OPTICAL PUBLISHING

by

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ABSTRACT

The dissemination of information has evolved from word-of-mouth through the printing press to the electronic communications systems of today. Although electronic media make available vast quantities of data, such systems lack the ability to present information in a personalized and useful way. Interactive computer environments in conjunction with rich information resources are instrumental in providing meaningful instruction.

The optical videodisc offers storage capabilities to support a local computer system with visual, auditory and textual information as well as to provide structural and programatic resources for interactive access. This thesis describes the role of the videodisc in information publishing and reports on the development of equipment for retrieving digital data from the disc.

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# Table of Contents

**Abstract** ........................................................................ 2

**Table of Contents** .......................................................... 3

1.0 Publishing ................................................................. 4

1.1 Electronic Publishing .................................................. 4

1.2 Interaction through Computer Systems ......................... 5

1.3 The Digitally Augmented Videodisc .............................. 7

1.4 Characteristics of Videodisc Publishing ......................... 8

1.5 The Movie-Manual .................................................... 10

1.6 Optical Storage ......................................................... 12

2.0 Digital Data on Optical Videodiscs ............................... 14

2.1 Modulation: Bits into Video ........................................ 17

2.2 Error Correction ...................................................... 20

3.0 Data Encoding and Decoding Techniques ....................... 26

3.1 An In-House Standard ............................................... 26

3.2 Decoder Design ....................................................... 28

3.3 Digital Audio Discs .................................................. 40

3.4 A Hypothetical Digital Disc ........................................ 43

4.0 Conclusion .............................................................. 44

Acknowledgments .......................................................... 45

Bibliography ..................................................................... 46
1.0 PUBLISHING

In most instances, the best means of communicating ideas between people is to do so in person. As the desire for people to communicate to a wide audience grew, such individualized attention became impossible. The printing press facilitated the distribution of information to the masses. Publishing today rests primarily on the printed page, through which text and pictures are communicated. Other media include radio, television, and film. Information in these forms are interpretable directly with more emphasis on content than access mechanics.

As the amount of information increases, our ability to access and process it in a useful way becomes more difficult. The electronics industry offers new modes for communication with the potential for simplifying understanding of growing information bases. Ideally, the vehicle for communication should be as effective as interpersonal interactions.

1.1 ELECTRONIC PUBLISHING

Electronic publishing is the distribution of information electronically rather than as hardcopy. Examples of this are teletext and videotex. Larger data bases than these are supported by the Lexis on-line information system through which magazine articles, entries in the Federal Register, the Encyclopedia Britannica and other texts may be requested via phone line. Subscribers have fast access to a vast collection of current
publications.

A more powerful aspect of having data in electronic form is that it can be indexed and accessed in sophisticated ways. The current demand for this is evident in the success of services like Dialog and Lexis. Not only is text accumulated for transmission, but is also indexed by keywords, date of publication, author and a variety of other attributes. A subscriber can specify areas of interest and other requirements such as year published and depth of presentation. The response is a list of references satisfying those criteria. This is far more complete and efficient than a manual search through the card catalogs of the local libraries and indexes of pertinent journals and periodicals.

1.2 INTERACTION THROUGH COMPUTER SYSTEMS

The lesson here is that although electronic media offer high densities, lower costs, and faster transmission from place to place of information, the real breakthrough is the way in which people will get at it. With the vast amounts of data, video, text, and sound being generated daily, the computer becomes the mediator between ourselves and the information resources. Current examples of electronic information systems vary in the quantity of those resources and in the sophistication of interaction.

The Dialog retrieval system must be able to draw from a large percentage of all current publications in order to be useful. Such data bases are accessed on-line, via a
computer terminal and modem, to the host computer. Charges include not only those from the vendor, but also the telephone company. The only information one can receive in this way is digital data, typically text, and maybe pictures at a very slow rate. An alternative to on-line access is to buy a copy of the data and use it locally.

Shoppers can "thumb" through a videodisc version of the Sears catalog in many stores. The catalog has a rich visual data base but rudimentary controls. A microprocessor internal to the player receives customer input from a keypad and controls the disc, without the need for any external communications.

On-line searches of patents is a popular feature offered by BRS and Lockheed but poses an interesting problem. Many patents have associated figures or drawings. The transmission of digitized pictures would require a local frame buffer for image display and lots of time on the phone. The solution, offered as Patsearch, was to master an optical video disc with still images to augment the central text data base. The text of a desired patent is transmitted to the researcher as well as the frame number(s) of related images on the disc if any. BRS's Medical Information Services operates in a similar fashion.

Perhaps the most innovative use of a videodisc data base has been the Movie Map project at MIT [9]. The videodisc contains movie footage of driving every street and every turn in Aspen. This was performed for both front and side views during both fall and winter. In addition,
still images of all buildings and slide tours of the more interesting ones are included. By searching to and playing various sequences in order, the viewer can drive around town. The computer again acts as the mediator by accepting instructions such as "turn left" and by then playing the proper sections of the disc. The Movie Map shows how dense image storage combined with computer interaction can give rise to unprecedented approaches to publication display. A map can become a visit; an experience rather than an artificial representation.

Information in various forms can be integrated more completely into the storage medium. A book can have index tabs built in to help you access it. Similarly the video, audio, text and digital data can be merged in an electronic medium.

1.3 THE DIGITALLY AUGMENTED VIDEODISC

The digitally augmented videodisc is a research project that exploits the digital data storage potential of a dense visual medium, the optical videodisc. Accepting the premise that the potential virtues of electronic publishing are (1) exploitation of alternative storage and delivery methods and (2) interactivity during information access, the challenge of this research is to merge both features in a single, readily usable medium. Equal attention to both aspects is often overlooked. The videodisc is optimized for movies and pays lip service to interaction by the inclusion of a microprocessor. The
system design assumes that the visual richness can obviate the need for an equally rich data base and computing environment. Similarly data base retrieval systems incorporate computerized access to data but by and large present static text only.

In order to experiment with such a unified medium, techniques for storing digital information on the videodisc were developed. The research included the evaluation of test discs, the establishment of a storage format and the design of hardware for data recovery. Section 2 gives a description of the issues involved in implementing this and Section 3 illustrates the system developed at this laboratory. Briefly, this scheme allows eight thousand bytes (or characters) to be encoded in each frame. If all 54,000 frames were used for data, then a side would contain 432 million bytes. The frames on the disc may of course be a mixture of data and images. Data can also be encoded in an image frame outside of the visible picture area. In this format, data associated with images will be available to the computer as needed.

A reader station is minimally a videodisc player, a data decoder box to recover data from the video, a monitor and a small computer. The system may also include a graphics frame buffer, a touch sensitive digitizing screen (TSD), and hard copy output capability.

1.4 CHARACTERISTICS OF VIDEODISC PUBLISHING

What types of applications lend themselves to the
videodisc as the distribution medium?

Not Time Critical: Although videodiscs can be replicated at a low cost, they are not writable. If a new diner were to open in Aspen, the Movie Map would not reflect that until the next edition or the disc. In situations where waiting for the next edition is not acceptable, then other paths must be sought including a return to on-line access.

Archiving: On the other hand, the read-only quality of the disc may be a virtue. Many institutions archive data at an ever growing rate. The videodisc may prove to be a medium which is both dense and stable over time.

Frequent and repeated access: The fixed cost of the disc system can compare favorably with the incremental costs of remote access, when the data use is high. A dictionary is a good example.

Isolated Locations: Again, if communication to a central facility is very costly, local storage is a solution. This includes mobile systems. The use of videodiscs to provide terrain data in a cruise missile guidance system was proposed by Ormsby and Long [21].

Privacy: Private on-line systems can attempt to protect themselves from unauthorized use by requiring passwords and codes. But if a password were to fall into the wrong hands, information could be obtained without the knowledge of the owner. Local, personal access is not amenable to monitoring or unauthorized access. Discs with data properly encrypted could keep the information out of
the communications network, forcing the electronic thief to resort to more drastic measures.

Repertoire: The alternatives to the videodisc sacrifice variety, quality and/or ease of use.

Possibilities for publishing on optical videodiscs include component data manuals like the widely used IC Master for electronic engineers, monthly real estate listings with pictures, engineering drawings and data for distribution to field service personnel, five years of stock market data for trend analysis, and an encyclopedia. The use of the disc for simple digital data base distribution as part of a larger computer system has it's place. But most exciting is the potential for the combination of video, audio and data into a coherent unit, containing not only text and images, but an underlying structure that associates and cross references these. The result is a book which presents the information contained therein under the reader's direction.

1.5 THE MOVIE-MANUAL

In order to investigate the possibilities for data storage on optical videodiscs equipment was constructed for the pre-mastering and later playback of data on the disc [2, 26]. The research environment is a project entitled the Movie-Manual [1,10]. In the manual, a videodisc contains both the text and images that completely describe a knowledge base. The particular one used for development is that of an automobile automatic transmission.
The disc contains a set of primatives, or objects, that are assembled into "pages" as they are used. Text and images from these pages are displayed on a TV screen. Constraints derived from the user interaction dictate what particular representational modes and intellectual breadth compose a description. Since the primatives are generally less than one page in extent, interaction within the page is the norm. Thus the electronic manual is not merely a user controllable sequence of pre-composed video screens. Each element on the screen can change independently. Review of a topic may also include a new illustration. A dictionary definition can replace a slide. This variably encourages activity during reading. The user "touches" text and pictures to explore, rather than simply to leave the page and go on. Fundamental to the project is that activity be continuous and productive.

To support this, the storage medium must be rich visually and also must contain the data base. Both are dense. Further, they overlap. Touching a wheel puller on the screen will cause the system to data contained in that frame. Depending on the context, the gesture may be interpreted as a request for a description of the tool and the objects describing how to use a wheel puller is then referenced. The data format was designed to support such frames of mixed visual and digital information for inclusion in the next Movie-Manual disc.

The video display is formatted with text in various fonts and can include quarter or full frame sized images.
from the video disc as desired. The disc, then, represents a flexible book which the reader assembles on the fly. In addition, a small amount of auxiliary writable storage enables the reader to create new associations between objects and so create new pages and chapters.

1.6 OPTICAL STORAGE

Most of the work currently being done under the title of optical storage is for Direct Read After Write systems. These DRAW storage devices are being developed to replace magnetic storage, both disk and tape. Presently available DRAW systems are non-erasable, i.e. write-once. As such, they find applications in the archiving of transactions, records and documents. Some examples of DRAW systems are the Xerox system in use at the Library of Congress card catalog and the Philips Megadoc storage system for document storage in an office automation system [6]. Toshiba now offers a similar system and there are about a dozen other ongoing efforts. The driving force behind these products is their low cost per bit of storage. They view optical storage as a step in the evolution of density in computer secondary storage.

Matsushita makes a write-once optical videodisc for storage and retrieval of still images. It is a prototype directed at the assembly of large, updatable picture files.

The videodisc differs in that it is read only. It is equally dense. A master video tape is prepared, and from that multiple copies can be produced at low cost. The
video signal is analog, but digital information can be imbedded within that format, as in the cases of Teletext and Closed Captions and as suggested by Kenney [7,17].

Although the two media use similar optics, data recovery techniques and materials (plastics), their applications are quite different. DRAW uses emphasize density and fast data transfer without the need for update. Typically these systems are online for reading and writing (i.e. transactions, records, landsat). Replication finds its place in situations where the data base is large, static and relatively time insensitive. The research work described herein includes the development of equipment to master discs with both video and data for later display and/or computer retrieval. We will also examine a recent addition to the replicated disc family, the optical audio disc.
2.0 DIGITAL DATA ON OPTICAL VIDEODISCS

In any storage system, the issues of modulation and error correction are fundamental. These issues will be discussed in the context of the videodisc, and will extend to the audio disc as well. First is a description of the basic videodisc.

The optical videodisc format was established in 1974 through an agreement between MCA and Philips. A video signal to be mastered is first Frequency Modulated (FM) and then limited to a square wave. The information is then contained in the size of the spacings between transitions. This signal is used to control a laser, exposing micron sized areas on a glass master disc coated with photoresist. The master disc is developed and metalized to form a master. From this, plastic replicas are made through one of a variety of processes. The relief side of the plastic disc is then aluminized. Two such discs are assembled back to back, with the relief sides in the middle. When the disc is played, a laser beam is reflected through the disc surface onto micron sized pits within. The beam reflected back will vary in intensity recovering the original FM signal. The demodulated signal is the video output. There are two mastering formats. Constant Linear Velocity (CLV) offers one hour of playing time on a side. Constant Angular Velocity (CAV) discs can store only one half hour of video, but allow the disc player to search to any given frame, play a frame in still mode, play backwards and play slow. These features have made the videodisc a useful computer.
peripheral.

Given the existing videodisc mastering facilities and commercially available players, the problem of inclusion of data on the disc is complicated. The players use the synchronization information in the video signal to establish the correct rotational speed of the disc. The data must therefore not interfere with player operation and be contained in the normal picture portion of the signal. Looked at another way, the portions of the signal that are not used for synchronization can contain user information, either video or digital.

In order to achieve optimal density and reliability, it is tempting to modulate the laser at the optical lathe with either video (as FM) or data (in some other scheme) with the provision that the sync signal appears on the disc in the correct place. When video information is required, the lathe operates as before. But for those lines during which digital data is to be inserted, the data could bypass the videotape and FM stages of mastering. This poses a number of problems. It requires data modulation hardware to be at the mastering facility, and the mastering station itself to be somewhat modified.

Barring problems at the mastering stage, a disc mastered in such a way will necessitate modification to the player in order to extract the signal directly from the optical reader, before it has been demodulated. Further, certain data patterns when send to the FM demodulator may appear to the player as sync information and cause it to
malfuction.

For the purposes of our research, this scheme would also have committed us to one disc manufacturer and prohibited the ability to make comparisons between different replication techniques. Since applications of the disc are growing, incorporating a mastering station into the research plan is unfeasible. Also, quality and technique vary widely as manufacturers evolve the process.

It would also seem that to take advantage of economies of scale, the data recovery hardware should be a separate component, receiving standard NTSC video from a non-modified, commercially available player. The signal supplied to mastering must likewise be a standard NTSC video tape, where data is encoded in such a way as to stay within the boundaries of NTSC.

By making this further constraint, we can take advantage of various commercial equipment. An author of an optical videodisc can prepare a videotape that contains both video and data, the data being modulated into video through the use of in-house modulation hardware. The pre-mastering or authoring is akin to the preparation done by a publisher before submitting a book for printing, combining pictures with text and an index. Video switching, mixing and editing equipment is readily available to perform the layout of the disc.

The problem of storing data on the disc is now reduced to storing data in an NTSC signal. The pre-mastering hardware must convert computer data into the NTSC format.
Once in NTSC, the signal is submitted on video tape to the mastering facility where it is FM'ed, recorded onto the glass master, replicated onto plastic, delivered to the reader, read back as FM, FM demodulated to NTSC, and either displayed or routed to a digital data decoder where the NTSC is demodulated back to the bits. Errors are bound to occur in such a signal chain and methods of increasing the reliability of data must be employed. Hence, for any storage system, a modulation and error correction scheme must be chosen in such a way as to optimize the trade-off between data reliability, storage capacity and cost.

2.1 MODULATION: BITS INTO VIDEO

Modulation is the conversion of data from one electronic form into another. Figure 1 represents one line of NTSC video. The active picture time is available for video or data. The color burst is a 3.58 MHz sine wave used as a phase reference for color information within the video signal.

Figure 2a shows three examples of modulation techniques. In NRZ, a high level denotes "1" and low denotes "0". In BiPhase, a transition during a bit interval denotes a "1" and there is always a transition between bits. In Delay or Miller Modulation, a transition during a bit interval also indicates a "1" and transitions appear between consecutive "0"'s. When the data is demodulated, the circuity must be able to derive the bit clock in order to determine where the bit intervals are in
relation to the signal. The latter two techniques are self-clocking, in that they provide a way to extract that bit clock as well as the data from the signal. NRZ requires that the clock be recovered in some other fashion. The most convenient clock available is the color burst mentioned above. Data decoder circuitry can lock to this reference using the same components found in a color television set. Since the self-clocking codes adjust the bit clock at each bit interval, they have the advantage of being tolerant of time base errors. In comparison, a clock
locked to color burst is corrected once per line. If the disc were changing speed dramatically while playing, the data may shift relative to the bit clock to the extent that errors will occur. Fortunately, because color is demodulated by comparing the burst phase with a color subcarrier in the video signal, most video equipment is designed to maintain time base stability. For the optical video disc, time base errors are held to under 10ns, small compared to the bit intervals we will be considering.

![Modulation Schemes and Spectra](a)

![Frequency Spectra](b)

Figure 2: Three Modulation Schemes and their Spectra

The bit interval is limited by the bandwidth of the NTSC signal, which is nominally 4.2 MHz. If we chose a bit interval of 144ns, or 7.16M bits/sec, then the resultant frequency spectra of each of these modulation schemes are as shown in figure 2b. The self-clocking codes both require higher bandwidth than NRZ. This is the price paid for self-clocking. Using either of these two schemes would
require a reduction in the bit rate.

Another form of non-self-clocking modulation is multi-level NRZ. Rather than one of two levels representing one bit, one of four levels can represent two bits. Each sample, or symbol, can represent \( n \) bits by assuming one of \( 2^n \) levels. The limit here is the signal to noise ratio of the medium. Assume that for one bit, the difference in signal level between "0" and "1" to be 1 unit. For 2 bits, there is 1/3 unit between each of four levels. Similarly, eight levels are separated by 1/7 unit or more generally \( 2^n \) levels are separated by \( 1/(2^n-1) \) units. The margin between adjacent bits goes down approximately as the square of the number of bits per symbol.

Not only must bit intervals be accurately clocked and data recovered, but the framing of bit strings must determined. In the context of video, where in each line is the first bit? Two methods are common. The first is to define the start of data to be a fixed time after the sync pulse for that line. A problem arises if some video equipment incorrectly re-inserts sync pulses and changes the relationship between data and sync. Although this is uncommon, it does occur. The second requires a preamble. This is found in many broadcast video data formats including teletext.

2.2 ERROR CORRECTION

Errors are caused by incorrect equalization and defects in the pre-mastering tape, master disc and
replicated disc. Error correction techniques can be applied that add parity data to user data before modulation onto the disc. When the disc is read, these additional bits allow errors to be detected and corrected. Once a modulation scheme has been determined, a test disc can be made and the raw data demodulated. Comparing this with the original data gives a description of the raw error characteristics of the system, including pre-master tape recording, mastering, replication and playback. Given these characteristics and the desired net user data reliability, an error correction code can be selected.

Error correcting codes are based on linear algebra. An (n,k) error correcting code is one that takes k data bits and generates an additional n-k parity bits. The result is an n bit code word which will be modulated onto the disc. The message bits are treated as coefficients of a polynomial, m(X).

\[
m = (m_0, m_1, m_2, \ldots, m_{k-1})
\]

\[
m(X) = m_0 + m_1X + m_2X^2 + \ldots + m_{k-1}X^{k-1}
\]

A particular code has a generator polynomial associated with it, g(X). Dividing \(X^{n-k}m(X)\) by g(X), we have

\[
x^{n-k}m(X) = q(X)g(X) + r(X)
\]

where q(X) and r(X) are the quotient and remainder
respectively. Since the degree of \( g(X) \) is \( n-k \), the degree of \( r(X) \) must be \( n-k-1 \) or less. Rearranging the above, we obtain

\[
c(X) = r(X) + x^{n-k}m(X) = q(X)g(X),
\]

\[
c = (r_0, r_1, r_2, \ldots, r_{n-k-1}, m_0, m_1, m_2, \ldots, m_{k-1}).
\]

This indicates that \( c(X) \) is a multiple of \( g(X) \) and has degree \( n-1 \) or less. \( c \) is the code word to be sent, and is a combination of the message word and additional check bits. The check bits are the remainder of dividing \( x^{n-k}m(X) \) by \( g(X) \).

An error correcting code can correct up to a certain number of errors, \( t \), in a received word. To determine the position of the errors, the syndrome of the received word must be determined. Suppose that \( v(X) \) was the received word.

\[
v(X) = c(X) + e(X)
\]

where \( e(X) \) is the error pattern. Since \( c(X) \) is a code polynomial, it must be a multiple of \( g(X) \),

\[
c(X) = q(X)g(X).
\]

From these, \( e(X) \) can be expressed as

\[
e(X) = (p(X)+m(X))g(X) + s(X).
\]
The syndrome of the received vector is the same as the syndrome of the error pattern. One simple way to apply this to correction is to use a lookup table, where every possible error pattern can be addressed by its syndrome. Other schemes exist for determining the error pattern of a received word such as error trapping-decoders (useful for Hamming codes) and majority-logic decoders.

The operations described above can be performed either in software or by digital circuitry. Shu Lin suggests many practical implementations [11]. Many complex correction schemes that would normally be expensive to implement with standard logic components can be realized in VLSI for a low cost. A notable example is the Sony CX-7935 error correction circuit developed for their consumer digital audio disc player [27].

If errors occur infrequently and as random, evenly distributed events, then a proper code can easily be selected that trades efficiency for reliability. Table 1 lists some error correcting codes and their relative user bit error rates. Note the differences in ratios between encoded and user bits. This is a measure of the code's efficiency.

One characteristic of the video disc is that errors tend to occur in bursts. Defects in the medium itself tend to affect many bits on the disc. If all the bits in a received word are corrupted, then there is little hope of reconstructing the original information. In order to overcome burst errors, the bits of a code word must be
distributed across the medium such that bursts of errors do not effect more bits in that code word than can be corrected by the code. The rearrangement of bits in this fashion is called interleaving.

<table>
<thead>
<tr>
<th>CODE NAME (N, K)</th>
<th>T</th>
<th>K/N</th>
<th>10^-2</th>
<th>10^-3</th>
<th>10^-4</th>
<th>10^-5</th>
<th>10^-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAMMING (22, 16)</td>
<td>1</td>
<td>72%</td>
<td>1.3x10^-3</td>
<td>1.4x10^-5</td>
<td>1.4x10^-7</td>
<td>1.4x10^-9</td>
<td>1.4x10^-11</td>
</tr>
<tr>
<td>REED-SOLOMON (21, 9)</td>
<td>2</td>
<td>43%</td>
<td>1.3x10^-4</td>
<td>1.4x10^-7</td>
<td>1.5x10^-10</td>
<td>1.5x10^-13</td>
<td>1.5x10^-16</td>
</tr>
<tr>
<td>BCH (15, 7)</td>
<td>2</td>
<td>47%</td>
<td>6.0x10^-5</td>
<td>6.4x10^-8</td>
<td>6.4x10^-11</td>
<td>6.4x10^-14</td>
<td>6.4x10^-17</td>
</tr>
<tr>
<td>BCH (15, 3)</td>
<td>3</td>
<td>20%</td>
<td>4.2x10^-6</td>
<td>4.5x10^-10</td>
<td>4.6x10^-14</td>
<td>4.6x10^-18</td>
<td>4.6x10^-21</td>
</tr>
<tr>
<td>BCH (31, 16)</td>
<td>3</td>
<td>52%</td>
<td>1.6x10^-5</td>
<td>1.9x10^-9</td>
<td>1.9x10^-13</td>
<td>1.9x10^-17</td>
<td>1.9x10^-21</td>
</tr>
<tr>
<td>GOLAY (23, 12)</td>
<td>3</td>
<td>52%</td>
<td>6.3x10^-6</td>
<td>7.3x10^-10</td>
<td>7.3x10^-14</td>
<td>7.3x10^-18</td>
<td>7.3x10^-22</td>
</tr>
</tbody>
</table>

Table 1: Error Rate per User Bit for Some Codes

Interleaving mixes the code word data around on the medium. From the code word's point of view, the medium and hence the burst errors are being distributed. If the order of interleaving, the distance between bits, is sufficient then the probability of an error occurring in one bit is independent of errors in the rest of the code word [11]. If the chance of a bit error is an independent event, then determining the probability of a combination of errors in a code word is straightforward.

Some codes can correct certain combinations of errors and detect others without being able to correct them. This is useful when detection can initiate a request for
retransmission as in computer networks. If the errors are permanent on the disc, then being able to detect them is of minimal value. The user had best call his publisher and ask for another copy. On the other hand, if the error were intermittent, e.g. marginal signal level, then re-reading would be another means of increasing data integrity. However, most videodisc errors are "pressed in" and are permanent. Such errors wherever they occur in the channel, during pre-mastering, mastering or replication, must be compensated for.

What level of data reliability is reasonable for optical publishing? Of course this depends on the application. Financial items such as catalog prices should be very reliable. Text on the other hand poses less stringent requirements. One stance may be to use maximal correction to cover all situations. Another might be to provide reasonable reliability for most applications and force more demanding applications to use yet another layer of correction implemented in system software.
3.0 DATA ENCODING AND DECODING TECHNIQUES

This section will describe in detail the techniques developed at the Architecture Machine for data storage on optical videodiscs. The disc authoring station, which converts user data into NTSC video for use in the pre-master tape, is documented by Steve Yelick in "The Authoring of Optical Videodiscs with Digital Data" [26].

This thesis introduces the data decoder and disc reading station.

Other similar systems are beginning to be developed in the commercial sector, and will be outlined. Finally, the digital audio disc (Compact Disc) and a hypothetical data only disc will be discussed.

3.1 AN IN-HOUSE STANDARD

Because of the ease of recovering sync and regenerated subcarrier through the use of integrated circuits made for television sets, these signals form the back bone of the demodulator. A bit clock derived from the subcarrier allows NRZ to be used as a modulation scheme at a bit rate of twice the subcarrier. For ease of design, one bit per sample was encoded. Raw data density is on the order of 7 gigabits. Based on this modulation technique, a disc was made and from this, the error rate was determined. 1000 frames of solid data, each containing 400 lines of 336 bits, were processed. The observed raw bit error rate is 3x10\(^{-4}\). First, we assume that sufficient interleaving can be done to reduce bit errors to independent, random events.
The digital data decoder uses the Extended Golay code (24, 12), which is the Golay (23,12) code with an additional parity bit. Although this additional parity bit does not directly aid correction, it facilitates ongoing assessment of disc reliability [19]. The resulting user bit error rate is $5.9 \times 10^{-12}$. Allowing for parity and framing bits, the disc has capacity for over 400 megabytes of data with an expected error once every 50 discs.

10 megabytes of data storage for software, text and cross referencing is sufficient for many interactive systems. The remainder of the disc contains video. This disc would have one expected error in every 2000 copies.

Now that the size and power of the correction code has been chosen, we return to interleaving. The largest blocks of continuous data with frequent errors, the burst error length, were 152 bits long. This corresponds to roughly one half of a line. An order of interleaving can be chosen such that the number of bits correctable by the ECC times the order of interleaving is large compared to the burst length. A value of 160 was chosen.

A packet is defined as 160, 24-bit code words arranged on 12 lines of video. The first line of a packet contains a 16-bit framing code, then the first bit of each of 160 code words followed by the second bit of each code word. The succeeding 11 lines contain the remaining data in a similar order. A packet is the minimum unit of disc real estate allotable to data. It is large enough to support a powerful error correction code and interleaving scheme.
while small enough to "hide" two packets at the bottom of a frame outside the visible TV save area at the bottom of the screen. Data is not encoded into the vertical blanking interval because some piece of video equipment may decide to blank it during authoring or pre-mastering.

3.2 DECODER DESIGN

The decoder is responsible for extracting data from a video signal and transferring it to a host computer. The computer must specify where the desired packets are in the frame by line number. The decoder responds with a request for data transfer when a packet has been decoded. Figure 3 is a block diagram of the decoder.

All memory sections are double buffered. Each section has a block of memory and address counters. Steering logic on the input and output sides of the buffer give write access to the preceding block in the data path and read access to the following block allowing data to be accessed asynchronously by adjacent sections.

A CPU specifies the location of packets in a frame through the Frame Descriptor Buffer (FDB). Each packet of 12 lines is identified by its starting line number and field, along with control flags for blanking and interrupt control. Pairs of bytes for each packet are written to the decoder, terminated by writing 255. Issuing a command to swap FDB's will take effect at the beginning of the next frame. After this, the CPU is free to prepare the next Frame Descriptor in anticipation of the next time the data
Figure 3: Decoder Block Diagram
format changes (e.g. from solid data to data mixed with video). The active Frame Descriptor is available to the Demodulator.

![Frame Descriptor Buffer Diagram]

**Figure 4: Frame Descriptor Buffer**

Video from a disc player, or any video source for that matter, is processed by the Video Front End. The section performs two functions. The first is to set a threshold level between video black and video white and supply a logic level to the Demodulator representing zeroes and ones based on the incoming video level. The second is to extract the synchronization signals and generate control lines for the Demodulator. The Genlock section from a
Panasonic WJ-4600A Special Effects Generator was used to lock onto the sync rate of the video and provided a stable set of sync signals as well a regenerated color subcarrier. The advantage of a Genlock circuit over a simple sync detector is its ability, as a phase locked loop, to compensate for sync errors due to dropouts on the disc. The 3.58 MHz subcarrier is then multiplied to generate the bit clock and demodulator system clock.

![Diagram](image)

**Figure 5: Video Front End**

The Demodulator begins each frame by reading two bytes from the FDB into control registers. The starting line number of this packet is compared to the current video line number until the start of the packet is detected. Serial
data is compared to the framing code, in anticipation of the start of data for that line. If, due to media errors, the framing code is not found, is it assumed to have appeared in the same place relative to sync tip as the last good framing code. 320 bits for each of 12 lines are written into the De-Interleaving Memory, after which the De-Interleaving Buffers are swapped and Data Ready is signaled to the Golay Error Corrector. The Golay circuit corrects a packet in under 12 line times, and hence will always be done before the next packet is ready.

![Diagram of Demodulator](image)

Figure 6: Demodulator

Each section of the De-Interleaving Memory is addressed by row and column, representing the code words and bit positions in them respectively. As the data is
being written by the Demodulator, the address counter for that section is counting in column major order. That is, the code word number is being incremented from 0 to 159 and then carries into the bit position counter. After the buffers have been swapped, the Golay Error Corrector counts data out in row major order. The bit position counts from 0 to 23 and carries into the code word counter. When the Golay Error Corrector has read a whole packet (e.g. when the code word counter carries), Data Ready is cleared and error correction stops.

**Figure 7: De-Interleaving Memory**
The Golay code is the only known multiple-error-correcting binary perfect code in its class. It encodes 12 message bits into 23 code bits and has the ability to correct up to 3 bit errors. An additional parity bit is included for future implementation of a Forward-Looking Error Corrector [19]. The Golay Error Corrector is based on an error-trapping decoder described by T. Kasami [5]. Our discussion of error correction above describes a class of codes known as linear codes. A subset of the linear codes are the cyclic codes, so called because any word which is a valid code word can be rotated cyclicly and will still be a valid code word. Assume the syndrome is s-bits long. An error-trapping circuit relies on being able to rotate the received word such that the errors are all in the first s bits. Then, if the code is properly chosen, the syndrome will be that error pattern. The Kasami scheme is a modified error-trapping decoder for the Golay code, and is described briefly here. The interested reader may find references to additional detail and theory in the bibliography [22,11].

The decoder shifts a received word into a 23-bit buffer and at the same time shifts the data through the syndrome register to compute the syndrome. The weight of a bit string is defined as the number of ones in it. If the weight of the syndrome is less than or equal to the number of bits that the code can correct, 3, then the error is in the first 11-bits of the received word and the error pattern is the syndrome. The syndrome and received word
are exclusive or'ed to correct the errors. The weight of s(X)+p1(X) is then determined, where

\[ p1(X) = X + X^2 + X^5 + X^6 + X^8 + X^9. \]

If this weight is 2 or less, then s(X)+p1(X) is the error pattern in the first 11-bits and the 18th bit is also in error. Failing this, the weight of s(X)+p2(X) is found, where

\[ p2(X) = p1(X) \cdot X. \]

If this weight is 2 or less, then the error pattern is s(X)+p2(X) with an additional error at the 17th bit.

The above tests are performed by table lookup. The syndrome is used as a ROM address, the output of which is three signals. FOUND indicates that one of the above three conditions has been satisfied and that the errors have been trapped. C0 and C1 are used as presets to register C, which acts to insert the polynomials p1(X) or p2(X) during correction as needed. If FOUND is false, then none of the above conditions were satisfied. The buffer register is rotated around one bit and the syndrome register is also clocked. Rotating the shift register computes the syndrome of the rotated buffer. This process is repeated, shifting, computing the syndrome and testing, until the error pattern is found. When FOUND is true, the buffer register is cyclically shifted 23 times, correcting errors in the
process. The buffer is then rotated back to its original position. The first 12-bits of the code are the corrected message bits. As the next received word is shifted in, the message bits are shifted out and written to the DMA Buffer. The decoder continues until the De-Interleaving Memory indicates that there is no more data.

Figure 8: Control Logic for Golay
Figure 9: Data Path and Control Sequences for Golay
Figures 8 and 9 illustrate the Golay Error Correction circuit. A finite state machine controls its operation. At each state of the FSM, one signal line determines what action should be taken and whether the sequencer should proceed to the next state. Branches override stepping forward. Those control lines which are marked with a star are derived from the output of the 4-to-16 de-multiplexor as shown in the FSM program as shown in Figure 9. After the last message word has been corrected, it is flushed out of the buffer register to the DMA Buffer. That packet is now ready for transfer to the host.

![DMA Buffer Diagram]  
**Figure 10:** DMA Buffer
When the DMA Buffer is told that it has received a complete packet, it swaps buffers and interrupts the processor, requesting a DMA transfer. The host has 12 line times or .76 milliseconds to transfer 240 bytes of data. Many small computers have DMA rates of three times this, and this number is likely to increase imposing less of a burden on bus traffic. If transfer of data from the Digital Data Decoder is done continuously into memory, then the applications program sees a "window" into the data on the disc.

In the cases where data at the bottom of a frame is used to describe the location of things within the image and also to connect this frame with other objects in the system, that data is ready for immediate access. The application may want to highlight and object within the image using a frame buffer. The location of the highlight would be refreshed each frame from the data in the window.

The real time capabilities of the decoder also facilitate fast access of large data or program segment from sequential frames.

Other commercial ventures have recently begun development of data storage schemes for optical videodiscs. This is an overview of some of the proposed systems. The specifications noted here are all preliminary.

LaserData: Bit clock locked to subcarrier frequency, two bits per sample. Error correction scheme selectable depending upon application. One gigabyte of raw storage
Matrox: Bit clock locked to subcarrier, eight bits per sample available for use in digitizing frames. Proposed one gigabyte per side. Error correction scheme being developed.

Access Unlimited: The Library Disc requires a modified player for reading. Proposed four gigabytes per side at a user hard error rate of $10^{-13}$.

3.3 DIGITAL AUDIO DISCS

For applications where video is not a requirement, the recently introduced optical audio disc may be more attractive. The optical audio disc, or Compact Disc, operates on many of the same principles as the videodisc. A glass master is made, and discs (made of Lexan) are replicated and metalized. They are presently single sided only. The disc rotates at Constant Linear Velocity for maximum density since no "still framing" is required. The audio information is stored differently than video on the videodisc. Audio is digitized into 16-bit samples at a rate of 44.1 KHz for each of two channels. This 1.4 megabit per second data stream is encoded onto the disc. A single disc contains one hour of stereo, or 635 megabytes of data. Modulation and error correction schemes are performed at the mastering station as the disc is mastered.

The CD standard [27] uses Eight-to-Fourteen Modulation (EFM) to encode bits into pits on the disc. That is, each eight bits of data after error encoding is translated into
a fourteen bit pattern, containing both data and timing information. To this, three additional bits are added for merging and low frequency suppression. This technique was developed to insure that the minimum feature size (the size of a pit or the space between pits) was not smaller than the capabilities of the medium and at the same time to make the maximum feature size small enough to generate an accurate clock.

Some outstanding work has been done towards developing an error correction scheme for the Compact Disc. An efficient error correcting system, called Cross Interleave Reed-Solomon Code or CIRC, enables a number of decoding strategies. The most ambitious of these was developed at Sony. The CX-7935 error correction circuit was implemented in LSI for inclusion in Sony's CD players [20]. It uses C1 and C2 Reed-Solomon correction and also receives information from the demodulator about dropouts. Given a conservative estimation of the symbol error rate to be $10^{-3}$, the Super Strategy achieves an error rate better than $10^{-16}$. A typical value of the symbol error rate at $10^{-4}$ yields a hard error rate of better than $10^{-21}$! Combining this with the low cost of consumer volume and the high density of .6 gigabytes, Compact Disc technology is sure to find a place in the computer industry both large and small.

The CD format does not immediately lend itself to computer applications. Because it was designed to play music, the consumer disc player's ability to search to particular place is limited to one of 99 "songs". There
are provisions for addressing much smaller segments and a professional player is being developed to support this. Access time is another issue. The disc's rotation speed must be adjusted as the read optics move in order to maintain a constant linear velocity. Finally, the disc manufacturers do not currently accept computer tapes for mastering.

Audio tapes may be submitted for mastering, but digital audio master tapes are also accepted. The Sony PCM-1610 [29] is used to convert analog audio to a video signal containing the digital audio information. This device is similar to the modulator one would have at the videodisc pre-mastering facility, in that it acquires user data, generates additional parity data for error correction, performs interleaving and modulates that data stream onto a video signal. The video output of the 1610 is recorded onto 3/4" tape for submission to the audio disc mastering plant.

Another 1610 at the mastering plant takes incoming video from a source tape and performs demodulation and error correction, correcting for errors due to tape dropouts and noise. The recovered PCM audio data is transmitted in digital form to the mastering hardware. Here, the CIRC and EFM schemes are performed and the resultant signal controls the mastering laser. The modulation and error correction methods used by the 1610 and by the CD are each selected to suit the medium.

The PCM-1610, then, should rightly come under the
discussion of digital data in the video domain. In contains the necessary encoding and decoding circuitry and also supports serial data in and out as well as audio and video. A 1610 combined with a computer could generate premaster tapes for either CD or videodiscs. In addition, the output of the 1610 could be transmitted via cable TV channels to a remote system, thus acting as a "video modem" for data communications.

3.4 A HYPOTHETICAL DIGITAL DISC

If there is a large demand for the publication of digital data bases for local access via computer, then a third format may yet arise. Foregoing the ability to access audio or video directly from the disc, the replicated optical data disc and reader could be optimised for reliability and access speed. A spiral track allows continuous data transfer, bother during mastering and playback. An interface compatible with winchester controllers would facilitate its introduction to the computer market, both large and small. Assume a disc size of 8 inches and a data density similar to the CD, keeping in mind that the disc would be have a constant rotational speed. The data disc could have a storage capacity of about 2 gigabytes at an error rate of better than $10^{-18}$. The manufacturers of replicated discs will first have to realize that data may be as high volume a market as movies and records.
4.0 CONCLUSION

The printing press was for a long time the sole means for widely and cheaply distributing text, images and data to people. Since then, other technologies such as broadcasting have developed. At the same time, computers have made possible new ways of accessing information, but the acquisition of large amounts of valuable data remained a problem. The optical media described here offer ways to distribute data that are competitive with telecommunications methods. The optical videodisc as a source of data, video and audio greatly enhances a local personal computer's ability to provide information for fruitful inquiry and interaction.
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