compared against the measured positions,  $\vec{X}$  ( $X_1, X_2, \dots, X_K$ ), of the pallets as determined by a pallet position feedback subsystem **152** which also samples pallet positions at a rate of approximately 1 KHz. This comparison results in the computation of a pallet position error vectors  $\Delta\vec{S}$  ( $\Delta S_1, \Delta S_2, \dots, \Delta S_K$ ). The pallet position error vectors  $\Delta\vec{S}$  is fed into a position compensator **154** which computes a force vector,  $\vec{F}$  ( $F_1, F_2, \dots, F_K$ ), specifying the force required to be applied to each pallet in order to minimize the pallet position error. The force vector  $\vec{F}$  is also computed at a rate of about 1 KHz.

In the preferred embodiment, the position compensator **154** employs a well-known proportional, integral, derivative (p.i.d.) control law, however, alternative control methods such as the state space technique may employed. FIG. **10** shows pseudocode for implementing a digital p.i.d. control loop in respect of one pallet. It will be seen that in order to compute a derivative term, D\_term, of the p.i.d. control law, the p.i.d. control loop employs an error history buffer or array  $E[1 \dots q]$  for retaining a set  $\{\Delta S_i[T], \Delta S_i[T-1], \Delta S_i[T-2], \dots, \Delta S_i[T-q]\}$  of position errors where  $T$  represents a latest received pallet position error and  $q$  corresponds to the size of the buffer. In addition, the p.i.d. control loop employs an accumulator, I\_term, for storing the integral term of the p.i.d. control law. This data assumes special significance when a pallet moves across control zones, as discussed in greater detail below.

The force vector  $\vec{F}$  and pallet position vector  $\vec{X}$  are fed (FIG. **9**) into a commutation controller **155** which provides current set point data for the coils **35**. FIG. **11** illustrates a preferred commutation control algorithm executed by the commutation controller **155**. Processing steps **158** and **162** set up nested loops. The inner loop is executed  $N$  times, where  $N$  is the number of coils **35** controlled by section controller **90**. The outer loop executes the inner loop  $K$  times, where  $K$  is the number of pallets presently located in the current control zone. At processing step **160** in the outer loop, the commutation controller **155** computes the centre

point, CPP(i), of permanent magnet pole pair **60** for pallet(i),  $1 \leq i \leq K$ . (See additionally FIG. **5**). This computation is based on (a) input parameter or signal  $X_i$ , the measured position of pallet(i), which, as described in greater detail below, is measured at a different reference point than the pallet pole pair centre point **87**; and (b) a constant which is dependent upon the physical dimensions of pallet(i). At processing step **164** in the inner loop (FIG. **11**), the commutation controller **155** computes the relative distance, RD(j), between centre point CPP(i) of pallet(i) and the centre point, CPC(j), of a given coil, coil(j),  $1 < j \leq N$ . At step **166**, a check is made whether or not  $-D \leq RD(j) \leq D$ . This, as described above with reference to FIG. **5**, indicates whether or not the pole pair **60** of pallet(i) is situated above coil (j). If the pole pair **60** of pallet(i) is not situated above coil(j), flow control is passed to the next iteration of the inner loop. If the pole pair **60** of pallet(i) is situated above coil(j), then (FIG. **11**) at steps **168**, **170** and **172** the commutation controller respectively reads a table **180** corresponding to the conduction cycle **80** (FIG. **5**) to extract a nominal current set point; scales the nominal current set point by input parameter  $F_j$ , the required force for pallet(i); and updates a current set point table **182**. This process is repeated for each pallet in the control zone in order to provide a current set point vector  $\vec{I}_S(I_{S1}, I_{S2}, I_{S3}, \dots, I_{SN})$ . The current set point vector  $\vec{I}_S$  is computed or updated at a 20 KHz rate.

The current set point vector  $\vec{I}_S$  is compared (FIG. **9**) to an actual or measured coil current vector  $\vec{I}_A(I_{A1}, I_{A2}, I_{A3}, \dots, I_{AN})$  generated by the current sensing circuitry **120** in order to compute a current error vector  $\Delta\vec{I}$  ( $\Delta I_1, \Delta I_2, \Delta I_3, \dots, \Delta I_N$ ) at a 20 KHz rate. The current error vector  $\Delta\vec{I}$  is fed into a current compensator **184** which computes a PWM duty cycle value for each current amplifier **114** of each coil **35** using a proportional, integral (p.i.) control law well known in this art. In the foregoing manner, the commutation controller **155** applies the conduction cycle **80** to the necessary stator armature coils **35** in order to provide a moving MMF for a given pallet in the control zone, even when the pallet straddles two coil pairs **75**.

#### Parallel Position Feedback Subsystem

The pallet position feedback subsystem **152** which supplies measured pallet position data to the trajectory generator **150**, position compensator **154** and commutation controller **155** is now discussed in greater detail. Referring to FIGS. **6**, **7** and **12**, when the reflective strip **45** of a given pallet **22** moves over a given optical read head **50**, two 90° out-of-phase signals are produced and quadrature decoding circuitry **186** causes a counter or register **188** associated therewith to count up or down in accordance with the direction of travel of the reflective strip **45**. For example, if a 400 lines-per-inch graded reflective strip moves one inch through a given optical read head **50**, such movement will cause the associated counter **188** to change by  $\pm 400$ , depending on the direction of travel. The optical read head **50** and decoding circuitry **186** and **188** (hereinafter "encoder") as well as the associated reflective strip **45** are commercially available, for instance, from the Hewlett Packard Company of Santa Clara, Calif., U.S.A.

As depicted in FIG. **6**, each control zone features a plurality,  $M$ , of the optical read heads **50** which are substantially equidistantly spaced at a distance,  $E$ , along every track unit **26**. The length  $R$ , of the reflective strip **45** is such that  $R$  is greater than  $E$  by a pre-determined amount,  $XR$ . Thus, the reflective strip associated with any given pallet can engage or trigger two encoders simultaneously at various



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points along the track. In addition, the length,  $L$ , of the pallet itself is at least equal to or greater than  $R$  in order to ensure that a reflective strip associated with an adjacent pallet does not interfere with the given pallet. In other words, the length  $L$  is chosen to ensure that no two reflective strips can trigger the same encoder.

As shown in FIG. 7, the FPGA 112 of each section controller 90 interfaces the linear encoders with the DSP 105 thereof. The DSP provides a parallel processing means for sampling the encoders and resolving the position of each pallet located in the associated track unit at a rate of approximately 1 KHz. Broadly speaking, the processing means associates the reflective strip 45 of any given pallet with only one encoder at any time so that the absolute position of the given pallet can be calculated based on a fixed position of the associated encoder (or more specifically its read head 50) and a relative position of the reflective strip in relation to the associated encoder. In addition, when the reflective strip simultaneously engages two encoders, at some point, as described in greater detail below, the processing means transfers or hands-off the association or "ownership" of the pallet from the current encoder to the adjacent engaged encoder. In this manner, the position of a given pallet can be continuously tracked across the control zone. When a pallet crosses control zones, a similar process occurs, with the addition that the adjacent section controller creates a data structure to keep track of the position of the given pallet, and at some point as described in greater detail below, once the hand-off is completed, the data structure for the pallet in the (now) previous control zone is deleted.

FIGS. 12 and 13 depict a method according to the preferred embodiment for accomplishing the hand-off or transfer of the ownership of a given pallet between adjacent encoders. More particularly, FIG. 12 depicts how a given encoder may assume various control states, and FIG. 13 is a diagram of an associated state transition table. In the illustrated embodiment, the reflective strip 45 features 3300 graduations, i.e. 3300 counts from start to finish, and a control zone features seven encoders (addressed from enc=0 to enc=6).

A "zone 2" state 200 represents a steady state condition wherein the reflective strip of a given pallet  $i$  engages a given encoder, encoder( $n$ ), and is not yet near encoder( $n-1$ ) or encoder( $n+1$ ). Considering the situation where the given pallet moves to the right in FIG. 12, at some point (i.e. when count=3060) the leading right edge of the associated reflective strip moves right into a "right-reset" state 202 where the adjacent right encoder( $n+1$ ) is continuously reset to zero in preparation for the hand-off. The reflective strip then enters a "zone 3" state 204 (at count=3120). At some point in this state, the leading edge of the reflective strip engages encoder ( $n+1$ ) which begins its count reflecting the distance the leading edge of the reflective strip has passed therethrough. However, encoder( $n$ ) still owns the given pallet. The ownership continues until the leading edge of the reflective strip reaches a "right hand-off" state 206 (at count=3240). Somewhere in this state, depending on the rate the DSP 105 samples the encoders, the ownership of the given pallet is handed-off to encoder( $n+1$ ). The transfer of ownership is shown in the changing state of table 220 (FIG. 12) before and after the hand-off (where  $i$  represents the given pallet).

A similar process occurs when the given pallet moves leftward. "Reset-left", "zone 1", and "left hand-off" states 208, 210 and 212 are the respective counterparts to the "reset-right", "zone 3", and "right hand-off" states 202, 204 and 206.

The preferred method provides a hysteresis effect when the given pallet backtracks soon after the hand-off is accom-

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plished. The extra distance  $XR$  by which the length  $R$  of each reflective strip exceeds the encoder spacing  $E$  enables the control state patterns 215 and 215' (FIG. 12) associated with each encoder to overlap and be partially temporarily conterminous, as illustrated. The relative lengths and positions of the control states or zones are selected such that when the hand-off is effected, encoder( $n+1$ ) is in the "zone 1" control state 210. If during this state the given pallet backtracks, it must traverse at least a minimum hysteresis distance  $H$  backwards before the ownership of the given pallet is transferred back to encoder( $n$ ). The hysteresis effect provides for a more stable pallet position feedback system by preventing the oscillation or flip-flopping of hand-offs when a pallet straddles two encoders and is commanded to move relatively small distances to and fro. Such a condition could occur, for instance, when the pallet is located at a processing station and the motion of the pallet along the axis of track 24 is coordinated by the PLC 100 with the motion of a station end effector or dispenser moving along a transverse axis.

The preferred method is carried out by each section controller 90 for each pallet located in the corresponding control zone.

Those skilled in the art will appreciate that devices other than the optical linear encoder reader 50 and the reflective strip 45 may be used in alternative embodiments. For example, the passive readable device can be a magnetic strip and the linear encoder readers can be corresponding magnetic detectors. Such an alternative embodiment could provide very fine resolution, e.g. graduations of about a micron, however the cost of such linear encoders is typically very high and may not be required for most applications given the good resolution, typically a thousandth of inch, provided by the optically reflective strips.

## Synchronizing Servocontrol Systems

The length of track 24 that a given section controller 90 can control is limited by various practical considerations, thereby complicating the production of moving MMFs for the pallets, which have to cross control zones. Accordingly, the preferred embodiment provides a means for synchronizing the servocontrol systems of adjacent section controllers and for passing control of a pallet crossing therebetween.

FIGS. 14 and 15 depict a method and protocol according to the preferred embodiment for synchronizing the servo control systems of adjacent section controllers and for passing control of a given pallet  $i$  crossing control zones. FIG. 14 depicts various control states assumed by section controller( $n$ ) of track section or control zone  $N$  and section controller( $n+1$ ) of track section or control zone  $N+1$  as a given pallet crosses from zone  $N$  into zone  $N+1$ , and vice versa. FIG. 15 illustrates an associated state transition table followed by each of controller( $n$ ) and controller( $n+1$ ). A "Solo Pallet" state 250 represents a steady state condition when the given pallet is fully under the control of one section controller.

When the given pallet moves to the right in FIG. 14 from zone  $N$  to zone  $N+1$ , the leading right edge of the associated reflective strip reaches a point  $t_1$  which is considered to be near to zone  $N+1$ . Upon the occurrence of this event, a message, termed PM\_CREATE, is transmitted by controller ( $n$ ) to controller( $n+1$ ) over the peer to peer communication link 92 using a predetermined handshaking protocol (for ensuring reliable communication), and controller( $n$ ) enters a "Pallet Struct" state 252. Correspondingly, controller( $n+1$ ) receives the PM\_CREATE message and enters a "Pallet Ready" state 260. During the time period  $t_1-t_2$  represented by the substantially conterminous states of the section

controllers, the following events occur: (1) controller(n+1) creates or initializes a data structure for the given pallet; and (2) controller(n) passes various static data from its data structure representing the given pallet to controller(n+1) over the peer-to-peer communications link **92** in accordance with a predetermined communications protocol. This data includes information such as the pallet destination point, current velocity and acceleration, maximum permissible velocity and acceleration, length, number of magnets and offset data, and envelope or buffer space data for collision avoidance purposes.

At point  $t_2$ , the leading edge of the pallet permanent magnet pole pair **60** reaches the leading turn of a border coil pair located in zone N+1. (See, for example, FIG. **5(a)**.) Upon the occurrence of this event, a message, termed PM\_COILSTART, is transmitted by controller(n) to controller(n+1), and controller(n) enters a "Send Coil Control" state **256**. Correspondingly, controller(n+1) receives the PM\_COILSTART message and enters a "Receive Coil Control" state **258**. During the time period  $t_2-t_3$  represented by the conterminous states of the section controllers, controller(n) is still responsible for executing the position control loop for the given pallet, which includes computing a force set point component  $F_i$  for the given pallet and measuring the position  $X_i$  thereof. Controller(n) uses this data as described above to regulate the border coil pair **75** in zone N. The force set point  $F_i$  and position  $X_i$  are also communicated to controller(n+1) at a rate of approximately 1 KHz over the peer-to-peer communication link **92**. Controller(n+1) uses this data in its commutation controller **155** and current compensator **184** in order to produce current step point components  $I_1$  and  $I_2$  in zone N+1 and regulate the border coil pair **75** in zone N+1 so as to properly servocontrol the given pallet. In this manner, controller(n) and controller(n+1) are synchronized to cooperatively execute the current control loop for the given pallet by regulating the border coil pairs in their respective zones.

At point  $t_2$ , the leading edge of the reflective strip of the given pallet reaches a point, as described above, where the ownership of the given pallet should be handed-off from a border encoder in zone N to a border encoder in zone N+1. Upon the occurrence of this event, a message, termed EM\_CHANGE\_ACTIVE\_ENCODER, is transmitted by controller(n) to controller(n+1), and controller(n) enters the "Receive Coil Control" state **258**. Correspondingly, controller(n+1) receives the EM\_CHANGE\_ACTIVE\_ENCODER message and enters the "Send Coil Control" state **256**. During the time period  $t_3-t_4$  represented by the substantially conterminous states of the section controllers, a number of steps occur:

- (1) The dynamic or memory-based data used by controller (n) for the position control loop of the given pallet is transferred over to controller(n+1). In the preferred embodiment this comprises (a) the accumulator,  $I\_term$ ; and (b) a portion of the error history buffer  $E[2 \dots q]$  in respect of the set  $\{\Delta S_i[T-1], \Delta S_i[T-2], \dots, \Delta S_i[T-q]\}$  of position errors for calculating the derivative term of the p.i.d. control law.
- (2) The dynamic or memory-based data used by controller (n) to generate the trajectory of the given pallet is transferred over to controller(n+1). In the preferred embodiment this comprises up-to-date velocity, acceleration, position and time base data.
- (3) Controller(n) sends controller(n+1) a message effective to transfer the ownership of the given pallet from the border encoder in zone N to the border encoder in zone N+1. This change of state is also shown in FIG.

**13** where, for instance, when the border encoder (enc=6) is in the "zone 3" state **204** and moves right into a hand-off zone, the border encoder enters into a "Right Hand-off Message" state **216** where the zone-crossing, controller ownership transfer message is transmitted.

- (4) Once step (3) is effected, controller(n+1) becomes responsible for executing the position control loop for the given pallet, which includes computing the force set point component  $F_i$  for the given pallet and measuring the position  $X_i$  thereof. Controller(n+1) uses this data as described above to regulate the border coil pair in zone N+1. Now, controller(n+1) communicates the force set point  $F_i$  and measured position  $X_i$  to controller (n) at a rate of approximately 1 KHz over the peer-to-peer communication link **92**. Controller(n) now uses this data in its commutation controller **155** and current compensator **184** in order to produce current step point components  $I_N$  and  $I_{N-1}$  in zone N and regulates the border coil pair in zone N so as to properly servocontrol the given pallet. In this manner, controller(n) and controller(n+1) remain synchronized to continue to cooperatively execute the current control loop for the given pallet.

At point  $t_4$ , the trailing edge of the pallet permanent magnet pole pair **60** passes the last turn of the border coil located in zone N. Upon the occurrence of this event, a message, termed PM\_COILSTOP, is transmitted by controller(n+1) to controller(n), whereby controller(n+1) enters into a "Pallet Control" state **254** and controller(n) enters into the "Pallet Ready" state **26**. As soon as this point is reached, position control loop set point data is no longer transferred from controller(n+1) to controller(n). Since there is no longer any need to regulate the border coil in Zone N. At point  $t_5$  controller(n+1) enters into the steady "Solo Pallet" state, wherein a message, termed PM\_DESTROY, is sent to controller(n) to terminate its data structure for the given pallet.

In the preferred method, the point at which any of the above described section controller states is triggered or entered into differs depending upon the direction the given pallet is moving. This provides a hysteresis effect, similar to that described above, for enabling a more stable control system by preventing the inefficient oscillation or flip-flopping between states when a pallet straddles two track sections and is commended to move relatively small distances to and fro.

The above process has been described a tone border between track units. A similar process can simultaneously occur at the opposite border between track units when a pallet travels thereacross.

It will be appreciated by those skilled in the art that while the preferred embodiment passes a position error minimizing signal such as  $F_i$  between adjacent section controllers when a pallet crosses control zones, an alternative embodiment may instead compute the current set points for the coil pair in an adjacent control zone which are spanned by a crossing pallet, and pass this data to the adjacent section controller. The current set point signals are linearly related to the position error minimizing set point or signal, and both types of signals can be viewed as instances of coil regulating signals. The advantage of the preferred embodiment is that less information has to be passed over the relative slow (compared to the processing speed of the DSP **105**) serial communication link **92**.

The preferred conveyor system **20** provides a number of advantages over the herein-disclosed prior art. For instance, the electromagnetic structure of the conveyor system pro-

vides relatively smooth thrust production capabilities, and the conveying speed is much improved over typical belt conveyor systems. For example, in a prototype system developed by the applicants, the pallets attained a 2 g acceleration and steady velocity of 2 m/s. In addition, the pallet position-detecting subsystem enables the absolute position of each pallet to be determined at high resolution at all times anywhere along the track, thereby enabling the pallets to be precisely positioned to any point along the track. Furthermore, the preferred distributed control system enables each pallet to be individually and separately controlled yet interface with manufacturing process controllers. Finally, these elements, in combination with the physical structure of the conveyor system, enable it to be constructed out of discrete, self-contained, modular track sections, with little practical restriction on the length of the conveyor system or the number of pallets controlled thereby.

The preferred embodiment has been disclosed with a certain degree of particularity for the purpose of description but not of limitation. Those skilled in the art will appreciate that numerous modifications and variation can be made to the preferred embodiment without departing from the spirit and scope of the invention.

What is claimed is:

1. Apparatus for detecting the position of a moving element relative to a stationary element, said apparatus comprising:

a plurality of linear encoder readers spaced generally along the stationary element at fixed positions relative thereto;

a device readable by the linear encoder readers, the readable device being mounted on the moving element and having a length which is greater than the spacing between any given pair of adjacent linear encoder readers;

a guide for aligning the readable device in order to interact with the linear encoder readers; and

circuitry, connected to each linear encoder reader, for associating the readable device with only one linear encoder reader in a state of interaction with the readable device at any time and for resolving and providing a reading of the overall position of the moving element based on the fixed position of the associated linear encoder reader and a relative position of the readable device in relation to the associated linear encoder reader;

*wherein, in a condition where the readable device is associated with a given linear encoder reader and simultaneously begins to interact with an adjacent linear encoder reader, the circuitry is operative to switch the association of the readable device with the given linear encoder reader to the adjacent linear encoder reader once the readable device has reached a pre-specified distance through one of the given linear encoder reader and the adjacent linear encoder reader, the circuitry being operative to initialize the adjacent linear encoder reader prior to the interaction of the readable device with the adjacent linear encoder reader.*

[2. Apparatus according to claim 1, wherein the readable device is an optical strip or a magnetic strip and the linear encoder readers respectively comprise optical read heads or magnetic detectors.]

[3. Apparatus according to claim 1, wherein the linear encoder readers are substantially equidistantly spaced along the stationary element and the readable device has a length

which is greater than the spacing between adjacent linear encoder readers and less than the spacing between three linear encoder readers.]

[4. Apparatus according to claim 1, wherein, in a condition where the readable device is associated with a given linear encoder reader and simultaneously begins to interact with an adjacent linear encoder reader, the circuitry is operative to switch the association of the readable device with the given linear encoder reader to the adjacent linear encoder reader once the readable device has reached a pre-specified distance through one of the given linear encoder reader and the adjacent linear encoder reader.]

[5. Apparatus according to claim 4, wherein the circuitry is operative to initialize the adjacent linear encoder reader prior to the interaction of the readable device with the adjacent linear encoder reader.]

6. Apparatus according to claim [4] 1, wherein, immediately after the association of the readable device is switched to the adjacent linear encoder reader, the circuitry is operative to require the readable device to backtrack for at least a minimum distance before the association of the readable device is switched back to the given linear encoder reader, to thereby provide a hysteresis effect.

7. Apparatus for detecting the positions of plural moving elements relative to a stationary element, said apparatus comprising:

a single row of linear encoder readers spaced generally along the stationary element at fixed positions relative thereto;

a device readable by the linear encoder readers mounted on each moving element, each readable device having a length which is greater than the spacing between any given pair of adjacent linear encoder readers;

a guide for aligning the readable devices in order to interact with the single row of linear encoder readers; and

circuitry, connected to each linear encoder reader, for associating any given readable device with only one linear encoder reader at any time and for resolving and providing a reading of the overall position of the corresponding moving element based on the fixed position of the associated linear encoder reader and a relative position of the given readable device in relation to the associated linear encoder reader;

*wherein, in a condition where a given readable device is associated with a given linear encoder reader and simultaneously begins to interact with an adjacent linear encoder reader, the circuitry is operative to switch the association of the given readable device with the given linear encoder reader to the adjacent linear encoder reader once the given readable device has reached a pre-specified distance through one of the given linear encoder reader and the adjacent linear encoder reader.*

[8. Apparatus according to claim 7, wherein the readable device is an optical strip or a magnetic strip and the linear encoder readers respectively comprise optical read heads or magnetic detectors.]

[9. Apparatus according to claim 7, wherein the linear encoder readers are substantially equidistantly spaced along the stationary element and each readable device has a length which is greater than the spacing between adjacent linear encoder readers and less than the spacing between three linear encoder readers.]

[10. Apparatus according to claim 7, wherein each moving element is sized longer than its corresponding readable

device in order to preclude readable devices of adjacent moving elements from interacting with the same linear encoder reader.]

[11. Apparatus according to claim 7, wherein, in a condition where a given readable device is associated with a given linear encoder reader and simultaneously begins to interact with an adjacent linear encoder reader, the circuitry is operative to switch the association of the given readable device with the given linear encoder reader to the adjacent linear encoder reader once the given readable device has reached a pre-specified distance through one of the given linear encoder reader and the adjacent linear encoder reader.]

12. Apparatus according to claim [11] 7, wherein the processing circuitry is operative to initialize the adjacent linear encoder reader prior to the interaction of the given readable device with the adjacent linear encoder reader.

13. Apparatus according to claim [11] 7, wherein, immediately after the association of the given readable device is switched to the adjacent linear encoder reader, the circuitry requires the given readable device to backtrack for at least a minimum distance before the association of the given readable device is switched back to the given linear encoder reader, to thereby provide a hysteresis effect.

14. *A moving-magnet type linear motor, comprising:*

*a plurality of moving elements traveling along a track; a stator armature provided substantially along the entire traveling track of moving elements;*

*wherein each moving element travels separately and independently and comprises n permanent magnets disposed face to face with the stator armature, said magnets being arranged in alternating North and South sequence and having a pole pitch P;*

*wherein the stator armature comprises a plurality of individual coils arranged in a substantially continuous sequence of individual polyphase-like sets, each set comprising p overlapping coils having centers thereof spaced apart by a distance P/p, wherein  $p \geq 2$ ; and*

*a servocontrol system for regulating and commutating the coils so as to produce a separate moving MMF for each moving element and independently control each moving element.*

15. *A linear motor according to claim 14, wherein the electrical pole pitch of each coil is P.*

16. *A linear motor according to claim 14, wherein  $n=2$ .*

17. *A linear motor according to claim 14, wherein  $p=2$ .*

18. *A linear motor according to claim 14, wherein the stator armature comprises a yoke having a plurality of slots orientated substantially normal to the track, wherein each coil comprises two legs, and wherein each coil leg is spatially distributed over a plurality of yoke slots.*

19. *A linear motor according to claim 18, wherein the width of each coil leg is sized so that there are substantially no unfilled yoke slots in each polyphase-like coil set.*

20. *A linear motor according to claim 19, wherein the width of each coil leg is substantially equal to the width of each moving element magnet.*

21. *A linear motor according to claim 19, wherein there are substantially no unfilled yoke slots in an inter-coil set region.*

22. *A linear motor according to claim 14, wherein said servocontrol system includes a moving-element position-detecting means, comprising:*

*a single row of linear encoder readers spaced generally along the stator armature at fixed positions relative thereto;*

*a device readable by the linear encoder readers mounted on each said moving element, each readable device*

*having a length which is greater than the spacing between any given pair of adjacent linear encoder readers;*

*guide means for aligning the readable devices in order to interact with the single row of linear encoder readers; and*

*plural processing means, for associating any given readable device with only one linear encoder reader at any time and for resolving and providing a reading of the overall position of the corresponding moving element based on the fixed position of the associated linear encoder reader and a relative position of the given readable device in relation to the associated linear encoder reader.*

23. *A linear motor according to claim 22, wherein the servocontrol system comprises:*

*a trajectory generator providing a position set point signal for each moving element;*

*a position compensator, connected to the moving-element position-detecting means and the trajectory generator, providing a position error minimizing signal for each moving element; and*

*a commutation controller, connected to the moving-element position-detecting means and the position compensator, for determining which of the coils are situated underneath each moving element and providing a current set point signal for those coils in accordance with the position error minimizing signal associated with each moving element; and*

*current control loop means, connected to the commutation controller, for regulating the coils in accordance with the current set point signals.*

24. *A linear motor according to claim 23, wherein said trajectory generator provides means to avoid collisions between adjacent moving elements.*

25. *A modular conveyor system, comprising:*

*n interconnected track sections, forming a substantially continuous track, wherein each track section comprises a stator armature having a plurality of individually controllable coils disposed substantially along the entire length of the track section;*

*a plurality of moving elements traveling separately and independently along the continuous track, each moving element having at least two thrust producing magnets arranged in alternating North and South sequence and disposed face to face with the stator armatures of the track sections;*

*n track section controllers, one per track section, for regulating and commutating the coils of the corresponding stator armature in order to produce a separate moving MMF for each moving element located in the corresponding track section and independently control each moving element located therein; and*

*communication means for interfacing the section controllers of adjacent track sections, wherein a given section controller is operative to utilize the communication means in order to transfer a servo responsibility for resolving the position of a given moving element to an adjacent section controller when the given moving element straddles the corresponding track sections, and wherein each of the given and adjacent section controller pair provides at least one coil regulating signal to the other of said pair in the event any portion of the magnets of the given moving element spans any portion of at least one coil situated in the track section*

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corresponding to the other of said pair, provided that the responsibility for resolving the position of the given moving element has not yet been transferred to the other of said pair.

26. A modular conveyor system according to claim 25, wherein the communication means comprises a peer-to-peer network.

27. A modular conveyor system according to claim 25, further comprising a central controller connected to each of the section controllers for initializing the section controllers.

28. A modular conveyor system according to claim 25, further comprising at least one station controller directly connected to at least one of the section controllers, wherein the at least one station controller provides movement commands to the at least one section controller in respect of at least one of the moving elements located in the corresponding track section.

29. A modular conveyor system according to claim 25, wherein:

the magnets of each moving elements have a pole pitch  $P$ ; the electrical pole pitch of each of the coils is  $P$ ; and

the coils of each track section stator armature are arranged in a substantially contiguous sequence of individual polyphase-like sets, each set comprising  $p$  overlapping coils having centers thereof spaced apart by a distance  $P/p$ , where  $p \geq 2$ , and wherein coils associated with one track section do not overlap onto an adjacent track section.

30. A modular conveyor system according to claim 25, wherein:

each track section comprises a single row of linear encoder readers spaced at fixed positions there along; each moving element includes a device readable by the linear encoder readers mounted thereon, each readable device having a length which is greater than the spacing between any given pair of adjacent linear encoder readers; and

each section controller provides a moving-element position-detection processing means for associating any given readable device of a moving element located in the corresponding track section with only one linear encoder reader located therein at any time and for resolving the position of the corresponding moving element based on the fixed position of the associated linear encoder reader and a relative position of the given readable device in relation to the associated linear encoder reader.

31. A modular conveyor system according to claim 30, wherein each moving element is sized longer than its corresponding readable device in order to preclude readable devices of adjacent moving elements from interacting with the same linear encoder reader.

32. A modular conveyor system according to claim 30, wherein, immediately after the association of the given readable device is switched to the adjacent linear encoder reader, the position-detecting processing means is operative to require the given readable device to backtrack for at least a minimum distance before the association of the given readable device is switched back to the given linear encoder reader, to thereby provide a hysteresis effect.

33. A modular conveyor system according to claim 30, wherein each section controller comprises:

a trajectory generator providing a position set point signal for each moving element located in the corresponding track section;

a position compensator, connected to the moving-element position-detecting processing means and the trajectory

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generator, providing a position error minimizing signal for each such moving element; and

a commutation controller, connected to the moving-element position-detecting processing means and the position compensator, for determining which of the coils in the corresponding track section are situated underneath each such moving element and for providing a current set point signal for such coils in accordance with the position error minimizing signal associated with each such moving element; and

current control loop means, connected to the commutation controller, for regulating the coils located in the corresponding track section in accordance with the current set point signals.

34. A modular conveyor system according to claim 30, wherein, in a condition where a readable device is associated with a first linear encoder reader in a first track section and simultaneously begins to interact with a second, adjacent linear encoder in a second, adjacent track section, the section controller corresponding to the first track section transfers the servo responsibility for resolving the position of the corresponding moving element to the section controller associated with the second, adjacent track section once the readable device has reached a pre-specified distance through one of the first and second linear encoder readers.

35. A modular conveyor system according to claim 34, wherein the coil regulating signals include:

(a) the measured position of the given moving element, and

(b) one of:

(i) the position error minimizing signal, and

(ii) the current set point signals for the spanned coils.

36. A modular conveyor system according to claim 25, wherein the given section controller is operative to transfer static data concerning the straddling moving element to the adjacent section controller prior to the transfer of the servo responsibility for resolving the position of the straddling moving element.

37. A modular conveyor system according to claim 36, wherein the given section controller is operative to transfer dynamic or memory based servocontrol data concerning the straddling moving element to the adjacent section controller substantially simultaneously with the transfer of the servo responsibility for resolving the position of the straddling moving element.

38. A modular conveyor system according to claim 25, wherein the given section controller is operative to bi-directionally transfer static, dynamic or memory-based data to an external device via a dedicated communication port, independent of any other section controller.

39. A modular conveyor system, comprising:

$n$  interconnected track sections, forming a substantially continuous track, wherein each track section comprises a stator armature having a plurality of individually controlled coils disposed substantially along the entire length of the track section, and wherein each track section comprises a plurality of linear encoder readers spaced at fixed positions there along;

a plurality of moving elements traveling separately and independently along the continuous track, each moving element having a plurality of thrust producing magnets arranged in alternating North and South sequence and disposed face to face with the stator armatures of the track sections, each moving element including a linear encoder strip having a length greater than the spacing between any given pair of adjacent linear encoder

readers, the length of each moving element being sized to prevent linear encoder strips from adjacent moving elements to interact with the same linear encoder readers;

*n* track section controllers, one per track section, each section controller providing:

(a) position-detection processing means for associating any given linear encoder strip of any moving element located in the corresponding track section with only one linear encoder reader located therein at any time and for resolving the position of such moving element based on the fixed position of the associated linear encoder reader and a relative position of the given linear encoder strip in relation to the associated linear encoder reader; and

(b) servo means, connected to the position-detection processing means, for regulating and commutating the coils of the corresponding stator armature in order to produce a separate moving MMF for each moving element located in the corresponding track section to thereby independently control each such moving element; and

communication means for interfacing the section controllers of adjacent track sections, wherein a given section controller is operative to utilize the communication means in order to transfer a responsibility of resolving the position of a given moving element to an adjacent section controller when the given moving element straddles the corresponding track sections, and wherein each of the given and adjacent section controller pair provides at least one coil regulating signal to the other of said pair in the event any portion of the magnets of the given moving element spans any portion of at least one coil situated in the track section corresponding to the other of said pair, provided that the responsibility for resolving the position of the given moving element has not yet been transferred to the other of said pair.

40. A modular conveyor system according to claim 39, wherein said servo means comprises:

a trajectory generator providing a position set point signal for each moving element located in the corresponding track section;

a position compensator, connected to the trajectory generator, providing a position error minimizing signal for each such moving element;

a commutation controller, connected to the position compensator, for determining which coils located in the corresponding track section are situated underneath each such moving element and providing a current set point signal for such coils in accordance with the position error minimizing signal associated with each such moving element; and

current control loop means, connected to the commutation controller, for regulating the coils in accordance with the current set point signals.

41. A modular conveyor system according to claim 40, wherein said coil regulating signals include:

(a) the measured position of the given moving element, and

(b) one of:

(i) the position error minimizing signal in respect of the given moving element, and

(ii) at least the current set point signal in respect of each such spanned coil.

42. A modular conveyor system according to claim 39, wherein, in a condition where an aforesaid linear encoder

strip is associated with a first linear encoder reader in a first track section and simultaneously begins to interact with a second, adjacent linear encoder in a second, adjacent track section, the section controller corresponding to the first track section transfers the responsibility for resolving the position of the corresponding moving element to the section controller associated with the second, adjacent track section once the linear encoder strip has reached a pre-specified distance through one of the first and second linear encoder readers.

43. A modular conveyor system according to claim 39, wherein the given section controller is operative to transfer static data concerning the straddling moving element to the adjacent section controller prior to the transfer of the responsibility for resolving the position of the straddling moving element.

44. A modular conveyor system according to claim 39, wherein the given section controller is operative to transfer dynamic or memory based servocontrol data concerning the straddling moving element to the adjacent section controller substantially simultaneously with the transfer of the responsibility for resolving the position of the straddling moving element.

45. A modular conveyor system according to claim 39, wherein the given section controller is operative to bi-directionally transfer static, dynamic or memory-based data to an external device via a dedicated communication port, independent of any other section controller.

46. A modular conveyor system, comprising:

a plurality of interconnectable track sections, each track section having a respective track section controller for regulating and commutating a plurality of individually controllable coils disposed along the length of its respective track section to provide a separate moving magneto-motive force to any one of a plurality of separately and independently moving elements traveling along the track section, each track section controller including bidirectional communication means for interfacing with section controllers of adjacent track sections to transfer servo responsibility for a given moving element to an adjacent track section controller, and including position detecting means for detecting the position of each moving element traveling thereon.

47. Apparatus for detecting the position of moving elements relative to a stationary element in a conveyor system, comprising:

a plurality of position detecting sensors spaced generally along the stationary element at fixed positions relative thereto;

position-indicating means mounted on said moving elements detectable by said sensors; and

circuitry connected to each position detecting sensor for resolving and providing readings of the position of each moving element;

said conveyor system comprising:

a track;

a plurality of said moving elements traveling separately and independently along said track, wherein said conveyor system comprises:

said track, formed from *n* interconnected track sections, forming a substantially continuous track, wherein each track section comprises a stator armature having a plurality of individually controllable coils disposed substantially along the entire length of the track section;

said moving elements each having at least two thrust producing magnets arranged in alternating North

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and South sequence and disposed face to face with the stator armatures of the track sections;

*n* track section controllers, one per track section, for regulating and commutating the coils of the corresponding stator armature in order to produce a separate moving MMF for each moving element located in the corresponding track section and independently control each moving element located therein; and

communication means for interfacing the section controllers of adjacent track sections, wherein a given section controller is operative to utilize the communication means in order to transfer a servo responsibility for resolving the position of a given moving element to an adjacent section controller when the given moving element straddles the corresponding track sections, and wherein each of the given and adjacent section controller pair provides at least one coil regulating signal to the other of said pair in the event any portion of the magnets of the given moving element spans any portion of at least one coil situated in the track section corresponding to the other of said pair, provided that the responsibility for resolving the position of the given moving element has not yet been transferred to the other of said pair.

48. Apparatus for detecting the position of moving elements relative to a stationary element, in combination with a moving-magnet type linear motor, said apparatus comprising:

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a plurality of position detecting sensors spaced generally along the stationary element at fixed positions relative thereto;

position-indicating means mounted on said moving elements detectable by said sensors; and

circuitry connected to each position detecting sensor for resolving and providing readings of the position of each moving element;

said linear motor comprising:

a stator armature provided substantially along the entire traveling track of moving elements;

wherein each moving element travels separately and independently and comprises *n* permanent magnets disposed face to face with the stator armature, said magnets being arranged in alternating North and South sequence and having a pole pitch *P*;

wherein the stator armature comprises a plurality of individual coils arranged in a substantially contiguous sequence of individual polyphase-like sets, each set comprising *p* overlapping coils having centers thereof spaced apart by a distance  $P/p$ , where  $p \geq 2$ ; and

a servocontrol system for regulating and commutating the coils so as to produce a separate moving MMF for each moving element and independently control each moving element.

\* \* \* \* \*