

"Improved Data Transducer Position Control System for Rotating Disk Data Storage Equipment"

5 THIS INVENTION relates to a position control system and a method for controlling the position of one member relative to another, and in particular to such a position control system and method for data storage equipment for moving a memory data device member such as a transducer head mounting structure relative to a frame of the data storage equipment so as to allow  
10 the member to move relative to a concentric track of a rotating disk of the data storage equipment and also so as to allow the member to be kept in alignment with a selected track.

15 Electromechanical devices such as rigid rotating memory drives have been disclosed wherein two basic approaches have been taken in order to position data transducers radially relative to the rotating magnetic disk surface. The first, high cost approach is to utilize a dedicated servo system with a servo head and a replicated servo surface on the disk to provide a high performance track-following transducer positioning scheme. The other  
20 more recent, low cost approach is to utilize completely open loop stepping motor positioners which operate to place the transducers at arbitrarily defined tracks without any actual position information being fed back from the disk to the head positioner. The main drawback of the prior art low cost open loop approach is the requirement that the tracks be spaced far enough  
25 apart to take into account all of the variations of the system, including mechanical tolerances in the stepping motor actuator, thermal expansion of the disk, and disk run-out. The result is a disk drive product which, while effective as a low cost unit, lacks the data storage capacity of the more expensive units, with the result that the cost of storage per bit stored of the  
30 low cost drives approaches the same cost as the earlier, more expensive storage units.

According to a first aspect of the invention, there is provided data

storage apparatus for emulating an open loop stepper motor based disk drive, the apparatus comprising a frame and a data storage disk journaled to the frame and rotatably drivable by motor means at a proper constant velocity, the disk having a plurality of concentric data tracks capable of being recorded in substantially unrestricted data format formed on the major surfaces thereof and being provided on one of the major surfaces thereof with a single data-masked servo sector region containing track centring servo information, at least one data transducer head device being provided in close proximity to the disk surfaces and a position control system, the position control system comprising: driver means drivingly connected to the transducer head device for moving the head to any one of the data tracks during a track seeking mode of operation and for maintaining the head within a given track during a maintained position mode of operation; and a fine position closed loop servo connected to the driver for operatively controlling the driver to keep the head positioned within a given track, the fine position closed loop servo including the single data-masked servo sector region on the surface of the disk which contains track centring servo information therein, sample and hold means connected to the head for sampling and holding the servo information read from the servo sector for each revolution of the disk, and correction signals generator means connected to the sample and hold means for generating offset signals, the loop of the closed loop servo being open during a track seeking mode of operation.

Preferably the loop is open or overridden during a track seeking operation.

Usually the data storage apparatus further comprises a bidirectionally movable electromechanical mover mounted to the frame adjacent to the disk; and a head mounting structure secured to the mover at one end thereof for moving the head across the plurality of concentric data tracks, the driver means comprising bidirectional driver means connected to the mover for moving the structure to maintain it within a selected data track during reading and/or writing operations and to move the structure from a departure track to a destination track during track seeking operations;

In a preferred arrangement, a head position sensor, usually a transducer, is provided, providing a polyphase position signal in response to a

sensed actual position of the head relative to the frame, the head controller means being connected to the head position sensor, the driver means and to an external source of track selection information for recording the present track position of the head for calculating a track seeking command in response to known head position and the track selection information, and for

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commanding the head to move from a known departure track to a requested destination track during a track seeking operation by commanding at the mover a first head position spatial increment of maximum forward direction acceleration followed by a similar head position spatial increment of maximum reverse direction acceleration and then by commanding adaptively a slewing rate dependent upon the polyphase incremental head structure position information from the head position until the destination track is reached. Conveniently, the position transducer comprises: a scale having equally spaced angular apertures thereon of equal width secured to either the frame or the structural elements movable by the driver means and a generally U-shaped structure having two parallel arms spaced apart for a distance slightly greater than the thickness of the scale and aligned and mounted to the other of the frame so that the scale is free to pass between the arms, the U-shaped structure including a light source in one of the arms for passing light through the scale in the direction of the other arm, an array of photosensitive detectors and a light-pattern-defining reticle placed between the detectors and the scale in the other of the arms, the reticle defining windows for the detectors which are so spaced as to provide the polyphase signal in quadrature as the scale moves between the arms. Usually data track stabilization means including the mover are provided for stabilizing the head structure within a range between the boundaries of each data track; and wherein the fine position closed loop servo is time sampled fine position closed loop servo including the head controller means, the single, data masked servo sector containing track centre line servo control data therein readable once per disk revolution by the transducer head the sample and hold circuit being connected to the head during passes over the sector for holding control data read therefrom, and the correction signal generator means being arranged to generate offset signals for application to the driver means to promote and maintain track centre line alignment of the head during reading and writing operations.

Preferably, a position dependent closed loop servo is provided which is connected to the head position sensor and to the driver means for operatively controlling the driver means to keep the head positioned within a selected one of the data tracks during reading and/or writing operations, the loop being open during track seeking operations until occurrence of adaptively commanding slewing, the position dependent closed servo being normally

arranged to apply offset signals to the driver means.

5        Generally the head controller means comprises a programmed micro-processor having a head position data input connection from the head  
10       position transducer, a binary data latch for receiving and holding the track seeking command, the microprocessor clocking the latch in accordance with position information derived from the transducer head and the external source of track selection information, a data connection from the latch directly to the driver means for enabling the controller means to command  
15       the acceleration increments in the track seeking operations and a digital to analog converter connected to the latch for converting slewing commands clocked into the latch into analog values and for applying said analog values to the position dependent closed loop servo to command the driver means to  
20       slew the head mounting structure at the position-adaptive slewing rate.

15       Preferably, the fine position closed loop servo comprises a pair of prerecorded track marking signals in the servo sector for each defined track, a first occurring marking signal being radially offset in one direction from track centre line, and a second occurring marking signal being radially  
20       offset in the other direction from track centre line, first sample and hold means for sampling and holding the amplitude of the first occurring marking signal with each revolution of the disk, second sample and hold means for sampling and holding the amplitude of the second occurring marking signal with each revolution of the disk, and differential comparator means  
25       connected to the first and second sample and hold means for comparing held amplitudes and for generating a head position correction signal proportional to the difference in held amplitudes, and for applying the correction signal to the mover through the driver means.

30       Preferably, the bidirectionally movable electromechanical mover is a rotor, in particular, a bidirectional, pure torque generating electro- ———

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mechanical rotor for electromechanical equipment rotably mounted to a frame for rotatingly moving a member relative to the frame over a locus defining a sector of a circle, which is less than 90 degrees, the rotor comprising: a flux return base plate, a flux return top plate, a generally annular permanent magnet secured to one of the base and top plates having an even number plurality of adjacently opposed field magnetic segments in which the north and south poles alternate at the major surfaces thereof, a generally annular, rotatable coil assembly placed and closely spaced from between the permanent magnet and the other of the base and top plates, the coil assembly containing the same even number plurality of coils as there are magnet segments in the permanent magnet, the coils being aligned adjacent to the magnetic segments at at least one position of rotation of the assembly and connected into two series of opposed windings equidistantly and symmetrically located about the assembly, and a movable member attached to the assembly and arranged to pass rotatably through at least one of the base plate and top plate, the member being rotated along the locus by passage of current through one of the series of windings, the torque from the coils being applied evenly to the movable member about its axis of rotation.

The coil segments, may be wound sequentially on a moving bobbin from a single strand of wire. The coil segments are preferably arranged into a thin disk and are connected to provide bidirectional, symmetrical torque. Potting compound may be used to encapsulate the coil structure and to provide a very high resonant frequency and thus a capability to absorb vibration energy from the rotatable member.

In a second aspect, the present invention data storage apparatus for emulating an open-loop stepper motor based disk drive, the apparatus including a rotatable data storage disk having a plurality of concentric data storage tracks capable of being recorded in substantially unrestricted data format formed on the major surfaces thereof, one of the major surfaces the disk having a single data-masked servo sector region containing track centring servo information, a read and write head held in close proximity to the surface of the disk by the air-bearing effect, a head mounting structure for positioning the head at one of the plurality of concentric data tracks

during data reading and/or writing operations in substantially unrestricted data format within each track and for moving the head from track to track during track seeking operations of the equipment and a position control system, the position control system comprising: driver means drivingly connected to the head mounting structure for arcuately moving the head from one track to a selected other track located beyond a predetermined minimum radial distance during an open loop servo track seek movement by a first spatial increment of maximum forward direction acceleration of the carriage for about half the radial distance between the tracks and by a second similar increment of maximum reverse direction acceleration until the head mounting structure reaches the vicinity of the selected other track, and for closed loop generally constant velocity microstepping of the head mounting structure within the minimum radial distance in small radial increments from track to track until the other track is reached, and for maintaining the head accurately within a selected track during data reading and writing operations; a summing circuit connected to drive the driver means; coarse servo control loop means including coarse position sensor means mechanically linked to the head mounting structure for sensing the radial position of the head relative to said tracks, and coarse position feedback control loop means connected to the driver means through the summing circuit for controlling the driver means to keep the head positioned within the selected one of said defined tracks during reading and writing operations; index detector means electromechanically coupled to the disk for detecting each rotation thereof and generating an index signal; fine position servo control loop means including the single data-masked servo sector region on the surface of the disk containing servo information therein, sample and hold means connected to the head for sampling and holding the servo information read in the servo sector for each revolution of the disk, correction signal generator means connected to the sample and hold means for generating offset signals, and analog-to-digital converter means connected to the correction signal generator means for converting said offset signals into digital values; and programmed digital microprocessor means connected to the analog-to-digital converter means, the index detector means, the coarse servo control loop means and a source of an externally supplied digital track selection command signal, including clocked latch means, and digital-to-analog converter means drivingly connected to the driver means through the summing network for calculating and

supplying a digital head positioning signal to the driver means in order to move the head from a predetermined departure track to a predetermined destination track, and for calculating and applying a fine position offset signal to the driver means through the digital-to-analog converter means and the summing network to maintain the head in centre line alignment in the track during reading and/or writing operations interactively with the coarse servo control loop means.

In a third aspect, the present invention provides a method of controlling the position of a data transducer head of data storage apparatus for emulating an open-loop stepper motor based disk drive, the method comprising: rotating at constant velocity a data storage disk rotatably mounted in a frame of the equipment, the disk having a plurality of concentric data tracks formed on the major surfaces thereof associated with at least one data transducer head device arranged in close proximity to the disk surfaces, the disk being provided on one of the major surfaces thereof with a single data-masked servo sector region; moving the head device across the plurality of concentric data tracks by means of a bidirectionally rotatable electromechanical rotor journaled to the frame adjacent to the disk and secured to the head device at the other end thereof; rotating the head device by means of driver means connected to the rotor to maintain the head within a selected data track during reading and/or writing operations and to move the head from a departure track to a destination track during track seeking operations; providing a polyphase signal responsive to position of the head device relative to the frame by means of a head position transducer; providing track selection information to head controller means connected to the head position transducer, the driver means and to an external source of track selection information; recording the track position of the head device; calculating a track seeking command in response to the known head position and the track selection information; commanding the head to move from a known departure track to a requested destination track during a track seeking operation by commanding at the rotor a first head position spatial increment of maximum forward direction acceleration followed by a similar head position spatial increment of maximum reverse direction acceleration and then by commanding adaptively a slewing rate dependent upon incremental head position information from the head position transducer until the destination track is reached; opera-

tively controlling the driver means to keep the head positioned within a selected one of the data tracks during reading and/or writing operations with a position dependent, coarse position closed loop servo connected to the head position transducer and to the driver means and overriding the  
5 coarse position loop to keep it open during track seeking operations; and providing a fine position closed loop servo connected to the driver means and a single, data masked servo sector on a data surface of the disk; prerecording track centre line servo control data in the servo sector;  
10 reading the data with the head adjacent the surface; sampling and holding data read by the head during passes over the sector and generating an offset correction signal; applying the offset signal to the driver means to promote and maintain track centre line alignment of the head during reading and/or writing operations; and overriding the fine position servo loop during track seeking operations.

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In order that the invention may be more readily understood, an embodiment thereof will now be described, by way of example, with reference to the accompanying drawings, in which:

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FIGURE 1 is a block diagram of a system embodying the invention;

FIGURE 2 is an enlarged broken diagrammatic plan view of a wedge shaped portion of a rigid disk, illustrating a servo sector pattern for inner and outer tracks of the disk;

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FIGURE 3 shows a series of timing and waveform diagrams related to the operation of the system in response to sensing the track servo sector information depicted in Figure 2;

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FIGURE 4 is a block schematic diagram of part of the circuitry of the system of Figure 1;

FIGURE 5 is an enlarged part-sectional view of a coarse head position sensor assembly of the system of Figure 1;

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FIGURE 6 illustrates graphically the operational states of the sensor assembly of Figure 5;

FIGURE 7 shows the waveform diagrams of the control signals generated by the system of Figure 1 in response to the sensor of Figure 5;

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Referring now to the drawings, Figure 1 illustrates a hard disk memory system 10 embodying the invention wherein the disc drive comprises a drive spindle 12 on which two magnetic disks 14 and 16 of approximately eight inch (20 cm) in diameter are mounted so as to rotate about the common axis of the spindle at for example 50 Hz when driven by a suitable disk drive motor 18 connected in a conventional manner by pulleys and a drive belt 20 to the spindle 12. The system 10 may include as many as four or more magnetic disks, and disk diameters such as fourteen (35.6 cm) or five and one quarter inches (13.3 cm) may be used, although eight inches (20 cm) is presently preferred. The disks 14 and 16 may be formed from thin aluminium sheet having an oriented ferric oxide or other suitable magnetic coating on the major surfaces thereof. Of course other kinds of data storage devices, for example laser etched disks or optical storage devices may be used. An index marker 22 provided on the spindle (Figure 9) is used to provide a tachometer or index clock signal to control servo operations in a manner to be described below. The index marker 22 also serves as a check to assure that the disks are rotating at the desired 50 Hz angular velocity.

A head carriage assembly or mounting structure 24 includes a pure-torque-generating rotor 26 to which head support beams 28 are mounted for radial movement relative to the disks 14 and 16. The rotor 26 will be described in greater detail hereafter in connection with Figures 9 to 12. Reading and writing transducers or heads 30 are secured at the periphery of the support beams 28. The heads 30 may be of the type which ride upon an air bearing effect in accordance with what has come to be known in the art as Winchester technology.

A coarse head position control in the form of an electro-optical transducer includes a controlled current light emitting diode source 32, a scale 34 having a series of equally closed spaced microscopic radial lines, and an integrated circuit photo-sensitive reticle-masked array 36, which in combination produce the light and dark polyphase (e.g. quadrature) patterns depicted in Figure 6 and are used to generate the sawtooth servo waveform depicted at G in Figure 7.

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There are five outputs from the photo sensitive array 36. Four of the outputs are quadrature track position signals which are processed by two

differential amplifiers 38 and 40. The fifth is a signal which indicates the location of the head 30 at track zero zero (that is the radially outermost usable data track) and is amplified and shaped by an amplifier 42. The quadrature signals from the differential amplifiers 38 and 40 are supplied to a position linearity switch detector circuit 44 the outputs of which are depicted in Figure 7 at B and C, and also to a position signal selector circuit 46, the operation of which is controlled by the switch detector circuit 44.

The scale 34 is rotatable with the head structure 28 relative to the frame. On rotation the scale microlines pass through and interrupt the light beams passing from the source 32 to the detector array 36. With the detector array geometry shown in Figure 6, four data tracks may be defined by each microline and space.

As shown in Figure 6, there are four pairs of detector windows, which are radially mutually offset by a distance of a half of a microline. Each window pair sees four phases of each line: first half line, full line (full dark), last half line, and no line (full light). The window pairs are further paired together diagonally. Thus the top left window pair and the bottom right window pair provide the two differential inputs to the amplifier 38, and the bottom left and top right pairs are the inputs to the amplifier 40. In Figure 6A equal and oppositely phased light and dark areas in the upper left and lower right detector pairs provide a null output defining one track. Figure 6B shows the pattern produced when the scale has moved to the next phase so that full lines are now seen in the top left windows. In this situation the bottom left and top right are equal and opposite, and the amplifier 42 is at null point defining the next data track. Figure 6C shows the pattern produced when the scale has moved yet another half line width and the third phase pattern presented is the same as Figure 6A except for phase reversal. The pattern shown in Figure 6D is produced when the scale has moved still another half line width to the fourth phase pattern, similar to the Figure 6B pattern except for phase reversal.

The wave forms B and C of Figure 7 illustrate the output of the position linearity switch detector 44. The output from the position signal selector 46 is an analog signal which is supplied to a summing network 48, and then via a loop compensation (damping) network 50, a bidirectional

moving coil motion driving amplifier 52 and ultimately to the armature of the rotor 26 via a bidirectional rotation driving line 54. The analog signal produces a correction torque to keep the heads 30 within the boundaries of each data track defined by the scale 34 and photodetector 36. The light  
5 emitting diode light source 34 is powered by a driver circuit 56 which includes an automatic light level (ALL) control developed from a sixth photodetector in the detector array 36.

The data read by one of the transducers 30 is selected, preamplified  
10 and low pass filtered by the circuits denoted by a circuit 58 (Figure 1). Thereafter, the reproduced MFM formatted data is recovered by a data recovery circuit 60 and sent to the computer or other appliance to which the system 10 is connected for random access data storage and retrieval.

15 One disk surface 14 may be provided with a narrow, 200 byte wide sector 62, as shown diagrammatically in Figure 2. Each data track, from track zero zero to track n (for example track 511) is provided with the two factory prerecorded frequency bursts, for example, a first occurring burst B1 on the radially outer half of the odd tracks and on the radially inner half of  
20 the even tracks, and a second occurring burst B2 on the radiating inner half of odd tracks and the outer half of the even tracks. The sector bursts are read on each revolution by the head 30 and are used to provide a fine head position servo loop control signal to the rotor 26 in the form of an offset voltage to urge the head 30 into alignment with the centre line of the track.  
25 Each burst is read in turn and passed via the circuit 58 and an amplifier 64 to a peak detector 66 for integration to provide the amplitudes thereof. These amplitudes are then sampled and held by respective sample and hold circuits 68 and 70. The held values are compared by an analog data selector 72, and a signed analog difference is converted to an eight bit digital value  
30 by an analog-to-digital converter 74. The digital value is processed in a digital system controller microprocessor 76, such as the Intel type 8048 which contains a 1K byte (kilo-byte) factory preprogrammed read only program memory and a 128 byte random access scratchpad memory.

35 A detector 78 detects the index mark 22 on the drive spindle 12 with each revolution. This index clock signal is passed through an amplifier 80 and sent to the microprocessor 76 to provide a digital tachometer to

determine whether the disks are rotating at correct speed and to mark the location in time of the servo sector on the disk. The index clock is also processed by a servo sample timer 82 which is used to enable and switch between the sample and hold circuits 68 and 70.

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The waveforms of Figure 3 illustrate the operation of the circuit elements 30, 58, 64, 66, 68, 70, 72, 74, 76, 78, 80, and 82 which provide the fine position servo control. Waveform A depicts the index pulse I generated by the index detector 78, while waveforms B and C depict the first occurring Burst 1 and second occurring Burst 2 respectively. Waveform D depicts the servo sector data window which immediately follows each index pulse and waveform E shows the control enable signal from the servo sample timer 82 applied to the sample and hold circuits 68 and 70 which divides the disc sector into two 100 byte halves. Waveform F illustrates the waveform amplitude of a first burst A stored in the first sample and hold circuit 68 while Waveform G shows the amplitude of the second burst B stored in the second sample and hold circuit 70. Waveform H depicts the equivalence of the sensed amplitudes obtained when the head is properly aligned within a data track. In this situation no offset value is required and none will be supplied by the microprocessor 76 to the rotor 26. Waveform I illustrates the waveform produced when the first burst is much larger than the second burst, which indicates the head is not centrally disposed within the track but is close to an edge of the track.

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It will be appreciated by inspection of Figure 2 that the servo bursts on the innermost tracks n-3, n-2, n-1 and n of the disc are much smaller in amplitude than the bursts on the outermost tracks 00, 01, 02, 03, and 04. Consequently, in order to calculate a valid offset signal for fine position servo purposes, it is necessary to calculate the percentage difference between burst amplitudes using the microprocessor 76. This calculation automatically provides an automatic gain control (AGC) signal for each track, a signal which may be applied to the data recovery circuit 60 or to other circuits for providing gain equalization for recovered data.

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A disk drive interface circuit 88 receives control information from the host computer, etc. and supplies that information, including track seek data to the microprocessor 76. Data surface/head select information is sent

directly to the head select circuit 58. A two bit quadrature signal line from the switch detector 44 provides the microprocessor 76 with information detailing the present location of the head 30. The microprocessor 76 determines how far and in what direction to move the head (seek) and then calculates a set of numbers which are put out in a sequence dependent upon actual head position during the seek operation.

Some of the major elements of the coarse position closed loop servo control and the digital override circuitry are depicted in Figure 4. Therein, the data latch 84 is depicted as a standard TTL octal D-type flip flop (74LS374) latch which is clocked by an input signal from the WRITE line of the microprocessor 76. The digital-to-analog converter (DAC) 86 is implemented as a Motorola type MC1408L8, and it receives the latched 8 bit digital numbers of offset values from the latch 84 and converts them to control currents. A voltage reference circuit 102 is utilized to reference the DAC 86 to system voltages. An operational amplifier current to voltage converter 106 buffers and scales the resultant analog control voltage from the DAC 86. The summing circuit 48 in the implementation depicted in Figure 4 occurs at the input of the driving amplifier circuit 52 which is supplied with the analog offset voltages from the DAC 86 and the coarse servo loop voltages from the position signal selector 46.

The bidirectional driving amplifier circuit 52 emulates the operation of a differential output amplifier. To do this, the circuit includes two operational amplifiers 108 and 110 connected as shown in Figure 4. The analog controls to the driving amplifier circuit 52 occur at the input of the operational amplifier 108, and the digital seek override controls are applied directly to the inputs of two Darlington pair power drivers 112 and 114 which drive the two windings A-B and B-C of the rotor. (See discussion of Figure 11, below). The operational amplifier 110 functions to make the characteristics of the driver 114 opposite and complementary to the input of the driver 112.

An operational amplifier 116 receives two complementary coarse servo loop control signals P and  $\bar{P}$  from the position signal selector 46. These values are equal and opposite and of minimum amplitude when the head carriage 28 is in general alignment within any given defined track. The

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P and  $\bar{P}$  values are derived by the position signal selector 46 from the digital quadrature waveforms K and L depicted in Figure 7.

5 An accelerate and decelerate combinatorial logic array 118 accepts a two bit word derived from the high order data bit clocked from the latch 84, and a binary control line from the microprocessor 75 designated the SEEK enable line. The logic array 118 provides digital outputs which are buffered and inverted and are then applied to the input of the power Darlington pair power driver 112 via a line 120 and to the inverted input of the power driver 114 via a line 122 (and the inverting operational amplifier 110). The power  
10 amplifiers 112 and 114 may be implemented as type TIP 140 power Darlington pairs which are thermally sumped into a cast aluminum frame 100 (Figure 9) of the system 10. The operational amplifiers 106, 108, 110 and 116 may be of type 741, or equivalent.

15 A power supply switch 124 switches on the power supply to the amplifier 52 only when it concurrently receives three enabling signals: a signal indicating presence of the required supply voltages, a READY control signal from the microprocessor 76, which denotes that the disks 14, 16 are  
20 spinning at operating velocity, and an Drive Inhibit Line (DIL) signal. In the event of a loss of operating velocity, power supply potential, or in case of a system reset, power is removed from the driver amplifier 52, and the head carriage assembly 28 automatically returns to the inner landing zone in response to a bias spring 194 (Figure 9) which operates in default of the rotor  
25 26.

The individual circuit components depicted in Figure 4 are connected as shown and will not be discussed further, since the values and connections are readily derived by those skilled in the art.

30 Referring again to Figure 1, and eight bit data word output from the microprocessor 76 is supplied to a data latch 84 which is clocked by the WRITE enable line  $\overline{WR}$  of the microprocessor 76. Each eight bit number held in the latch 84 is converted to an analog value by the digital-to-analog  
35 converter 86. The high order latched bit, along with another control line direct from the microprocessor 76, is applied directly to the driving amplifier 52 so as to override the coarse position servo system (elements 24,

38, 40, 44, 46, 48, 50) during the maximum accelerative and decelerative phases of a track seeking operation. In the final phase of the track seeking operation, a predetermined velocity slewing rate is achieved by recurrent number series which are converted to analog values by the converter 86 and applied to the summing circuit 48. During the initial maximum accelerative and decelerative step function portion, the coarse servo loop is completely overridden. At about eight tracks from the destination track, the maximum deceleration command is removed just before the carriage assembly 24 ceases to move. Thereafter, the coarse servo is commanded to slew across each track by a progressive analog staircase signal which is reset to zero with each detected track crossing. In this way, the coarse servo, under the command of the microprocessor 76, operates solely upon the position information derived from the transducer 24 and irrespective of actual instantaneous velocity of the head carriage assembly 24.

If a track crossing occurs sooner than expected, then the staircase command resets to zero before a maximum value is reached. If a track crossing is delayed, then the staircase reaches and holds its maximum value until the transition. These conditions are illustrated in Figure 8A.

Finally, a short deceleration step function may be applied to stop the carriage assembly 24 at the destination track should its velocity not then have reached zero. Figure 8A depicts the digital and analog waveform utilized to command a track seek across e.g. 120 tracks. Figure 8B portrays the velocity of the head carriage 24 relative to radial distance across the 120 tracks.

When the destination track has been reached, the system 10 enters a track extension control mode. One implementation of this mode is to select the appropriate monophase of the quadrature signal and servo over its full cycle (i.e. a distance of plus or minus two tracks). In this way the radial range of servo loop control covers a full four tracks, and only in the event that the head structure 28 is significantly jarred or otherwise is externally caused to move beyond plus or minus two tracks, will the coarse servo lose control. Upon a loss of servo control the system 10 enters a reset mode which resets the system and then returns the head 30 to the last selected track.

The microprocessor 76 has essentially five modes of operation or tasks: initialization, fine servo offset supervision, track seeking, emulation of other disk drive products, and self diagnostics. In the initialization or start-up mode when power is first applied, the microprocessor 76 counts index pulses and compares them with an internal clock, to be sure that the disk spindle 12 is rotating at the proper velocity (50 Hz). The head 30 is initially located in an nonabrasive landing zone L (Figure 2). The microprocessor 76 initially commands a seek to the outermost track (track 00). When the head 30 reaches this outermost track, a special output shown as waveform J in Figure 7 is obtained from the transducer 24 through the amplifier 42. The microprocessor 76 then calibrates the fine servo by measuring, establishing and remembering offsets for the four outermost tracks 00, 01, 02, 03 and then for the four innermost tracks n-3, n-2, n-1, n. If there is any difference in initial calibration between the outermost and innermost tracks, the microprocessor spreads this difference e.g. linearly over the total number of tracks of the system. The microprocessor 76 then commands the head 30 back to the track 00. Initialization is then complete.

During reading and writing operations, the microprocessor 76 reads the fine servo continuously and updates the offset, to take into account position errors such as thermal expansion of the disks 14, 16 as internal ambient temperatures rise.

As already explained, the microprocessor 76 receives seek commands digitally from the host computer via the disk drive interface 88. The microprocessor 76 maintains head position data in a register which counts the tracks from information derived from the coarse position transducer 24. The difference between the track at which the head is presently located and the track sought, together with the signed value of the difference, which indicates the direction of head movement required to accomplish the seek, is used to calculate the series of commands from the microprocessor 76 to the rotor 26.

The emulation function of the microprocessor 76 enables the system to emulate the characteristics of other disk drives, for example the SA 1000 eight inch (20 cm) disk drive manufactured by Shugart Associates, a XEROX Corporation subsidiary located in Sunnyvale, California. The SA

1000 product utilizes two adjacent read/write heads, and the microprocessor 76 enables the system 10 to appear to a user as if two heads are actually physically present in the system. This emulation is readily provided by redefining the track counting structure in the microprocessor 76 into two series of interleaved odd and even tracks, and then reading the tracks, and then reading the tracks such that it appears as through the odd tracks are read with one head and the even tracks with another head. Other competitive disk drive equipment may be emulated by special programming of the microprocessor 76.

10 The self diagnosis function of the microprocessor 76 has short term and long term aspects. During operation, the microprocessor 76 constantly monitors the disk rotating speed and head position. In the event of a discrepancy in either parameter, the microprocessor takes the disk out of service and informs the host machinery of the detection of an error. Other errors and error messages are easily included, including those particularly adapted to a data format or end use. Diagnostic routines may be contained in the read only memory of the microprocessor 76 or they may be recorded on one or more of the tracks of the disk 14, and called by the microprocessor 76 as required.

Referring now to Figure 5, the transducer 24 is a U-shaped assembly comprising an upper member 132 which supports the photodetector and reticle array 36, and a lower member 134 which is keyed to hold the LED light source 32 in vertical alignment with the photodetector 36. The scale 34 is a glass member having equally spaced apart chrome microlines deposited thereon. The scale 34 is precisely and securely attached to the head support structure 28 at, for example, the rotor 26. The transducer 24 is mounted on a post 136 embedded in the cast aluminium frame 100 which securely supports all of the disk drive machinery.

A feature of the system is that the transducer 24 is adjustable in two dimensions with but one point of attachment to the frame 100. A vertical height setting screw 138 and lock washer 140 enable the members 132 and 134 to be adjusted up and down, so that the photodetector can be adjusted to within five thousandths of inch (127 $\mu$ m) of the scale 34 to achieve the required resolution. A spring 142 biases the members 132 and 134 away from the frame 100.

Sideways alignment of the transducer 24 with respect to the scale 34 is achieved by rotating the members 132 and 134 about the axis of the post 136. A locking screw mechanism 144 locks the members 132 and 134 to the post 136 at the desired sideways alignment.

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The structural configuration of the system 10 is depicted in Figure 9. The drive hub 12 supports four disks, a top servo sector containing disk 14 and three lower disks 16. The index detector 22 is provided in a lower outer flange of the spindle 12, and the sensor 78 is secured through the frame 100. The spindle 12 is mounted to a spindle shaft 152 by a screw 154 and a washer 156. Ball bearing assemblies 158, 160 are placed in a cylindrical portion of the frame 100 and are held in a spaced-apart configuration by a spring 162. A magnetic fluid seal 164 is placed above the bearing 158 and seals the bearings by magnetic cohesion of the sealing fluid. A bottom screw 166 secures a pulley, not illustrated, to the shaft, for the drive belt 20 from the motor 18.

The rotor 26 depicted in Figures 9, 10, 11 and 12 includes a hub 172 (Figure 9) to which the head structure assembly 28 is mounted. A flat coil assembly 174 is secured by a bonding means such as adhesive to the base of the hub 172. Immediately below the coil assembly 174 is a ferroceramic permanent magnet 176 which is fabricated as a unitary structure and then magnetized into a series of adjacent even-number opposed field magnetic segments in which the north and south poles alternate at the top and bottom of the magnet 176. The number of separate segments in the magnet 176 corresponds to the number of coil windings in the coil assembly 174. Thus, for example as shown in Figures 10 and 11 there are six coil windings and six corresponding separate magnetic segments in the magnet 176. An annular flux return plate 178 of low carbon steel forms a base for the magnet 176. In fabrication, a ceramic blank is glued to the base plate 178 and then the resultant structure is permanently magnetized. A fixed shaft 180 extends from a ribbed portion of the frame 100. The hub 172 is journaled to the shaft 180 by ball bearing assemblies 182 and 184 which are initially held in place during fabrication by an axial prestressed spring 186 and spacer 188, with adhesive locking the bearings 182 and 184 to the hub 172.

A flux return top plate 192 is secured to the frame 100. A bias spring 194 extends from a standoff on the top plate 192 to the head carriage assembly 28 and biases it to return to the inner landing zone of the disks when power is removed from the rotor 26. Crash stops may be formed in the top plate 192 to limit range of head structure travel.

Other elements depicted in Figure 9 include a printed circuit board 196 which carries the circuitry immediately associated with the optical transducer 24 including the elements 38, 40, 42 and 56 depicted in Figure 1 and also the wiring connection for the heads 30. A main printed circuit board 198 carrying the rest of the circuitry of Figure 1 is plugged into the board 196 by a plug 200. A plastic case 202 mates with the base 100 and provides an airtight seal throughout, which is required for the reliable operation of the flying head Winchester drive technology. An air filter 202<sup>1</sup> fits into a recess of the frame, and fins 204 extending from the flange at the base of the spindle 12 force air within the plastic enclosure 202 to pass through the filter. A breather filter 206 enables internal and external pressures to equalize.

To develop balanced torque, herein defined as "pure torque", which minimizes loading of bearings 182 and 184 and enables very inexpensive bearings to be utilized, a coil assembly 174 has been developed comprising six separate coil windings 212, 214, 216, 218, 220 and 222 each of which is generally triangular as shown in plan view in Figure 10 and all of which may be wound from a single continuous wire strand, as shown schematically in Figure 11. Three of the coils 212, 214, and 216 are connected together in series as shown in Figure 11 (A to B), while the other three coils 218, 220 222 are connected together in series (B to C) in opposite phase to the first three coils. It will be appreciated that the rotor 26 must rotate in both directions. Use of two sets of opposed geometrically symmetrical coils enables this movement through a simple switching of the power supply from one winding set to the other. Each coil segment may be wound upon a generally triangular bobbin, the three connections A, B, C, established and then leads connected extending to the outside. Each segment, as shown in cross-section in Figure 12 is approximately nine turns across by 22 turns high and is formed from 29 gauge copper wire. The coil assembly 174 is then placed in a forming mould, and an epoxy potting compound 224 is then placed and

pressed into the mould to form the assembly 174 (Figure 12). Adhesive is used to bind the coil assembly 174 to the hub 172. By utilizing the potting compound 224 to form the assembly 174, a very high mechanical resonant frequency is achieved, and the assembly 174 dampens resonant vibration otherwise occurring in the head structure 28, thereby increasing the mechanical bandwidth of the coarse servo loop.

The coil assembly 174 is configured so that adjacent coil windings will produce equal and opposite forces resulting in a pure torque evenly applied about the axis of rotation of the rotor 26. If equal currents are present in both sides of the coil assembly 174 (A to B and C to B) the forces produced cancel out, and no resultant torque is produced. During seeking, in the event of any position error or disturbance occurring while the system 10 is operating in the closed loop track following or slewing modes, the current in the winding becomes imbalanced, and this condition yields a restoring torque which moves the head structure until a position yielding equilibrium in current is again reached.

Counterweights, not shown, are added to the rotor hub 172 to place the centre of mass of the head structure 28 in alignment with the axis of rotation of the rotor 26. In this way, no unbalanced forces pass through the rotor bearings 182 and 184 as the rotor rotates about its axis.

It will be apparent to those skilled in the art that the present invention may be embodied physically in a wide variety of ways and with many different elements and components. For example, the optical transducer 24 may be implemented magnetically. Alternatively, transducer information may be provided in the servo sector 62 and read with each rotation of the disk 14. The rotor 26 may be replaced with an electrical detent, microstep providing stepping motor, and the combination of such a stepping motor with the time sampled fine servo loop will vastly improve track centre line following performance in a disk drive. The servo loop systems are advantageously, but not necessarily, embodied in rotating magnetic disk storage devices. Of course, the system embodying the invention may be used for servo applications, for example in spectrophotometers and other machines characterized by highly interactive mechanical elements.

Thus, the present invention provides a low cost closed loop servo control system which improves the accuracy of maintaining a transducer head in alignment with a data track during reading and/or writing operations of a disk having high data track densities and provides a more reliable open loop position seeking system which overrides a closed loop position maintaining servo control during track seeking.

Also, an improved, yet simplified high speed and pure torque producing position translator or rotor is provided for positioning the head mounting structure.

Further the present invention combines readily available and inexpensive electrical and mechanical components in a unique way to provide an improved position control system which occupies a small physical space, which requires only a modest power supply, which is inexpensive to manufacture and which operates reliably over a long useful life.

CLAIMS

1. Data storage apparatus for emulating an open-loop stepper motor based disk drive, the apparatus comprising a frame and a data storage disk journaled to the frame and rotatably drivable by motor means at a proper constant velocity, the disk having a plurality of concentric data tracks capable of being recorded in substantially unrestricted data format formed on the major surfaces thereof and being provided on one of the major surfaces thereof with a single data-masked servo sector region containing track centring servo information, at least one data transducer head device being provided in close proximity to the disk surfaces and a position control system, the position control system comprising: driver means drivingly connected to the transducer head device for moving the head to any one of the data tracks during a track seeking mode of operation and for maintaining the head within a given track during a maintained position mode of operation; and a fine position closed loop servo connected to the driver for operatively controlling the driver to keep the head positioned within a given track, the fine position closed loop servo including the single data-masked servo sector region on the surface of the disk which contains track centring servo information therein, sample and hold means connected to the head for sampling and holding the servo information read from the servo sector for each revolution of the disk, and correction signals generator means connected to the sample and hold means for generating offset signals, the loop of the closed loop servo being open during a track seeking mode of operation.
2. Data storage apparatus according to claim 1, further comprising a bidirectionally movable electromechanical mover mounted to the frame adjacent to the disk; and a head mounting structure secured to the mover at one end thereof for moving the head across the plurality of concentric data tracks; the driver means comprising bidirectional driver means connected to the mover for moving the structure to maintain it within a selected data track during reading and/or writing operations and to move the structure from a departure track to a destination track during track seeking operations;
3. Data storage apparatus according to Claim 2, wherein the mover is stabilized at a position related to each data track.



4. Data storage apparatus according to claim 2 or 3 wherein the bidirectionally movable electromechanical mover is a rotor.
5. Data storage apparatus according to claim 4, wherein the rotor is  
5 journaled to the frame adjacent the disk and has an axis of rotation parallel with the axis of the disk.
6. Data storage apparatus according to claim 4 or 5, wherein the rotor  
10 comprises a bidirectional, pure torque generating electromechanical rotor rotatably mounted to the frame for rotatingly moving the head mounting structure relative to the frame over a locus defining a sector of a circle, which is less than 90 degrees, the rotor comprising: a flux return base plate, a flux return top plate, a generally annular permanent magnet secured to  
15 one of the base and top plates having an even number plurality of adjacently opposed field magnetic segments in which the north and south poles alternate at the major surfaces thereof, generally annular, rotatable coil assembly placed and closely spaced from between the permanent magnet and the other of the base and top plates, the coil assembly containing the same even number plurality of coils as there are magnet segments in the  
20 permanent magnet, the coils being aligned adjacent to the magnetic segments at at least one position of rotation of the assembly and connected into two series of opposed windings equidistantly and symmetrically located about said assembly and a movable member attached to the assembly and arranged to pass rotatably through at least one of the base plate and top  
25 plate, the member being rotated along said locus by passage of current through one of the series of windings, the torque from the coils being applied evenly to the moving member about its axis of rotation.
7. Data storage apparatus according to claim 6, wherein the rotor is  
30 rotationally aligned relative to the magnet to linearize torque amplitude over the range of the locus of movement.
8. Data storage apparatus according to any one of claims 2 to 7  
35 comprising head controller means connected to the mover driver means and to an external source of track position and selection information, for commanding the head to move from a known departure track to a requested destination track during a track seeking operation until the destination track



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is reached.

9. Data storage apparatus according to claim 8, comprising a head position sensor providing a polyphase position signal in response to a sensed actual position of the head relative to the frame, the head controller means being connected to the head position sensor, the driver means and to an external source of track selection information for recording the present track position of the head for calculating a track seeking command in response to known head position and the track selection information, and for commanding the head to move from a known departure track to a requested destination track during a track seeking operation by commanding at the mover a first head position spatial increment of maximum forward direction acceleration followed by a similar head position spatial increment of maximum reverse direction acceleration and then by commanding adaptively a slewing rate dependent upon the polyphase incremental head structure position information from the head position until the destination track is reached.

10. Data storage apparatus according to Claim 9, wherein the head position sensor is a transducer.

11. Data storage apparatus according to claim 10, wherein the position transducer comprises: a scale having equally spaced angular apertures thereon of equal width secured to either the frame or the structural elements movable by the driver means and a generally U-shaped structure having two parallel arms spaced apart for a distance slightly greater than the thickness of the scale and aligned and mounted to the other of the frame so that the scale is free to pass between the arms, the U-shaped structure including a light source in one of the arms for passing light through the scale in the direction of the other arm, an array of photosensitive detectors and a light-pattern-defining reticle placed between the detectors and the scale in the other of the arms, the reticle defining windows for the detectors which are so spaced as to provide the polyphase signal in quadrature as the scale moves between the arms.

12. Data storage apparatus according to claim 11, wherein the scale is secured to the structural elements movable by the mover and the U-shaped



structure is secured to the frame at a single location of attachment and is adjustable with respect to the frame in two spatial dimensions.

5 13. Data storage apparatus according to any one of claims 9 to 12 further comprising a coarse position dependent closed loop servo connected to the head position sensor and to the driver means for operatively controlling the driver means to keep the head positioned within a selected one of the data tracks during reading and/or writing operations, the loop being open during track seeking operations until occurrence of adaptively commanded slewing.

10 14. Data storage apparatus according to claim 13, wherein the head controller means comprises a programmed microprocessor having a head position data input connection from the head position transducer, a binary data latch for receiving and holding the track seeking command, the  
15 microprocessor clocking the latch in accordance with position information derived from the transducer head and the external source of track selection information, a data connection from the latch directly to the driver means for enabling the controller means to command the acceleration increments in the track seeking operations and a digital to analog converter connected  
20 to the latch for converting slewing commands clocked into the latch into analog values and for applying said analog values to the position dependent closed loop servo to command the driver means to slew the head mounting structure at the position-adaptive slewing rate.

25 15. Data storage apparatus according to any one of claims 9 to 14, wherein the head mounting structure is a beam having one end secured to the head the other end being counterbalanced and secured to the mover for arcuately moving the head across the tracks.

30 16. Data storage apparatus according to claim 15, wherein the head position sensor is mechanically linked to the beam and is responsive to the position of the head relative to the frame to provide two track position signals and their inverses in quadrature.

35 17. Data storage apparatus according to any preceding claim wherein the transducer head is a reading and writing head held in close proximity to one of the disks surfaces by an air bearing effect.



18. Data storage apparatus according to any one of the preceding claims wherein the fine position closed loop servo comprises a pair of prerecorded track marking signals in the servo sector for each defined track, a first occurring marking signal being radially offset in one direction from track centre line, and a second occurring marking signal being radially offset in the other direction from track centre line, first sample and hold means for sampling and holding the amplitude of the first occurring marking signal with each revolution of the disk, second sample and hold means for sampling and holding the amplitude of the second occurring marking signal with each revolution of the disk, and differential comparator means connected to the first and second sample and hold means for comparing held amplitudes and for generating a head position correction signal proportional to the difference in held amplitudes, and for applying the correction signal to the mover through the driver means.

19. Data storage apparatus according to claim 18, wherein the differential comparator generates an automatic gain control signal for automatically controlling and regulating amplitudes of data recovered in the reading operations of said disk by operatively regulating data recovery circuits of the data storage equipment.

20. Data storage apparatus according to any preceding claim, wherein analog-to-digital converter means are connected to the correction signal generator means for converting the offset signals into digital values.

21. Data storage apparatus for emulating an open loop stepper motor based disk drive, the apparatus including a rotatable data storage disk having a plurality of concentric data storage tracks capable of being recorded in substantially unrestricted data format formed on the major surfaces thereof, one of the major surfaces the disk having a single data-masked servo sector region containing track centring servo information, a read and write head held in close proximity to the surface of the disk by the air-bearing effect, a head mounting structure for positioning the head at one of the plurality of concentric data tracks during data reading and/or writing operations in substantially unrestricted data format within each track and for moving the head from track to track during track seeking operations of the equipment and a position control system, the position control system



comprising: driver means drivingly connected to the head mounting structure for arcuately moving the head from one track to a selected other track located beyond a predetermined minimum radial distance during an open loop servo track seek movement by a first spatial increment of maximum forward direction acceleration of the carriage for about half the radial distance between the tracks and by a second similar increment of maximum reverse direction acceleration until the head mounting structure reaches the vicinity of the selected other track, and for closed loop generally constant velocity microstepping of the head mounting structure within the minimum radial distance in small radial increments from track to track until the other track is reached, and for maintaining the head accurately within a selected track during data reading and writing operations; a summing circuit connected to drive the driver means; coarse servo control loop means including coarse position sensor means mechanically linked to the head mounting structure for sensing the radial position of the head relative to said tracks, and coarse position feedback control loop means connected to the driver means through the summing circuit for controlling the driver means to keep the head positioned within the selected one of said defined tracks during reading and writing operations; index detector means electromechanically coupled to the disk for detecting each rotation thereof and generating an index signal; fine position servo control loop means including the single data-masked servo sector region on the surface of the disk containing servo information therein, sample and hold means connected to the head for sampling and holding the servo information read in the servo sector for each revolution of the disk, correction signal generator means connected to the sample and hold means for generating offset signals, and analog-to-digital converter means connected to the correction signal generator means for converting said offset signals into digital values; and programmed digital microprocessor means connected to the analog-to-digital converter means, the index detector means, the coarse servo control loop means and a source of an externally supplied digital track selection command signal, including clocked latch means, and digital-to-analog converter means drivingly connected to the driver means through the summing network for calculating and supplying a digital head positioning signal to the driver means in order to move the head from a predetermined departure track to a predetermined destination track, and for calculating and applying a fine position offset signal to the driver means through the



digital-to-analog converter means and the summing network to maintain the head in centre line alignment in the track during reading and/or writing operations interactively with the coarse servo control loop means.

- 5 22. A method of controlling the position of a data transducer head of data storage apparatus for emulating an open loop stepper motor based disk drive, the method comprising: rotating at constant velocity a data storage disk rotatably mounted in a frame of the equipment, the disk having a plurality of concentric data tracks formed on the major surfaces thereof
- 10 associated with at least one data transducer head device arranged in close proximity to the disk surfaces, the disk being provided on one of the major surfaces thereof with a single data-masked servo sector region; moving the head device across the plurality of concentric data tracks by means of a bidirectionally rotatable electromechanical rotor journaled to the frame
- 15 adjacent to the disk and secured to the head device at the other end thereof; rotating the head device by means of driver means connected to the rotor to maintain the head within a selected data track during reading and/or writing operations and to move the head from a departure track to a destination track during track seeking operations; providing a polyphase signal responsive to position of the head device relative to the frame by means of a
- 20 head position transducer; providing track selection information to head controller means connected to the head position transducer, the driver means and to an external source of track selection information; recording the track position of the head device; calculating a track seeking command
- 25 in response to the known head position and the track selection information; commanding the head to move from a known departure track to a requested destination track during a track seeking operation by commanding at the rotor a first head position spatial increment of maximum forward direction acceleration followed by a similar head position spatial increment of
- 30 maximum reverse direction acceleration and then by commanding adaptively a slewing rate dependent upon incremental head position information from the head position transducer until the destination track is reached; operatively controlling the driver means to keep the head positioned within a selected one of the data tracks during reading and/or writing operations
- 35 with a position dependent, coarse position closed loop servo connected to the head position transducer and to the driver means and overriding the coarse position loop to keep it open during track seeking operations; and



providing a fine position closed loop servo connected to the driver means and a single, data masked servo sector on a data surface of the disk; prerecording track centre line servo control data in the servo sector; reading the data with the head adjacent the surface; sampling and holding data read by the head during passes over the sector and generating an offset correction signal; applying the offset signal to the driver means to promote and maintain track centre line alignment of the head during reading and/or writing operations; and overriding the fine position servo loop during track seeking operations.

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23. A method according to claim 22 and further comprising: providing a pair of prerecorded track marking signals in the servo sector for each defined track by providing a first occurring marking signal radially offset in one direction from the track centre line, and providing a second occurring marking signal radially offset in the other direction from track centre line; separately sampling and holding the amplitudes of the first and second occurring marking signals; and comparing the held amplitudes and generating therefrom a head position correction signal proportional to the difference in held amplitudes of the marking signals, and applying the correction signal to correct head position until it coincides with the track centre line.

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24. A method according to claim 23 and further comprising utilizing the comparison of held amplitudes to generate an automatic gain control signal for automatic control and regulation of amplitude of recovered data.

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25. A method according to Claim 22, 23 or 24 wherein the step of operatively controlling the driver to keep the head positioned within a selected one of the data tracks during read and/or write operations with a position dependant, coarse position closed loop servo includes the step of providing a track extension control mode by selecting an appropriate monophase of the polyphase position with responsive signal and servoing over the full cycle thereof.

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26. A method according to Claim 22, 23, 24 or 25 further comprising an emulation step for emulating operation of a disk drive having two adjacent read/write heads, the step comprising electrically assigning odd numbered

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tracks to correspond with tracks read by one of the emulated adjacent heads and electrically assigning even numbered tracks to correspond with tracks read by the other of the emulated adjacent heads.

5 27. Data storage apparatus for emulating an open-loop stepper motor based disk drive, the apparatus including a frame a data storage disk  
10 journaled to the frame rotatably drivable by motor means at a constant velocity and having a plurality of concentric data tracks on the major surfaces thereof and at least one data transducer head device in close proximity to the disk surfaces, substantially as hereinbefore described with reference to and as illustrated in the accompanying drawings.

15 28. A method of controlling the position of a data transducer head of data storage apparatus for emulating an open-loop stepper motor based disk drive, substantially as hereinbefore described with reference to the accompanying drawings.

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