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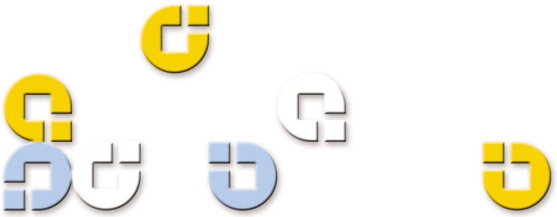
WHITE PAPER

Ensuring Data Integrity While Maximizing Performance in Tape Drive Operation



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A number of recent innovations in tape drive design offer substantial improvements in performance while eliminating the potential for data loss during backup. The latest generation of Quantum Linear Tape Open (LTO) drives offer virtually total assurance that the drive will be able to read any data that it writes to the tape. This is accomplished, first of all, by using each module of the tape drive to check the operation of the previous module. Cyclical redundancy checking (CRC) provides protection against corruption and errors in the ring buffer, data processing, and compression/decompression modules of the tape drive. The Quantum LTO tracking servo system provides a unique vibration suppression algorithm that makes it possible for the drive to operate at full transfer rates without generating any data rewrites due to off-track events at force levels up to 1 G. The Tracking Suppression algorithm achieves a near-ideal suppression function by providing high suppression at low frequencies and avoiding amplification at high frequencies. The Fast Sense algorithm reduces the time required for under-runs, when the tape stops writing because the buffer is empty, by calculating the next writing speed and moving the tape back the minimum amount required to ramp to that speed.

A comprehensive approach to data protection

The very nature of a tape drive makes protecting against data loss the primary measure of its performance. There are several steps in the tape writing process in which data loss is theoretically possible and drive manufacturers need to provide safeguards to secure each of these steps. The first area is the electronic modules that process the data prior to its being written onto the tape and after it's read. A design error or a static hit in any of these modules could potentially cause data to be written in the wrong format so that it could not be read. Quantum is the only tape drive manufacturer to provide end-to-end protection for all modules of the drive, eliminating the possibility of writing data that later can't be written.

The data integrity checks begin as soon as data is received in the drive's SCSI direct memory access (DMA) interface when a record CRC is calculated and added to each SCSI block. The CRC is stored in the descriptor for each record. The SCSI DMA logic also puts the record length into the descriptor of each record that it receives. The data processing module later uses this record length to encode the exact number of bytes that are in each record. Every record transferred to the SCSI DMA is temporarily stored in the SCSI ring buffer that is used for speed matching between the SCSI and data processing interfaces and to simplify SCSI bus error handling. Each record in the ring buffer is preceded by an 8-byte descriptor that contains the length of the record, record CRC and flag bits used to control data compression and signal partial records.

Eliminating errors in data processing and compression

As the data moves from the ring buffer into the data processing module, the CRC of each record is computed and compared to the value in the descriptor. If they do not match, an error is reported to the host. This protects the data in the ring buffer from corruption such as could conceivably be caused by intermittent dropouts in the ring buffer. The data processing module never even needs to be aware that the SCSI interface may have performed a restore SCSI pointers operation in order to re-transmit SCSI data that had a parity error. Next, the data is compressed in a data processing module that contains independent compression and decompression engines and stored in a first-in first-out (FIFO) memory register. At the same time as the data is being compressed, the block that was just compressed is being decompressed and then another CRC and general check is performed to check for invalid codes and to make sure the length and CRC of the decompressed data match the values in the descriptor. If any problems are detected, compression is halted and an error is reported to the host.

As the data moves out of the FIFO the last step in the data processing module involves the generation of a C1 Reed-Solomon ECC as the data is compressed into the data set buffers. Mathematically, Reed-Solomon codes are based on the arithmetic of finite fields and convert a message into a polynomial that it specifies by plotting a large number of points. Just as the eye can recognize and correct for a couple of bad points in what is otherwise a smooth parabola, the code can identify incorrect values and recover the original message in spite of errors. The C1 stage is used to recover from random errors caused by noise in the signal while the C2 stage is used to recover from larger errors caused by physical defects. These codes are stored in the same track as the data.

Once all of the user data in a data set is written to the buffer, the C2 ECC engine computes the value of the C2 code word pairs (CWPs) including both the data and the C1 ECC parts. Due to the linear nature of the Reed-Solomon ECC, the C1 ECC of the C2 CWPs can be that the C2 ECC engine correctly encoded the data. As the data is read by the formatter to be written to tape, the C1 ECC is used to protect against data corruption of both the data and the C2 ECC CWPs. At this point, the buffer contains 404K in user data and 112K of ECC codes. The data set is then transferred to the formatter which splits it into eight tracks so it can be written to the tape by the heads. The read data path works in an analogous manner but in the opposite direction.

Ensuring written data tracks meet LTO specifications

Another critical data reliability requirement is that written data tracks meet LTO specifications. This ensures that the drive be able to append and write to an existing set of tracks, even if it was produced by another manufacturer's drive, without generating a hard read error that may result from incorrect placement of data tracks on a drive. LTO drives can recover from off-track events by disabling writing when off-track conditions are detected, but at a loss of data transfer speed and capacity. Lateral tape motion is a major challenge for reel-to-reel drives with short tape paths. Higher tape speeds result in very high lateral slew rates that are challenging for the tracking servo to follow. Disturbances that occur such as tension, surface media roughness and tape path motion may result in some of the tape layers being packed higher or lower than the previous ones, resulting in a condition known as staggered wrap. The drive's tracking servo system must be able to keep the heads on the data track while keeping up with the host data transfer rates. Another goal is to minimize the number of off-track events with the drive subjected to a wide range of vibrational frequencies while writing.

The Quantum LTO tracking servo system uses a timing-based position error signal (PES) to determine error between the desired and actual relative head/tape lateral position. The position of the head and a reference plane are captured by sensors that feed position information to a PES detection Application Specific Integrated Circuit (ASIC) that in turn feeds another ASIC with dual ARM processors that run the servo control algorithm. The tracking suppression function in the servo control algorithm defines the drives attenuation capabilities for a range of disturbance frequencies. For example, suppose a disturbance occurs once per roller revolution that causes the tape to move in the lateral direction by 2 microns. If the tracking servo system can reduce this error to 0.2 microns, then the drive has a tracking suppression value at this frequency of 10X or 20 db. The ideal suppression function is a brick wall that strongly attenuates frequencies below the critical value and from there on passes all disturbances without amplifying them. Generally, control algorithms with higher critical frequencies will provide better performance at lower frequencies. But as the critical frequency increases, the higher frequencies are amplified, which increases noise and reduces performance, and requires the use of higher performing, more expensive actuators.

The Quantum LTO tracking system overcomes these tradeoffs by delivering a near-ideal tracking suppression curve without having to increase the critical frequency. This was accomplished through a patent-pending design methodology that combines classical and modern control techniques such as State Space and H-infinity designs. A dual stage actuator minimizes moving mass and lowers the operating power while providing a dynamic performance that is nearly equal to actuators used on enterprise drives. A tension control algorithm maintains accurate and constant tension to ensure uniform tape wrapping. A unique patent pending vibration suppression algorithm makes it possible for the drive to operate at full transfer rates at up to 1GB. Testing showed that the LTO full height drive did not have even a single off track event in writing 75GB of data until vibration levels exceeded 1.0GB. Even at vibration levels between 1.0GB and 1.2GB, only 3 off-track events were seen.

Meeting bit cell density requirements while maintaining high performance

The other critical parameter that must be maintained to ensure data integrity and performance is bit cell density. The LTO format specification has requirements for long-term average bit cell length, short-term average bit cell length, and the rate of change of short term average bit cell length. The challenge is keeping performance at optimum levels while maintaining bit cell density during appends and under-runs. Under-runs occur when a data buffer empties and the drive must stop the tape. It's particularly difficult to append to a previous recording that was done with a different manufacturer's drive. Simply starting writing at the point where the previous drive stopped may create a step change at the splice point that will fail the rate of change requirement even though both drives meet all requirements within their own recordings. The Quantum Adaptive Bit Cell Density Control algorithm corrects for this case by computing the actual written bit cell density just before it starts the append operation, adapting its write clock to match the previous section density, and then ramping from this density toward the nominal density.

Under-runs are critical from a performance standpoint. The drive first stops writing, ramps to a stationary position, then moves back to reposition the magnetic head in front of the last place the data was written in order to allow room to ramp up to speed before beginning writing. With traditional drives, the head is moved far enough back during the reposition to provide plenty of distance to move up to whatever speed is required to maintain the bit density. Quantum has developed a new solution that reduces the time required for under-runs by taking the next speed that the drive must use into account. When the drive stops because of the lack of data to write to tape, it saves the physical location of the last written data set. The drive executes a ramp to zero speed with the maximum-allowed deceleration while keeping the tape tension at the desired value. The Fast Sense Algorithm calculates the next speed that the drive must use, based on historical data about the number of data sets written to tape, tape speed, and buffer level. It then calculates the minimum distance the tape must move back, based on the maximum acceleration, deceleration, and peak velocity limitations. The drive then moves the tape back to this location and ramps up to the next step to continue with writing. The result is that data integrity is assured while maintaining backup performance at optimum levels.

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