HEWLETT-PACKARD
JOURNAL

AUGUST 1989

This is a NewWave document containing text, graphics and scanned image objects as an illustration of a document that contains data from several sources.

HEWLETT PACKARD

HEWLETT-PACKARD
JOURNAL

August 1989 Volume 40 • Number 4

Articles

Departments

The **Hewlett-Packard Journal** is published bimonthly by the Hewlett-Packard Company to recognize technical contributions made by Hewlett-Packard (HP) personnel. While the information found in this publication is believed to be accurate, the Hewlett-Packard Company makes no warranties, express or implied, as to the accuracy or reliability of such information. The Hewlett-Packard Company disclaims all warranties of merchantability and fitness for a particular purpose and all obligations and liabilities for damages, including but not limited to indirect, special, or consequential damages, attorney's and expert's fees, and court costs, arising out of or in connection with this publication.

Subscriptions: The Hewlett-Packard Journal is distributed free of charge to HP research, design, and manufacturing engineering personnel, as well as to qualified non-HP individuals, libraries, and educational institutions. Please address subscription or change of address requests on printed letterhead (or include a business card) to the HP address on the back cover that is closest to you. When submitting a change of address, please include your zip or postal code and a copy of your old label.

Submissions: Although articles in the Hewlett-Packard Journal are primarily authored by HP employees, articles from non-HP authors dealing with HP-related research or solutions to technical problems made possible by using HP equipment are also considered for publication. Please contact the Editor before submitting such articles. Also, the Hewlett-Packard Journal encourages technical discussions of the topics presented in recent articles and may publish letters expected to be of interest to readers. Letters should be brief, and are subject to editing by HP.

Please address inquiries, submissions, and requests to: Editor, Hewlett-Packard Journal, 3200 Hillview Avenue, Palo Alto, CA 94304, U.S.A.

NewWave environment clearly defines the applications environment of the future, and the complete range of encapsulation services provides a clear, well-lighted path for today's personal computer users.

Acknowledgments

Yitzchak Ehrlich is responsible for much of the design and implementation for HP NewWave encapsulation technology and the generic encapsulation facility. Tony Day designed and implemented the DOS programs service. Scott Hanson designed and implemented the configuration utility used to install generic encapsulation applications. Doug Smith implemented a shared library of DOS file management routines used by all encapsulation programs. Andy Dysart and Chuck Whelan implemented new facilities in the OMF to support encapsulated applications. Several enhancements to support encapsulation features were made to MS Windows by Tom Battle's team at HP's Sunnyvale Personal Computer Operation. Many more engineers at HP's Personal Software Division have contributed to the design and implementation of the encapsulation services for the HP NewWave environment.

Authors

August 1989

6 — NewWave Overview

Ian J. Fuller

On the NewWave project, Ian Fuller served as project manager for the NewWave Office, OMF, and DOS application support. He has since become project manager for distributed object-based systems. Ian joined HP's Office Productivity Division in his native England in 1980. Work as an engineer and as a project manager on HPDeskManager and AdvanceLink were among his early assignments. Before coming to HP, he was an engineer on message switches and telephone exchanges for ITT Business Systems. Ian was born in Gosport, Hampshire, and attended Oxford Polytechnic, where he received his BSc degree in 1978. Describing himself as an "adopted Californian," he now resides in Santa Clara, California, and is recently married. As his leisure activities, he likes travel and photography.

9 — NewWave User Interface

Peter S. Showman

With HP since 1967, Pete Showman managed the design committees responsible for the NewWave environment's architecture, user model, and user interface specifications. He has since moved on to projects involving the definition of future application environments and architectures. In past assignments, he has worked as a hardware engineer and project manager on such HP products as the HP 8542A Network Analyzer, the HP 8500 Graphics System console, the HP 2648 and HP 2700 graphics terminals, and the HP 150 Touchscreen PC. Pete is a member of the IEEE and the ACM. His BSEE degree is from Cornell University (1965) and his MSEE degree is from the Massachusetts Institute of Technology (1967). He has authored or coauthored two previous articles for the HP Journal. Pete was born in Madison, Wisconsin. He, his wife, and his two teenage sons live in Cupertino, California. Among his varied hobbies are woodworking, recreational computer programming, skiing, and playing old-time music on a fiddle and other instruments. He has also been studying Chinese for two years.

17 — NewWave Object Management

John A. Dysart

Andy Dysart came to HP in 1982, after receiving his bachelor's degree in computer science from the New Mexico Institute of Mining and Technology. After initially serving on the NewWave user interface design committee, he worked on design of the object management facility. He continues to contribute to NewWave design. Andy is a coinventor on two pending patents for the NewWave OMF. Past responsibilities include design and implementation of HP ExecuDesk and HP FormsMaster software. He is a member of the ACM and considers software architectures, object-based systems, and productivity his professional specialties. Born in Temple, Texas, Andy is married and lives in Santa Clara, California. He likes the outdoors, reading science fiction, and what he calls "recreational computing."

23 — NewWave Office

Scott A. Hanson

Scott Hanson worked on the screen display and data structures of the NewWave Office facility. As a development engineer, some aspects of the project continue to be his responsibility. In the past, he contributed to development of VisiCalc software for both HP 150 and HP 3000 Computers. Scott attended the University of California at Davis, where in 1983 he received his BS degree in mathematics and computer science. He joined HP the same year. Born in Sacramento, California, he lives in Sunnyvale, California. Scott spends his leisure time scuba diving, jogging, or reading science fiction.

Anthony J. Day

NewWave desktop and creator facilities and DOS programs have been Tony Day's focus of responsibility as a development engineer. He joined HP in 1984, shortly after receiving his BA degree in computer science from the University of California at Santa Cruz. Software reliability, reuse, and project control are his professional interests. In a previous career, he worked for the U.S. Navy, first as personnel manager in London, England, then as budget and accounting manager in Monterey, California. Tony was born in London and lives in San Jose, California. He's married and has a child. He spends his off-hours with recreational computer programming and gardening.

Beatrice Lam

The Office facility was Bea Lam's focal interest in the development of the NewWave environment, and she has since become project manager for NewWave architecture components. In the years since she joined HP in 1980, she has worked as development engineer on software projects such as HPWord and Executive MemoMaker for the HP Vectra PC. Bea earned her BSEE degree at Cornell University (1973) and her MSEE at Purdue University (1974). Previous professional experience includes firmware design at Control Data Corporation and a position as translator and coordinator for the National Council on U.S.-China Trade. Born in Canton, China, Bea is married and lives in Sunnyvale, California. Her diverse recreational interests include opera, sophisticated audio equipment, bridge, Chinese cooking, restaurant sampling and critique, and learning Japanese.

32 Application Program Interface

Glenn R. Stearns

Glenn Stearns' professional interests focus on autonomous systems, software architectures, and artificial intelligence. He was a software engineer on the NewWave project and became a project manager at the time of its release. Before joining HP in 1984, his professional activities involved mini- and microprocessors, multi-CPU applications, radio data communications, and PC environments. Glenn is the named inventor on one software patent and a coinventor on two others. Studying computer science, philosophy, and psychology, he attended California State University at Hayward for four years. He is a member of the ACM and the American Association for Artificial Intelligence. Born in New York, he is married, has a daughter, and lives in Scotts Valley, California. Motorcycles and philosophy provide his off-hours recreation.

38 Agent Task Language

Charles H. Whelan

Microcomputer systems software is Chuck Whelan's main professional interest, and his contributions to the NewWave project focused on the object management facility, agent recorder, and diagnostic utility. Since joining HP in 1973, his projects have included the development of RTE-L and RTE-VI operating systems for the HP 1000 Computer, DS/1000 networking software for the HP 1000, and BIOS for the HP 150 PC. Chuck's BA degree in mathematics is from Oregon State University (1964). Born in New York, he is married, has four children, and lives in Placerville, California.

Barbara B. Packard

A development engineer at the Personal Software Division, Barbara Packard's NewWave assignments included NewWave agents and task language compilers. She came to HP in 1973 and spent seven years working on the COBOL compiler and COBOL toolset for the HP 3000 Computer, partly as project manager. She also served as project manager for a cross-Pascal compiler and MemoMaker software developments. Before coming to HP, Barbara was an aeronautical research engineer for the U.S. National Aeronautics and Space Administration. Her BS degree in mathematics is from Stanford University (1954), as are her two master's degrees, one in mathematics (1955) and one in computer science/computer engineering (1977). She is a member of the ACM and the American Association for Artificial Intelligence. Barbara was born in Orange, California, and lives in Los Altos Hills, California. She is married and has four children; one of her daughters is an application engineering manager for HP. Her hobbies include hiking, birdwatching, and traveling. Recent trips took her to the Himalayas in Nepal and on safari in Kenya and Tanzania.

43 NewWave Help Facility

Vicky Spilman

As a software engineer at the Personal Software Division, Vicky Spilman worked on the help system for the NewWave environment. She came to HP in 1982, soon after graduating from California State University at Chico with a BS degree in computer science. In the past, Vicky has been involved with graphics systems and independent-software-vendor products as a support engineer and has worked on software for the HP 150 Personal Computer. Vicky lives in Sunnyvale, California, and enjoys gardening, aerobics, and bicycling.

Eugene J. Wong

Eugene Wong was project manager for the NewWave help facility, formatter, builds, and system performance and installation. He also served as system manager for the NewWave developer system. In past assignments, he has served as engineer and as project manager for automatic test systems and real-time systems. He also managed the development of third-party software ports to the HP 150 Personal Computer. Eugene's BA degree in mathematics is from San Francisco State College; he came to HP after receiving his degree in 1970. He is a member of the ACM and the IEEE. The HP 1000 RTE-IV operating system is the subject of a previous article he has written for the HP Journal. Eugene was born in Stockton, California, and lives in Cupertino, California. He is married and has two daughters. In his off-hours, he likes to play go, read, and study medieval calligraphy.

48 Computer-Based Training

Lawrence A. Lynch-Freshner

A software engineer assigned to the NewWave project, Larry Lynch-Freshner focused his attention on design and implementation of the animation and computer-based training display functions. In projects before he joined the Personal Software Division, he supported the operating systems for HP 150 and HP Vectra PCs. He studied computer science at Oregon State University and came to HP in 1983. He is a member of the ACM, SIGPLAN, and SIGGRAPH, and his professional interests include computer languages, computer graphics, and windowing systems. Larry has served in the U.S. Air Force Reserve. He was born in Salem, Oregon, and makes his home in Mountain View, California. He is married and has a son. Among his many avocations are beer brewing, ancient history and ancients war-gaming, electronics, robotics, science fiction, and jewelry-making.

R. Thomas Watson

As software development engineer, Tom Watson was responsible for the agent facility for computer-based training, and he continues to be involved with NewWave development. His past professional experience includes positions as computer sales manager and as computer programmer. He came to HP in 1984. His BS degree in computer science is from Pennsylvania State University. He is a member of the ACM. Tom was born in Upper Darby, Pennsylvania, is married, and lives in San Jose, California. His after-hours interest is synthesized music.

John J. Jencek

The most recent addition to the NewWave CBT development team, John Jencek joined HP in June 1988 as a software engineer. The computer-based training software was his first assignment. He developed the parsers and the CBT menu object and continues to work on NewWave design objectives. His previous experience includes work as computer programmer at IBM Corporation and as instructor at Texas Instruments. John was born in Prague, Czechoslovakia. He attended the California State University at San Francisco, where he earned his BS degree in computer science (1988). He lives in San Francisco, California, and enjoys scuba diving in his off-hours.

Brian B. Egan

Brian Egan is product manager for interactive learning systems at HP's Personal Software Division. His role in the development of the NewWave environment was that of manager and editor of the computer-based training software and courseware. His past positions include publications manager, support manager, and customer engineer. His professional interests focus on computer-based and classroom instruction, user interfaces, and teaching. Brian's

BS degree in computer science engineering is from California State University at San Jose, earned after seventeen years of attending night school. He served seven years in the U.S. Air Force, where he was a technician and instructor in metrology. He was born in New York City, is married, and has two children. Brian lives in San Jose, California. As an avocation, he teaches writing classes for engineers at California State University. He also likes hiking and mountain bicycling, and plays bass guitar in a rock band.

57 Encapsulation of Applications

William M. Crow

As an R&D project manager on the NewWave project, Bill Crow was responsible for OMF and Office software and the generic encapsulation. He continues to serve as project manager on other NewWave assignments. He attended the University of Vermont where in 1974 he received his BS degree in mathematics. He joined HP's Personal Software Division in 1984, where his responsibilities included the development of graphics products for the HP 3000 Computer. Bill's past professional experience includes positions as director of computer systems at The Austin Company and as software designer for an aerospace company. He has authored numerous papers and articles about data communications, office automation, and personal computers. He is named coinventor in two patents relating to navigational systems and three pending patents on the NewWave environment. Bill was born in Newark, New Jersey, is married, and lives in San Jose, California. His major hobby is personal computers.

67 Tape Drive Design

Andrew D. Topham

Tape head and cartridge technology were Andy Topham's focal points as an R&D engineer on the HP 9145A project. He has been a manufacturing engineer on a similar product, the HP 9144A, and is now responsible for a new product involving a tape drive. Before he joined HP in 1985, he worked for Racal Research Ltd. as an R&D engineer for digital signal processing and for Research Machines Ltd. on the design of microcomputers. The tape head mounting system described in this issue of the HP Journal is the subject of a pending patent that names Andy as a coinventor. He obtained his degree in physics at the Imperial College in London in 1981 and is an associate member of the IEE. Born in Birmingham, he now resides in Dursley, Gloucestershire. He is married and has an infant son. His hobbies include boardsailing, gardening, running, and photography.

74 Tape Drive Reliability

David Gills

For over four years, Dave Gills has been a reliability engineer and has worked in both R&D and quality control departments in HP's Bristol facility. He was the project reliability engineer for the HP 9145A and has since moved to a new digital audio tape project. His past assignments include the HP 35401A Cartridge Tape Drive. In his earlier career, Dave was a range and flight trials engineer working on guided weapons for the British aerospace company. Some years before graduating from Coventry Polytechnic with a BSc degree in 1983, he served a four-year mechanical-engineering apprenticeship with ICI Fibres Ltd. He is an associate member of the Institute of Mechanical Engineers and a member of the Safety and Reliability Society. Dave was born in Cheltenham, is married, and has an infant son. He lives in Dursley, Gloucestershire. Golf is his favorite pastime.

82 Real-Time Peripheral Firmware

Tracey A. Hains

As an R&D engineer on the HP 9145A, Tracey Hains' responsibilities included analysis, design, and development of firmware for the device task and the operating system. She has since begun designing the digital data storage format for new products. Other assignments Tracey has worked on include the design of software for a networked backup product. She came to HP in 1985, after receiving her BSc degree in mathematics and computer science from the University of Bristol. A pending patent describes algorithms Tracey originated. She was born in Dorset, is married, and lives in Bristol.

Mark J. Simms

Design, test, and debugging of the buffer management software for the HP 9145A Cartridge Tape Drive was Mark Simms' responsibility. A software engineer at the Computer Peripherals Bristol facility, his cognizance now includes the overall analysis and architectural design for other tape drives and the design of buffer management software. In past assignments, he was responsible for the data spooling software used in earlier products. Two patents are based on Mark's ideas, one for remote backup software and another for a file system search method. He received his BSc degree in computer science/mathematics from Bristol University in 1984, the same year he joined HP. Born in Leeds, he is married and lives in Bristol.

Paul F. Bartlett

As an R&D software quality engineer, Paul Bartlett was responsible for the design, implementation and testing of the HP-IB interface handling process used with the HP 9145A. He is now working on the development of a process aimed at assuring quality and reliability of firmware design. Before coming to HP in 1985, Paul designed telephone switching systems software for C.E.C. Telecommunications and software for mobile radio applications for Pye Telecommunications. He is named inventor in a pending patent describing algorithms used in remote backup software. Paul received his BSc degree in mathematics from the Imperial College in 1977, and he is a member of the British Computer Society. He was born in Aldershot and lives in Bristol, the home of HP's computer peripherals facility. He's married and has three children, a boy and twin girls. His hobbies include bicycling and photography.

Paul F. Robinson

As one of the project managers for the HP 9145A Cartridge Tape Drive, Paul Robinson was responsible for firmware development. In a previous assignment, he worked as an R&D engineer on a cost reduction project. Before joining the HP Computer Peripherals Bristol Division in 1985, he designed CAD software for a number of electronics companies, among them Phillips and Racal Corporations. Paul studied computer science at the Loughborough University of Technology and is a member of the British Computer Society. His professional interests focus on software methods, metrics, and R&D processes.

87 Object-Oriented Software Technology

Thomas F. Kraemer

Tom Kraemer was the project manager of the HP Vista software development at HP's Lake Stevens facility. He has contributed to the development of many HP calculator, computer, and instrument products as an engineer, project manager, and section manager. Currently a section manager in HP's Logic Systems Division, he is responsible for R&D on HP Teamwork SA/SD and HP 64700 emulator products. Tom joined HP in 1978, after earning his MSEE degree from Oregon State University, where he also worked on a U.S. Navy research program. Before starting college, he was a professional animator and became interested in applying computer technology to animation. He is married and resides in Sunnyvale, California.

Mechanical Design of a New Quarter-Inch Cartridge Tape Drive

The design of the HP 9145A Tape Drive required doubling both the track density and the tape speed of the existing HP 9144A, thereby doubling the older drive's 67-Mbyte capacity and 2-Mbyte-per-minute transfer rate.

by Andrew D. Topham

THE EVER-INCREASING VOLUMES OF DATA being handled by computer systems make it mandatory for backup tape devices to continue to match the growing disc capacities being projected. Both data transfer rate and tape cartridge capacity must continually be improved.

The HP 9145A ¼-Inch Cartridge Tape Drive (Fig. 1) was developed in response to this need. Before the HP 9145A was developed, HP's entry level and midrange commercial computer systems and technical workstations were usually configured with either an HP 9144A Tape Drive or an HP 35401A Autochanger for backup, depending on disc capacity. The HP 9144A has a cartridge capacity of 67 Mbytes and a data transfer rate of 2 Mbytes per minute. The autochanger uses the same mechanism and has the same transfer rate, but achieves a capacity of 536 Mbytes by changing eight tape cartridges without operator attention.

The HP 9145A provides full compatibility with the HP 9144A and the HP 35401A while also providing twice the data transfer rate. This is achieved by doubling the tape speed from 60 to 120 inches per second. As a result, users can back up their systems in half the time.

The HP 9145A has twice the data capacity per cartridge of the HP 9144A. This is achieved by doubling the number of recording tracks from 16 to 32. The HP 9145A can read the older 16-track tapes, but the older drives cannot read the new 32-track tapes.

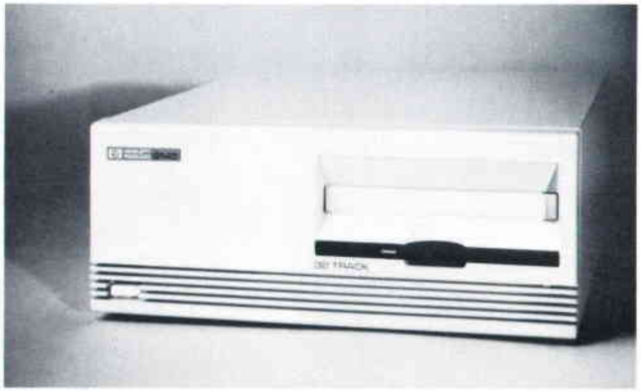


Fig. 1. *The HP 9145A ¼-Inch Tape Drive provides a storage capacity of 133 Mbytes per cartridge and a data transfer rate of 4 Mbytes per minute for backing up disc memory in entry level and midrange computer systems.*

Technical Challenges

When the development team started the task of designing the HP 9145A, there were several key areas where major design changes were required.

Mechanical Design. To achieve the increased capacity, the number of tracks across the tape width had to be doubled within the same ¼-inch tape width. To achieve the increased data transfer rate, the tape speed had to be doubled. The design had to accommodate variations in components, manufacturing processes, and operating environments and remain capable of accurately positioning the read/write

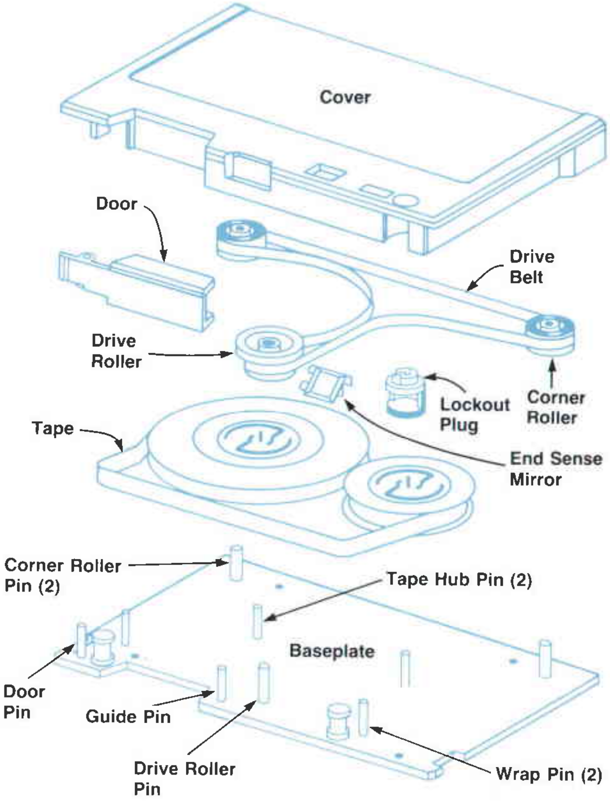


Fig. 2. *Exploded view of the new HP 92245L/S cartridge.*

head within the data tracks to guarantee data reliability.

New Cartridge. An improved cartridge design had to be introduced to support the increased tape speed and capacity requirements. This implied complete qualification and testing as well as the setup of formatting and certification lines by the cartridge manufacturers. At the same time, to maintain compatibility, the drive design had to guarantee that HP 9144A-written tapes could be read. The new cartridge features an improved mechanical design and new tape media. The tape offers higher reliability with a new oxide formulation, which reduces the signal decay that occurs each time the cartridge is used. The cartridge has a new belt and corner rollers to accommodate the increased tape speed, and an extra tape guide for better read/write accuracy.

Increased Reliability. The HP 9145A had to satisfy the user needs that had been identified. This required designing to much tighter tolerances and higher performance. At the same time, we had to ensure that the new product incorporated the lessons learned from the existing line and product range with regard to reliability and manufacturability. Reliability issues are discussed in the article on page 74.

Time to Market. To meet market needs, reliable prototypes of the HP 9145A had to be ready for testing with the target computer systems in under 12 months. Thus the design team had less than a year to design hardware and firmware from concept to reliable implementation.

HP 9144A Design

The HP 9144A Tape Drive's tape transport mechanism has design concepts common to all ¼-inch cartridge tape drives. The cartridge itself (Fig. 2) provides a reference plane in the form of the cartridge baseplate against which the tape path and servo interface are closely aligned. The drive takes advantage of this by clamping the baseplate against accurately defined stops within the mechanism. This ensures that the tape path aligns precisely with the tape head magnetic cores used to read data from and write to the tape, and that the servo motor puck aligns with the drive roller within the cartridge.

Sixteen tracks of data are written across the quarter inch of tape width. To read and write each of these tracks independently, the tape head in the drive is driven vertically by a stepper motor and leadscrew arrangement.

HP 9145A Improvements

Because the development cycle had to be short and the HP 9144A design offered a good starting point for many of the design requirements, it was decided to leverage off this product as much as possible. This approach was particularly pronounced in the mechanism area where, for example, the casting used to align all the mechanical components and the cartridge clamping assembly were left totally unchanged. Fig. 3 shows the HP 9145A drive mechanism with its associated electronics removed.

The development of an enhanced ¼-inch cartridge from the cartridge manufacturer, dubbed the HP 92245L/S, made possible the doubling of the track density. Evaluation of this cartridge was in itself a major task which was run in parallel with the drive development.

Tape Speed

The HP 9144A data transfer rate was identified as a priority area to be improved upon. With the HP 9145A providing double the cartridge capacity, keeping the data transfer rate constant would have resulted in a doubling of the time for

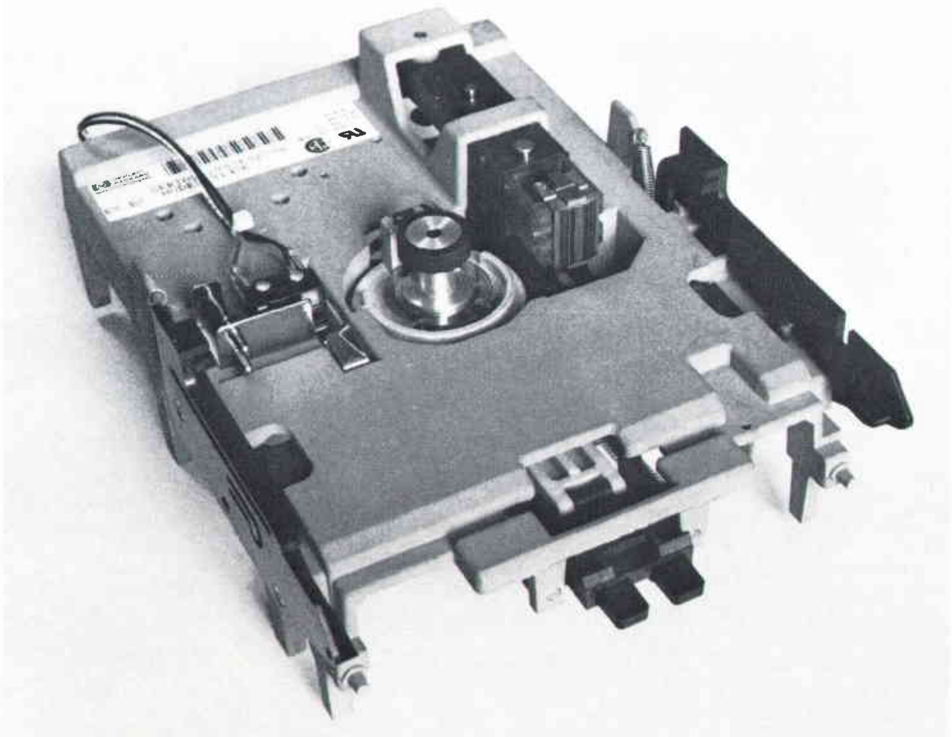


Fig. 3. *HP 9145A drive mechanism.*

reading or writing a cartridge.

One approach that could have been taken would have been to increase the linear transition density of the data on the media, resulting in a correspondingly higher data rate for a constant tape speed. However, this was rejected for two reasons. First, it would have led to complications in the read channel filtering and data recovery side of the drive, because of the need to continue to be able to read HP 9144A data with its lower transition density. Second, the media had not been proved able to perform sufficiently well at the higher transition density. The cartridge manufacturer was actively evaluating the media for this density, but there would inevitably have been an increased risk to the project.

The approach taken to improve the data transfer rate was to double the tape speed while keeping the transition density the same as in the HP 9144A drive. This led to a twofold transfer rate improvement, and took the drive from the 60 ips (inches per second) used by the HP 9144A to 120 ips.

Running the tape at this speed raised some technical concerns about the cartridge. Would the mechanics of the cartridge be able to handle this speed without either instabilities in the tape transport or degradation of cartridge operating lifetime? Would an air bearing form between the head and the tape, causing signal loss?

Cartridge Mechanics

The new HP 92245L/S cartridge was developed by the cartridge manufacturer with one of its major goals being continuous, reliable operation at a tape speed of 120 ips. During the testing of the HP 9145A drive the design team was able to provide valuable feedback to the cartridge manufacturer on the performance of the cartridge, with the result that several design modifications were made to boost the long-term reliability.

Critical parameters in the cartridge evaluation were the tape tension, the drive force, and acoustic noise. The tape tension had to be high enough to prevent the formation of an air bearing between the head and the tape, and yet low enough to prevent excessive head wear and hence short drive lifetimes. The drive force (the drag applied by the cartridge on the servo motor) had to be sufficiently low that the servo drive motor and associated control electronics that control the tape speed at 120 ips were not unduly stressed. Doubling the tape speed was found to have a substantial effect on the audible noise emitted from the cartridge. The HP 9144A and HP 9145A drives are bound by the HP specification for office environment operation and so have to satisfy a very low noise requirement. A joint development program, with the drive design team supplying test data to the manufacturer concerning the noise emissions from the cartridge in the HP 9145A drive, allowed the cartridge manufacturer to modify the cartridge to bring the noise level down to an acceptable level (Fig. 4).

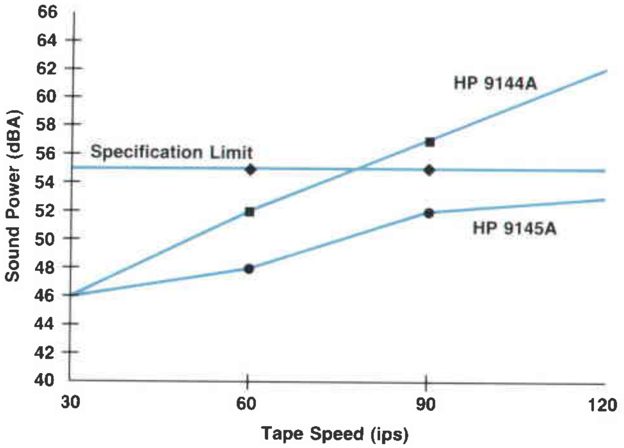


Fig. 4. *Noise level of the new HP 92245L/S cartridge compared with its predecessor.*

The overall result of the work that went into solving all the above problems was that the HP 92245L/S cartridge has emerged as a substantial improvement over its predecessor. Many of the changes that have been implemented in the HP 92245L/S cartridge are now being adopted for the HP 9144A cartridge.

There was concern whether older cartridges used in HP 9144A drives could be read in the HP 9145A drive. These had only been rated at a maximum tape speed of 90 ips by the cartridge manufacturer. However, an extensive testing program during the development of the HP 9145A drive confirmed initial indications that these cartridges were very conservatively rated, and the majority performed well in the test program. In a very small number of cases there was some cause for concern over the longer-term use of such cartridges at 120 ips. An unacceptable increase in drive force could occur after running continuously for several days at the maximum rated operating temperature. This problem was avoided by specifying that the new drive would only be required to offload data from an HP 9144A cartridge once. This is backed up by instructions to this effect in the user manual.

Head-to-Tape Contact

Intimate contact between the tape head and the media is essential in any tape drive to provide maximum read signal and minimum distortion. Head-to-tape contact is dependent on three factors:

- Tape speed. A higher speed produces greater spacing.
- Tape tension. Higher tension pulls the tape closer to the head.

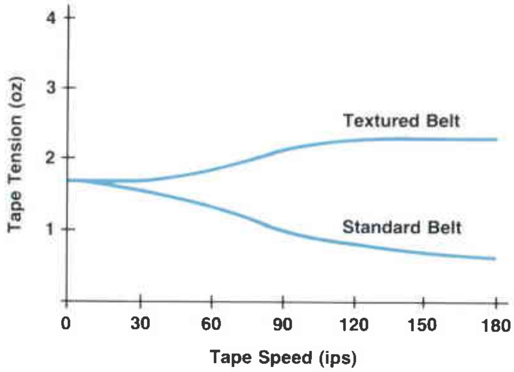


Fig. 5. *Steady-state tape tension of the HP 92245L/S data cartridge, comparing the improved textured drive belt with the standard belt used in older cartridges.*

- Head profile. The shape of the front face of the head in contact with the tape has a complex effect on the tape spacing.

The development program for the HP 92245L/S cartridge resulted in that cartridge having such an excellent tape tension characteristic that head-to-media separation is not a problem, even at 120 ips (Fig. 5).

The testing program showed that for the vast majority of the older HP 9144A cartridges, there was no problem in running at 120 ips. A very small number of exceptions to this rule were found. The problem cartridges were from a few batches that the cartridge manufacturer was able to trace back to a time when there had been minor problems in the cartridge production process. These cartridges exhibited very low tape tension so that, at 120 ips, there was a tendency for the tape to lift off the read/write head slightly. This led to reduced read signal amplitude (spacing loss) and so occasionally to read errors.

One attempt to keep the spacing loss to a minimum was through experimenting with the tape head profile. This profile must be accurately designed and machined to offer a surface that does not abrade the media, will withstand a lifetime's use, and maintains intimate contact with the media. The wear requirement and the intimate contact requirement tend to favor opposing profile shapes, so that any solution is inevitably a compromise between the two. Some experimentation with profiles that exhibited radii both sharper and more gentle than that used on the HP 9144A tape head showed that the existing profile, as shown in Fig. 6, was a good approximation to the ideal. The adoption of this profile removed another risk area in that this profile is already well-understood and in large-scale production.

The spacing loss problems were overcome by building into the drive a 90-ips read mode option. Dropping the speed causes the tape to drop closer to the head, thereby improving the read signal. This option is automatically invoked by the drive when it detects that errors are occurring because of the above phenomenon. Extensive testing has proved the capability of this approach.

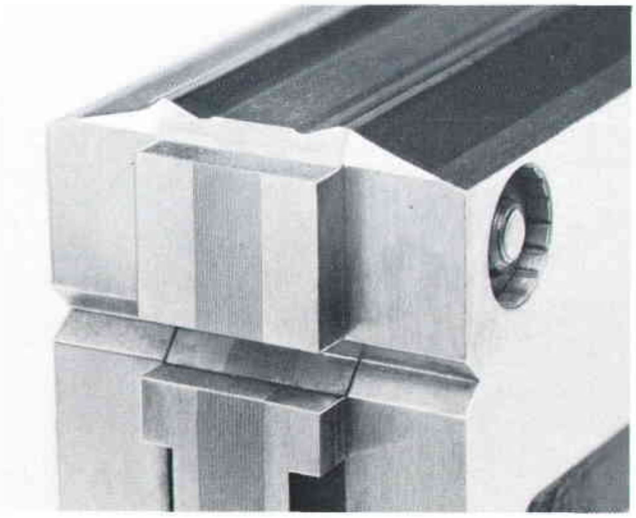


Fig. 6. *HP 9145A tape head profile.*

Track Density

The HP 9144A drive places 16 tracks across a ¼-inch media width. To double the capacity of the drive without increasing the linear bit density it was necessary to fit 32 tracks across the media. This was achieved by:

- Reduced written track width
- Improved head positioning accuracy
- Improved cartridge tracking specifications
- Improved cartridge media defect specifications
- A new track layout
- Track seeking
- Improved core alignment
- Improved tape head mounting.

Track Width. The track width of a tape drive is defined by the width of the magnetic core within the tape head. Both the HP 9144A and the HP 9145A use a system of wide write, narrow read, whereby the read core width is less than the width of the written track. This ensures that the read core will be over the written track even if there are positional errors between the core and the center of the track (Fig. 7). If the read core falls outside the written track, the signal amplitude from the track will be reduced and the core may also pick up the remains of previously written data. This would degrade the drive's signal-to-noise ratio and compromise its recovery capability.

The track width specified for the HP 9145A drive is, as far as we know, the narrowest used in the industry on ¼-inch cartridges, and is about half that in the HP 9144A drive. To achieve this we need to hold the tape head core width and core alignment tolerances tighter than in any comparable head. This was achieved by working very closely with the tape head vendor to refine their existing HP 9144A head manufacturing process until it was capable of producing HP 9145A heads with consistently good yields. In a year the vendor went from doubting that adequate yields could ever be achieved to producing heads that fully met the specification with good yields.

Head Positioning Accuracy. Head positioning to select between tracks in the HP 9144A drive is achieved by a stepper motor driving a lead screw. Riding up and down the lead screw is the head carrier assembly with the tape head mounted at one extreme.

This approach was maintained for the HP 9145A. However, the resolution of the stepper had to be at least doubled to place the head accurately over tracks that were half as far apart. Stepper motors with small angular stepping increments are now fairly common. However, the real challenges

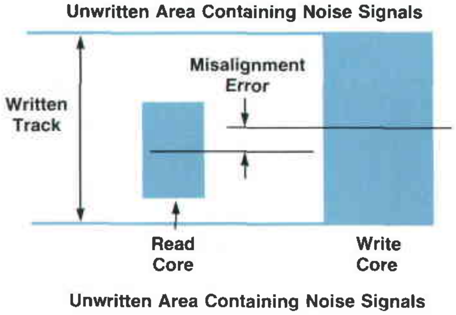


Fig. 7. *Misalignment error.*

here proved to be obtaining a leadscrew that maintains a constant thread pitch along its length and improving the head carrier movement to minimize the variation in linear displacement for each step of the stepper motor. This is essential if the track-to-track spacing is to be constant across the width of the tape.

After much evaluation of various leadscrews and modifications to the head carrier system, a head positioning system was developed that exhibits minimal errors that are highly predictable and repeatable across all mechanisms. Fig. 8 shows a typical final positioning accuracy plot.

Cartridge Tracking Specifications. The greatest single improvement of the HP 92245L/S cartridge over the HP 9144A cartridge is the replacement of a simple pin at the front of the cartridge with a guide roller. This part supports the tape on one side of the read/write head. This has allowed the cartridge to be respecified by the manufacturer so that the maximum vertical tape movement (tracking) is cut in half.

Clearly, vertical tape movement results in the tape head being slightly off the data track to be read. The improved cartridge specification is essential to be able to put 32 tracks on the tape and repeatably recover the data. Testing both at the cartridge manufacturer's laboratories and at HP showed that the new cartridge performs well within the new specification, as shown in Fig. 9.

Cartridge Media Defect Specifications. The HP 9145A drive is far more prone to data errors arising from media defects because of its narrow track size. Any drive can recover a read data signal until it goes below a certain threshold voltage that is set as a fraction of the peak read signal amplitude (typically 25 to 50%). The read signal level is proportional to the effective read track width. This effective track width is reduced by the presence of any defect. The drive is sensitive to media defects that occupy such a large proportion of the track width that the read signal falls below the threshold voltage (Fig. 10). This makes the HP 9145A drive, with its smaller track width, susceptible to smaller defects. In addition, the number of defects on a given piece of media dramatically increases as the defect size decreases. Fig. 11 shows the defect characteristics for the HP 92245L/S media.

The HP 9144A and HP 9145A drives have two main weapons with which to tackle these defects. First, all the HP-labeled cartridges that are supplied to customers are certified by the cartridge manufacturer. Certification takes the form of writing to the tape and then reading the signal back. Any errors are assumed to be because of media defects; these positions on the tape are marked and "spared out" so that they will not be used again. If any cartridge has an unusually high number of blocks spared it is rejected. In the case of the HP 92245L/S cartridges supplied to HP, this certification is performed by the cartridge manufacturer using unmodified HP 9145A drives. This immediately removes any concern about the unknown relationship between the certifying drive and a customer drive in reading data from the certified cartridge. Second, when writing data to a cartridge, both the HP 9144A and the HP 9145A drives immediately read back the written signal to verify its integrity using their read-after-write capability.[2] Any errors cause the drive to mark that area of tape as bad and then rewrite the affected data farther down the tape.

The HP 9145A drive's narrow track width makes it more prone to small-scale media errors than the HP 9144A. This is overcome by the higher-quality media in the HP 92245L/S cartridge, which has a lower proportion of defects at the HP 9145A read core dimension. To cope with the slightly inferior media in the HP 9144A cartridges, all HP 9144A-written data is read back with the write core of the HP 9145A head. This core is larger than the HP 9145A read core and so is less affected by the smaller defects. This write core approaches the size of the HP 9144A drive read core and so, when coupled with the HP 9145A's track seeking capability (discussed later), results in the HP 9145A's being able to recover a signal from an HP 9144A cartridge at least as well as an HP 9144A drive can.

Track Layout. The HP 9144A drive lays down data on tape in a serpentine fashion, that is, one track is written in one direction from one end of tape to the other, then the next track is written directly above in the opposite direction, and so on up the tape (see Fig. 12a).

A problem with this format is that the tape has a natural

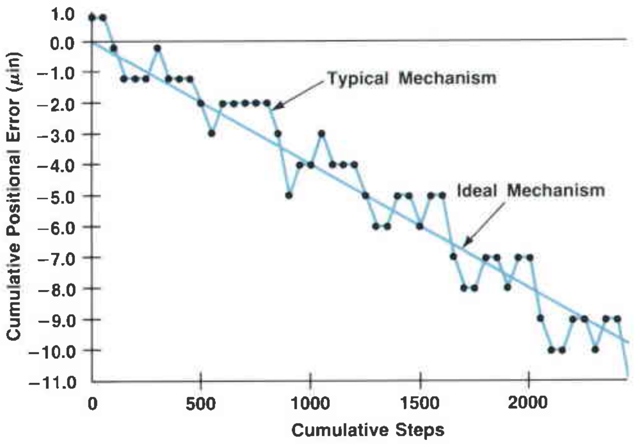


Fig. 8. *Typical head positioning error plot for an HP 9145A Tape Drive.*

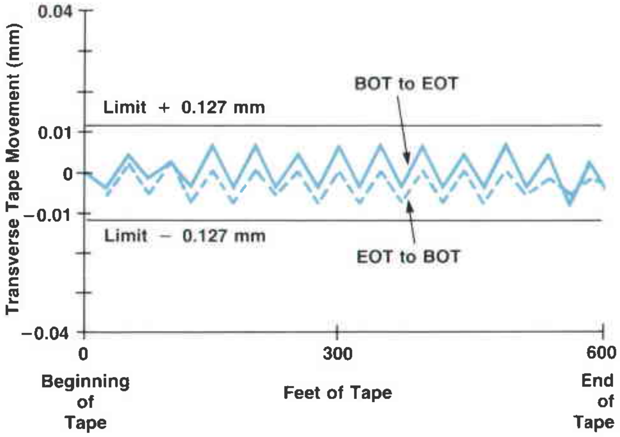


Fig. 9. *Transverse tape movement plot for an HP 92245L/S cartridge shows that vertical tape movement (tracking error) is well within specifications.*

tendency to step up or down as the direction is reversed because of the reversal of direction of tape pull. This leads to an error in the relative positions of two adjacent tracks that is at its maximum since these tracks are in opposite directions.

In the HP 9145A drive this problem was alleviated by writing all the tracks in the forward direction in the lower half of the tape, and all the tracks in the reverse direction in the upper half of the tape (Fig. 12b). Thus, adjacent tracks are generally written in the same direction and so do not suffer from this step error.

There is still a problem in the center of the tape where tracks 30 and 1 run alongside each other in opposite directions. This is overcome by allowing a slightly increased track spacing between these two tracks. This increased spacing does not impact the track density, since the allowance only has to be incurred once rather than 32 times.

Track Seeking. Both the HP 9144A and the HP 9145A drives locate the edge of the tape when each new cartridge is loaded. This edge is found by moving the tape head down until the read signal disappears. From this edge-of-tape position, the drive firmware is programmed with the number of stepper motor steps needed to reach each track.

This dead reckoning approach for locating any track from the located edge of tape has been perfectly adequate for the HP 9144A drive. In addition, it offers sufficient accuracy in positioning the head for the HP 9145A during a write operation. However, during reads, the HP 9145A may be attempting to read data that has been written by another drive. It is possible for the writing drive to have written the data to one extreme of the allowed tolerances, and then the reading HP 9145A to have positioned its read head to the opposite extreme. With the narrower data tracks used by the HP 9145A, this can lead to such poor alignment of the head over the written track that read data errors occur.

The HP 9145A overcomes this track misregistration by a technique known as track seeking. Initially, the track is located in the normal way as described above. If read errors occur, the drive attempts to find the track by stepping the head alternately above the nominal position and then below the nominal. The step size is progressively increased until the errors disappear. This new position is then considered to be the correct position for subsequent reads of the cartridge.

Core Alignment. To ensure that both the read and write cores of the appropriate channel in the tape head are always centered on the data track, the horizontal alignment between the write core and the read core must be held very tightly (Fig. 7). Although the write core is made slightly larger than the read core to minimize this problem, a limit is imposed by the need to fit 32 tracks across the tape. A tolerance analysis of the existing HP 9144A head manufacturing process showed that the write-to-read core alignment was already at the extremes of the process capability. For

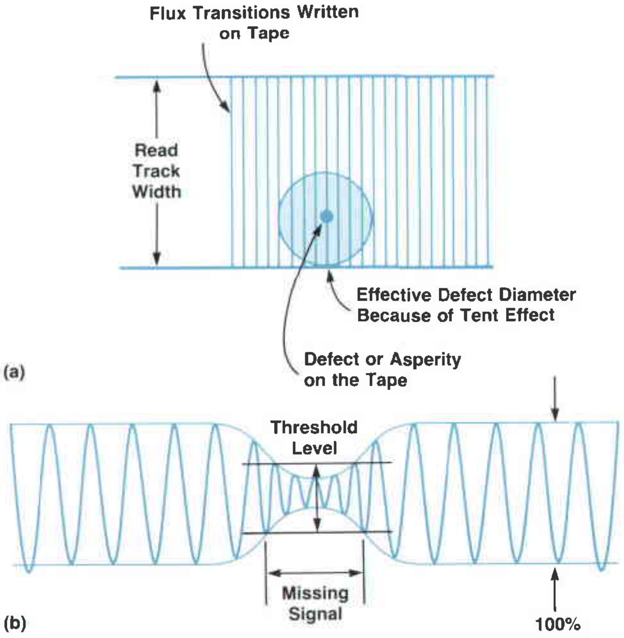
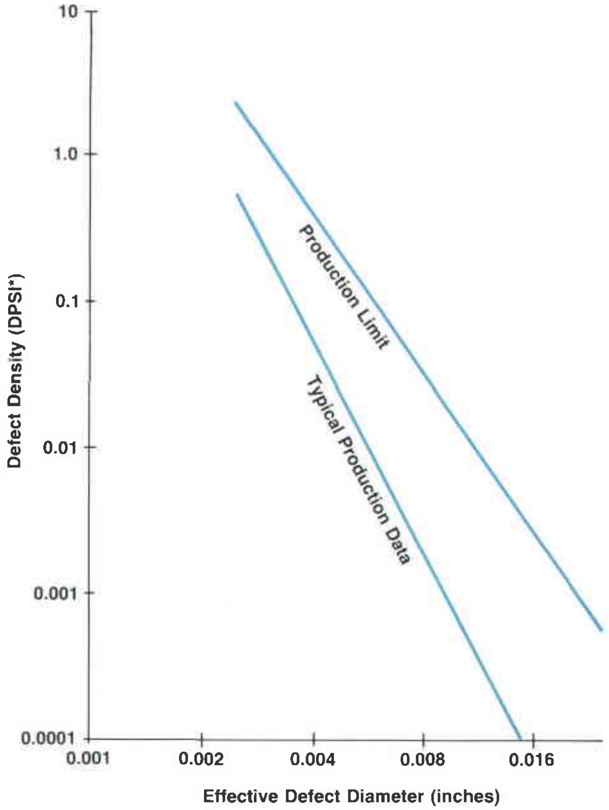


Fig. 10. *Effect of a media defect on the read signal. (a) The tent effect is where a defect on the media (effectively a lump) causes the media to be lifted away from the tape head surface. The resulting shape that the media takes (looking at a cross-section) as it is lifted in the middle and pulled back to the tape head surface looks like a wigwam, hence the name tent. (b) An analog display of the output of the read head with a defect on the media. A defect results in a reduction of the signal below the threshold level, causing lost read data.*



*DPSI = Dropouts Per Square Inch

Fig. 11. *Defect density characteristics for the HP 92245L/S cartridge. Defect density is the number of defects per square inch of readback area. The readback area is calculated from the read track width, the tape length, and the number of tracks.*

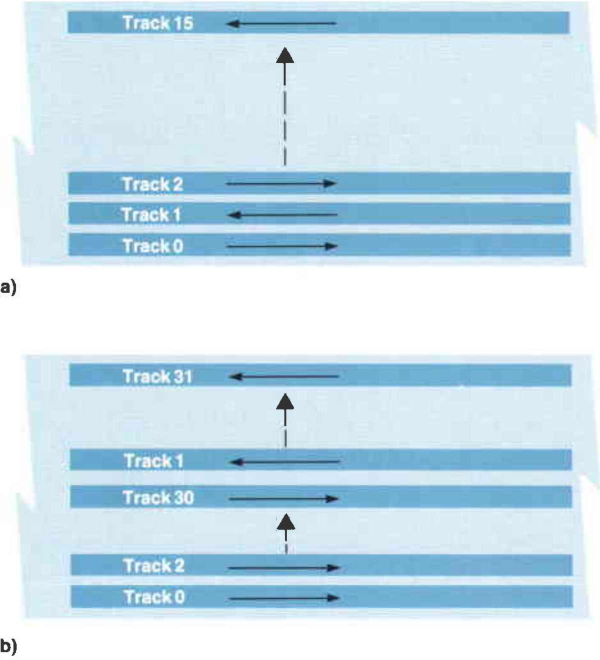


Fig. 12. *Track layouts. (a) HP 9144A. (b) HP 9145A.*

the HP 9145A, the tolerances had to be halved, necessitating a radical approach to the manufacturing process.

Several lengthy meetings with the head vendor resulted in an agreement to adopt a new manufacturing process that an exhaustive tolerance analysis showed should achieve the yields required. Subsequent manufacturing runs indicate that the original analyses were very accurate.

Tape Head Mounting. As previously mentioned, the tape head uses a read core that immediately follows a write core to provide read-after-write capability. To minimize pickup of the write signal through direct flux linkage into the read core it is desirable to maximize the separation between the read and write cores. This separation will cause the read core to be offset from the written track if the head is not mounted perfectly perpendicular to the tape motion (zero azimuth angle, see Fig. 13). This problem is twice as acute in the HP 9145A mechanism because its written track is half as wide as that of the HP 9144A drive.

In the manufacturing process for the HP 9144A the azimuth angle of the tape head is set by running a tape past the head and measuring the relative times at which the four cores see patterns prerecorded on the tape. While this process provides a good method for measuring the required accuracy, it takes a fairly long time to perform for each head and the adjustment of the head position to achieve zero azimuth is extremely difficult.

A design change to the head greatly simplifies this requirement while also speeding the head mounting process. The central section of the head was increased in size so that it protrudes above and below the outer sections. Since the interfaces between these sections define the core gaps and hence the effective positions of the read and write cores, a tool was designed that references off the exposed sides of the central head section to set the azimuth angle of the head accurately. This design change to the head also allows a simple mechanical means of verifying the accuracy of the azimuth angle of the mounted head.

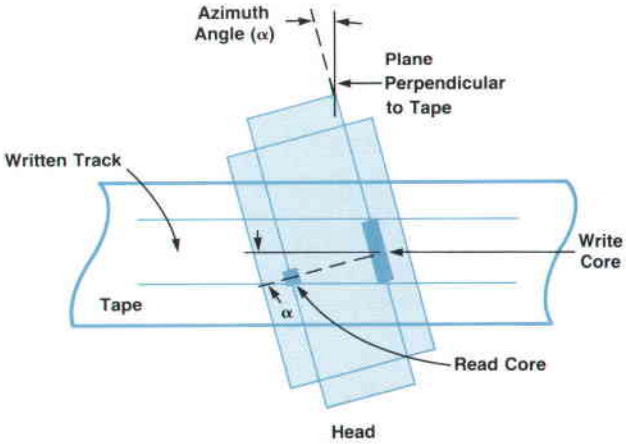


Fig. 13. *Azimuth angle. For clarity, only one of the two pairs of cores is shown.*

Conclusion

The HP 9145A drive is now shipping to customers. Strict quality control measures are being used throughout the manufacturing process and further stressed-environment audit testing is being applied to the drives produced. So far these tests have verified the ability of the HP 9145A drive to achieve its original performance and reliability goals.

Acknowledgments

I would like to take this opportunity to recognize the considerable design achievements of the HP 9145A mechanism design team, specifically Jack McGinley, Simon Gittens, Henry Higgins, Alex Clark, and Steve Langford. In addition, I would like to thank the transition team of Geoff Mansbridge and Chris Martin, who devised the HP 9145A manufacturing process, which is key to being able to manufacture these mechanisms repeatably to the tight tolerances required.

References

1. W.L. Auyer, et al, "Controlling the Head/Tape Interface," *Hewlett-Packard Journal*, Vol. 36, no. 3, March 1985, pp. 44-47.
2. K.D. Gennetten, "Cartridge Tape Data Integrity Ensured at Five Levels," *Hewlett-Packard Journal*, Vol. 36, no. 3, March 1985, pp. 39-43.

Reliability Assessment of a Quarter-Inch Cartridge Tape Drive

Aggressive quality standards were verified by over 97,000 test hours before manufacturing release and are audited continually in production.

by David Gills

THE QUALITY GOALS FOR THE HP 9145A Tape Drive included a failure rate that was half that of the earlier HP 9144A, an error rate performance that was 10 times better than the HP 9144A's, the same useful life as the HP 9144A, and full backwards compatibility with all HP ¼-inch data cartridges.

The reliability test plan showed that to be able to halve the failure rate value within the development time of just over 1.5 years, then approximately 100 prototype units would be needed, resulting in an accumulation of 97,000 test hours before manufacturing release. Reliability growth was monitored using the Duane plot technique,[1] and there were interim goals at each of several checkpoints within the development program.

The reliability of this product is also being continuously assessed during manufacturing. For this purpose a detailed manufacturing reliability audit test schedule was developed. This will be discussed in more detail later in this article.

Tape Head

As described in the article on page 67, the tape head had to be totally redesigned because of the reduction in the track width and the increase in the tape speed. The effect of the tape head on the track placement accuracy is governed mostly by the mechanical tolerances of the core sizes and the positioning of the cores on the head. Shock, vibration, and temperature can lead to inaccuracies in the track placement. A full test program was carried out to explore and quantify all these effects on the performance of the drive.

The temperature margin above the storage specifications of the HP 9144A tape head before damage is incurred is well-understood from past test data. The elements of the manufacturing process that affect this margin are also well-understood.

The first mode of failure of the HP 9144A tape head when the temperature is increased outside the nonoperating temperature limits is a deformation of the profile of the head. This is caused by stress relieving of the plates that make up the structure of the head. It is a permanent failure, making the head unsuitable for further service. The manufacturing process has been radically changed to eliminate this mode of failure, which is now well-understood. By eliminating this mode of failure in the design of the new head, a much wider reliability margin has been achieved, making the head less sensitive to manufacturing variations. This was clearly demonstrated during the testing. No permanent damage was seen on any of the data heads following extensive strife (stress + life) testing.

Head Wear

Wear of the head is accommodated until the depth of the wear reaches the throat depth of the core. When this occurs, the head performance drops off dramatically and without warning.

Since the speed of the tape over the head has doubled from the existing HP 9144A, head wear characteristics have become an issue. As the tape speed increases, the frictional forces on the interface increase. However, aerodynamic compression of the air behind the tape at these higher speeds can have the opposite effect on the wear rate. This phenomenon is very difficult to describe theoretically, so the relationship had to be confirmed by a controlled experiment.

Testing showed that the rate of wear of the head took on the standard exponential shape when plotted as a function of time, as shown in Fig. 1. The measurements were taken using a Rank Taylor Hobson Talysurf 10 machine. A typical profile is shown in Fig. 2.

The throat depth of the core is nominally 40 μm, so it can be seen from Fig. 1 that there is considerable margin, even based on the small sample of drives tested. Therefore, head wear is unlikely to be the first mode of wearout failure. This was confirmed during testing. The capstan motor was found to be the first mode of wearout failure in the product.

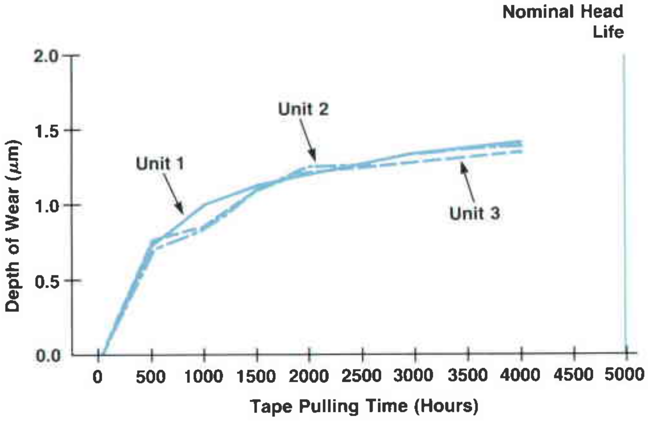


Fig. 1. *Head wear as a function of test hours for production HP 9145A heads.*

This will be discussed later in more detail.

Positioning Tolerance

Because of the increase in the requirement for track placement accuracy, the tolerances on the design and manufacture of the leadscrew that drives the head up and down across the tape had to be tightened significantly.

The leadscrew design for the HP 9145A is the same as for the HP 9144A. However, because of the precision required, the manufacturing tolerances were tightened significantly. On the HP 9144A, the thread pitch dimension has a ±5-μm tolerance, which is accumulated along the length of the thread. This will obviously give a large overall tolerance on the length of the leadscrew. On the HP 9145A, the thread pitch dimension also has a ±5-μm tolerance, except that it is not accumulated along the length of the leadscrew. This gives an overall tolerance for the length of the leadscrew of ±5 μm.

The manufacturing processes that influence this precision have to be controlled using statistical process control techniques to maintain the required accuracy. The data from the control charts is continually being monitored.

Repeatability of the track placement was critical to the success of the project, so a rigorous test program was adopted to assess its impact on the reliability of the drive. The leadscrew is machined and ground precisely from nonmagnetic stainless steel, but the nut that runs along it is made out of acetyl. The two main problems that arise are the accuracy of the leadscrew and the long-term accuracy of the nut. Since the nut is made of a much softer material than the leadscrew, we needed to ensure that there was no significant wear or load deformation. A key factor in the design of the head positioning system is that the head carrier is preloaded with a spring. This ensures that there is no mechanical hysteresis or backlash in the system, thereby driving the nut on one face of the thread only.

Shock and vibration testing was carried out to check for these issues, and it was found that this design has a very wide margin of safety over the quoted operating specifications before track placement becomes an issue.

Capstan Motor

Since the tape speed of the HP 9145A is twice that of the HP 9144A, that is, 120 ips compared with 60 ips, the

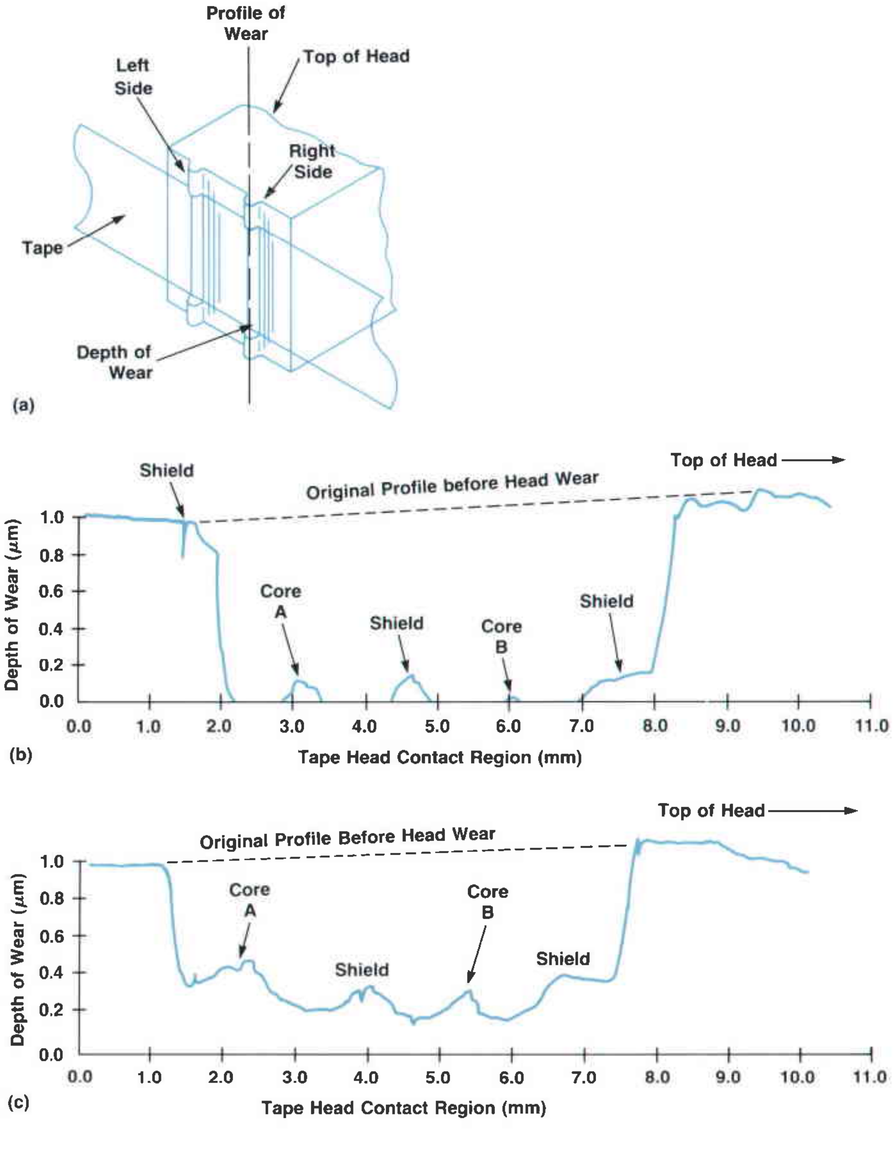


Fig. 2. *Profile of HP 9145A head wear after 2000 hours. (a) Area being profiled. (b) Left side of head. (c) Right side of head.*

capstan motor is required to run faster and have a higher torque. This allows the tape mechanism to start and stop more rapidly and accelerate to normal operating tape speed more quickly. These factors affect the overall life of the product, and since the goal for the useful life of the HP 9145A is the same as that of the HP 9144A, we needed to assess these parameters.

Working closely with our vendor, we were able to feed back test data from the development work being carried out in the laboratory from failures that were uncovered. The increase in speed and start-up torque showed that the current density at the brushes of the motor was too high, resulting in an unacceptable rate of brush wear. It was also found that the debris from the brushes was finding its way into the motor bearings, pointing to a need for shielded bearings.

The vendor was able to change the brush shape and material to extend the life to meet the goals. This was subsequently verified by extensive testing by the motor manufacturer and HP.

Printed Circuit Assemblies

Both the servo control printed circuit assembly and the main controller printed circuit assembly are newly designed boards, and as such had to be tested by a rigorous performance and stress test program. Again, working closely with our vendors, we were able to attack potential failure modes before the design was put into full production. An example of a typical component failure that was uncovered and eliminated is a crystal oscillator that failed during strife testing. Subsequent analysis showed that the failure had been caused by thermomechanical expansion of the terminals that support the crystal plate within the device. The movement of the terminals had resulted in a fracturing of the brittle crystal plate, rendering the component unserviceable. Since the vendor was unable to help in this instance, the component was second-sourced, resulting in much better quality.

Cartridge

The design of the HP 9145A relies very heavily on the quality of the media that it uses. With the performance of the drive increased so dramatically, the existing tape was inadequate. Although the older tape is compatible with the HP 9145A, its longer-term reliability was questionable. A reduction in defect size was critical to the reliability goals that were set for data integrity. The media defect size becomes far more critical as the width of the track decreases.

The project was discussed with the vendor that supplies the media, and jointly we agreed that a new tape needed to be introduced. This was a very extensive development program, carried out by the media manufacturer in parallel with the development of the drive at HP. Some of the problems associated with this development work have already been outlined in the article on page 67.

The cartridge mechanics were also redesigned to give better tape handling characteristics, resulting in better tape tension and drive force control.

The hubs that support the tape were redesigned from a new material, so that the cartridge is able to cope with the additional tape speed without wearing the hubs at an unacceptable rate.

The drive belt that runs on the tape (wound around the hubs), was also redesigned from a new material, and is being manufactured with a new process, giving more stable belt tension.

An additional tape guide was designed in to provide better tape placement accuracy. Since the tracks on the HP 9145A are half the width of the tracks on the HP 9144A, this was a critical area in the design of the cartridge.

The guide rollers were also redesigned, since the increase in tape speed caused the rollers to become a source of unacceptable acoustic noise. Resonances were built up from out-of-balance forces of the rollers running at high speed, and were transmitted through the case and baseplate of the cartridge.

Backwards Compatibility

Since the HP 9145A is intended as a natural upgrade path from the HP 9144A, it must be able to read existing tapes that have been written by the HP 9144A and other HP ¼-inch tape drives. Complexity is added by the variety of revisions of each product and of the ¼-inch cartridge. The HP 9145A has to be compatible with the entire ¼-inch tape product family over the operating temperature range, for any data pattern written by any other compatible drive. To prove the error rate performance over all possible combinations, the testing required would take over five years!

Some of the variables to be considered when concerned with interchange and backwards compatibility are temperature, humidity, data pattern, length of tape, data source, tape age, tape type, revision of unit, altitude, shock and vibration, 120V/240V, and age of drive. Using Graeco-Latin square (statistical design of experiments) techniques,[2] we were able to get this test program down from 260 combinations to a program of 16 representative combinations.

On each of the 16 runs, 10^{11} bits of data was handled by each drive (the error rate specification is 1 bit in error for 10^{11} bits of data handled). The tests were designed to find combinations that did not work at all or any trend or pattern that could indicate a combination that would potentially not meet specification.

The program was very extensive, and the testing was not able to find a combination that indicated that the specifications could not be met. The HP 9145A showed that it was able to read data from any combination that it was tested

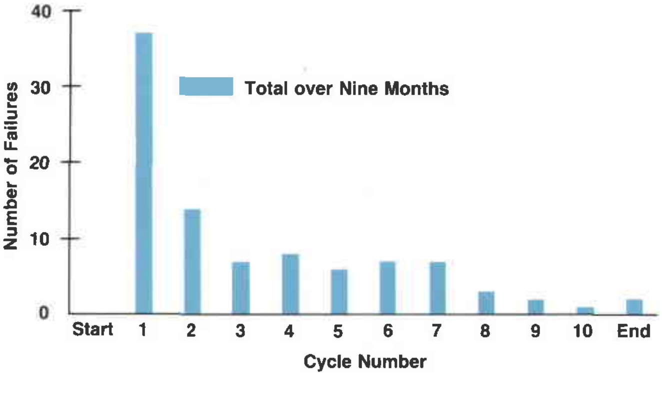


Fig. 3. *Typical distribution of faults in burn-in testing.*

against.

Test Program

At the completion of the test program, 97 prototype units had been tested, accumulating over 97,000 test hours. Over 500 tapes were used during the performance and interchange testing, and a total of over 150 failures were found. These failures can be broken down as follows:

Mechanism related failures: 70%
Controller related failures: 20%
Firmware related failures: 10%

Audit Testing

Although the tests described so far confirmed the reliability of a sample of prototype and early production drives, they in no way reflect the factors that will affect the reliability of the product in the long term, that is, factors related to the manufacturing process. Although the HP 9145A has been highly leveraged from the HP 9144A, with many improvements to the product and the process based on the wealth of information available, the reliability of the product in the long term cannot be measured or quantified unless real data is at hand. The warranty system, which records the numbers of failures in the field, provides data that is obviously too late. What is needed is a means of controlling the reliability of the drives with a closed-loop system that has a response that is almost immediate. The only way to do this is by continued unit testing on an audit basis.

An audit test strategy was devised for the HP 9145A that will enable manufacturing engineering to keep a tight control on process variations that affect the reliability of the product. A secondary objective of the audit testing is to ensure that the data being collected correlates closely with the data that is being continually collected from the warranty claims.

Much data is available from the prototype testing, and this was used as a basis for determining the general content and duration of each audit test. Also, a comparison was made with other divisions of Hewlett-Packard to appreciate some of the problems encountered in such testing.

The audit testing has three phases: burn-in, customer environment, and life tests.

Burn-In. This is performed on 100% of all units manufactured, and lasts for approximately 14 hours. This test is solely designed to catch the dead-on-arrival or infant mortality failures that somehow escape the manufacturing final test. Although the final test is considered to be adequately thorough in testing the total functionality of the unit, there are often intermittent faults or failures caused by weak materials that survive the final test. These intermittent faults often appear very early in the product's service life.

The format of the burn-in test is based on data from the prototype testing. It consists of ten cycles of power cycling and self-tests, loading tapes, performing read/write and read-only error rate tests, performing locate and read and/or write operations, comparing data with the host system, and unloading and unlocking the cartridge.

The results from the initial nine months of testing show that the faults are being uncovered very early in the test cycles (see Fig. 3). This obviously means that there is a real opportunity for shortening this test after more confidence is built up from a bigger test history.

Customer Environment. These tests are designed to simulate more closely the environment seen by the product during the warranty period. Hence, the failures found are intended to mirror the failures found in the warranty system. The duration of this test has been established from an assumed typical use of the product. The test is not performed on all units, but on a sample of approximately 5% of production. The testing simulates the time from when the unit leaves the end of the production line to the end of the warranty period. Therefore, the shipping of the product, the end-use handling, and the in-service operation of the product are simulated. The details of the customer environment are as follows:

- Book out unit from finished goods.
- Drop unit in packaging onto concrete from a height of 1.2 m.
- Make visual and functional inspection for cosmetic damage, accessories completeness, failure to power-up and pass self-test.
- Thermal cycle between the operating limits of the drive for 40 hours.
- Apply nonoperating vibration at 1.5 times specification for one hour.
- Compare data at ambient temperature between host and drive for 100 hours.
- Interchange data between drives in product family for 24 hours.

The test cycle lasts for one week, after which the units are returned to the production line for shipment. These units are considered to be some of the most reliable to leave the factory, since they have had all the infant mortality problems removed, and have proved to work reliably for a significant period of time.

Life. The life testing of the HP 9145A is currently being carried out by the suppliers of the media. This is because the media suppliers own many HP 9145As and use them at a very high duty cycle to certify all the tapes that are manufactured by them. This enables HP to use this information without cost. Obviously we need to be working very closely with these suppliers to ensure that the information that they supply to us is accurate and complete. The collection of this data will continue into the foreseeable

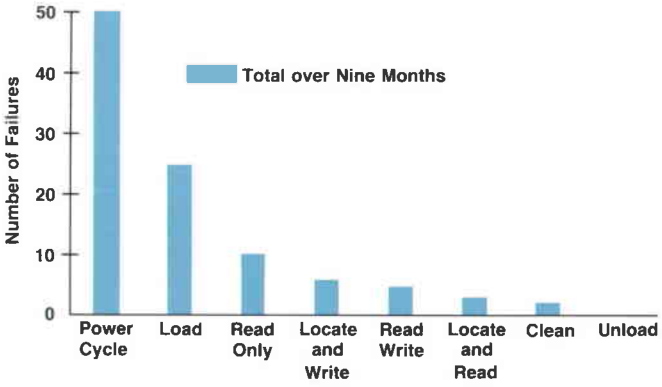


Fig. 4. *Distribution of faults among the various subtests of the burn-in test.*

future since the data is obtained free and will be needed to ensure that any changes in the manufacturing process do not affect the long-term reliability of the drives.

Results of Audit Testing

The first nine months of data has shown some interesting results. Problems are being uncovered in the burn-in test, as expected. This justifies its presence and quantifies the costs saved from warranty claims arising from very early failures, not to mention the hidden costs of customer dissatisfaction.

It can be seen from Fig. 3 that the majority of failures that have been uncovered so far have occurred very early in the test program. After the fourth cycle, which is 1.3 hours after the start of the test, most of the problems seem to have been found. This data indicates that a reduction in the test time will find the same level of faults, but will save substantial cost in manufacturing overhead (the cost of the tapes is probably the biggest factor here).

Fig. 4 shows the tests that are most effective in producing the faults. This data agrees with the test data from the earlier prototype testing, and is useful feedback for reliability planning on future projects.

The customer environment testing is currently showing a very similar trend in the results. One year after introduction over 8,000 units have been shipped to customers. The warranty data shows that the actual failure rate of the HP 9145A is better than the failure rate goal at introduction. As a result of the audit testing strategy, the warranty failure rate continues to fall to a point where today the warranty failure rate is half of that measured a year ago.

Acknowledgments

The successful development of the 9145A was a result of substantial contributions from many people in different functional areas. Recognition should go to the R&D mechanism design team, led by Jack McGinley. Simon Gittens, Andy Topham, Henry Higgins, and Alex Clark designed the new head, servo control with associated read/write electronics, stepper motor, and front panel. Thanks go to the controller design team, led by Ben Wilkinson, and the firmware design team, led by Paul Robinson. In particular, we would like to acknowledge the efforts of Tracey Hains and Kevin Jones, whose work in failure diagnosis helped to make this project run so smoothly. Particular thanks in the materials department go to Ian Russell for his work on the development and qualification of the new tape cartridge, and to Steve Daniels and Robin Longdin, whose hard work and dedication in running the test program, ensured that the project was successful. There are many more people whose contributions were invaluable to this project, but there are just too many to mention individually.

References

1. P.D. O'Connor, *Practical Reliability Engineering, 2nd Edition*, John Wiley & Sons, Inc., 1985, p. 285.
2. G.P. Box, et. al., *Statistics for Experiments*, John Wiley & Sons, Inc., 1978, pp. 253-261.

Use of Structured Methods for Real-Time Peripheral Firmware

HP's Computer Peripherals Bristol Division made some significant changes in their firmware development process to ensure that they met a demanding development schedule and still produced a quality product.

by Paul F. Bartlett, Paul F. Robinson, Tracey A. Hains, and Mark J. Simms

PRODUCTIVITY AND CONCERNS about quality may seem to be opposing concepts when product development time is short. However, with planning, the proper tools and a good development method, productivity and quality objectives can be achieved and still meet the time-to-market goals. In the development of the HP 9145A Cartridge Tape Drive at HP Computer Peripherals Bristol Division (CPB) the firmware was always on the critical path during the entire product development time. We had to produce reliable prototypes of the HP 9145A for testing with the target machines one year after the project start date. We realized at the beginning of the project that if we used the firmware development process we had at the time, we could not meet the schedule and still produce a quality product. Some of the problems we had in our development process at the time included:

- Total reliance on text for firmware specifications. There were very few graphical representations for the system architecture, data, and module organizations.
- Firmware testing was different for each project and the effectiveness of testing was not measured. Also, there was no overall test planning process.
- Except for the number of noncomment source statements (NCCS), no metrics were collected.
- Tool support consisted of emulation, source code control, and editing on HP 64000 Logic Development Systems. There were some tools for text documentation and structured design which existed on a variety of systems.

Improvements were made to our development process in the areas of planning, methods (analysis, design, and testing), and metrics (process measurement). The most significant changes involved the use of structured analysis, structured design, and structured testing. Structured design had been used on past projects for module design and the technique had worked well.

Each engineer on the project was equipped with an HP 9000 Series 300 workstation which was used for program development and emulation. A network of workstations was created with one workstation dedicated as a central data base for configuration management (i.e., keeping track of all versions of our documentation and code). To enable us to use the structured analysis and structured design (SA/SD) methods effectively, HP Teamwork/SA was installed on each workstation. This product allowed us to produce all of the real-time structured analysis and structured design documentation for the HP 9145A firmware, and assisted in ensuring analysis and design consistency between the members of the team. Other software tools that we used included a code-efficient cross compiler from C to 68000 assembly language and a 68000 emulator.

This paper describes our experiences with applying SA/SD techniques and tools to the development of the HP 9145A firmware.

Real-time Structured Analysis

Structured analysis is a method that enables designers to partition a system into manageable component processes. It helps to identify the system requirements and functionality so that consideration about implementation details, such as system architecture and module design, is delayed until necessary. This allows the designer to keep as many design options open as possible. Structured analysis[1] has been successfully applied to business and commercial systems where the emphasis is primarily on data flows and processes. In real-time systems, in addition to data flows and processes, control and timing are also major considerations. For the HP 9145A firmware development we used some parts of the structured analysis real-

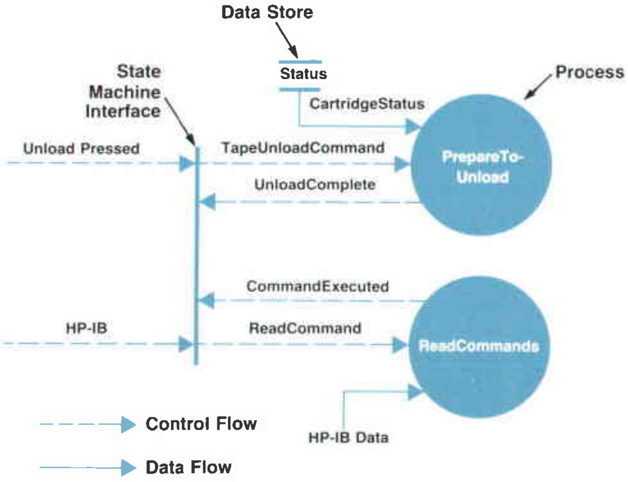


Fig. 1. *Modelling control flows and data flows in real-time structured analysis. The function of a process is to perform the operation implied by its name. The vertical bar represents the interface to a state machine.*

time extensions described in references 2 and 3.

Real-time systems have two features that nonreal-time structured analysis cannot model. One is the ability to distinguish between the flow of control signals such as interrupts, and simple data flow such as flags or values. In real-time structured analysis, information flow between processes is represented by control flows for control signals and events and data flows for plain data (see Fig. 1). The control flows shown in Fig. 1 send a signal to activate or deactivate a process. For example, when a user presses the **Unload** button on the front panel, the state machine sends the TapeUnloadCommand signal to activate the process PrepareToUnload. The data flows represent information a process must retrieve from elsewhere in the system (e.g., a data store or another process) to perform its operation. For example, in Fig. 1 the process PrepareToUnload retrieves data about the CartridgeStatus from the Status data store.

The other deficiency of ordinary structured analysis is in modeling sequences of real-time operations. These are situations where timing or the order of responding to events and actions is very important. Starting a servo motor and waiting until it is up to speed before proceeding, or enabling DMA transfer of data to tape, are examples where timing and sequence are critical. One method used in real-time structured analysis to model sequence control is the state transition diagram (STD). State transition diagrams are used to model state machine behavior and to show how different system states are influenced by control signals. Fig. 2 shows the state transition diagram for the model shown in Fig. 1. This state machine is designed to respond to events such as **Unload** button pressed, **Self Test** button pressed, cartridge inserted, and so on, and still read commands from the HP-IB.

Real-time structured analysis can be used to help partition the hardware and software functionality for a whole system. In our situation the division between the hardware and firmware functions had already been decided before we began using the method. Therefore, we concentrated on using the methods only on the firmware.

Context and Data Flow Diagrams

Our first task was to define a context diagram for the HP 9145A firmware. A context diagram enables the designer to identify all the external entities such as other systems, users, and peripherals, with which a system must communicate. The context diagram for the HP 9145A firmware is shown in Fig. 3. There are three components to a context diagram: terminators, data and control flows, and a single process. Terminators represent external entities that can be either sources or sinks depending on whether they transmit or receive data. The data and control flows represent the communication paths between the terminators and the single process. The single process defines the central role of the system being designed. In our case the firmware is used to control and monitor the HP 9145A tape drive.

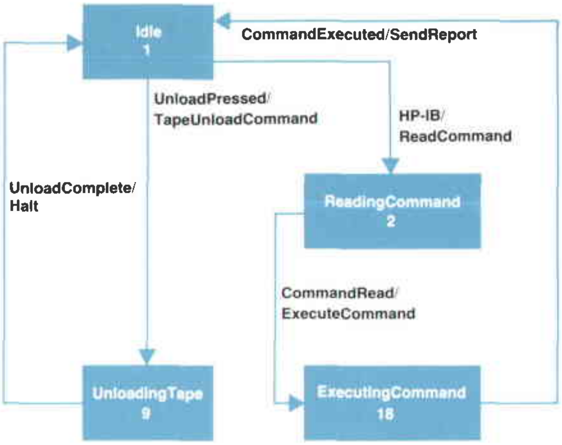


Fig. 2. *A portion of the state transition diagram for the model shown in Fig. 1. The number in each block is a state identifier. There are at least 18 states in this state machine, but for clarity, only four essential ones are shown.*

From the context diagram we developed a top-level data flow diagram (DFD) which defines the main firmware tasks and the interfaces between them (see Fig. 4). The interfaces between the tasks consist of messages passed via an interprocess communication module in the operating system. The effort involved in developing the data flow diagram enabled us to understand how to divide the system into manageable pieces for development and further analysis. Our development plan was refined so that the analysis phase was divided into smaller stages in which functions within each task could be analyzed. This enabled us to plan reviews to occur whenever one of these stages was

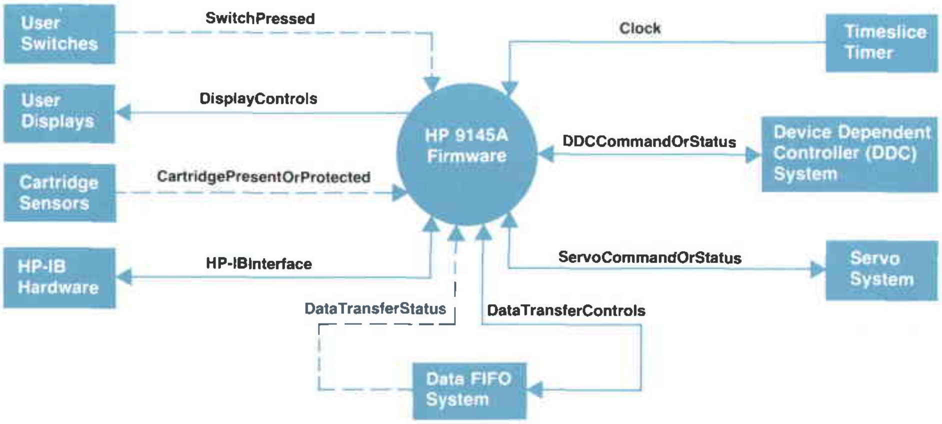


Fig. 3. *Context diagram for the HP 9145A firmware.*

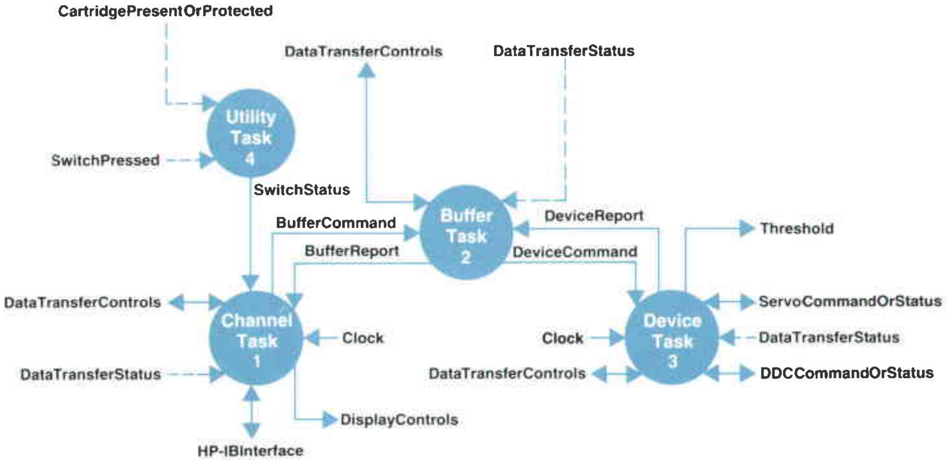


Fig. 4. *Data flow diagram for the HP 9145A firmware.*

completed. We could review a small amount of documentation every two or three weeks, instead of waiting for months to review a vast amount of information.

The tasks shown in Fig. 4 perform the following functions:

- Channel Task. The channel task controls the interface between the operator, the host computer system, and the HP 9145A firmware.
- Buffer Task. The buffer task controls the flow of data between the HP-IB interface, an internal data buffer, and the magnetic medium (tape).
- Device Task. The device task controls the read/write circuitry and the tape mechanism.
- Utility Task. The utility task contains functions used to perform switch and button debouncing and control the operation of the lights on the front panel of the drive.

The data and control flows in Fig. 4 represent the interprocess communication between the tasks. Interprocess communication in the HP 9145A firmware is implemented by a number of mailboxes used for holding messages or commands.

Each of the tasks has its own context diagram and its own set of external entities. Fig. 5 shows the context diagram for the device task. From these context diagrams detailed DFDs were generated for each task. Fig. 6 shows a portion of the DFD for the device task and Fig. 7 shows a portion of the DFD for the process Read/Write Operations which appears in Fig. 6. When the DFDs were leveled to primitive processes (processes that cannot be decomposed any further) process specifications were created like the one shown in Fig. 8 for the process ExecSingleShotRead which appears in Fig. 7. The number and complexity of the data and control flows increased as the design became more detailed. For example, the data flow diagram in Fig. 6 actually contains 24 control flows and 46 data flows between the processes. HP Teamwork/SA was used to create and maintain a central data dictionary data base for the whole firmware system. A data dictionary is a method for defining every data flow, control flow, and data store used in a system. The central data base allowed us to maintain data consistency between the various tasks. Because we were putting a great deal of effort into analysis, the data dictionaries became colossal. HP Teamwork/SA was really helpful here because it provides a checking facility that makes sure the data and control flows are consistent between levels of the system model. We ran the checking facility before each review so that the reviewers could concentrate on checking for correct functionality instead of spelling and consistency errors. Fig. 9 shows some of the data dictionary entries for the context diagram shown in Fig. 5.

A large proportion of the analysis of the firmware for the project involved the analysis of control. State transition diagrams served as a major part of this analysis. These diagrams allowed us to concentrate our control structures in a small number of places. To ensure manageability and readability most of our STDs consist of less than 20 states. An STD with more than 20 states becomes very confusing and hard to read. A portion of of an STD for the process ExecSingleShotRead from Fig. 7 is shown in Fig. 10.

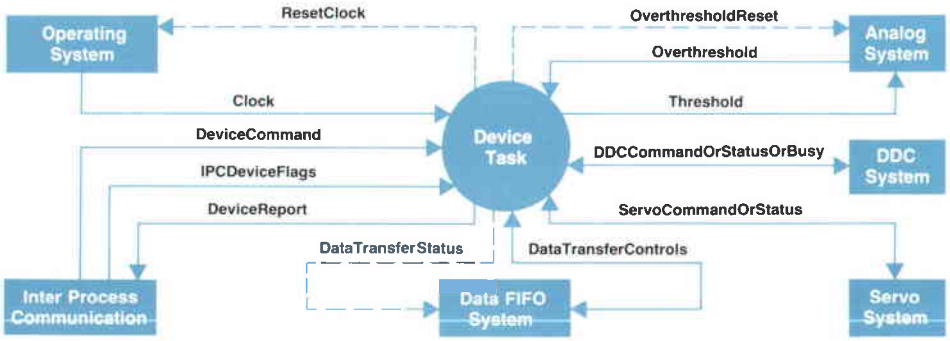


Fig. 5. *Device task context diagram.*

Lessons Learned

Five months had been allocated for the structured analysis portion of the firmware development and we managed to finish on time with two weeks to spare. Had we been more experienced with the methods and tools we would have finished sooner. Some of the observations and lessons we learned from using real-time structured analysis include:

- A lot of effort, maybe too much, was expended at the very top level of each task. One reason for this is that we had to do some informal lower level analysis to decide whether the top level solution produced was good enough. Having spent this effort early we found that when it came time to do formal lower level analysis the task was much easier.
- In some areas of the analysis we found that it was very difficult to produce a solution because of the amount of fan-in* to most processes associated with hardware dependent areas. We encountered some difficulty with using structured analysis for analyzing functionality associated with time-critical control of hardware. There are some techniques in the SA/SD real-time extensions^3 that can be used to analyze critical hardware/software timing situations. However, we did not get a chance to use these methods. In addition, we were trying to specify detailed algorithms using data flow diagrams, which is not the intention of the method.
- Too much effort was expended considering the implementation aspects of the system instead of defining the system functionality. This resulted in process specifications that tended to be trivial and not very useful.
- By the end of the structured analysis phase all of the engineers on the team thoroughly understood what their portion of the firmware was expected to do as well as what some of the rest of the firmware was doing.
- Because of the thorough analysis that had taken place a large number of anomalies were discovered and fixed in the original project specifications (external reference specifications).
- After structured analysis there were very few changes to the functionality of the product, except in areas where the characteristics of the mechanism or the tape were not fully understood.

Structured Design

In this phase of the development the data flow diagrams developed during the structured analysis phase were used to design the architecture and hierarchy of functions for the HP 9145A firmware. In most cases this process resulted in structure charts like the one shown in Fig. 11 for the process ExecSingleShotRead. In one task we found that there was no need to develop structure charts because the structured analysis produced such a flat structure, all based on

---

*Fan-in is defined as a large number of processes all making calls to one common process.

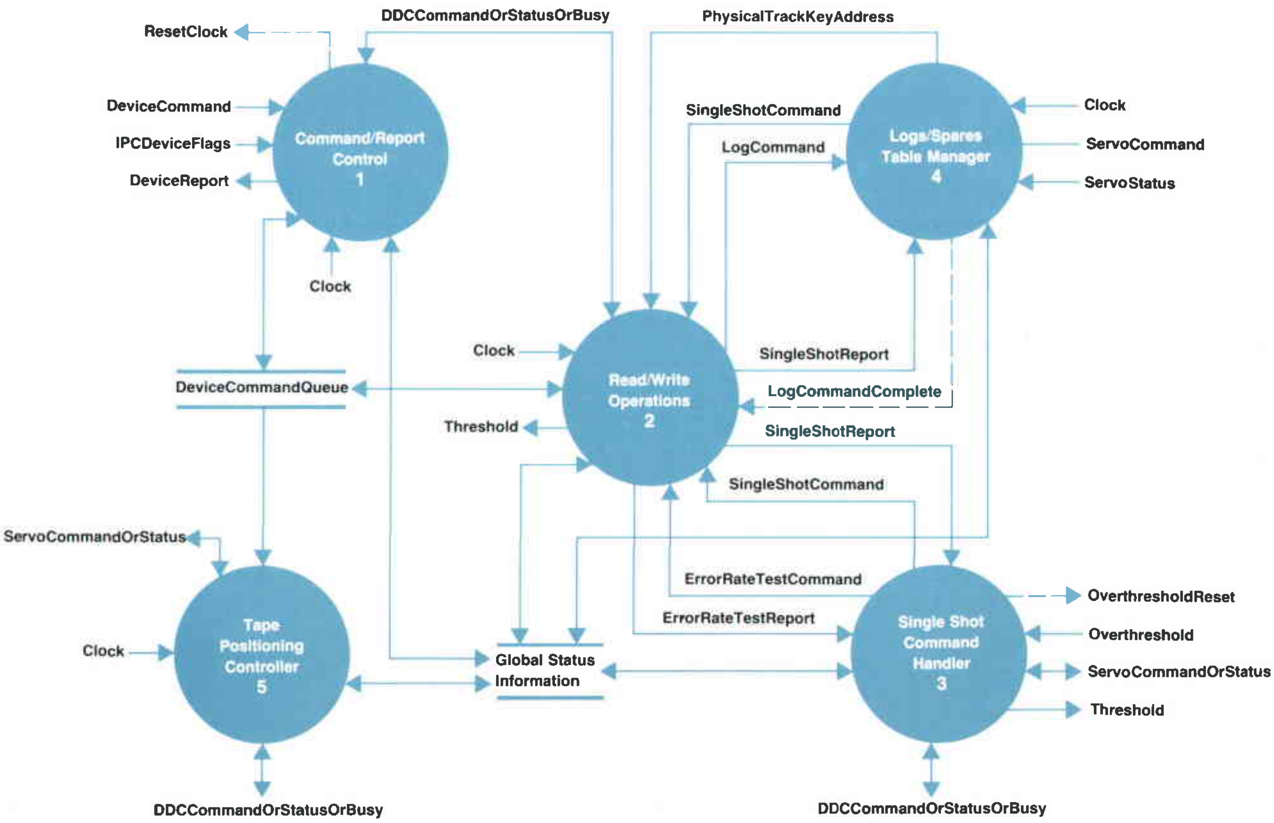


Fig. 6. *A portion of the detailed data flow diagram for the device task. There are actually 24 control flows and 46 data flows associated with this DFD. The number within each process bubble is used for identification and traceability.*

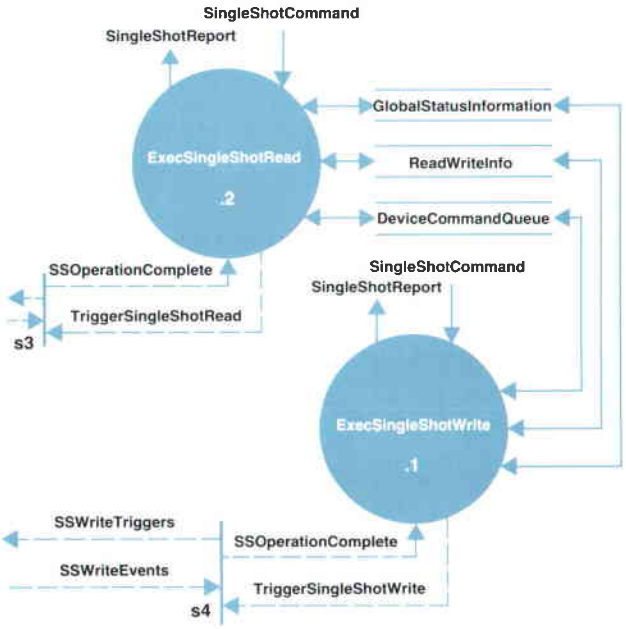


Fig. 7. *The data flow diagram for two of the processes associated with the process* **Read/Write Operations** *shown in Fig. 6.*

calls from a state machine, that we felt that the exercise would not yield any useful extra information.

The production of structure charts was limited only by the speed with which information could be put into HP Teamwork/SA. This was because there was so much detail from the structured analysis phase that the design came together with very little effort. Also, as in the structured analysis phase, the data dictionary proved to be invaluable and the HP Teamwork/SA checking facility helped to ensure that consistent designs were produced.

In parallel with producing structure charts, detailed module specifications were written for all the procedures. These module specifications were written so that they could be used as procedure headers for the code. Fig. 12 shows the module specification for the state machine **SSReadInitialize** shown in Fig. 10. In many instances part of the module specification was extracted directly from the process specifications written during the structured analysis phase. At this point of the project module specifications became the most important documentation. All changes that were made to the code were documented in the module specification for the affected function. Keeping the structured analysis documentation up to date was relatively tedious and time-consuming. However, towards the end of the testing phase this documentation was updated to match the final design of the firmware. This showed that even with an automated tool to enter a design, there must be a mechanism to update the design documentation automatically when changes are made during implementation.

```
Namc: 2.2;2

Title: ExecSingleShotRead

Input/Output:

TriggerSingleShotRead   : control_out   *control flow out*
SSOperationComplete     : control_in    *control flow in*
DeviceCommandQueue      : data_inout    *bidirectional data flow*
SingleShotCommand       : data_in       *data flow in*
SingleShotReport        : data_out      *data flow out*
GlobalStatusInformation: data_inout
GoodBlocksRequired      : data_out
ReadWriteInfo           : data_inout

Body:

Translate parameters into the appropriate command queue settings
and other stored information.

Trigger the single shot read state machine.

Wait for completion.

Compile status return value derived from Comfail and abort
conditions.

Reset Comfail and any other abort conditions generated during the
test.

Get more status from ReadWriteInfo (MaintenanceTrackOverflow and
TapeNotWrittenTo).

Gather status.

Return result.
```

Fig. 8. *The process specification for the process* **ExecSingleShotRead.**

Structured Testing

Structured testing encompasses the planning, design, documentation, and execution of tests. It is a method for managing the overall testing process and for providing traceability between the various types of test documenta-

```
Clock (data flow, cel) =
   *A continuous data flow indicating the number of ticks of the
    clock. *

ResetClock (control flow) =
   * Control from device tells the operating system *
   * to zero the millisecond timer.                 *

DDCCommandorStatusororBusy (data flow) =
   [ DDCCommand ¦ BusyStatusBit ¦ DDCReport ¦ ReportStatusBit]

DeviceCommand (data flow) =
   * The DeviceCommand splits into six groups of commands.    *
   * Each command in each group contains an opcode identifying *
   * the type of command, a subcode identifying the command    *
    * itself and a number (sometimes 0) of parameters.          *
    [ DiagnosticCommand ¦ TapeLoadCommand ¦ ReadBlockCommand ¦
      ResetDeviceCommand ¦ TapeUnloadCommand ¦ UtilityCommand ¦
      WriteBlockCommand ]

DeviceReport (data flow ) =
   *Report contains 10 16-bit words where the order of the words *
   *is significant. There is a seperate report for each class of *
   *command.                                                      *
    [ DiagnosticReport ¦ TapeLoadReport  ¦ ReadWriteReport ¦
      ResetReport  ¦ TapeUnloadReport  ¦ UtilityReport  ]

IPCDeviceFlags (data flow, del) =
   * Flag value - True or False.   *.

Threshhold (data flow, pel) =
   *Hardware *
   *8-bit numeric valus to adjust the effective gain of the read *
   *amplifier.                                                   *.

OverThresholdReset (control flow, del) =
   *Hardware *
   *Control to reset the overthreshold latch *

ServoCommand (data flow) =
    [NormalOperationCommand ¦ SpecialFunctionCommand ¦
     ServoTransparentCommand ¦ UtilityDiagnosticCommand]

Data Dictionary Notation

cel   : Continuous element. An attribute that indicates that the
item can take on a large number of values.

del   : Discrete element. An attribute that indicates that the item
can take on a finite number of values.

pel   : Primitive element. An item that cannot take on any other
values or be be further decomposed.

  =   : Is-Equivalent-To.

 [¦]  : Either-Or selection.

  +   : And (sequence selection).

 * *  : Comments.
```

Fig. 9. *A portion of the data dictionary definitions for the data and control flows for the process* **ExecSingleShotRead.**

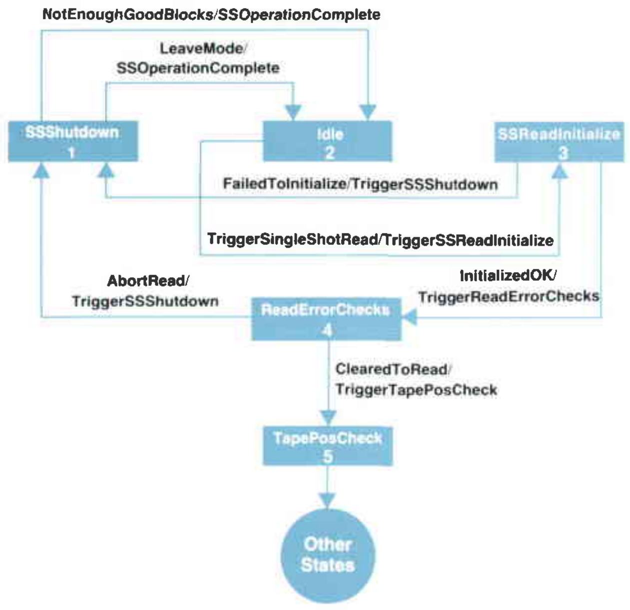


Fig. 10. *A portion of the state transition diagram for* ExecSingleShotRead.

tion. Structured testing tends to minimize the cost of product development by finding problems as early as possible before the cost of rework is high. An example of this might be when a test designer is writing a test and discovers that a specification is incomplete or ambiguous. If the specification defect is removed before coding takes place the cost of defect removal is low.

Our test strategy was based on traditional structural and functional test techniques[4] and well-coordinated test planning.[5] A hierarchy of test plans (Fig. 13) was produced for the whole product. Each sector of the system, mechanical, electronics, and firmware, had a similar hierarchy of test plans. These test plans were produced from the top down so that the overall firmware test plan was produced before the test plans of any individual tasks. Once the code had been written, the tests described in the test plans were executed starting from the bottom. By writing the test plans in parallel with designing the firmware we found a lot of problems that otherwise might have been overlooked.

To minimize the effort required during the testing phase an automatic test package was developed to run most of the tests. This test package accepted test scripts, exercised the product, checked for correct responses, and reported any anomalies to the test engineer. This enabled us to run tests during periods when there were no engineers available to monitor the tests.

All problems were recorded in a defect tracking system. This system was used to monitor the number of defects found, their severity, and the reason for each defect. It was also used to monitor the current status of each defect so that we could determine how many defects still had to be resolved. From this information we were able to monitor the progress of the project, and to tell whether the defect rate was under control.

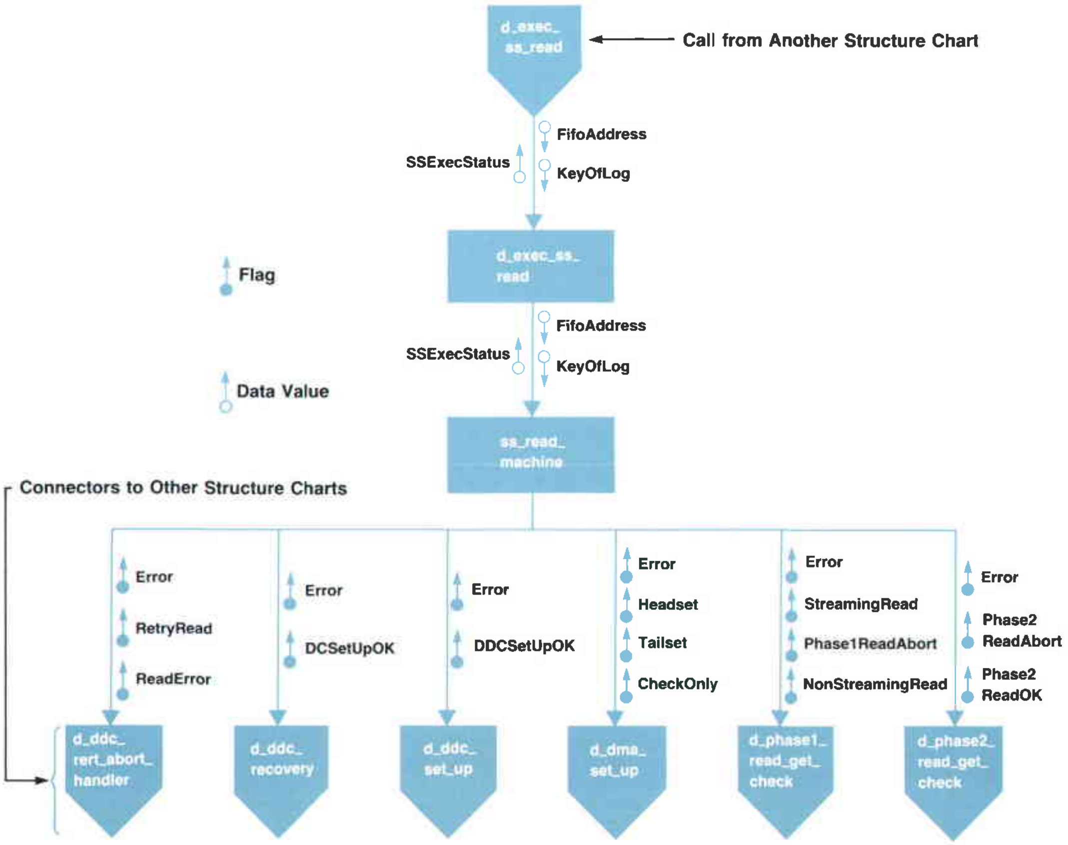


Fig. 11. *A portion of the structure chart for* ExecSingle ShotRead.

Results

As mentioned earlier, the firmware for this project was on the critical path from the beginning. As it turned out, our progress was so good that we were able to meet all major deadlines. Table I shows that our original estimates were very accurate and we achieved very respectable figures for our estimation quality factors (EQFs)* for each phase of the project.

Table I
Project Estimation Quality Factors (EQFs)

Activity	EQF	Estimated Elapsed Months	Actual Elapsed Months	Estimated Engineer Months	Actual Engineer Months
Analysis	9.0	4.5	5.0	20.0	22.5
Design	7.5	1.7	2.0	6.5	7.5
Coding	9.3	1.1	1.25	6.25	7.0
Functional Testing	11.5	4.2	4.6	21.0	23.0
System Integration	5.0	4.0	5.0	12.0	15.0
Total Project	8.1	15.5	17.85	65.75	75.0

During the analysis phase we defined over 420 processes on the data flow diagrams which resulted in about 570 procedures in the final product. The final code consisted of 24 KNCSS (thousand lines of noncomment source statements), and 123 kilobytes of object code.

Defects were tracked and a chart maintained to show the cumulative number of defects detected as a function of elapsed time. A code path monitor, which kept a count of the number of code statements tested, was run while the regression test package was being run. When the total test package was run, 85% of the statements were being exercised. The code path monitor enabled us to verify that 100% of the most critical areas of the code were being exercised. These figures do not take into account the extra code coverage that individual engineers achieved during their module testing activities. Our expectation at the outset of the project was that we would achieve 70% code coverage. Fig. 14 shows the cumulative number of defects found and the known code coverage, and compares the actual

```
/**************************************************************/
/* Module  Name : d_ss_read_initialise        File : k_smc_init */
/* Function     : Set up the head conmand for a single shot    */
/*                read from tape. Check the DDC to make sure   */
/*                it is working.                               */
/**************************************************************/
/*                                                             */
/* Parameters   : None                                         */
/*                                                             */
/**************************************************************/
/*                                                             */
/* Globals :                                                   */
/*                                                             */
/* Global  Name             I/O Status          Type           */
/* -----------              ----------          ----           */
/*                                                             */
/* d_report_record            write        device_report_type */
/* d_headcom                  write        command_record      */
/*                                                             */
/**************************************************************/
/*                                                             */
/* Function Result:                                            */
/*                                                             */
/* 0 - SSReadInitOK                                            */
/* 1 - FailedToInitSSRead                                      */
/*                                                             */
/**************************************************************/
/*                                                             */
/* Process :                                                   */
/*                                                             */
/*  Use  d_ss_initialise to do most of the initialisation.     */
/*  If this succeeds,  then                                    */
/*     d_headcom->command_status.read_flag = TRUE              */
/*     d_headcom->comnand_status.write_flag = FALSE            */
/*     Set the mode for ddc head select according to tape type. */
/*     For old HC tapes, reads should use the write heads,     */
/*     otherwise use the  read heads.                          */
/*     RETURN  InitialisedOK.                                  */
/*  otherwise                                                  */
/*  set d_report_record.device_status.comfail = TRUE           */
/*  return FailedTo Initialise.                                */
/*                                                             */
/**************************************************************/
/*                                                             */
/*  Notes:                                                     */
/*                                                             */
/*                                                             */
/**************************************************************/
/*                                                             */
/*  Author : Kevin Jones                    Date : 5 June 1987 */
/*                                                             */
/*  Modification History                                       */
/*  --------------------                                       */
/*  Modifier              Version         Date      Reason     */
/*                                                             */
/**************************************************************/
```

Fig. 12. *One of the module specifications for the state transition diagram shown in Fig. 10.*

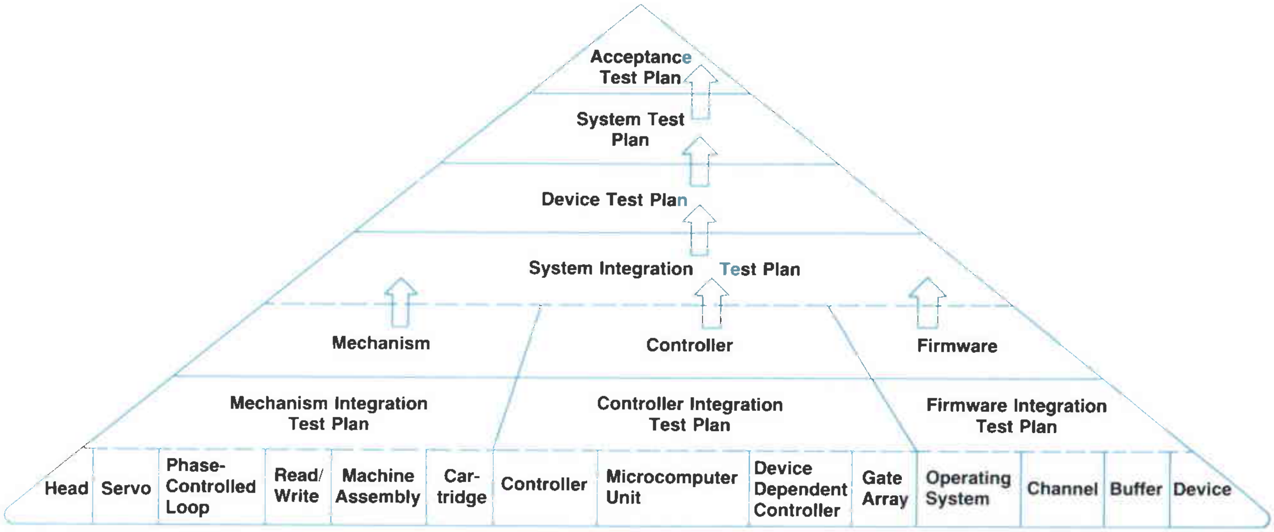


Fig. 13. *Hierarchy of test plans.*

---

*EQF gives the reciprocal of the average discrepancy between the estimated and the actual duration of a phase. An EQF of 8 is considered to be good for software estimates. See reference 6 for more information about EQF.

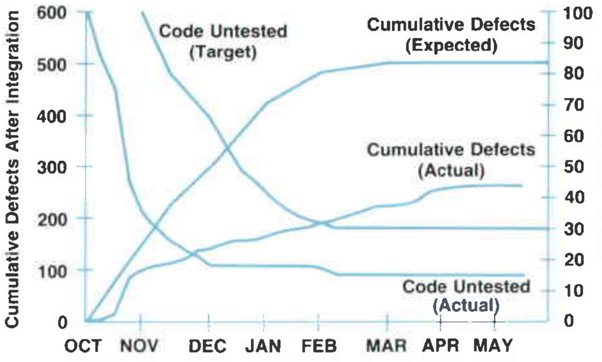


Fig. 14. *Cumulative defect and code coverage.*

figures against the expected figures. This data illustrates the completeness of testing performed.

Conclusion

Structured methods really are appropriate for the development of firmware on major projects. The mistakes that we made were mainly caused by our inexperience with the methods and tools. Access to an experienced practitioner as a consultant or as a member of the team would have eliminated many of our problems. We carried out these firmware development process changes to meet the needs of a particular product development. Our challenge now is to continue to improve our firmware development process and extend what we have learned to future projects.

Acknowledgments

The authors would like to acknowledge the contributions made by Kevin Jones, who worked on the development of the low-level device controller firmware and whose approach to firmware design enabled us to identify the problems involved in using structured methods on real-time firmware, and Ken O'Neill, who developed the automatic test package that enabled us to test the firmware comprehensively and quickly.

References

1. T. DeMarco, *Controlling Software Projects*, Yourdon Press, 1982.
2. P.T. Ward and S.J. Mellor, *Structured Development for Real-Time Systems*, Yourdon Press, 1986.
3. D.J. Hatley and I. A. Pirbhai, *Strategies for Real-Time System Specification*, Dorset House Publishing, 1987.
4. G. J. Myers, *The Art of Software Testing*, John Wiley & Sons, 1979.
5. W. C. Hetzel, *The Complete Guide To Software Testing*, QED Information Sciences, 1984.
6. R. M. Levitt, "Process Measures to Improve R&D Scheduling Accuracy," *Hewlett-Packard Journal*, Vol. 39, no. 2, April 1988, pp. 61-65.