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AUDIO-VISUAL DISK DRIVE OPTIMIZED FOR RESPONSE TO AN OFF-COURSE HEAD DURING A WRITE COMMAND**Field of the Invention**

5 This application relates to hard disc drives and more particularly to an apparatus and method for efficiently storing and retrieving audio-visual data on a hard disc drive.

Background of the Invention

10 Traditionally, disc drives have been designed in accordance with certain fundamental assumptions regarding the importance of data integrity and data flow. For example, it has traditionally been assumed that informational integrity is of paramount concern; even a single-bit error in loading an executable file could cause untold run-time ramifications. As a result, a traditional disc drive would attempt to
15 read target data, perhaps multiple times, if the drive determined that a data error had occurred during a read operation. Additionally, conventional disc drive performance has been measured by assessing the average time consumed in performing a command. As a consequence, it is acceptable—even desirable—for a conventional disc drive to attempt to read and re-read data until the data is either read correctly, or
20 until there is a miniscule probability that the data can actually be read properly. The time consumed in multiple re-attempts of a single read operation is of little consequence to average command times (the metric against which conventional disc drives are measured), if this sort of multiple-retry event occurs infrequently.

 A disc drive which is optimized for audio-visual data storage and retrieval
25 should be designed according to different fundamental assumptions regarding the importance of data integrity and data flow. Data integrity is of diminished importance for such a disc drive. A minor inaccuracy stemming from a small error would be minimally observable, if at all, by a viewer of the visual signal. However, reliable data flow is critical for an audio-visual drive. For the sake of illustration,
30 consider an individual viewing a video signal. Such a viewer may not be able to notice a small error in a data stream, but the viewer will notice a three-second delay introduced into the data stream by a drive which repetitively attempts to correctly re-read an errant bit. Accordingly, the performance of an audio-visual drive should be



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measured against the maximum time consumed to complete a command. Worst-case scenarios for command completion, rather than average-case scenarios, are of central concern in an audio-visual disc drive.

The decision to optimize data integrity and minimize average command
5 times in conventional disc drives has influenced many design considerations in such drives. Many of the design choices made to accommodate the requirements of a conventional disc drive are inappropriate for an audio-visual disc drive.

A conventional disc drive is designed to minimize average seek times. To accomplish this, the actuator arm is designed to be light, so as to minimize its
10 rotational inertia. Also, the magnetic force imparted on the actuator arm is maximized by immersing the coils on the windings of the actuator arm in a strong magnetic field. Both of these mechanical choices, taken in concert, maximize the acceleration of the actuator arm, thereby minimizing average seek times. A consequence of those design choices is that the actuator arm approaches an unstable
15 state. As a result of this instability, a small fraction of disc commands may occasionally require many retries to function properly, thereby yielding a very high maximum command completion time (a property undesirable in audio-visual disc drives).

Conventional disc drives have also been designed to operate at relatively
20 high spin rates, so as to minimize rotational latency. An effect of operating at a high spin rate is that track following is made less reliable, meaning that an occasional command may take several retries to be properly effectuated. Once again, since audio-visual disc drives need to minimize command completion times for worst-case scenarios, this effect is undesirable.

25 Additionally, conventional disc drives have been designed to optimize informational integrity with respect to the manner in which such drives react to read-time and write-time errors. As will be discussed in greater detail, conventional disc drives behave sequentially during read and write operations. As an example of sequential behavior, a conventional disc drive will not attempt to read a
30 particular sector until the previous sector has been correctly read. If a read-time error occurs with respect to a given sector, a conventional drive will cease further attempts at reading successive sectors, until the disc has completely rotated and the

errant sector can be properly read. Only then, will a conventional disc drive attempt to read successive sectors. A conventional disc drive behaves in a parallel manner during write commands, as well. In short, a conventional disc drive preserves data integrity at the expense of data flow. Accordingly, there is a need for a disc drive that responds to certain read-time and write-time errors in a manner that preserves data flow.

Summary of the Invention

The method and apparatus in accordance with the present invention solves the aforementioned problem and other problems by responding to a certain write-time error in a manner that preserves data flow. More specifically, in response to a write-time error in which information obtained from a servo burst indicates that the disc drive's head was either off course or anticipated to go off course, the disc drive responds by ceasing to write to the disc in synchronization with the end of writing a sector, so that a sector is not left half-written. The disc drive then transfers the sector numbers of the sectors which were improperly written or unwritten to the host. The disc drive attempts to continue writing to the disc in subsequent sectors, as soon as servo sectors once again indicate that the head is sufficiently re-centered on the track. Further, if the servo data indicates that the head may not have been well-centered between a current and previous servo burst, the sectors between those servo bursts will also be indicated to the host.

The aforementioned behavior is a departure from the traditional sequential paradigm of a conventional disc drive. The new behavior preserves data flow, a quality important to audio-visual drives.

These and various other features as well as advantages which characterize the present invention will be apparent from a reading of the following detailed description and a review of the associated drawings.

Brief Description of the Drawings

FIG. 1 is a depiction of track space, represented linearly.

FIG. 2 is a depiction of adjacent tracks on a disc, represented linearly.

FIG. 3 is a depiction of an audio-visual disc drive constructed in accordance

with one embodiment of the present invention.

FIG. 4 is a flowchart depicting a method of behaving to a particular read-time error, in accordance with one embodiment of one aspect of the present invention.

5 FIG. 5 is a flowchart depicting a method of behaving to another read-time error, in accordance with one embodiment of another aspect of the present invention.

FIG. 6 is a flowchart depicting a method of behaving to a write-time error, in accordance with one embodiment of yet another aspect of the present invention.

10 Detailed Description

permits the disc drive to anticipate the location of each bit within the data field 116 immediately following the sync field 102, 104. In other words, each sync field 102, 104 is used as a timing reference to permit synchronous decoding of the data field by the detection circuitry. As is illustrated upon line 118, which represents time, the disc drive opens time windows 120, during which it anticipates encountering subsequent sync fields 114. These time windows 120 are positioned using the last servo burst 102 as a point of reference. If a time window 120 expires without a sync field 114 being encountered, a conventional disc drive will not be able to read the data in the following data field 116, nor will it attempt to read data in subsequent sectors 106, 108. A conventional disc drive is designed to behave sequentially, meaning that it will read a given sector 106, 108 only if it was able to read the sector preceding it. If a time window 120 expires without a sync field 114 being encountered, a traditional disc drive will wait one entire revolution of the disc to attempt to reacquire the sync field 114 on the next revolution. A conventional disc drive is unable to reset its detection hardware to seek the sync field 114 immediately following the missed sync field 114. This form of behavior in response to a missing sync field 114 is undesirable in an audio-visual disc drive, which in some cases values data flow over data integrity.

A conventional disc drive displays behavior in response to an ECC-indicated error similar to the behavior in failing to detect a sync field 114. Normally, in a conventional disc drive, the integrity of a read operation is verified by making use of an ECC. After a conventional disc drive reads data from a data field 116, the data is verified against an associated ECC field 117. The ECC field 117 may be in the form of a cyclic redundancy code (CRC) or another appropriate error correction format. In a conventional disc drive, if the ECC field 117 indicates that the data from the data field 116 was incorrectly read, then the disc drive will cease reading subsequent sectors. Once again, because a conventional disc drive behaves sequentially, it will respond to a read-time error by waiting for the disc to make a complete revolution, and attempting to re-read the data on the subsequent pass. As in the aforementioned missing sync field scenario, this form of behavior in response to an errant ECC field 117 is sometimes undesirable in an audio-visual disc drive, because data flow is valued over data integrity.

Conventional disc drives have also been designed to optimize informational integrity with respect to the manner in which such drives react to write-time errors. To illustrate the design choices applied in a conventional disc drive, the write-time behavior of a conventional drive will be discussed with regard to FIG. 2. In FIG. 2, two adjacent tracks 200, 202 are depicted. Although the tracks 200, 202 are generally circular and concentric with the center of the disc, they are depicted linearly in FIG. 2. Each track is separated by a guard band 201. The center 204, 206 of each track 200, 202 is illustrated as dashed lines. Data is intended to be stored on regions of the disc, centered about the center 204, 206 of each track 200, 202.

During a write operation, a conventional disc drive detects servo bursts 208 as they pass under the head of the disc drive. The servo bursts 208 contain information from which the radial alignment of the head, velocity of the head, and the track number over which the head is oriented can be determined. From that information, the disc drive makes two determinations each time a servo burst 208 is detected: (1) whether the head is oriented over the proper track 200, 202 and (2) whether the head is anticipated to be centered about the track 200, 202 as it traverses the region of disc space preceding the next servo burst 208 and whether the head was centered about the track 200, 202 during traversal of the region of disc space following the preceding servo burst 208. Assuming these determinations are affirmative, the drive will write the sectors 210 which precede the next servo burst 208. Upon detecting the next servo burst 208, the same inquiry will be made again.

The reason that a conventional drive makes the aforementioned two-part inquiry is two-fold. First, a conventional drive is designed to maximize the probability that the data it writes to the disc can be subsequently properly read. Therefore, a conventional drive will attempt to write data to a region of disc space centered about the center 204, 206 of each track 200, 202, so that during a read operation the head will detect a maximally strong signal if the head is centered about the track's 200, 202 center 204, 206. Second, a conventional disc drive is designed to protect the overwriting of data stored on an adjacent track 200, 202. The disc drive will stop writing as soon as it determines that any one of the above-identified determinations is negative. Since, in a conventional disc drive, the firmware that monitors the orientation of the head is executed by a processor that multi-tasks

between many tasks, the determination that a head is off-track may not be made until the disc drive is already writing a portion of sector 210 following the servo burst 208, which allowed the drive to determine that its head was off course. Even in that scenario, a conventional disc drive would immediately cease writing, potentially
5 leaving old data in a portion of the sector 210 which the disc drive was in the middle of writing; a conventional disc drive would then wait a revolution, and retry the write operation on any sectors that fully or partially exist between the servo burst 208 that led to this decision and the previous servo burst 208. If not re-written, a half-written sector 210 would certainly be corrupt when read, because its ECC field
10 117 would correspond to the old data, and any data just written between the servo burst 208 that led to this decision and the previous servo burst 208 may be written off-track-center. This form of response to a write-time error is undesirable in an audio-visual drive, where data may not have time to be re-written.

A disc drive 300, addressing the data-flow issues identified in the discussion
15 regarding Figures 1 and 2, and constructed in accordance with one embodiment of the present invention is shown in FIG. 3. The disc drive 300 is optimized for storage and retrieval of audio-visual data, and has an embedded microprocessor 302, which controls the operation of the audio-visual disc drive 300. The embedded microprocessor 302 communicates with a host microprocessor 304, which issues
20 commands (such as read and write commands) to the embedded microprocessor 302. Firmware running on the embedded microprocessor 302 interprets the commands from the host microprocessor 304, and, in turn, controls the operation of the audio-visual disc drive 300.

The audio-visual disc drive 300 records and retrieves data from a disc (not
25 illustrated in FIG. 3) via a read/write head 306, which is sensitive to the presence of localized magnetic fields on the disc. The read/write head 306 is located at the tip of an actuator arm 308. The actuator arm has a conductive coil 310, which is immersed in a magnetic field that is brought about by a neighboring magnet 312. When a current is driven through the coil 310, the actuator arm is subjected to a force
30 resulting from the cross-product of the current and the magnetic field. The aforementioned force causes the actuator arm 308 to slew, and therefore causes the head 306 to change its location over the disc. The actuator arm 308, read/write head

306, conductive coil 310, and magnet 312 may be referred to collectively as a "servo actuator assembly" 311.

Assuming, for the sake of illustration, that the host microprocessor 304 were to issue a write command, that command would be received by the embedded microprocessor 302. The embedded microprocessor 302 would respond by supplying a voltage to the driver circuit 314, which would, in turn, supply a current to the coil 310, causing the actuator arm 308 to slew toward the proper location. When the embedded microprocessor 302 determined that the head 306 was located over the proper region of the disc, the embedded microprocessor 302 would control the head 306 to permit it to write the desired data to the appropriate location of the disc. The embedded microprocessor 302 communicates with the head 306 via a data path 316.

One important aspect of the present embodiment of the invention is that, unlike a conventional disc drive, the audio-visual disc drive 300 is not designed to maximize the acceleration of the actuator arm 308. Rather than being designed to maximize acceleration of the actuator arm 308 (and therefore minimize the average seek time), the audio-visual disc drive 300 is designed to ensure actuator arm 308 stability, for the purpose of minimizing the maximum or "worst-case" number of retries required for any one operation to be performed properly. Because a command time is equal to

command time = seek time + rotate time + data transfer time + retry time,
minimizing the number of retries has the effect of ensuring that the command time for a worst-case command is minimized.

Other aspects of the present invention are also directed toward minimizing the worst-case command time for the audio-visual disc drive 300. Firmware that effects this minimization operates on the embedded microprocessor 302. Individual electronic modules could embody the various aspects of the present invention in a manner analogous to its expression through the firmware operating on the embedded microprocessor 302. Whether the various aspects of the present invention be embodied in firmware or hardware, the flowcharts of FIGS. 4, 5, and 6, depict the operation of those various aspects.

FIG. 4 depicts the operation of firmware which is in accordance with one

embodiment of another aspect of the invention. In FIG. 4, a flowchart depicts a manner by which the audio-visual disc drive 300 is controlled to react to a scenario in which a sync field is not detected during a read operation. The behavior depicted in FIG. 4 may be best understood by simultaneous reference to the track space representation presented in FIG. 1.

In search operation 400, a particular sync field 114 corresponding with a particular sector number, is sought. At intervals, control is transferred from search operation 400 to sync query operation 402, wherein it is determined whether or not the sync field of interest has been detected.

If the sync field 114 of interest was determined to have been detected, then control is transferred to data transfer operation 404, wherein data from the following data field 116 is communicated to a buffer. Thereafter, the sector number to be sought is incremented in increment operation 406, and control returns to search operation 400.

If the sync field 114 of interest was not determined to have been detected, then control is transferred to window expiration query 408, wherein it is determined if the durational time window 120 for detecting the sync field 114 has expired. If the durational time window 120 has not expired, then control is re-transferred to search operation 400, and the sync field 114 is once again sought.

If the durational time window 120 has expired, then the audio-visual disc drive 300 will act so as to simply pass along some sort of indicator that data within the given sector 106 is unreadable due to a missing sync field 114, and will reset itself to begin looking for the next sync field. The host microprocessor 304 may undertake to interpolate the missing data, if that reaction is desired. This form of behavior is a departure from the traditionally sequential behavior of a typical disc drive, and is aimed at minimizing the command time of the worst-case read scenario.

Returning to the issue of the specific steps taken if the durational time window 120 expires without the sync field 114 of interest having been detected, control is passed to transfer pattern operation 410, wherein a particular "fill pattern" is communicated to a buffer. The fill pattern may be programmable by the host microprocessor 304 and may be chosen to minimize the negative impact to the host, should it use the flawed data anyway. Upon completion of transfer pattern operation

410, control is optionally transferred to record error location operation 412, wherein the sector number of the unread data may be transferred to a buffer. The sector number of the unread data may or may not be communicated to host microprocessor 304 depending on whether the host microprocessor 304 is able to make use of the information. Finally, the sector number to be sought is incremented in increment operation 414, and control returns to search operation 400.

FIG. 5 depicts the operation of firmware which is in accordance with one embodiment of yet another aspect of the invention. In FIG. 5, a flowchart depicts a manner by which the audio-visual disc drive 300 is controlled to react to a scenario in which an ECC field indicates that the data field was misread. Once again, the behavior depicted in FIG. 5 may be best understood by simultaneous reference to the track space representation presented in FIG. 1.

In ECC verification operation 500, the ECC field 117 is checked against the data from the corresponding data field 116, so as to indicate whether the data field 116 was correctly read. Next, control is transferred ECC query operation 502, wherein it is determined whether or not the ECC field 117 corresponds with the data field 116.

If the ECC field 117 corresponds with the data field 116, then the data was indeed correctly read, and control is transferred to release data operation 504, wherein data from the data field 116 is enabled to be communicated to the host microprocessor 304, and set up to be flushed from the read buffer once the data field is communicated to the host. Thereafter, control returns to ECC verification operation 500.

If the ECC field 117 does not correspond with the data field 116, then the data was incorrectly read, but the audio-visual disc drive 300 will nonetheless communicate the errant data to the host microprocessor 304, and the data will simply be marked as incorrectly read, so that data from the subsequent sector may be read without waiting for the disc to make another entire revolution. Improperly read data may be replaced with data estimated, interpolated, or extrapolated by the downstream audio-visual system, if that response is desired. Once again, this is a departure from the traditionally sequential operation of a conventional disc drive, wherein data of a given sector 108 would be attempted to be read only after data

from the preceding sector 106 was properly read. In order to effectuate the result just recited, control would transfer to optional ECC correction operation 512, which may attempt to provide error correction. Error correction may be incomplete, yielding only partially-corrected data. Control then transfers to release data operation 508, wherein the errant data (or partially corrected data) from the data field 116 is communicated to the host microprocessor 304, and flushed from the read buffer. Thereafter, control is transferred to record error location operation 510, so that the sector number of the errant data field 116 can be recorded and communicated to the host microprocessor 304. Finally, control returns to ECC verification operation 500.

FIG. 6 depicts the operation of firmware which is in accordance with one embodiment of yet another aspect of the invention. In FIG. 6, a flowchart illustrates a manner by which the audio-visual disc drive 300 is controlled to react to a scenario in which, after writing a sector to a disc, the subsequent servo burst indicates that either the head was off course during its traversal of the sectors immediately preceding the servo burst, or that the head is anticipated to be off course during its traversal of the following sectors. The behavior depicted in FIG. 6 may be best understood by simultaneous reference to the track space representation presented in FIG. 2.

In write operation 602, at least one sector is written to the disc. Control is next transferred to validation operation 604, wherein a two-part determination is made; it is determined (1) whether the head is oriented over the proper track 200, 202 and (2) whether the head is anticipated to be centered about the track 200, 202 as it traverses the region of disc space preceding the next servo burst 208 and whether the head was centered about the track 200, 202 during traversal of the region of disc space following the preceding servo burst 208. In validation query 606, the preceding determinations are conjunctively examined, for the purpose of determining the flow of operation. If both determinations are affirmative, the head has stayed on course during its travel to the servo burst 208 and that the head is anticipated to remain on course throughout its travel to the next servo burst 208. As previously discussed, a conventional disc drive undertook this inquiry for two reasons: (1) to maximize the likelihood that the data would be properly retrieved in

the future (by ensuring that the data was written to regions of the disc which were within a certain distance from the centerline 204, 206 of the track 200, 202), and (2) to protect adjacent tracks 200, 202 from being overwritten. In the audio-visual disc drive 300, however, since data flow is a consideration of greater importance than data integrity, it is only the consideration regarding protecting adjacent tracks 200, 202 from being overwritten which motivates the two-part inquiry. Accordingly, the audio-visual disc drive 300 will have a looser tolerance with regard to how closely centered the head must be to the centerline 204, 206 of a track. The audio-visual disc drive 300 will allow the head to stray from the centerline 204, 206 of the track until the data integrity of the adjacent track 200, 202 is jeopardized. Although that tolerance should be determined empirically for each disc drive, the tolerance is anticipated to be about 20% off-track.

If, in validation query 606, the servo burst is determined to be valid, control is passed to increment operation 608, wherein the servo burst number to be sought is incremented, so that the next servo burst will be sought. Finally, in data release operation 610, the data that was just written between the servo burst leading to this decision and the prior servo burst is released from the write buffer, and the audio-visual disc drive 300 waits at wait operation 612 until it is time to write new data, whereupon control will return to write operation 602.

If, on the other hand, validation query 606 yields a result indicating an invalid servo burst (i.e. an off-track condition did, or will, happen), the control is passed to deassertion operation 614. In deassertion operation 614, a gate controlling whether or not data is written to the disc is deasserted so as to prevent data from overwriting the adjacent track. In the audio-visual disc drive 300, this deassertion step is performed synchronously with the end of sector 210, so that a sector is never left half-written. This is a departure from the operation of a conventional disc drive, in which the write gate would be immediately deasserted because data integrity was the most important consideration. Next, control is transferred to record error location operation 616, in which the host microprocessor 304 is informed of the location of the improperly written data. Finally, control is passed to increment operation 608, whereupon the normal flow of operation is resumed. Resuming a normal flow of operation is also a departure from the operation of a conventional

disc drive, because conventional disc drives were designed to operate sequentially, not proceeding on to write a subsequent sector of a wedge (a wedge is a set of sectors interposed between two servo bursts) until the preceding wedge's sector had been properly written.

5 To summarize one embodiment of the present invention, a method for a disc drive to optimally handle a write-time error in which information obtained from a servo burst (such as 102, 104) indicates that the disc drive's head (such as 306) is either off course or anticipated to head off course, may be effected by performing the following acts. First, the disc drive (such as 300) writes to a sector of a disc (such as
10 in operation 602). Next, the disc drive (such as 300) validates the course and anticipated course of the head (such as in operation 604). The validation operation may include a tripartite inquiry in which it is determined (1) if the head is oriented over the proper track, (2) if the head is adequately centered within the track the head is located over, and (3) if the cross-track velocity is sufficiently small. If it is
15 determined that the head is either off course or anticipated to head off course, then the disc drive (such as 300) stops writing to the disc in synchronization with the end of writing a sector, so that a sector is not left half-written (such as in operation 614), transfers the sector number which was improperly written to the host microprocessor (such as 304), increments the servo burst number (such as in operation 608), and
20 reports the error to the host.

In an audio-visual disc drive (such as 300), an embedded microprocessor (such as 302) is used to execute firmware responsible for the operation of the disc drive (such as 300). The firmware performs the steps summarized in each aspect of the invention referred to above. The embedded microprocessor (such as 302) is
25 operably coupled to a host microprocessor (such as 304), to a driver circuit (such as 314), and to a data path connecting running to a servo actuator assembly (such as 311).

It will be clear that the present invention is well adapted to attain the ends and advantages mentioned as well as those inherent therein. While presently
30 preferred embodiments have been described for purposes of this disclosure, numerous changes may be made which will readily suggest themselves to those

skilled in the art and which are encompassed in the spirit of the invention disclosed and as defined in the appended claims.

WHAT IS CLAIMED IS:

1. A method for a disc drive, in data communication with a host, to optimally handle a write-time error, in which information obtained from a servo burst indicates that the disc drive's head was either off course or anticipated to head off course, comprising acts of:
 - (a) validating the course and anticipated course of the head;
 - (b) upon determining that the head was either off course or anticipated to go off course performing the following acts:
 - (i) halting the disc writing operation in synchronization with the end of writing a sector, so that a sector is not left half-written;
 - (ii) transferring information representing the sectors which were improperly written to the host; and
 - (iii) incrementing a value, which represents the servo burst number to be detected, thereby inducing a condition wherein the disc drive will attempt to write immediately upon properly validating the next burst.
2. The method of claim 1 wherein act (a) further comprises:
 - (a)(i) determining if the head is oriented over the proper track;
 - (a)(ii) determining if the head is centered within the track the head is located over; and
 - (a)(iii) determining if the head velocity is proper.
3. A disc drive optimized to handle a write-time error, in which information obtained from a servo burst indicates that the disc drive's head was either off course or is anticipated to head off course, comprising:
 - (a) a servo actuator assembly for orienting the head over a disc, to permit reading and writing to the disc;
 - (b) a driver circuit, operably coupled to the servo actuator assembly, for driving the servo actuator assembly with a current, thereby orienting the head over a proper location of the disc;
 - (c) an embedded microprocessor in the disc drive, the embedded microprocessor receiving commands from a host microprocessor, the embedded microprocessor operably coupled to the driver circuit, the embedded microprocessor also coupled to a data path between the servo actuator assembly and the embedded microprocessor, the embedded microprocessor being programmed to
 - (i) write to a sector of a disc;
 - (ii) validate the course and anticipated course of the head;
 - (iii) upon determining that the head was either off course or is anticipated to head off course, perform the following acts:

- (iii)(b) transfer information representing the sectors which
were improperly written to the host;
- (iii)(c) increment a value, which represents the servo burst
number to be detected, thereby inducing a condition
wherein the disc drive will attempt to write
immediately upon properly validating the next burst.
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4. The disc drive of claim 3, wherein the embedded microprocessor is
programmed to validate the course and anticipated course of the head by
performing the following acts:
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- (ii)(a) determine if the head is oriented over the proper track;
- (ii)(b) determine if the head is centered within the track the head is located
over; and
- (ii)(c) determine if the head velocity is proper.
- 15
5. A disc drive optimized to store and retrieve audio-visual data, comprising:
- (a) a servo actuator assembly; and
- (b) a means for optimally handling a write-time error, so as to ensure reliable
data flow.