IN THE UNITED STATES DISTRICT COURT
FOR THE DISTRICT OF DELAWARE

U.S. PHILIPS CORPORATION, Plaintiff, v. EASTMAN KODAK COMPANY, Defendant.	)	Civil Action No. 06-251-GMS

NOTICE OF SERVICE OF SUBPOENA

TO: COUNSEL OF RECORD ON ATTACHED SERVICE LIST

PLEASE TAKE NOTICE that pursuant to Rule 45 of the Federal Rules of Civil Procedure, defendant Eastman Kodak Company provides notice of service of subpoena on the following persons or entities as indicated on July 18, 2007:

1. Xerox Corporation. A copy of the subpoena is attached hereto as Exhibit A.

Dated: July 19, 2007

/s/ Kristen Healey Cramer

Francis DiGiovanni (#3189)
Kristen Healey Cramer (#4512)
CONNOLLY BOVE LODGE & HUTZ LLP
The Nemours Building
1007 N. Orange Street
Wilmington, DE 19899
Phone (302) 658-9141
e-mail: kcramer@cblh.com

John Allcock
Sean C. Cunningham
Tim Lohse
John D. Kinton
Jesse Hindman
DLA Piper US LLP
401 B Street, Suite 1700
San Diego, CA 92101-4297
Phone (619) 699-2700

Attorneys for Defendant/Counterclaimant
Eastman Kodak Company

CERTIFICATE OF SERVICE

I, Kristen H. Cramer, hereby certify that on July 19, 2007, I caused to be electronically filed a true and correct copy of the foregoing document with the Clerk of the Court using CM/ECF, which will send notification that such filing is available for viewing and downloading to registered counsel of record via e-mail.

I hereby further certify that on July 19, 2007, I caused a copy of the foregoing document to be served on the following counsel of record by the manner so indicated:

BY E-MAIL AND HAND DELIVERY:
Steven J. Balick
John G. Day
Tiffany Geyer Lydon
222 Delaware Avenue, 17th Floor
P.O. Box 1150
Wilmington, DE 19899

BY E-MAIL AND U.S. MAIL:
Thomas W. Winland
Steven M. Anzalone
Frank A. DeCosta, III
Joyce Craig-Rient
Finnegan Henderson Farabow Garrett and Dunner LLP
901 New York Avenue, NW
Washington, DC 20001

Kristen Healey Cramer
Kristen Healey Cramer (#4512)

EXHIBIT A

Issued by the

UNITED STATES DISTRICT COURT

DISTRICT OF CONNECTICUT (BRIDGEPORT)

U.S. PHILIPS CORPORATION

Plaintiff
V.
EASTMAN KODAK COMPANY

Defendant.

SUBPOENA IN A CIVIL CASE

Case Number:[1] Civil Action No. 06-00251
USDC, District of Delaware

TO: Xerox Corporation
800 Long Ridge Road
Stamford, CT 06904
203.968.3000

Service of Process on:
The Prentice-Hall Corporation System, Inc.
Attn: Service of Process
2730 Gateway Oaks Drive
Suite 100
Sacramento, CA 95833

☐ YOU ARE COMMANDED to appear in the United States District court at the place, date, and time specified below to testify in the above case.

PLACE OF TESTIMONY	COURTROOM
	DATE AND TIME

☒ YOU ARE COMMANDED to appear at the place, date, and time specified below to testify at the taking of a deposition in the above case. See Attachment A for deposition topics.

PLACE OF DEPOSITION	DATE AND TIME
DLA Piper US LLP 1251 Avenue of the Americas, 27th Floor New York, NY 10020-1104 212.335.4500	August 16, 2007 at 9:00 a.m.

☒ YOU ARE COMMANDED to produce and permit inspection and copying of the following documents or objects at the place, date, and time specified below (list documents or objects):

See Attachment A

PLACE	DATE AND TIME
DLA Piper US LLP 401 B Street, Suite 1700 San Diego, CA 92101 619.699.2700	August 9, 2007

☐ YOU ARE COMMANDED to permit inspection of the following premises at the date and time specified below.

PREMISES	DATE AND TIME

PREMISES	DATE AND TIME

Any organization not a party to this suit that is subpoenaed for the taking of a deposition shall designate one or more officers, directors, or managing agents, or other persons who consent to testify on its behalf, and may set forth, for each person designated, the matters on which the person will testify. Federal Rules of Civil Procedure, 30(b)(6).

ISSUING OFFICER'S SIGNATURE AND TITLE (INDICATE IF ATTORNEY FOR PLAINTIFF OR DEFENDANT)	DATE
Attorney for Defendant Eastman Kodak Company Kristen Healey Cramer	July 18, 2007

ISSUING OFFICER'S NAME, ADDRESS AND PHONE NUMBER

Kristen Healey Cramer (DE Bar No. 4512)
Connolly Bove Lodge & Hutz LLP
1007 North Orange Street
PO Box 2207
Wilmington, DE 19899
302.888.6317

(See Rule 45, Federal Rules of Civil Procedure, Subdivisions (c), (d), and (e), on next page)

[1] If action is pending in district other than district of issuance, state district under case number.

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PROOF OF SERVICE

DATE PLACE

SERVED

SERVED ON (PRINT NAME) MANNER OF SERVICE

SERVED BY (PRINT NAME) TITLE

DECLARATION OF SERVER

I declare under penalty of perjury under the laws of the United States of America that the foregoing information contained in the Proof of Service is true and correct.

Executed on _____
DATE

SIGNATURE OF SERVER

ADDRESS OF SERVER

Rule 45, Federal Rules of Civil Procedure, Subdivisions (c), (d), and (e), as amended on December 1, 2006:

(C) PROTECTION OF PERSONS SUBJECT TO SUBPOENAS.

(1) A party or an attorney responsible for the issuance and service of a subpoena shall take reasonable steps to avoid imposing undue burden or expense on a person subject to that subpoena. The court on behalf of which the subpoena was issued shall enforce this duty and impose upon the party or attorney in breach of this duty an appropriate sanction, which may include, but is not limited to, lost earnings and a reasonable attorney's fee.

(2) (A) A person commanded to produce and permit inspection, copying, testing, or sampling of designated electronically stored information, books, papers, documents or tangible things, or inspection of premises need not appear in person at the place of production or inspection unless commanded to appear for deposition, hearing or trial.

(B) Subject to paragraph (d)(2) of this rule, a person commanded to produce and permit inspection, copying, testing, or sampling may, within 14 days after service of the subpoena or before the time specified for compliance if such time is less than 14 days after service, serve upon the party or attorney designated in the subpoena written objection to producing any or all of the designated materials or inspection of the premises — or to producing electronically stored information in the form or forms requested. If objection is made, the party serving the subpoena shall not be entitled to inspect, copy, test, or sample the materials or inspect the premises except pursuant to an order of the court by which the subpoena was issued. If objection has been made, the party serving the subpoena may, upon notice to the person commanded to produce, move at any time for an order to compel the production, inspection, copying, testing, or sampling. Such an order to compel shall protect any person who is not a party or an officer of a party from significant expense resulting from the inspection, copying, testing, or sampling commanded.

(3) (A) On timely motion, the court by which a subpoena was issued shall quash or modify the subpoena if it

(i) fails to allow reasonable time for compliance;

(ii) requires a person who is not a party or an officer of a party to travel to a place more than 100 miles from the place where that person resides, is employed or regularly transacts business in person, except that, subject to the provisions of clause (c)(3)(B)(iii) of this rule, such a person may in order to attend trial be commanded to travel from any such place within the state in which the trial is held;

(iii) requires disclosure of privileged or other protected matter and no exception or waiver applies; or

(iv) subjects a person to undue burden.

(B) If a subpoena

(i) requires disclosure of a trade secret or other confidential research, development, or commercial information, or

(ii) requires disclosure of an unretained expert's opinion or information not describing specific events or occurrences in dispute and resulting from the expert's study made not at the request of any party, or

(iii) requires a person who is not a party or an officer of a party to incur substantial expense to travel more than 100 miles to attend trial, the court may, to protect a person subject to or affected by the subpoena, quash or modify the subpoena or, if the party in whose behalf the subpoena is issued shows a substantial need for the testimony or material that cannot be otherwise met without undue hardship and assures that the person to whom the subpoena is addressed will be reasonably compensated, the court may order appearance or production only upon specified conditions.

(D) DUTIES IN RESPONDING TO SUBPOENA.

(1) (A) A person responding to a subpoena to produce documents shall produce them as they are kept in the usual course of business or shall organize and label them to correspond with the categories in the demand.

(B) If a subpoena does not specify the form or forms for producing electronically stored information, a person responding to a subpoena must produce the information in a form or forms in which the person ordinarily maintains it or in a form or forms that are reasonably usable.

(C) A person responding to a subpoena need not produce the same electronically stored information in more than one form.

(D) A person responding to a subpoena need not provide discovery of electronically stored information from sources that the person identifies as not reasonably accessible because of undue burden or cost. On motion to compel discovery or to quash, the person from whom discovery is sought must show that the information sought is not reasonably accessible because of undue burden or cost. If that showing is made, the court may nonetheless order discovery from such sources if the requesting party shows good cause, considering the limitations of Rule 26(b)(2)(C). The court may specify conditions for the discovery.

(2) (A) When information subject to a subpoena is withheld on a claim that it is privileged or subject to protection as trial-preparation materials, the claim shall be made expressly and shall be supported by a description of the nature of the documents, communications, or things not produced that is sufficient to enable the demanding party to contest the claim.

(B) If information is produced in response to a subpoena that is subject to a claim of privilege or of protection as trial-preparation material, the person making the claim may notify any party that received the information of the claim and the basis for it. After being notified, a party must promptly return, sequester, or destroy the specified information and any copies it has and may not use or disclose the information until the claim is resolved. A receiving party may promptly present the information to the court under seal for a determination of the claim. If the receiving party disclosed the information before being notified, it must take reasonable steps to retrieve it. The person who produced the information must preserve the information until the claim is resolved.

(e) CONTEMPT Failure of any person without adequate excuse to obey a subpoena served upon that person may be deemed a contempt of the court from which the subpoena issued. An adequate cause for failure to obey exists when a subpoena purports to require a nonparty to attend or produce at a place not within the limits provided by clause (ii) of subparagraph (c)(3)(A).

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IN THE UNITED STATES DISTRICT COURT

FOR THE DISTRICT OF DELAWARE

U.S. PHILIPS CORPORATION, Plaintiff, v. EASTMAN KODAK COMPANY, Defendant.	)	Civil Action No. 06-00251-GMS

EASTMAN KODAK COMPANY'S SUBPOENA *AD TESTIFICANDUM* AND *DUCES TECUM* OF XEROX CORPORATION

PLEASE TAKE NOTICE THAT, pursuant to Rules 30 and 45 of the Federal Rules of Civil Procedure, Eastman Kodak Company ("Kodak"), by and through its counsel, will take the deposition of Xerox Corporation ("Xerox"), on August 16, 2007 at 9:00 a.m. at the offices of DLA Piper US LLP, 1251 Avenue of the Americas, 27th Floor, New York, NY 10020-1104, (212) 335-4500 (or at a time and place as otherwise agreed by the parties).

The deposition, on the deposition topics listed in Attachment A, will take place upon oral examination pursuant to the Federal Rules of Civil Procedure before an officer duly authorized by law to administer oaths, and will continue from day to day until completed. Some or all of the deposition may be recorded stenographically and may be recorded by videotape. Some or all of the deposition testimony may involve real-time computer connection between the deposition-taker and stenographer using software such as "LiveNote."

On August 9, 2007 at the offices of DLA Piper US LLP, 401 B Street, Suite 1700, San Diego, CA 92101, (619) 699-2700 (or at the time and place as otherwise agreed by the parties), Xerox must produce documents in its possession, custody and control in response to the document requests listed in Attachment A. Fed.R.Civ.P. 45(a)(1)(C).

Dated: July 17, 2007

John Allcock
Sean C. Cunningham
Tim Lohse
John D. Kinton
Jesse Hindman
Nicole Wyll
DLA PIPER US LLP
401 B Street, Suite 1700
San Diego, CA 92101-4297
Tel: 619.699.2700
Fax: 619.699.2701
Attorneys for Defendant
Eastman Kodak Company

ATTACHMENT A

TO THE SUBPOENA FOR XEROX CORPORATION

DEFINITIONS

1. "Xerox," "you" or "your" means Xerox Corporation, including without limitation all of its corporate locations, predecessors, affiliates, successors, subsidiaries, divisions or parts thereof; all past or present directors, officers, agents, representatives, employees, consultants, attorneys, and entities acting in joint-venture or partnership relationships with Xerox; and others acting on behalf of Xerox.

2. The term "Philips" means U.S. Philips Corporation including its predecessors, successors, assigns, past and present subsidiaries, past and present corporate parents, past or present subsidiaries of its corporate parents, divisions, affiliates, officers, directors, agents and employees, attorneys and other persons acting on its behalf, including Royal Philips Electronics, Philips Kommunikations Industrie AG (Germany), Philips Research Laboratories (United Kingdom), Philips Data Systems, Philips International B.V. (Netherlands), Philips Telecommuicatie Industrie (Netherlands), Philips Consumer Electronics B.V. (Netherlands), Philips Patentverwaltung GmbH, N. V. Philips Gloeilampenfabrieken and Peter Vogel.

3. As used herein, "product" refers to any system, apparatus, method, device, software, encoder, decoder, codec, and/or process using Image Coding Technology.

4. "Image Coding Technology" means any technology for compressing and/or decompressing data representing moving images, still images and/or facsimile images, including but not limited to the coding methods described in the JPEG Standard and MPEG Standards.

5. "Standard" or "Standards" or "Recommendation" refers to any documented agreements containing technical specifications or other precise criteria to be used consistently as

rules, guidelines, or definitions of characteristics, to ensure that materials, products, processes and/or services are fit for their purpose.

6. "ITU-T" means the International Telecommunication Union Telecommunication Standardization Sector and all predecessors, including the International Telephone and Telegraph Consultative Committee ("CCITT").

7. "ISO" means the International Organization for Standardization.

8. "IEC" means the International Electrotechnical Commission.

9. The phrase "JPEG Standard" refers to the Standard Recommendation ISO/IEC 10918-1|ITU-T Rec. T.81, entitled "Information Technology - Digital Compression and Coding of Continuous-Tone Still Images - Requirements and Guidelines."

10. The phrase "MPEG Standards" refer collectively to one or more of the ISO/IEC 11172-2 Standard for "MPEG-1," the ISO/IEC 13818-2 Standard for "MPEG-2," and the ISO/IEC 14496-2 Standard for "MPEG-4."

11. "Saran patent" means United States Patent No. 4,136,363 to Amitabh Saran, entitled "Truncated Run Length Encoding," issued January 23, 1979, attached hereto as Exhibit A.

12. "Liao patent" means United States Patent No. 4,494,151 to Henry H. Liao, entitled "4-Pixel Run-Length Code for Data Compression," issued January 15, 1985, attached hereto as Exhibit B.

13. "Liao article" means "Upper Bound, Lower Bound, and Run-Length Substitution Coding" by Henry H. J. Liao, published in NTC, 49:3-1 (1977), including such article published in NTC'77 Conference Record, Volume 3, pages 1-6 (1977), attached hereto as Exhibit C.

14. "Xerox patents and article" means any one or a combination of the Saran patent, the Liao patent, and/or the Liao article.

15. The term "Widcom" means Widcom, Inc., including its predecessors, successors, assigns, past and present subsidiaries, past and present corporate parents, divisions, affiliates, officers, directors, agents and employees, attorneys and other persons acting on its behalf, including Widergren Communications, Inc., and Robert Widergren.

16. "Widcom VTC-56" and "VTC-56" mean the coder-decoder, or "codec," that was developed by Widcom and was claimed to be capable of compressing a video image and transmitting it over 56 kilobits-per-second lines or links, and includes all of its prototypes as well as its previous, predecessor, and subsequent models.

17. "Widcom's Personal Videoconferencing Station" and "PVS" mean the videoconferencing system developed by Widcom and referred to by those names, and includes all of its prototypes as well as its previous, predecessor, and subsequent models.

INSTRUCTIONS

1. This subpoena calls for you to produce all documents identified below that are within your possession, custody, or control, or are otherwise available to you.

2. Electronic records and computerized information that are produced must be readable with standard commercial software or must be accompanied by a description of the system from which it was derived sufficient to render such materials readable.

3. If, after exercising due diligence to secure the information requested, you cannot fully comply with a specific Request, or any part thereof, please state the reason(s) for your inability to reply and respond to the fullest extent possible.

DOCUMENTS REQUESTED- GENERAL

1. All documents authored by Xerox or by any of its employees concerning Image Coding Technology prior to September 11, 1987.

2. Documents sufficient to fully describe the methods for image encoding and decoding used by any Image Coding Technology for: (1) any projects or products that led to the inventions of the Xerox patents and article; (2) any projects or products that were based on the inventions of the Xerox patents and article prior to September 11, 1987; (3) any other products made by or at the direction of Xerox that used Image Coding Technology prior to September 11, 1987; and (4) any other projects of Xerox that used Image Coding Technology prior to September 11, 1987.

3. Documents sufficient to describe any Xerox projects or products disclosed in documents produced in response to Document Request No. 2, including documents sufficient to describe the project and/or product names and model numbers.

4. Documents sufficient to demonstrate the public use, knowledge, availability, offer for sale and/or sale of any project or product disclosed in documents produced in response to Document Request No. 2 and which occurred prior to September 11, 1987, including documents sufficient to demonstrate such use, knowledge, availability, offer for sale and/or sale that occurred prior to September 11, 1987.

5. All documents concerning patent licenses from Xerox for (1) United States Patent No. 4,136,363 to Amitabh Saran, entitled "Truncated Run Length Encoding," issued January 23, 1979; and (2) United States Patent No. 4,494,151 to Henry H. Liao, entitled "4-Pixel Run-Length Code for Data Compression," issued January 15, 1985, regardless of whether a license was actually executed, including patent licenses for each patent.

6. All documents concerning any device, apparatus or product made by or otherwise associated with Widcom, including but not limited to the Widcom VTC-56 and/or the Widcom Personal Videoconferencing Station, and including but not limited to documents concerning the research, development, conception, reduction to practice, use, sale, offer for sale, distribution, display, and marketing thereof by any person or entity.

7. All documents concerning papers, articles, publications, public statements, reviews, announcements, and news reports by anyone regarding any product associated with Widcom, including but not limited to the Widcom VTC-56, the Widcom Personal Videoconferencing Station, any video compressor developed by Widcom for Bell & Howell, or any video conferencing codec developed by Widcom for DARPA, including but not limited to all drafts and final versions of any such materials and any memoranda or correspondence between co-authors or others concerning either the work reflected in the materials or the publications themselves.

DOCUMENTS REQUESTED- STANDARDS RELATED

8. All documents relating to any disclosure by You of Image Coding Technology to the ISO and/or CCITT Standards Bodies concerning the JPEG Standard prior to February 15, 1994, including but not limited to any proposal, submission, description, contribution and/or technical specification.

9. All documents relating to any participation by Xerox, or any employee of Xerox, in any ISO and/or CCITT Standards Bodies and any subgroup of those Standards Bodies including but not limited to the ISO Working Group 8, ISO Working Group 10, the CCITT Study Group VIII, the CCITT Study Group XV, and/or the joint ISO/CCITT JPEG Committee, prior to February 15, 1994, with respect to Image Coding Technology concerning the JPEG

Standard and/or MPEG Standards, including but not limited to any communication, proposal, submission, contribution, and/or technical specification, including participation by Bruce J. DeGrasse.

10. All Communications between Xerox and any of its employees and the ISO and/or CCITT Standards Bodies and any subgroup of those Standards Bodies including but not limited to the ISO Working Group 8, ISO Working Group 10, the CCITT Study Group VIII, the CCITT Study Group XV, and/or the joint ISO/CCITT JPEG Committee relating to the JPEG Standard and/or MPEG Standards, including communications to or from Bruce J. DeGrasse.

11. All documents relating to any participation by Philips, or any employee of Philips, in any ISO and/or CCITT Standards Bodies and any subgroup of those Standards Bodies including but not limited to the ISO Working Group 8, ISO Working Group 10, the CCITT Study Group VIII, the CCITT Study Group XV, and/or the joint ISO/CCITT JPEG Committee, prior to February 15, 1994, with respect to Image Coding Technology concerning the JPEG Standard and/or MPEG Standards, including but not limited to any communication, proposal, submission, contribution, and/or technical specification, and including participation by current or former Philips employees, including, but not limited to, Loeck Zeckendorf, Gerald Weth, Ulf Rothgordt, Peter Vogel, Karl Heinz Wenzel, Dr. Cord Brandis, Jan van der Meer, Norman Richards, John Morris, Simon Turner, Hendrick Eisema, Louis Van Loon, Erik Schylander, P. De Wit, Burkhard Krupa and Joachim Spiedel.

DEPOSITION TOPICS- GENERAL

1. The authenticity of any documents produced by Xerox in response to this subpoena.

2. The search for and collection of any documents relevant or responsive to this subpoena.

3. The methods for image encoding and decoding used by any Image Coding Technology for: (1) any projects or products that led to the inventions of the Xerox patents and article; (2) any projects or products that were based on the inventions of the Xerox patents and article prior to September 11, 1987; (3) any other products made by or at the direction of Xerox that used Image Coding Technology prior to September 11, 1987; and (4) any other projects of Xerox that used Image Coding Technology prior to September 11, 1987.

4. Any Xerox projects or products disclosed in documents produced in response to Document Request No. 2, including project and/or product names and model numbers.

5. The public use, knowledge, availability, offer for sale and/or sale of any project or product disclosed in documents produced in response to Document Request No. 4 and which occurred prior to September 11, 1987, including such use, knowledge, availability, offer for sale and/or sale that occurred prior to September 11, 1987.

6. Xerox's purchase or knowledge of any Widcom product, including without limitation the Widcom VTC-56 and the Widcom Personal Videoconferencing Station.

DEPOSITION TOPICS- STANDARDS RELATED

7. Participation by Xerox, or any employee of Xerox, in any ISO and/or CCITT Standards Bodies prior to February 15, 1994 with respect to Image Coding Technology concerning the JPEG Standard and/or MPEG Standards, including but not limited to any communication, proposal, submission, contribution, and/or technical specification, including those documents currently or formerly in the possession of Bruce J. DeGrasse.

8. Communications between Xerox and any of its employees and the ISO and/or CCITT Standards Bodies and any sub-group of those Standards Bodies relating to the JPEG Standard and/or MPEG Standards.

9. Participation by Philips, or any employee of Philips, including those employees listed in Document Request No. 11 above, in any ISO and/or CCITT Standards Bodies and any subgroup of those Standards Bodies including, but not limited to, the ISO Working Group 8, ISO Working Group 10, the CCITT Study Group VIII, the CCITT Study Group XV, and/or the joint ISO/CCITT JPEG Committee, prior to February 15, 1994 with respect to Image Coding Technology concerning the JPEG Standard and/or MPEG Standards, including, but not limited to, any communication, proposal, submission, contribution, and/or technical specification.

10. Communications between Philips and any of its employees and the ISO and/or CCITT Standards Bodies and any subgroup of those Standards Bodies relating to the JPEG Standard and/or MPEG Standards, including those employees listed in Document Request No. 11 above.

EXHIBIT A

United States Patent [19]

Saran

[11] **4,136,363**

[45] **Jan. 23, 1979**

[54] **TRUNCATED RUN LENGTH ENCODING**

[75] Inventor: **Amitabh Saran**, Cpyress, Calif.

[73] Assignee: **Xerox Corporation**, Stamford, Conn.

[21] Appl. No.: **756,664**

[22] Filed: **Dec. 29, 1976**

[51] **Int. Cl.**[2] **H04N 1/40; H04N 7/12**

[52] **U.S. Cl.** ..... **358/261; 340/347 DD; 358/260; 358/135**

[58] **Field of Search** ..... 358/260, 261, 135; 340/347 DD

[56] **References Cited**

U.S. PATENT DOCUMENTS

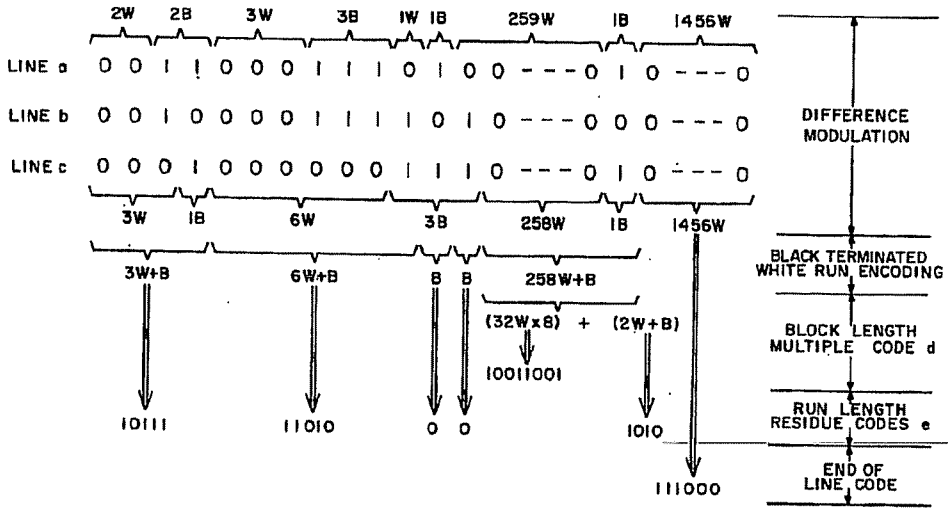
3,925,780	12/1975	Van Voorhis	340/347 DD
3,984,833	10/1976	Van Voorhis	340/347 DD
4,034,406	5/1977	Tsuchiya	358/261

Primary Examiner—Howard W. Britton

[57] **ABSTRACT**

A binary video signal having a raster scan format with some scan lines of difference modulated picture elements and other scan lines of unmodulated picture elements is encoded by converting black terminated white runs into block length multiple plus run length residue message codes, non-terminating black picture elements into individual message bits, and unterminated white runs into end-of-line message codes. Different end-of-line message codes are provided for the unterminated white runs of difference modulated and unmodulated picture elements to distinguish between the scan lines of difference modulated and unmodulated picture elements on a scan line-by-scan line basis, but otherwise the encoding is carried out in the same way for both the difference modulated and unmodulated picture elements.

10 Claims, 4 Drawing Figures



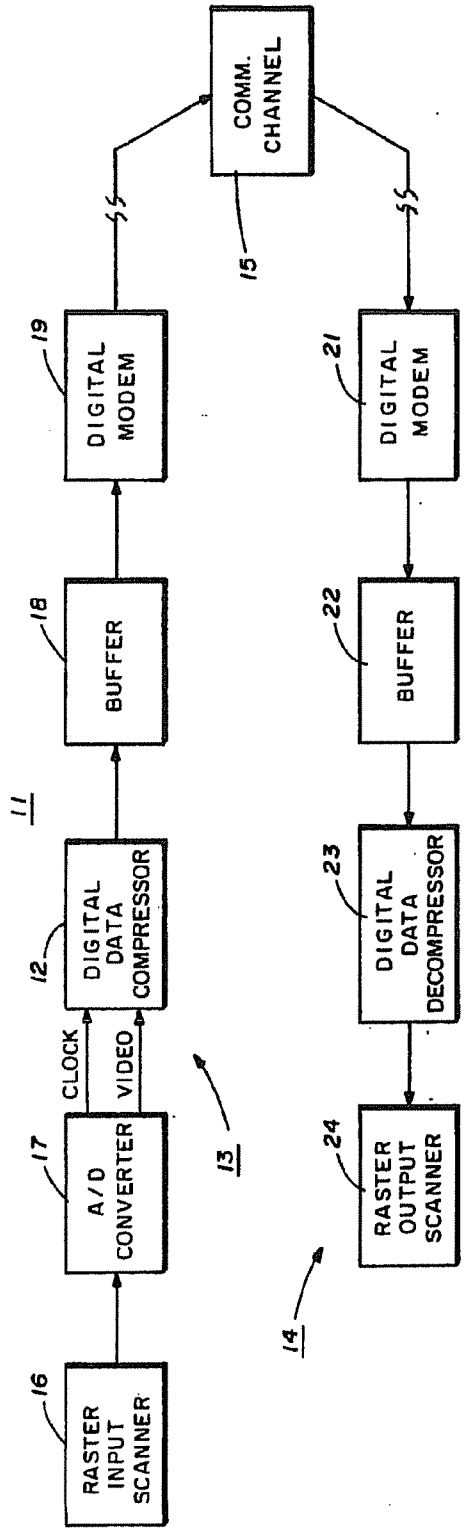

COMM. CHANNEL
15
DIGITAL MODEM
19
DIGITAL MODEM
21
BUFFER
18
BUFFER
22
11
DIGITAL DATA COMPRESSOR
12
DIGITAL DATA DECOMPRESSOR
23
CLOCK
VIDEO
13
A/D CONVERTER
17
RASTER OUTPUT SCANNER
24
14
RASTER INPUT SCANNER
16

FIG. 1

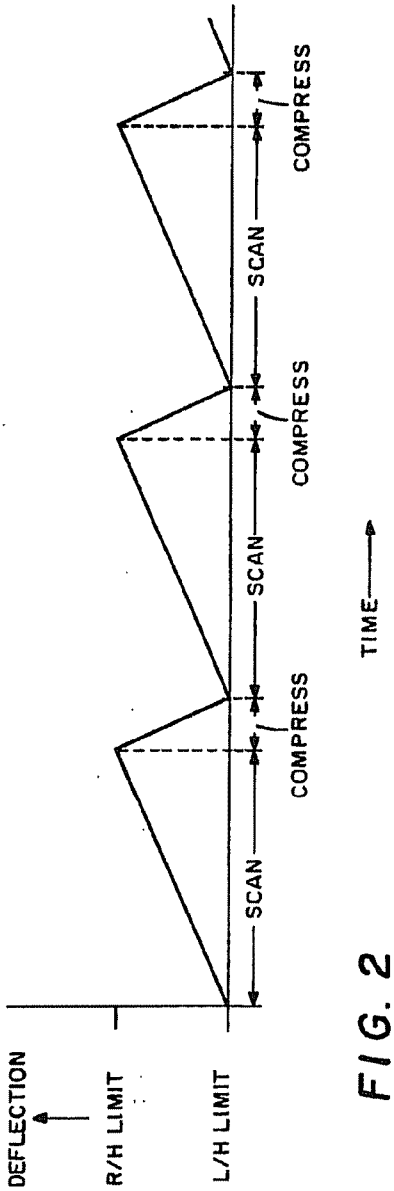

COMPRESS
SCAN
COMPRESS
SCAN
COMPRESS
SCAN
TIME
DEFLECTION
R/H LIMIT
L/H LIMIT

FIG. 2

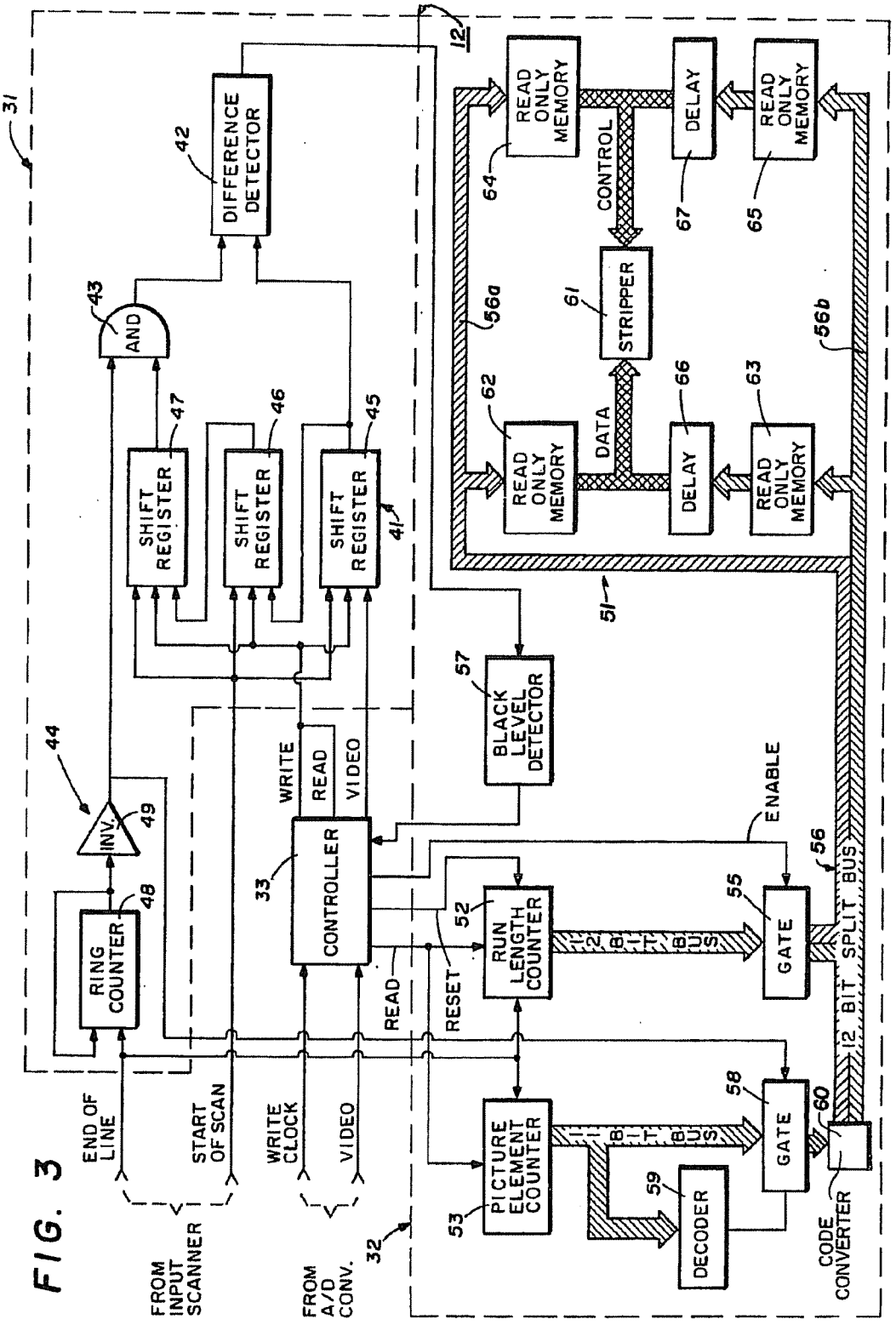

12
31
42
DIFFERENCE DETECTOR
43
AND
47
46
45
SHIFT REGISTER
SHIFT REGISTER
SHIFT REGISTER
41
READ ONLY MEMORY
64
CONTROL
DELAY
67
READ ONLY MEMORY
65
61
STRIPPER
56a
56b
62
READ ONLY MEMORY
DATA
66
DELAY
63
READ ONLY MEMORY
51
57
BLACK LEVEL DETECTOR
44
INV.
49
WRITE
READ
VIDEO
ENABLE
56
33
CONTROLLER
52
RUN LENGTH COUNTER
55
GATE
12 BIT SPLIT BUS
48
RING COUNTER
READ
RESET
58
60
PICTURE ELEMENT COUNTER
GATE
59
DECODER
53
CODE CONVERTER
END OF LINE
START OF SCAN
WRITE CLOCK
VIDEO
FROM INPUT SCANNER
FROM A/D CONV.
32

FIG. 3

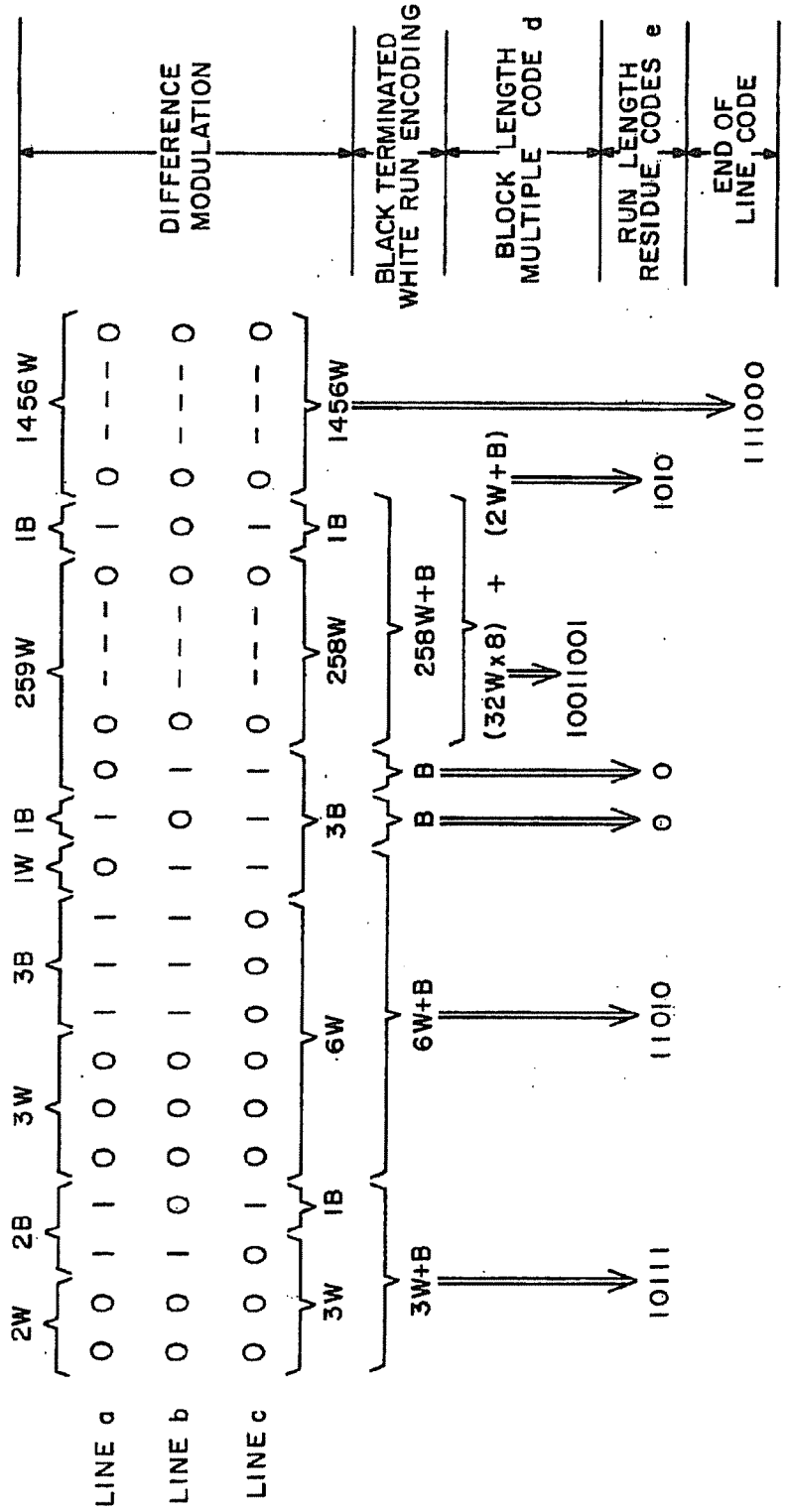

DIFFERENCE MODULATION
BLACK TERMINATED WHITE RUN ENCODING
BLOCK LENGTH MULTIPLE CODE d
RUN LENGTH RESIDUE CODES e
END OF LINE CODE
LINE a
LINE b
LINE c
2W 2B 3W 3B 1W 1B 259W 1B 1456W
3W 1B 6W 3B 258W 1B 1456W
3W+B 6W+B B B 258W+B
(32W x 8) + (2W+B)
10011001
1010
111000
10111
11010
0 0

FIG. 4

TRUNCATED RUN LENGTH ENCODING

CROSS REFERENCE TO RELATED APPLICATIONS

Related, commonly assigned and concurrently filed U.S. patent applications are Ser. No. 755,309 on "Block Length Multiple Plus Run Length Residue Codes for Run Length Coding"; Ser. No. 755,313 on "Method and Means for Extracting Variable Length Data from Fixed Length Bytes"; Ser. No. 756,662 on "Truncated Run Length Encoding for Fractionally Difference Modulated Video Signals"; and Ser. No. 756,663 on "Truncated Run Length Encoding with a Modular Variable Length Code Format".

BACKGROUND OF THE INVENTION

This invention relates to data compression for imaginal data processing systems and, more particularly, to digital data compression for binary raster scanned imaging systems and the like.

Documents (e.g., printed and written pages, drawings, and photographs) essentially are more or less continuous, two dimensional patterns of reflectance. Accordingly, imaginal data processing systems classically include raster input scanners for serially remapping or converting the information content (i.e., graphic images) of input documents into corresponding, one dimensional video signals and raster output scanners for serially printing replicas or facsimiles of the input documents in response to the video signals. There are hybrid systems in which provision is made for converting to or from a raster scan video signalling format so that raster input and output scanners may be interfaced with devices having other signalling formats, such teletypewriter terminals using an ASCII code. Usually, however, raster input and output scanners are employed in complementary combinations to form so-called raster scanned imaging systems.

Raster input and output scanning feature a characteristic scan structure, whereby a graphic image is represented by a video signal containing a predetermined number of picture elements (sometimes referred to as "pixels") for each of a plurality of substantially equidistantly spaced scan lines. Thus, the resolution of a raster scanner is customarily expressed in terms of a given number of scan lines/inch along, say, a vertical axis by a given number of picture elements or line pairs/inch along an orthogonal or horizontal axis. For example, the Xerox 200 Telecopier facsimile transceiver, which is manufactured and sold by Xerox Corporation, offers a choice of speed dependent resolutions which are conventionally specified (with reference to nominal document transmission times for a standard 8½" × 11" document) in units of scan lines/inch vertically by picture elements/inch horizontally as being approximately: 96 × 96 for document transmission times of three and six minutes; 64 × 96 for a document transmission time of four minutes; and 77 × 80 for a document transmission time of two minutes. While those are more or less standard resolutions for existing facsimile systems, it should be understood that they are close to the lower end of the useful range of resolutions for raster scanners in general. Significantly coarser resolutions are normally avoided because they involve an unacceptably high risk of losing essential image detail.

Raw video signals of the foregoing type commonly contain a significant amount of redundant information.

Therefore, if a video circuit for a raster input or output scanner comprises a limited bandwidth transmission medium or a limited capacity storage medium, increased data handling efficiency can often be realized by including an upstream data compression stage for removing redundant information from the video signal and a downstream data decompression stage for restoring that information. Binary video signals are especially well suited to data compression and decompression because the picture elements are either black or white ("1" or "0"), thereby excluding all intermediate shades of gray. For that reason, substantial effort and expense have been devoted to the development of digital data compression and decompression methods and means.

Run length encoding and decoding have gained widespread attention as techniques for compressing and decompressing, respectively, binary video signals having a raster scan format. Basically, the encoding converts the white and/or black runs of a binary video signal into corresponding message codes, and the decoding reconverts those codes into white and/or black runs of the appropriate length to reconstruct the video signal. In that context, a "run" is defined as being an uninterrupted series of one or more picture elements at the same logic level, and the "length" of a run is determined by the number of picture elements therein.

To carry out the encoding, the message codes are preselected to uniquely identify the lengths of the encoded runs. Preferably, in keeping with the teachings of D. A. Huffman, "A Method for the Construction of Minimum — Redundancy Codes", *Proceedings of the I.R.E.*, September 1952, pp. 1098–1101, the message codes are of variable length (i.e., different bit counts) and are assigned to the run lengths which are to be encoded in accordance with a predetermined run length probability distribution to the end that the code assigned to a given run length is no longer than the code assigned to a less probable run length.

Unfortunately, however, an unbounded set of documents does not yield a meaningful run length probability distribution because the redundancy of all graphic images, as an unlimited class, is completely random. Thus, to take advantage of a run length probability distribution in assigning the message codes, it is necessary to focus on a subset of documents which share a common image characteristic. For example, to optimize the data compression provided for ordinary business correspondence, the run length probability distribution may be based on run length frequency statistics gathered by prescanning a relatively few sample documents composed primarily of alphanumeric characters. Of course, that subset still permits of sufficient variations in page coverage and formatting and in character size and style to warrant weighting the run length frequency statistics in favor of those samples which are subjectively judged to most closely approach a preconceived norm.

Others have recognized that the basic run length encoding process can be modified to achieve increased data compression. In general, the proposed modifications have been directed toward increasing the average length of the runs which are presented for encoding.

More particularly, H. E. White et al., "Dictionary Look-Up Encoding of Graphic Data," *Picture Bandwidth Compression*, ed. T. S. Huang, Gordon and Breach, 1972, pp. 267–281, suggest the encoding of the "derivative or transitional equivalent" of the original image. To accomplish that, the definition of a run is

expanded to include not only an uninterrupted series of picture elements of one logic level, but also a single terminating picture element of the opposite logic level.

Another interesting proposal relates to a pre-encoding process known as difference modulation. To perform that process, corresponding picture elements for successive scan lines are differentially compared, thereby generating a binary prediction signal (hereinafter referred to as a difference modulated video signal) which distinguishes the picture elements for the later scan line which are at the same logic level as the corresponding picture elements for the preceding scan line from those that are not. Run length encoding of the difference signal can usually be carried out with relatively few message code bits because there normally is sufficient inter-scan line redundancy to cause the difference signal to have relatively long runs at a logic level indicating that the picture elements for the two scan lines are the same. However, there is the risk that errors made in recovering the picture elements for one scan line will be propogated through subsequent scan lines. Consequently, to limit the propogation of those errors, it is desirable to periodically encode and decode a scan line of raw or unmodulated picture elements, such as suggested in U.S. Pat. No. 3,830,966 of W. H. Aldrich et al., which issued Aug. 30, 1974, for "Apparatus and Method for Transmitting a Bandwidth Compressed Digital Signal Representation of a Visible Image."

SUMMARY OF THE INVENTION

Against that background, the primary goal of this invention is to provide improved methods and means for compressing binary video signals having a raster scan format.

More pointedly, in keeping with one aspect of the present invention, an object is to provide truncated run length encoding methods and means for converting terminated runs into run length message codes and unterminated runs into end of line message codes. A related object is to provide truncated run length encoding methods and means for encoding scan lines of difference modulated and unmodulated picture elements.

In keeping with another aspect of this invention an object is to provide methods and means for reducing the number of unique message codes required for run length encoding. A more detailed object is to provide methods and means for generating modular block length multiple plus residue run length message codes.

In keeping with still another aspect of this invention, a further object is to provide methods and means for extracting variable length data from fixed length bytes. A more specific, related object is to provide methods and means for taking advantage of a word oriented memory to store a look-up table of tree-type message codes for a run length encoder.

Briefly, to carry out these and other aspects of the invention, the picture elements of a binary video signal having a raster scan format are serially applied to a difference modulator which is cyclically enabled and disabled to sequentially feed scan lines of difference modulated and unmodulated picture elements to a truncated run length encoder where terminated runs are converted into run length message codes and unterminated runs are converted into end of line message codes. The same run length message codes are employed to encode the terminated runs of modulated and unmodulated picture elements, but there are different end of line message codes to signal whether difference demodulation of the scan line is or is not necessary to reconstruct the video signal. To limit the number of unique message codes required for encoding terminated runs, the run length message codes have a modular structure so that those runs are represented by block length multiple codes, if in excess of a predetermined block length, plus run length residue codes, if not an integer multiple of the block length.

BRIEF DESCRIPTION OF THE DRAWINGS

Still further objects and advantages of this invention will become apparent when the following detailed description is read in conjunction with the attached drawings, in which:

FIG. 1 is a functional block diagram of a digital facsimile system in which a data compressor embodying this invention may be used to substantial advantage;

FIG. 2 is a basic timing diagram for a typical raster input scanner for the system shown in FIG. 1;

FIG. 3 is a more detailed functional block diagram of a digital data compressor constructed in accordance with the present invention; and

FIG. 4 is a simplified encoding chart illustrating the operation of the encoder shown in FIG. 3.

DETAILED DESCRIPTION OF THE ILLUSTRATED EMBODIMENT

While the various aspects of this invention are described in some detail hereinbelow with specific reference to a single exemplary embodiment, it should be clearly understood that there is no intent to limit it to that embodiment. On the contrary, the aim is to cover all modifications, alternatives, and equivalents falling within the spirit and scope of the invention as defined by the appended claims.

Turning now to the drawings, and at this point especially to FIG. 1, there is a imaginal data processing system 11 including a digital data compressor 12 for compressing raster scan formatted, binary video signals in accordance with this invention. As shown, the data processing system 11 is a raster scanned imaging system or, even more specifically, a digital facsimile system having a transmitting terminal 13 and a receiving terminal 14 which are interconnected on, say, a demand basis by a communications link 15. Typically, the communications link 15 is a limited bandwidth transmission channel furnished by the public switched telephone network.

Reviewing the transmitting terminal 13 on a functional level, there is a raster input scanner 16 for converting the information content of an original document (i.e., a "subject copy") into a corresponding video signal. An analog-to-digtal converter 17 samples that signal at a predetermined rate in response to internally generated clock pulses and quantizes those samples, thereby providing a raw binary video signal having a raster scan format to represent the information content of the subject copy. As a practical example, if will be assumed that the scan pitch of the input scanner 16 and the sampling rate of the analog-to-digital converter 17 are selected to achieve a resolution of 96 scan lines/inch vertically by 204 picture elements/inch horizontally. Under those circumstances, the scanning of a standard 8½" × 11" document provides a binary video signal having 1,728 picture elements/scan line for 1,056 scan lines or, in other words, a total of 1,824,768 picture elements/page. Typically, however, a substantial por-

tion of those picture elements merely represent redundant information.

Accordingly, to reduce the redundancy, the binary video signal is encoded by the digital data compressor **12** to provide an encoded, data compressed video signal which is fed through a speed matching buffer **18** to a digital modem **19**. A suitable carrier signal is modulated in accordance with the encoded video signal by the modem **19** to supply a passband signal for transmission to the receiving terminal **14** via the communication channel **15**. As will be appreciated, the buffer **18** is included to isolate the modem **19** from the upstream components of the transmitting terminal **13** so that the passband data transmission rate may be selected more or less independently of the input scanning/sampling rate.

At the receiving terminal **14**, there is a complementary modem **21** for demodulating the incoming passband signal, thereby recovering the encoded video signal. That signal is, in turn, fed through an appropriate speed matching buffer **22** to a digital data decompressor **23** which performs the decoding necessary to reconstruct the raw binary video signal. A raster output scanner **24** then prints a replica or "facsimile" of the subject copy in response to the reconstructed video signal.

As shown in FIG. **2**, in keeping with accepted practices, the input scanner **16** cyclically scans the subject copy scan line-by-scan line. Preferably, each scanning cycle is sequenced so that the scanner **16** first actively scans across the subject copy in one direction (say, from left-to-right) and then passively returns or flies back in the opposite direction to prepare for the next cycle. An input/output scanner of that type is used in the aforementioned Xerox 200 Telecopier facsimile transceiver and is disclosed in a commonly assigned U.S. Pat. No. 3,869,569 which issued Mar. 4, 1975, to Peter J. Mason et al. for "Facsimile Transceiving Apparatus." Hence, that patent and the foregoing commercially available equipment are hereby incorporated by reference. Nevertheless, in the interest of completeness, it is noted that the above-identified scanner comprises a laser which is optically aligned with a scan mirror of a galvanometer-type deflection mechanism. Thus, when the scanner is operating in a scan mode, the scan mirror is cyclically oscillated to sweep back and forth across a laterally elongated scanning aperture, and the laser is activated and extinguished in timed synchronism with the oscillation of the scan mirror to selectively provide a light beam for illuminating the subject copy while the scan mirror is sweeping from left-to-right across the scanning aperture, but not while the scan mirror is flying back in the opposite or right-to-left direction. The subject copy is incrementally advanced longitudinally of the scanning aperture, thereby cooperating with the scan mirror in providing the orthogonal motion necessary to create a raster scanning pattern.

Referring to FIG. **3**, the digital data compressor **12** includes a difference modulator **31** and a truncated run length encoder **32** which are controlled by a controller **33** to accumulate and encode the binary picture elements for consecutive scan lines during the active and passive portions, respectively, of successive scanning cycles. As will be seen, provision is made for periodically enabling and disabling the difference modulator **31** so that the encoding of scan lines of difference modulated picture elements is regularly interrupted to allow for the encoding of at least one scan line of unmodulated picture elements, thereby limiting the inter-scan line propogation of decoding errors. The encoder **32**, on the other hand, features a modular run length message code structure for the encoding of "black terminated white runs" of delta modulated and unmodulated picture elements and a truncated run length encoding process characterized by the use of different, run length independent, end of line message codes to represent unterminated white runs of difference modulated and unmodulated picture elements.

"Black" and "white" are used herein as convenient terms for distinguishing between difference modulated and unmodulated picture elements of opposite logic levels (i.e., "1" and "0"). However, the only color significance those terms are intended to imply is that raw or unmodulated black and white picture elements represent image and background information, respectively. Even that limited correlation is lacking in the case of difference modulated picture elements because that modulation attaches an error significance to the logic levels of those picture elements.

More particularly, as shown, the difference modulator **31** comprises a serial input/parallel output shift register means **41** for sequentially feeding spatially corresponding picture elements for successive pairs of adjacent scan lines in parallel to a difference detector **42**. The picture elements for one scan line of each of those pairs are directly applied to a first input of the detector **42**. Advantageously, however, to limit the inter-scan line propogation of decoding errors, the picture elements for the other scan line are gated to a second input of the detector **42** via an AND gate **43** which is periodically disabled by a self-resetting line counter **44**. When the AND gate **43** is enabled, the detector **42** generates a binary signal representing the modulo-2 difference between the two adjacent scan lines. In contrast, when the gate **43** is disabled, the difference detector **42** passes the raw picture elements for the ungated or current scan line in unmodulated form.

Concentrating first on the shift register means **41**, it will be seen that the raw binary picure elements supplied by the analog-to-digital converter **17** are serially shifted through the shift register means **41** in response to write and read clock pulses which are applied to one or more clock inputs for the shift register means **41** by the controller **33** during the active and passive portions, respectively, of each scanning cycle. Thus, to supply a parallel flow of spatially corresponding picture elements for a current and an immediately preceding scan line, the shift register means **41** includes $3n$ serially connected stages, where "n" equals the number of picture elements/scan line, and parallel outputs are taken from the n th and the $3n$ th stages. Suitably, the write clock pulses for the shift register means **41** are derived from the analog-to-digital converter **17**, but provision is made for generating the read clock pulses internally of the controller **33**.

While a single multi-stage shift register could be configured to perform the above-described process, it is somewhat easier to trace the flow of picture elements if the shift register means **41** is visualized as being formed from three serially connected, line length or n-stage shift registers **45–47**. At the outset of each scanning operation, all of the stages of the shift registers **45–47** are, of course, cleared to a low ("0") logic level in response to, say, a start of scan signal received from the input scanner **16**. Thereafter, the raw binary picture elements for an initial scan line are serially shifted into the n-stages of the first shift register **45** in response to the write clock pulses provided during the active por-

tion of a first scanning cycle. Those picture elements are subsequently shifted through the n-stages of the second shift register 46 and into the n-stages of the third shift register 47 as a result of the read clock pulses and the additional write clock pulses furnished during the passive portion of the first scanning cycle and during the active portion of a second scanning cycle, respectively. Furthermore, the raw binary picture elements for the next scan line are serially loaded into the n-stages of the first shift register 45 in response to the write clock pulses supplied during the active portion of the second scanning cycle. Picture elements provided during later scanning cycles follow the same path. Thus, it will be understood that spatially corresponding, raw binary picture elements for a current and an immediately preceding scan line are fed in parallel from the final stages of the shift registers 45 and 47, respectively, in response to the read clock pulses supplied during the passive portion of each scanning cycle, except the first. The first cycle is an exception simply because there are no picture elements for a preceding scan line at that time which means that the n-stages of the third shift register 47 remain at a low ("0") logic level throughout that cycle.

At this point it may be helpful to mention that "spatially corresponding" is used herein as a convenient description for picture elements which occupy the same relative positions in different scan lines. In the context of a one-dimensional video signal, spatially corresponding picture elements occupy identical numerical positions in separate scan lines. Similarly, in the context of a two-dimensional subject copy, spatially corresponding picture elements represent the information content of spaced apart areas of the subject copy which are aligned in the scan pitch direction. For example, if the scan pitch is measured vertically of the subject copy, spatially corresponding picture elements represent the information content of vertically aligned areas of the subject copy.

Inter-scan line redundancy characteristically results in a statistically significant degree of duplication between spatially corresponding binary picture elements for adjacent scan lines. Hence, to obtain white or low ("0") logic level runs of increased average length, the difference detector 42 is included for transforming certain of the scan lines of raw binary picture elements into scan lines of difference modulated picture elements representing the modulo-2 difference between spatially corresponding binary picture elements for the scan line being transformed and the immediately preceding scan line. As will be appreciated, the increased average run length tends to reduce the number of bits required to convey a given amount of information in run length encoded form or, in other words, provides an opportunity for achieving increased data compression. Nevertheless, there is an attendant risk that errors made in decoding the picture elements for one scan line will propogate through all subsequent difference modulated scan lines. That follows from the fact that the recovery of the binary video signal depends on a complementary difference demodulation process -viz., a modulo-2 summation of the difference modulated picture elements for the scan line being demodulated with the spatially corresponding, raw binary picture elements previously recovered for the immediately preceding scan line.

For that reason, a balance is struck between the competing goals of maximizing the data compression and limiting the inter-scan line propogation of decoding errors. In keeping with that objective, one input of the difference detector 42 is connected to receive the raw binary picture elements for the so-called current scan line directly from the output or final stage of the shift register 45. However, the raw binary picture elements for the preceding scan line are gated from the output or final stage of the shift register 47 to the other input of the detector 42 via the AND gate 43 which, as previously mentioned, is periodically disabled by the line counter 44. To perform the gating function, the AND gate 43 has one input coupled to the output of the shift register 47, another input coupled to the output of the line counter 44, and an output coupled to the second input of the difference detector 42.

Functionally reviewing the difference modulator 31, it will be understood that the difference detector 42 generates a binary output signal representing the modulo-2 difference between input signals received from the AND gate 43 and the shift register 45. Raw binary picture elements for a current scan line are serially shifted out of the shift register 45 during the passive portion of each scanning cycle. However, the AND gate 43 is disabled throughout the first scanning cycle by a low ("0") logic level input signal supplied by the shift register 47. Consequently, the raw binary picture elements for the initial scan line are regenerated at the output of the detector 42 during the passive portion of the first cycle. In contrast, as shown in FIG. 4, spatially corresponding picture elements for a current scan line a and an immediately preceding scan line b are fed in parallel from the shift registers 45 and 47, respectively, during the passive portion of each subsequent scanning cycle. Therefore, the difference detector 42 responds by generating a scan line c of difference modulated picture elments, unless the AND gate 43 is disabled by the line counter 44.

As will be recalled, the line counter 44 periodically disables the AND gate 43 to limit the inter-scan line propogation of decoding errors. For that purpose, the line counter 44 suitably comprises a multi-stage ring counter 48 which has its last stage coupled to an input of the AND gate 43 via an inverter 49. Typically, the ring counter 48 is reset or cleared at the outset of each scanning operation in response to the aforementioned start of scan signal and is thereafter incremented once each scanning cycle in response to, say, an end of scan line signal provided by the input scanner 16 at the conclusion of the active portion of each scanning cycle. In that event, there is a recirculating high ("1") logic level pulse which advances from stage-to-stage of the ring counter 48 at the line scanning rate, thereby causing the inverter 49 to supply a low ("0") logic level signal for disabling the AND gate 43 during one out of every predetermined number of scanning cycles. As a result, the difference detector 42 is periodically inhibited from receiving the picture elements for the so-called preceding scan line from the shift register 47. In effect, therefore, the detector 42 is cyclically switched between operating in a modulating mode and a non-modulating mode to generate a recurring sequence of a predetermined number of scan lines of difference modulated picture elements followed by a scan line of raw or unmodulated picture elements. As will be appreciated, decoding errors will not propogate through scan lines of unmodulated picture elements because those picture elements are recovered without referring to the picture elements for any other scan line. For example, if the ring counter 48 has five stages, a scan line of raw binary

picture elements will be regenerated by the difference detector **42** during the passive portion of every fifth scanning cycle, thereby limiting the inter-scan line propogation of decoding errors to five scan lines at most, while still allowing for difference modulation of roughly eighty percent of the picture elements.

To compress the delta modulated and unmodulated picture elements furnished by the delta modulator **31**, the encoder **32** comprises a memory means **51** which is selectively addressed by means including a binary run length counter **52** and a binary picture element counter **53** to serially convert (a) black terminated white runs into corresponding run length message codes, (b) unterminated white runs into corresponding end of line message codes, and (c) non-terminating black picture elements into individual message bits of a predetermined logic level. There is no need to distinguish between the difference modulated and unmodulated picture elements while processing black terminated white runs and non-terminating black picture elements. Instead, an adequate scan line-by-scan line indication of whether the picture elements are difference modulated or not is obtained merely by employing different end of line message codes for encoding the unterminated white runs of difference modulated and unmodulated picture elements.

Preferably, the run length message codes, the end of line message codes, and the individual message bits are mutually exclusive so that the boundaries therebetween are self-identifying, even after they have been assembled into a serial video data stream by the encoder **32**. For that reason, as indicated in FIG. **4**, each run length and end of line message code is selected to have an initial bit of the opposite logic level from the message bits and a unique bit sequence differing from the prefixes of all other codes. Of course, those guidelines are consistent with the use of so called tree codes viz., variable length (i.e., bit count) run length message codes. Thus, it should be recalled that the basic Huffman rule for taking advantage of variable length run length message codes is that the code assigned to any given run length should be no longer than the code assigned to any less probable run length. The implications of the Huffman rule have already been discussed and, therefore, need not be restated at this point.

Black terminated white runs and non-terminating black picture elements can be generically classified as being black terminated sequences of one or more picture elements. In recognition of that, the run length counter **52** serially generates fixed length binary counts which numerically represent the number of picture elements within successive ones of any black terminated sequences of difference modulated or unmodulated picture elements appearing at the output of the difference modulator **31**. The bits of each of these counts are fed in parallel to the memory means **51** via a gate **55** and an address bus **56**, thereby serially supplying address codes for reading out of the memory means **51** the run length message codes and the individual message bits called for by the black terminated white runs and the non-terminating black picture elements, respectively. Assuming again that there are 1728 picture elements/-scan line, a twelve bit binary count is a suitable format for the address codes. Indeed, it will be understood from the subsequent discussion that the twelfth bit is included in this particular case merely to simplify the address interface of the memory means **51** inasmuch as eleven bits are ample to uniquely define any count up to and including 1728 — viz., the eleven bit binary equivalent of 1728 is 11011000000 and the twelve bit equivalent is 011011000000.

For converting any black terminated difference modulated and unmodulated picture element sequence appearing at the output of the difference modulator **31** into a corresponding binary count-like address code, the run length counter **52** is synchronously reset or cleared at the conclusion of the active portion of each scanning cycle in response to, say, the aforementioned end of scan line signal furnished by the input scanner **16** and is incremented during the passive portion of each scanning cycle in response to the read clock pulses supplied by the controller **33**. Furthermore, a black level detector **57** monitors the logic level of the picture elements which are fed from the delta detector **42** in response to the read clock pulses, thereby providing an asynchronous control signal which causes the controller **33** to sequentially enable the gate **55** and then reset the counter **52** whenever a black (e.g., a high ("1") logic level) difference modulated or unmodulated picture element is detected at the output of the difference detector **42**.

Accordingly, it will be evident that the run length counter **52** generates successive binary counts and that a new count is started not only with the appearance at the output of the difference detector **42** of the initial picture element of each scan line, but also with the appearance of the first picture element following each black picture element. The read clock pulses increase the count accumulated by the counter **52** by one for each white (low ("0") logic level) and each black (high ("1") logic level) difference modulated or unmodulated picture element which is fed from the difference detector **42**. Normally, the gate **55** is opened or disabled, thereby isolating the counter **52** from the memory means **51**. However, when the level detector **57** detects the presence of a black modulated or unmodulated picture element at the output of the difference detector **42**, the controller **33** enables or closes the gate **55** so that the bits defining the count accumulated by the counter **52** at that time are fed in parallel through the address bus **56** to address the memory means **51**. Thereafter, the controller **33** resets the counter **52** prior to supplying the next read clock pulse so that a new count starts when the next picture element is fed from the difference detector **42**. As will be appreciated, if the normal interval between successive read clock pulses fails to allow sufficient time for sequentially addressing the memory means **51** and then resetting the counter **52**, provision may be made within the controller **33** for delaying the next read clock pulse upon the appearance of a black picture element at the output of the detector **42**.

Similarly, to convert the unterminated runs of white (low ("0") logic level) picture elements appearing at the output of the modulator **31** into appropriate address codes for reading the preassigned end of line message codes out of the memory means **51**, the picture element counter **53** is cleared or reset at the conclusion of the active portion of each scanning cycle in response, for example, to the end of scan line signal furnished by the input scanner **16** and is incremented during the passive portion of each scanning cycle in response to the read clock pulses supplied by the controller **33**. Again, there is a normally opened or disabled gate **58**, which is coupled between the output of the counter **53** and the address bus **56**, for isolating the counter **53** from the memory means **51** until an unterminated white run is de-

tected. However, the detection function is performed inferentially in reliance on an assumption that each scan line will conclude with one or more white picture elements. Specifically, to carry out the unterminated white run detection function, there is a decoder **59**, which is coupled between the output of the counter **53** and a control input of the gate **58**, for enabling or closing the gate **58** whenever the counter **53** accumulates a predetermined binary count equal to the number of picture elements allotted to each scan line. For example, if there are 1728 picture elements/scan line, the decoder **59** is selected to enable or close the gate **58** in response to the binary equivalent count of 11011000000 from the picture element counter **53**.

As will be recalled, unterminated white runs of difference modulated and unmodulated picture elements advantageously are represented by different end of line message codes. Consequently, to provide address codes which distinguish between those two cases, the bits supplied by the picture element counter **53** are supplemented by an additional bit having a logic level which depends on whether modulated or unmodulated picture elements are being fed from the difference modulator **31**. As shown, the additional or supplemental bit suitably is derived from the output of the line counter **44** and typically is assembled at the input of the gate **58** in parallel with the bits defining the binary count accumulated by the counter **53**. An eleven bit binary count from the counter **53** is sufficient to express the binary equivalent of the assumed allottment of 1728 picture elements/scan line. Hence, it will be understood that the supplemental bit may be added to form a twelve bit address code, without exceeding the twelve bit capacity of the address bus **56**.

In view of the organization of the memory means **51**, as described hereinbelow, the supplemental bit preferably occupies one of the more significant bit positions of the end of line address codes, although that means that there is a potential conflict with an address code (011011000000) which represents a black terminated picture element sequence comprising a full scan line of difference modulated or unmodulated picture elements. Thus, to avoid the conflict, there is a code converter **60** with a built in delay connected between the gate **58** and the address bus **56** for converting the end of line address codes to non-conflicting bit sequences (e.g., 011011100000 and 0111111000000) and for delaying the application of the end of line address codes for a period of time sufficient to allow for priority handling of all run length address codes.

Referring to the memory means **51**, it is noted that provision is made for extracting variable length data from fixed length data bytes or words. While this feature is generally applicable to the storage of variable length data in and the retrieval of such data from a word oriented memory, a description of a specific application adequately discloses the broad underlying concept. Here, of course, the application of special interest involves the storage and recovery of the run length message codes, the individual message bit, and the end of line message codes from which a compressed video signal is constructed.

Focusing on that application, it will be seen that there is a stripper circuit **61** for extracting the run length message codes, the individual message bits, and the end of line message codes for the compressed video signal from fixed length data words under the control of fixed length control words. The data words and control words are read out of first and second word oriented memory banks **62**, **63** and **64**,**65**, respectively, by the address codes which are generated in response to the black terminated picture element sequences and the unterminated white runs. Thus, the stripper circuit **61** is provided with a predetermined data word and control word for each such sequence and run. The data word contains the message code or bit representing the particular black terminated picture element sequence or unterminated white run and the control word distinguishes between the relevant and irrelevant bits of the data word, thereby enabling the stripper circuit **61** to extract the message code or bit from the data word.

More particularly, the run length message codes, the individual message bit, and the end of line message codes are contained by separate data words. As shown, there is a set of read only memories (ROMs) **62** and **63** for storing those data words at different, predetermined addresses or storage locations. The data word length is selected to at least equal the longest of the message codes, and each of the data words is organized so that the relevant bits (i.e., those defining the message code or message bit) precede any irrelevant, filler bits (e.g., low ("0") logic level bits) which are included merely to achieve the selected word length. Furthermore, the storage locations for the data words are selected on the basis of the address codes so that the data word containing the appropriate message code or message bit for any given black terminated picture element sequence or unterminated white run is selectively read out of the memory bank **62**, **63** in response to the address code which is generated as a result of that particular sequence or run.

For distinguishing between the relevant bits and the filler bits of the data words, there are an equal number of control words. The control words are stored within another set of ROMs **64** and **65** at addresses or storage locations which are selected so that each control word is associated with a respective one of the data words by virtue of sharing a common address code. Hence, each control word is responsible for distinguishing between the relevant and irrelevant bits of its associated data word. For example, one way in which such a distinction can be made is to select each control word to have high ("1") and low ("o") logic level bits positionally corresponding with the relevant and irrelevant bits, respectively, of the associated data word.

In operation, the address codes generated in response to the black terminated picture element sequences and the unterminated white runs are sequentially applied in parallel to the first and second memory banks **62**, **63** and **64**, **65**, respectively, whereby successive sets of associated data words and control words are sequentially read out in parallel and applied in parallel to the stripper circuit **61**. The stripper circuit **61**, in turn, relies on the control words for extracting the run length message codes, the individual message bits, and the end of line message codes from the data words, thereby serially constructing the compressed video signal. To perform that function, the stripper circuit **61** suitably comprises a gate controlled parallel input/serial output shift register or the like (not shown) for serially shifting out the relevant bits of the data words in response to read clock pulses received from the controller **33** via a gate (also not shown) which is selectively enabled and disabled under the control of the control words. In that event, the shift register is cleared in preparation for extracting the relevant bits from each of the successive data words.

For conserving on the storage capacity required of the memory banks 62,63 and 64,65, a block length multiple plus run length residue code format is utilized in encoding the black terminated white runs of difference modulated and unmodulated picture elements. The advantage of that format is, as shown in FIG. 4, that black terminated white runs in excess of a predetermined block length are represented by a block length multiple code d plus, if the run happens to be a noninteger multiple of the block length, a run length residue code e. Shorter runs are, on the other hand, represented solely by a run length residue code e. In other words, the block length multiple plus run length residue code format avoids the necessity of having a separate data word and control word for each of the possible black terminated white run lengths.

To carry out the encoding of the black terminated white runs in accordance with a block length multiple plus run length residue code format, the address bus 56 is split to furnish a first branch 56*a* for routing the more significant bits of the basic twelve bit address codes to the ROMs 62 and 64 and a second branch 56*b* for routing the less significant bits of the address codes to the ROMs 63 and 65. The data words and the control words for the block length multiple codes are stored within and read out from ROMs 62 and 64, respectively, as previously described. Similarly, the ROMs 63 and 65 are used to accommodate the data words and the control words, respectively, for the run length residue codes. Sequencing of the block length multiple and the run length residue codes is accomplished by delaying the read out of the data word and control word for one of the other of those codes. Here, for example, provision (schematically illustrated at 66 and 67) is made for delaying the read out of the data word and control word for the run length residue code, whereby the stripper circuit 61 first extracts any block length multiple code d that is called for before turning to any run length residue code e.

A practical block length for the illustrated embodiment is thirty-two picture elements long. For that particular case, the seven most significant bits of each twelve bit address code are applied in parallel to the ROMs 62 and 64 to derive the block length multiple codes for the integer multiples of thirty-two (i.e., the sums of anyone or more of the binary place values of 32, 64, 128, 256, 512 and 1,024). The other or five least significant bits of each address code are applied in parallel to the ROMs 63 and 65 to derive the run length residue codes. To complete this example, it should be noted that the address codes which are here provided in response to the unterminated white runs lead to the use of the ROMs 62 and 64 for storing the data words and control words, respectively, from which the end of line message codes are derived. Likewise, the specific address code that is generated in response to a non-terminating black picture element dictates that the data word and control word dedicated to the individual message bit be stored within the ROMs 63 and 65, respectively.

CONCLUSION

In view of the foregoing, it will now be evident that this invention provides methods and means for performing truncated run length encoding.

What is claimed is:

1. In combination with raster scanning means for converting the information content of a subject copy into a binary video signal containing a predetermined number of serial picture elements for each of a plurality of successive scan lines and having black and white picture elements of opposite logic levels; the improvement comprising truncated run length encoding means including

run length dependent means for converting black terminated intra-scan line runs of white picture elements into corresponding run length message codes, and

run length independent means for converting unterminated intra-scan line runs of white picture elements into corresponding end of line message codes.

2. The improvement of claim 1 wherein said truncated run length encoding means comprises

memory means for storing a plurality of preselected run length message codes and at least one end of line message code at different, predetermined addresses;

run length counting means for sequentially generating run length dependent binary counts in response to successive black terminated runs of white picture elements;

picture element counting means for sequentially generating run length independent binary counts in response to the picture elements of successive scan lines; and

means for applying count related address codes to said memory means in response to said run length dependent and independent counts, whereby appropriates ones of said one length and end of line message codes are selectively read out from said memory means.

3. The improvement of claim 1 wherein said truncated run length encoding means further supplies single individual message bits in response to non-terminating black picture elements.

4. The improvement of claim 3 wherein said truncated run length encoding means comprises

memory means for storing a plurality of preselected run length message codes, at least one end of line message code, and a preselected message bit at different, predetermined addresses;

an address bus for applying address codes to said memory means;

first and second binary counters for accumulating respective binary counts; each of said counters having a clock input, a reset input, and an output;

first and second normally open gates for coupling the outputs of said first and second counters, respectively, to said address bus;

means coupled to the clock inputs of said first and second counters for incrementally increasing each of said counts by one in response to each of said picture elements;

means coupled to the reset inputs of said first and second counters for synchronously clearing said counters at the outset of each new scan line of picture elements;

detector means coupled to said raster scanning means for monitoring the logic level of said picture elements to provide a control signal in response to each of said black picture elements;

means coupled between said detector means, a control input of said first gate means, and the reset input of said first counter for asynchronously and sequentially closing said first gate and then clearing

said first counter in response to said control signal, whereby said first counter serially supplies run length dependent binary counts in response to successive non-terminating black picture elements and black terminated intra-scan line runs of white picture elements to provide address codes for selectively reading out said individual message bit and appropriate ones of said run length message codes from said memory means; and

decoder means coupled between the output of said second counter and a control input of said second gate for closing said second gate whenever the binary count accumulated by said second counter reaches said predetermined number, whereby said second counter serially supplies line length independent binary counts in response to successive scan lines of picture elements to provide address codes for selectively reading out said end of line message code from said memory means.

5. The improvement of claim 4 wherein

said raster scanning means cycles to serially generate picture elements for a scan line while actively scanning in one direction relative to said subject copy and to then passively fly back in the opposite direction; and

further including

multi-stage shift register means coupled between said raster scanning means and said detector means,

means for applying write clock pulses to said shift register means while said scanning means is actively scanning, thereby shifting said picture elements into said register means, and

additional means for applying read clock pulses to said shift register means while said scanning means is passively flying back, thereby shifting said picture elements out of said register means; said additional means being connected to feed said read clock pulses to the clock inputs of said first and second counters, whereby the counts accumulated by said counters are each increased by one for each picture element shifted out of said shift register means.

6. The improvement of claim 5 wherein said individual message bit, run length message codes, and end of line message code are selected to be mutually exclusive.

7. The improvement of claim 6 wherein said raster scanning means and said truncated run length encoding means are included in a facsimile terminal for transmitting a data compressed video signal representing the information content of said subject copy.

8. A truncated run length encoder for compressing a binary video signal composed of a predetermined number of serial picture elements for each of a plurality of successive scan lines and having black and white picture elements of opposite logic levels; said picture elements being serially applied to said encoder in response to successive clock pulses; said encoder comprising the combination of

memory means for storing preselected run length message codes and at least one end of line message code at run length and line length related addresses, respectively;

detector means for monitoring the logic level of said picture elements to supply a control signal in response to each black picture element;

run length counter means responsive to said clock pulses and to said control signal for sequentially accumulating run length dependent binary counts representing the number of picture elements within successive black terminated intra-scan line runs of white picture elements;

means coupled between said run length counter means and said memory means for applying run length dependent address codes to said memory means in reponse to said run length dependent counts, whereby run length message codes corresponding to said black terminated white runs are selectively read out from said memory means;

picture element counter means for sequentially accumulating run length independent counts equal to said predetermined number in response to said clock pulses, and

means coupled between said picture element counter and said memory means for applying run length independent address codes to said memory means in response to said run length independent binary counts, whereby said end of line message code is selectively read out from said memory means to represent unterminated intra-scan line runs of white picture elements.

9. The encoder of claim 8 in combination with

shift register means,

means for alternately applying write and read clock pulses to said shift register means for shifting said picture elements into and out of, respectively, said shift register means scan line-by-scan line, and

means for applying the picture elements shifted out of said shift register means to said detector means.

10. The combination of claim 9 wherein

said read clock pulses are applied to said run length counter means and to said picture element counter means for incrementally increasing said run length dependent and independent counts by one for each picture element applied to said detector means.

* * * * *

EXHIBIT B

United States Patent [19]

Liao

[11] **Patent Number: 4,494,151**

[45] **Date of Patent: Jan. 15, 1985**

[54] **4-PIXEL RUN-LENGTH CODE FOR DATA COMPRESSION**

[75] Inventor: **Henry H. Liao**, Rossmore, Calif.

[73] Assignee: **Xerox Corporation**, Stamford, Conn.

[21] Appl. No.: **347,203**

[22] Filed: **Feb. 9, 1982**

Related U.S. Application Data

[63] Continuation of Ser. No. 54,389, Jul. 2, 1979, abandoned, and Ser. No. 150,780, May 19, 1980, abandoned.

[51] **Int. Cl.**³ **H04N 7/12**

[52] **U.S. Cl.** ..... **358/261**; 340/347 DD

[58] **Field of Search** ..... 340/347 DD; 358/260, 358/261, 133

[56] **References Cited**

U.S. PATENT DOCUMENTS

3,588,329	6/1971	Monk	358/260
4,057,834	11/1977	Nakagome et al.	358/261 X
4,060,834	11/1977	Mounts et al.	358/261
4,092,676	5/1978	Saran	358/261

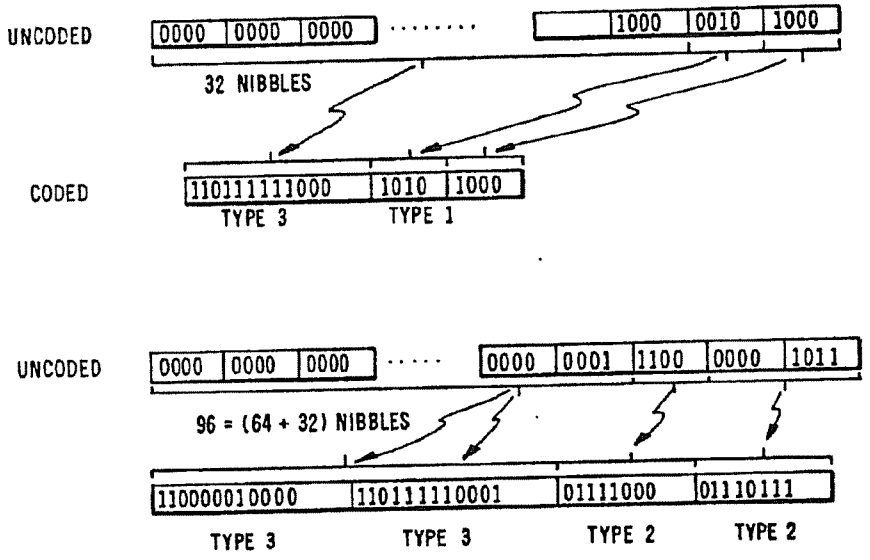
Primary Examiner—T. J. Sloyan

Attorney, Agent, or Firm—Robert E. Cunha

[57] **ABSTRACT**

A circuit to encode image data. The circuit receives image data in four bit nibbles which are either all-zero nibbles or terminating nibbles containing at least one non-zero bit. The circuit output is a series of code words, each a multiple of four bits and up to twenty-four bits long, packed into eight bit output words. Each code word contains a first part containing a run length specifying the number of received all-zero nibbles and a second part specifying the bit pattern of the terminating nibble. The circuit uses PROMs for the look-up and control elements and a pipeline of registers to allow high speed operation.

20 Claims, 14 Drawing Figures



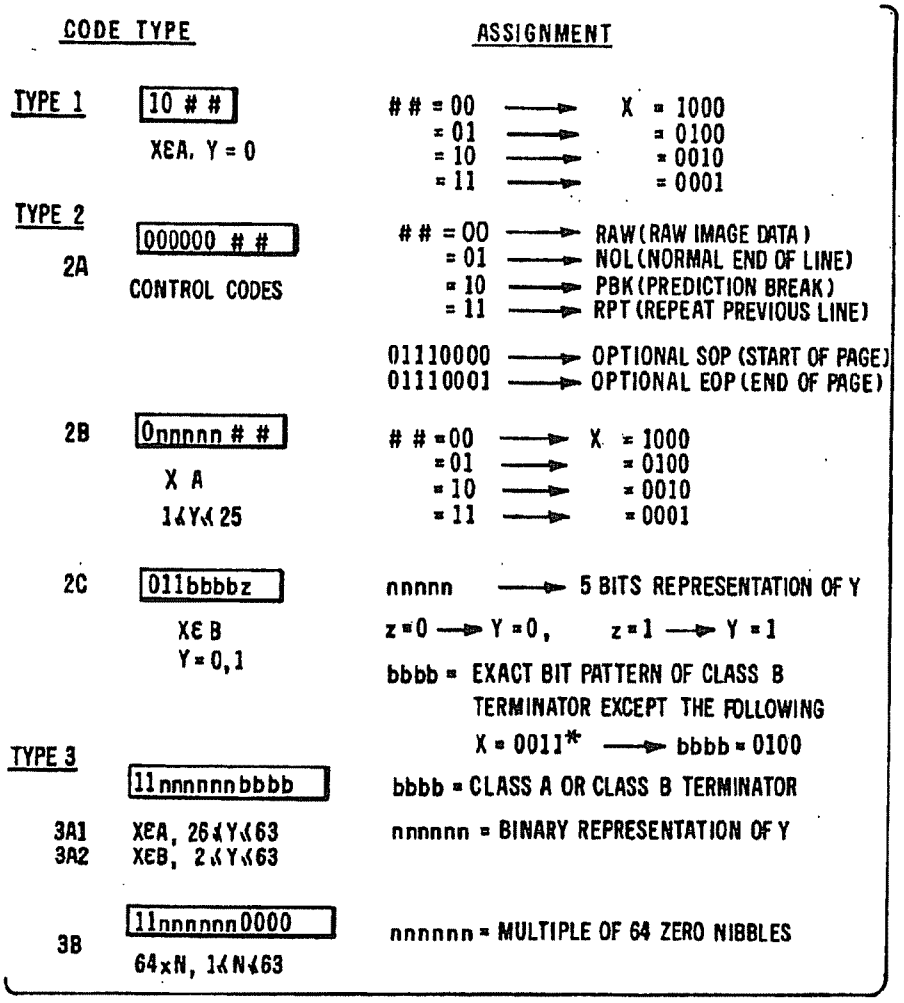

CODE TYPE
ASSIGNMENT
TYPE 1
10 # #
XεA, Y = 0
= 00 → X = 1000
= 01 → = 0100
= 10 → = 0010
= 11 → = 0001
TYPE 2
2A
000000 # #
CONTROL CODES
= 00 → RAW (RAW IMAGE DATA)
= 01 → NOL (NORMAL END OF LINE)
= 10 → PBK (PREDICTION BREAK)
= 11 → RPT (REPEAT PREVIOUS LINE)
01110000 → OPTIONAL SOP (START OF PAGE)
01110001 → OPTIONAL EOP (END OF PAGE)
2B
0nnnnn # #
X A
1≤Y≤25
= 00 → X = 1000
= 01 → = 0100
= 10 → = 0010
= 11 → = 0001
2C
011bbbbz
XεB
Y = 0,1
nnnnn → 5 BITS REPRESENTATION OF Y
z = 0 → Y = 0, z = 1 → Y = 1
bbbb = EXACT BIT PATTERN OF CLASS B TERMINATOR EXCEPT THE FOLLOWING
X = 0011* → bbbb = 0100
TYPE 3
11nnnnnnbbbb
bbbb = CLASS A OR CLASS B TERMINATOR
3A1 XεA, 26≤Y≤63
3A2 XεB, 2≤Y≤63
nnnnnn = BINARY REPRESENTATION OF Y
3B
11nnnnnn0000
64xN, 1≤N≤63
nnnnnn = MULTIPLE OF 64 ZERO NIBBLES

FIG. 1A

CODE ASSIGNMENT TABLE

DEFINITIONS

TYPE A TERMINATOR (0001, 0010, 0100, 1000)
TYPE B TERMINATOR (NOT A, NOT 0000)

Y	X

NIBBLE RUN-LENGTH FORMAT

A NIBBLE RUN LENGTH IS Y ZERO NIBBLES (0000) TERMINATED BY X NIBBLE
WHERE XεA OR XεB, Y IS ALWAYS INTEGER MULTIPLE OF (0000) NIBBLE
IF Y IS GREATER THAN OR EQUAL TO 64, THEN Y=64xN+Y'
Y IS CODED BY N BLOCKS OF 64 AND THE REMAINDER Y' CODED AS USUAL

FIG. 1B

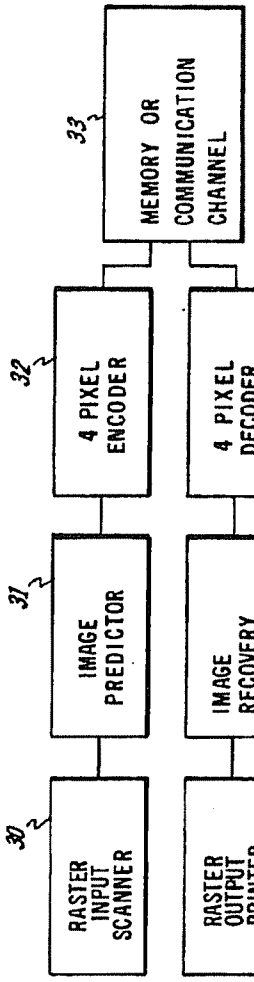


FIG. 3

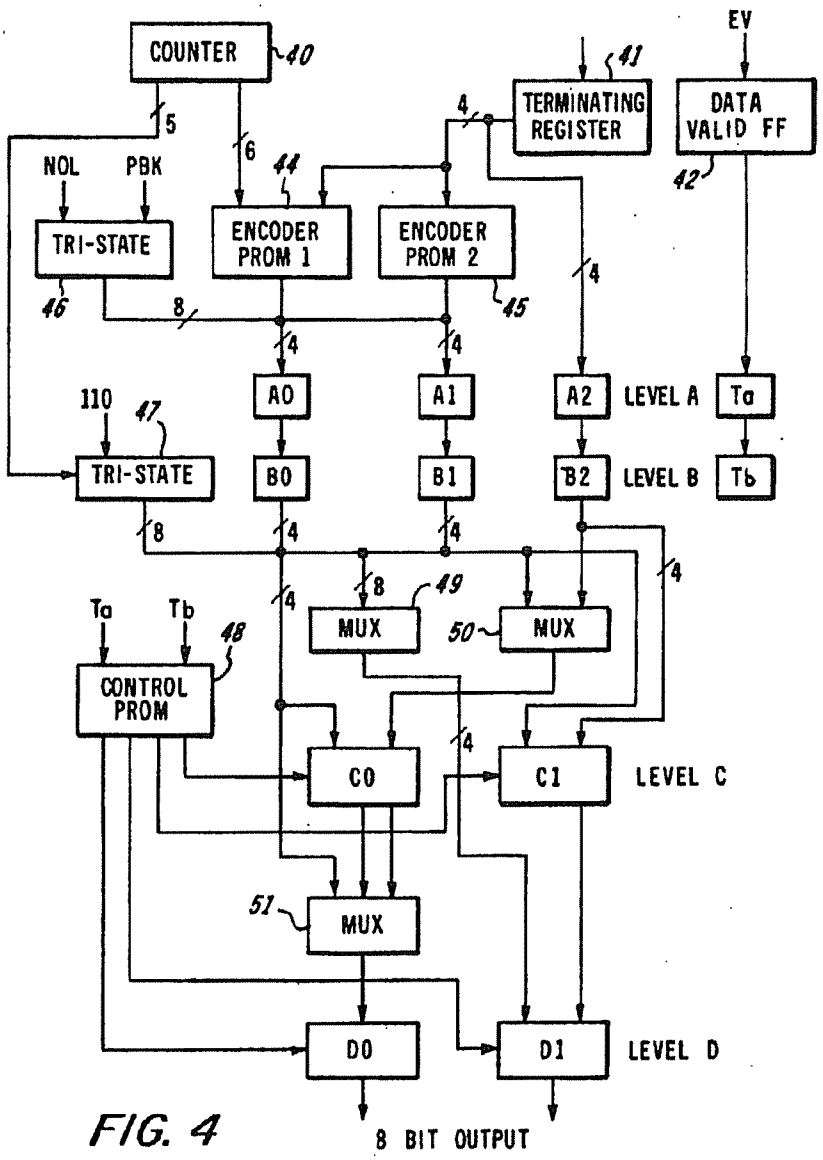
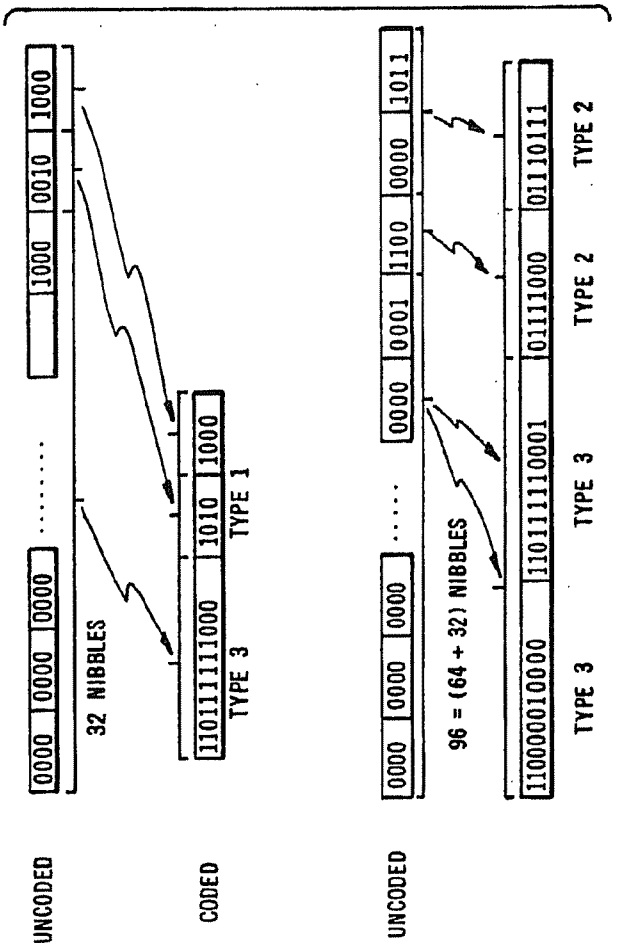

COUNTER
40
41
EV
TERMINATING REGISTER
DATA VALID FF
42
5
6
4
NOL
PBK
44
TRI-STATE
ENCODER PROM 1
ENCODER PROM 2
46
8
45
4
4
4
A0
A1
A2
LEVEL A
Ta
110
47
TRI-STATE
B0
B1
B2
LEVEL B
Tb
8
4
4
4
8
49
4
MUX
50
MUX
Ta
Tb
48
CONTROL PROM
C0
4
C1
LEVEL C
51
MUX
D0
D1
LEVEL D
8 BIT OUTPUT

FIG. 4

		CONDITIONS	CODE	TYPE
5 MSB ZERO	XεA	Y = 0	1	
		1 ≤ Y ≤ 25	2B	
		26 ≤ Y ≤ 63	3A1	
	XεB	Y = 0 OR 1	2C	
		2 ≤ Y ≤ 63	3A2	
MSB NOT ZERO	XεA	Y = 0	3B, 1	
		1 ≤ Y ≤ 25	3B, 2B	
		26 ≤ Y ≤ 63	3B, 3A1	
	XεB	Y = 0 OR 1	3B, 2C	
		2 ≤ Y ≤ 63	3B, 3A2	

FIG. 5

FIG. 2


UNCODED
0000 0000 0000 ..... 1000 0010 1000
32 NIBBLES
CODED
1101111111000 1010 1000
TYPE 3 TYPE 1
UNCODED
0000 0000 0000 ..... 0000 0001 1100 0000 1011
96 = (64 + 32) NIBBLES
TYPE 3 TYPE 3 TYPE 2 TYPE 2
1100000010000 1101111110001 01111000 01110111

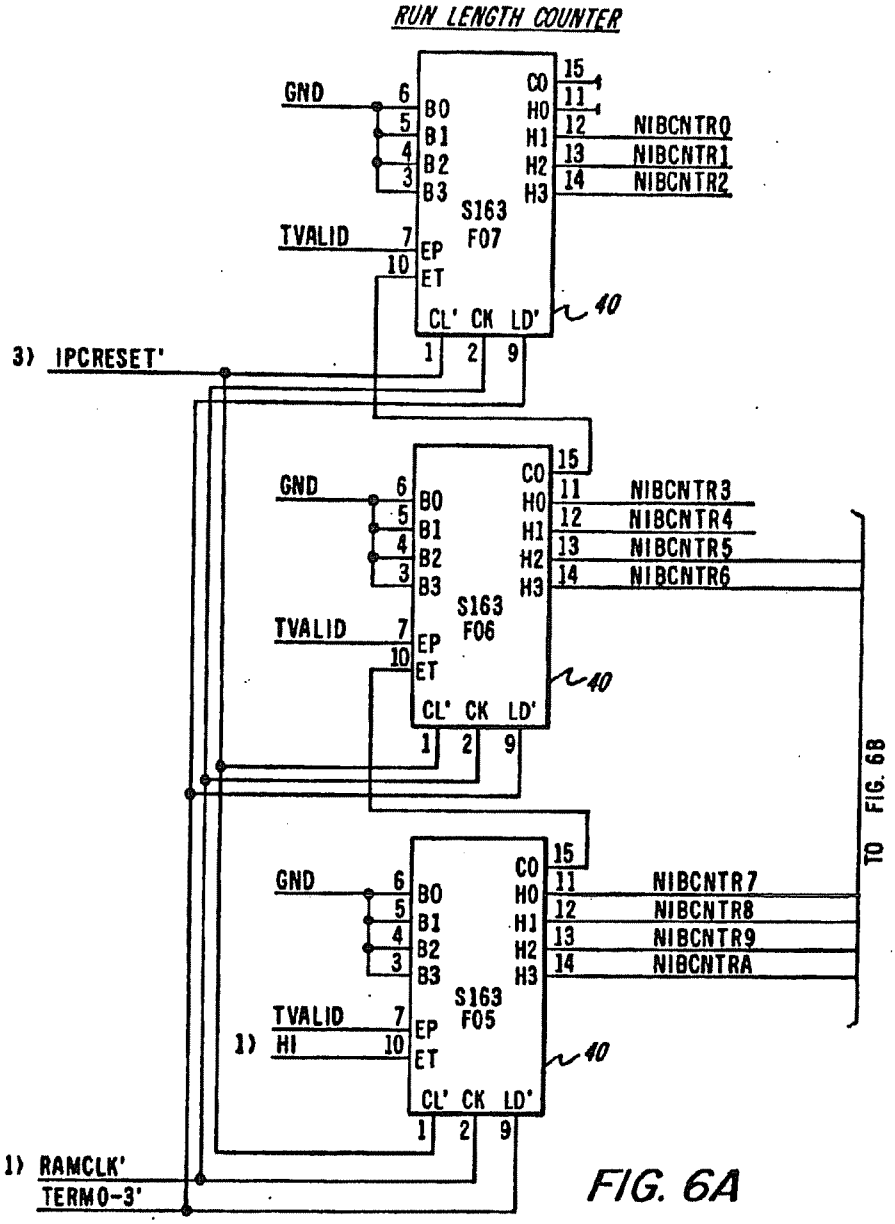

RUN LENGTH COUNTER
GND
TVALID
3) IPCRESET'
1) HI
1) RAMCLK'
TERM0-3'
S163 F07
S163 F06
S163 F05
NIBCNTR0
NIBCNTR1
NIBCNTR2
NIBCNTR3
NIBCNTR4
NIBCNTR5
NIBCNTR6
NIBCNTR7
NIBCNTR8
NIBCNTR9
NIBCNTRA
TO FIG. 6B
40

FIG. 6A

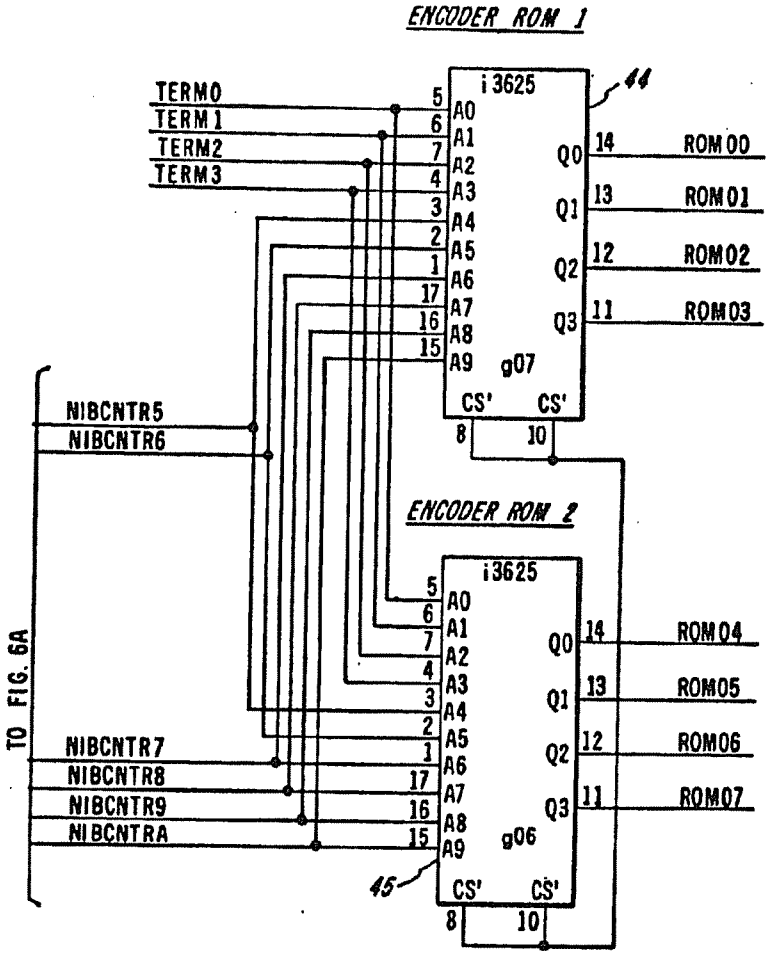

ENCODER ROM 1
i3625
44
TERM0
TERM1
TERM2
TERM3
A0
A1
A2
A3
A4
A5
A6
A7
A8
A9
g07
Q0
Q1
Q2
Q3
ROM00
ROM01
ROM02
ROM03
CS'
CS'
NIBCNTR5
NIBCNTR6
ENCODER ROM 2
i3625
ROM04
ROM05
ROM06
ROM07
g06
45
NIBCNTR7
NIBCNTR8
NIBCNTR9
NIBCNTRA
TO FIG. 6A

FIG. 6B

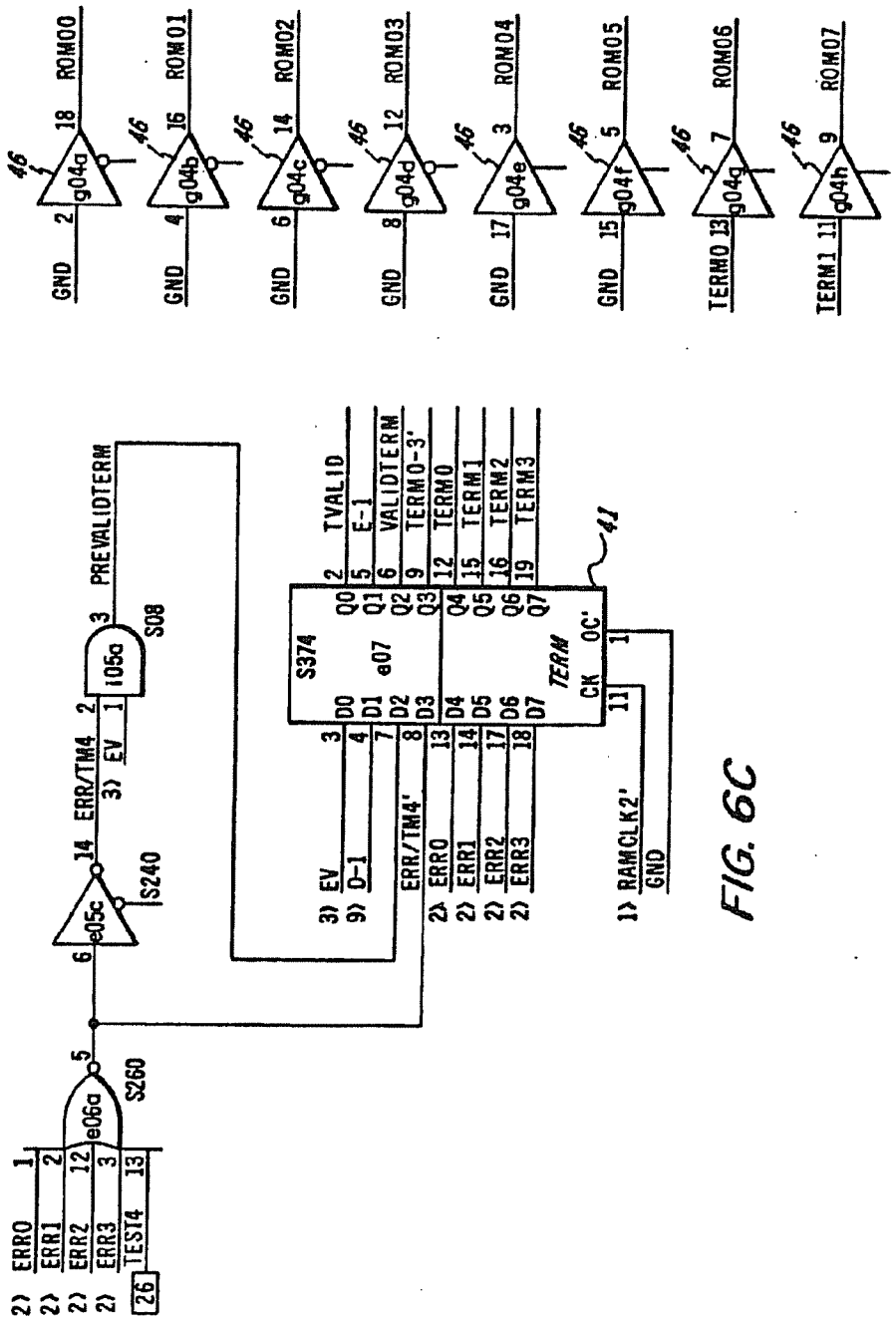

ROM00
ROM01
ROM02
ROM03
ROM04
ROM05
ROM06
ROM07
g04a
g04b
g04c
g04d
g04e
g04f
g04g
g04h
GND
TERM0
TERM1
PREVALIDTERM
S08
105a
ERR/TM4
EV
S240
e05c
S260
e06a
ERR0
ERR1
ERR2
ERR3
TEST4
S374
e07
TVALID
E-1
VALIDTERM
TERM0-3'
TERM0
TERM1
TERM2
TERM3
ERR/TM4'
TERM
OC'
RAMCLK2'
41

FIG. 6C

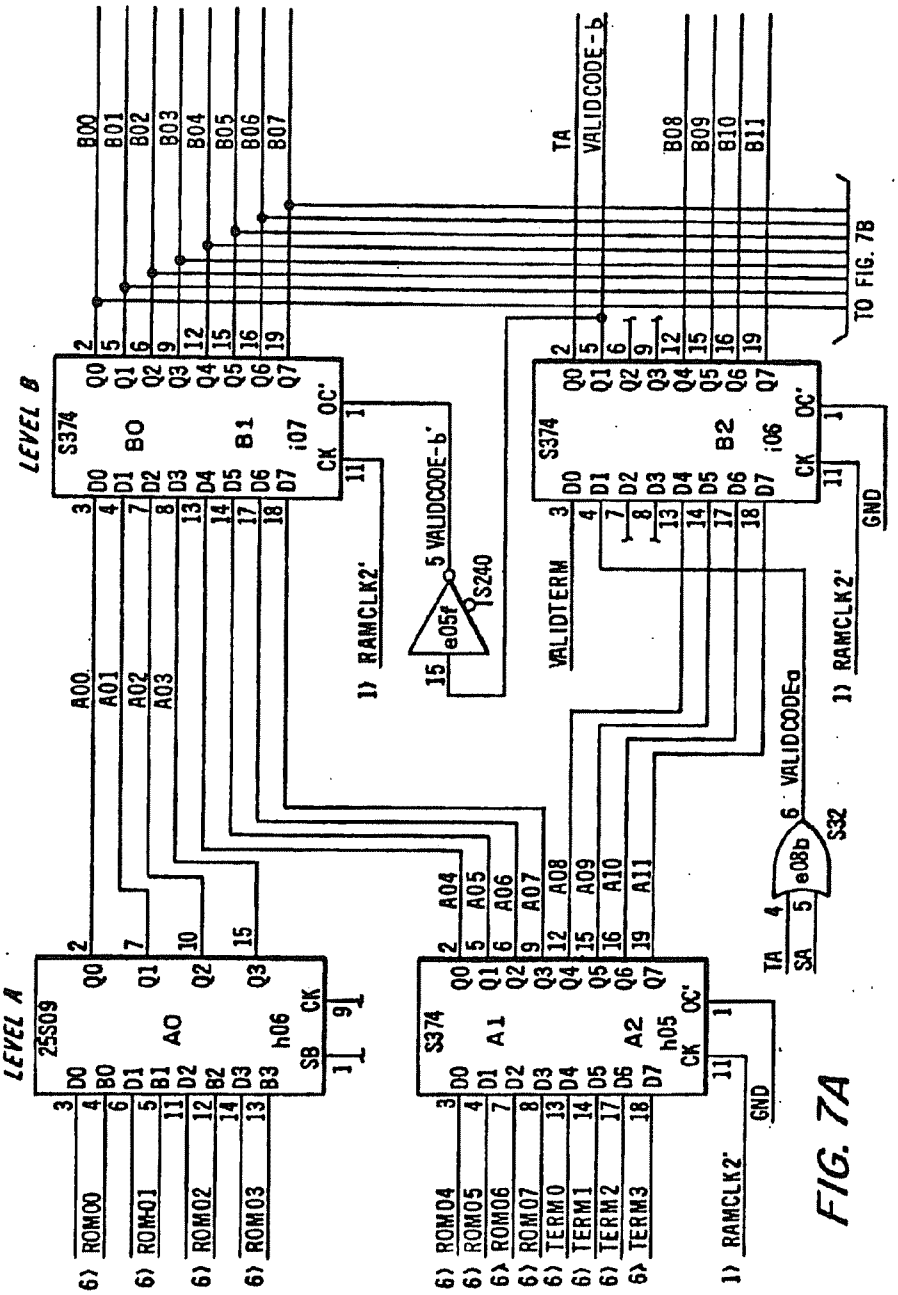

LEVEL A
LEVEL B
25S09
S374
S240
S32
B00
B01
B02
B03
B04
B05
B06
B07
B08
B09
B10
B11
TA
VALIDCODE-b
TO FIG. 7B
RAMCLK2'
VALIDTERM
VALIDCODEa
GND
ROM00
ROM01
ROM02
ROM03
ROM04
ROM05
ROM06
ROM07
TERM0
TERM1
TERM2
TERM3

FIG. 7A

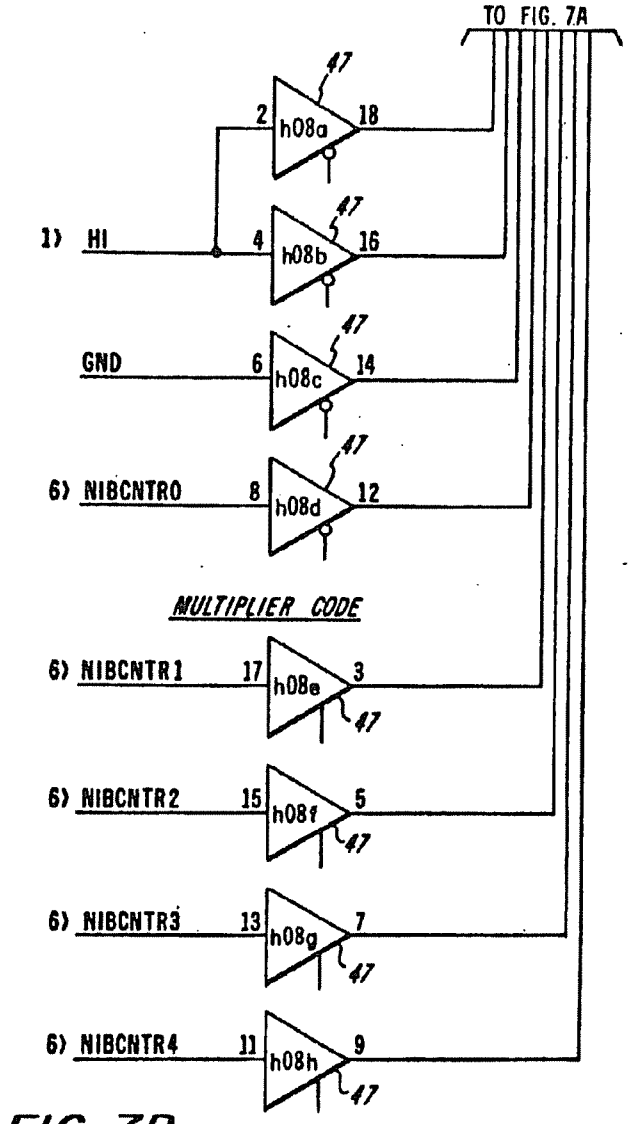

TO FIG. 7A
47
2
h08a
18
1) HI
4
h08b
16
GND
6
h08c
14
6) NIBCNTR0
8
h08d
12
MULTIPLIER CODE
6) NIBCNTR1
17
h08e
3
6) NIBCNTR2
15
h08f
5
6) NIBCNTR3
13
h08g
7
6) NIBCNTR4
11
h08h
9

FIG. 7B

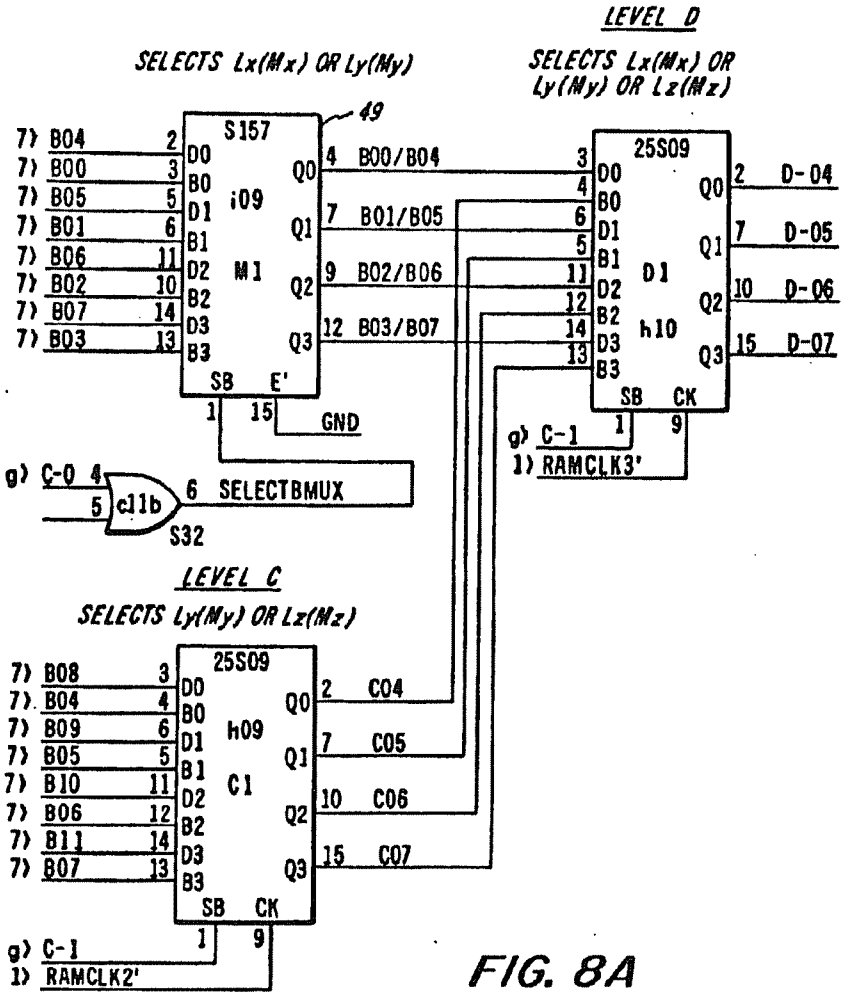

LEVEL D
SELECTS Lx(Mx) OR Ly(My)
SELECTS Lx(Mx) OR Ly(My) OR Lz(Mz)
49
S157
M1
i09
25S09
D1
h10
B04
B00
B05
B01
B06
B02
B07
B03
B00/B04
B01/B05
B02/B06
B03/B07
GND
C-0
cllb
SELECTBMUX
S32
D-04
D-05
D-06
D-07
C-1
RAMCLK3'
LEVEL C
SELECTS Ly(My) OR Lz(Mz)
25S09
C1
h09
B08
B04
B09
B05
B10
B06
B11
B07
C04
C05
C06
C07
C-1
RAMCLK2'

FIG. 8A

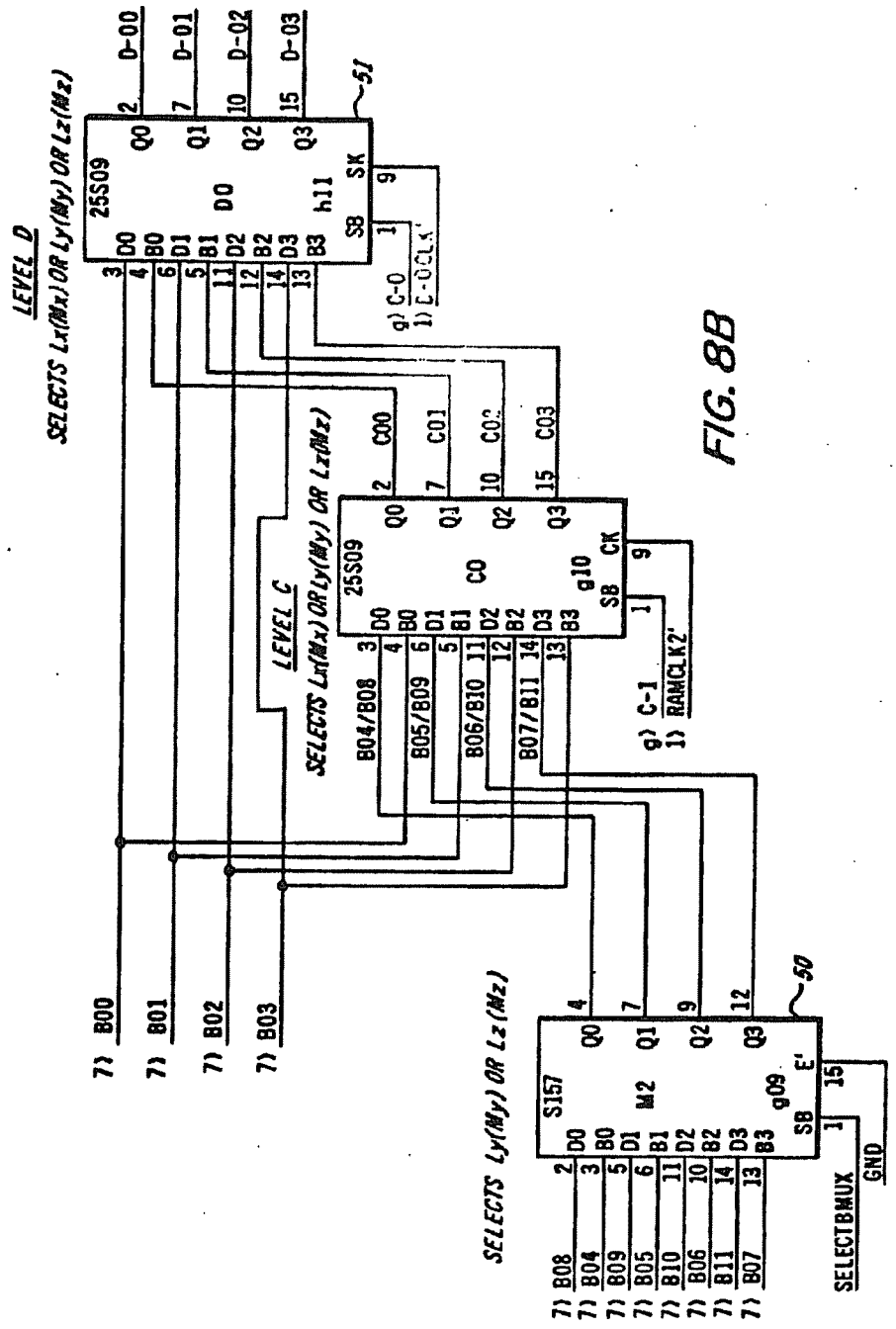

LEVEL D
SELECTS Lx(Mx) OR Ly(My) OR Lz(Mz)
LEVEL C
SELECTS Lx(Mx) OR Ly(My) OR Lx(Mz)
SELECTS Ly(My) OR Lz(Mz)
25S09
S157
D-00
D-01
D-02
D-03
C-0
C-1
RAMCLK2'
SELECTBMUX
GND
B00
B01
B02
B03
B04/B08
B05/B09
B06/B10
B07/B11

FIG. 8B

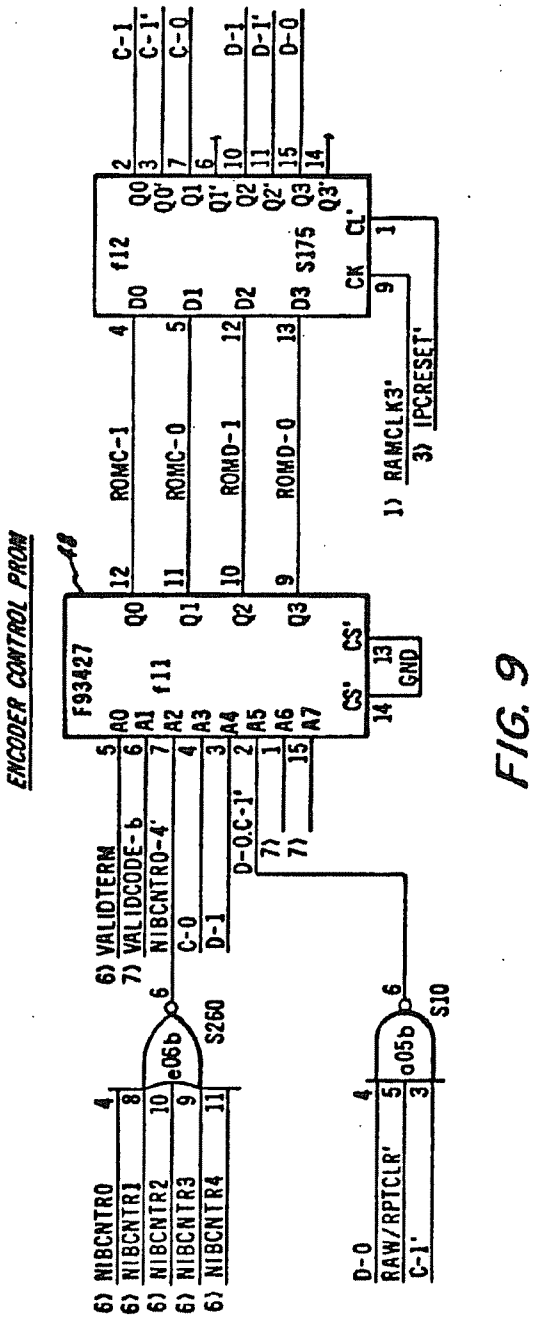

ENCODER CONTROL PROM
F93427
f11
f12
S175
S260
S10
o06b
o05b
ROMC-1
ROMC-0
ROMD-1
ROMD-0
RAMCLK3'
IPCRESET'
VALIDTERM
VALIDCODE-b
NIBCNTRO-4'
NIBCNTRO
NIBCNTR1
NIBCNTR2
NIBCNTR3
NIBCNTR4
RAW/RPTCLR'
GND

FIG. 9

4-PIXEL RUN-LENGTH CODE FOR DATA COMPRESSION

BACKGROUND OF THE INVENTION

This is a continuation of copending Patent Application, "A 4-Pixel Run-Length Code for Data Compression", Ser. No. 054,389, filed on July 2, 1979 now abandoned and Ser. No. 150,780, filed May 19, 1980 now abandoned.

This invention relates to the compression of binary data and more particularly to an improved run-length coding circuit.

There is a need in electronic systems for compacting data so that the information contained within said data may be stored in less memory space or transmitted at a higher rate.

One technique is the use of a simple run-length code where the number of bits is transmitted rather than the bits themselves. In other words, the number "64" would be transmitted instead of the 64 bits.

A predictor may be used before the run-length encoder to increase the compression. A predictor examines the previous bits and then predicts the state of the instant bit. The prediction and the instant bit are then compared, a successful prediction being coded as a "0" bit, an unsuccessful prediction being coded as a "1" bit. A well designed predictor increases the average run length and therefore, improves the efficiency of the encoder. In the system described herein a predictor is used ahead of the encoder but the claims are directed to the encoder alone since the encoder may be used with or without the predictor in any actual transmission or recording system.

A problem with a simple run-length encoder is that it must process each input bit as it is received. For example, after the reception of a string of 0s, the next bit must be inspected. If it is a 0, a run-length counter is incremented; if it is a one, the previous counter total is transmitted and the counter is initialized.

To speed up the data rate, the run-length encoder may be designed to process data bits in parallel. One example of this technique is described by John Monk in U.S. Pat. No. 3,588,329. The input bits are inspected in blocks of 64, 16, or 4 bits at a time and a variable length output word is produced containing the compressed data in the form of modified run-lengths.

The parallel processing of data in the form of data blocks increases the data rate, but ultimately a limit is reached based on the number of bits per block, which must be optimized for the particular application, and the circuit complexity, which must be minimized. An example of a commercially useful encoder is one that can operate in excess of 50M bits per second in the compression of image data.

SUMMARY OF THE INVENTION

The circuit described herein receives the output of a predictor in the form of four-bit nibbles, and produces an encoded and compressed output which is formatted into four, eight or twelve bits per word.

Because the data is first processed by a predictor, there is an increased likelihood of the encoder input comprising long strings of 0s. The encoder maximizes the compression of these strings by grouping the input data into data words compromising an uninterrupted line of nibbles containing all 0s, regardless of how many that may be, followed by a terminating nibble having at least one 1 bit. A first code word portion is assigned to the number of all-zero nibbles, and a second code word portion is assigned to the data pattern of the terminating nibble. The final code word is the combination of the first and second code word portions.

The circuit used to generate this composite code is capable of high data rates for two reasons. First, the input data is always received as a multiple of 4 bits and the output code words are always formed as four, eight or twelve bit words so that both input and output words may be processed and transmitted in words of four parallel bits. Second, the encoding process is a table look-up, resulting in a simple circuit and a high data rate.

The object of the invention, therefore, is to provide a modified run-length encoding circuit which allows the efficient encoding/decoding of binary data at high data rates.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A is a code assignment.

FIG. 1B is a set of definitions for the symbols used in FIG. 1A.

FIG. 2 comprises two examples of the encoding process.

FIG. 3 is a block diagram of a system in which the invention may be used.

FIG. 4 is a block diagram of the encoding circuit.

FIG. 5 is a decision tree showing the multiplexer sequencing. FIGS. 6 through 9 are schematic diagrams of the circuit.

DETAILED DESCRIPTION OF THE DRAWINGS

In the particular embodiment described herein, the specific rules for converting an input data string into coded words are illustrated in FIGS. 1A and 1B, and summarized in FIG. 5. An input data string is defined as a series of Y all-zero nibbles followed by one terminating nibble X that contains at least one 1 bit. As shown, a Type 1 output word has four bits, a Type 2 output word has eight bits and a Type 3 output word has twelve bits.

A Type 1 output word is generated if there are no leading all-zero nibbles (Y=0) and the terminating non-zero nibble, X, belongs to the set of A, where A={1000, 0100, 0010, 0001}. If these conditions are satisfied (that is XϵA, Y=0) then the output is in the form of 10## where the ## bits are assigned as shown in FIG. 1B.

If Y=0 or 1 and X is in the set of B, where the set of B is all four-bit combinations except A and all zeros, then a Type 2C output word will be produced. The output word will be in the form of 011bbbbZ where bbbb is the actual four bit pattern of the terminating nibble, except that bbbb=0100 when X=0011. Finally, Z=Y.

If $1 \leqq Y \leqq 25$ and X is in the set of A, a Type 2B word of the form 0nnnnn## will be reproduced, where nnnnn is the five bit representation of Y, and ## are assigned as shown.

If X is in the set of A and $26 \leqq Y \leqq 63$, or if X is in the set of B and $2 \leqq Y \leqq 63$, then a Type 3A output word is reproduced of the form 11nnnnnnbbbb where nnnnnn is the binary representation of Y and bbbb is the pattern of bits in the terminating nibble.

The above rules apply where there is a maximum of 63 all-zero nibbles before the terminating nibble. If there are 64 or more all-zero nibbles before a non-zero terminating nibble, the data string is converted into a first part comprising a number of sets of 64 all-zero nibbles and a second part comprising the remaining 0 to 63 all-zero nibbles and the terminating nibble. The first part is encoded into a Type 3B output word of the form 11nnnnnn000 where nnnnnn is the binary representation of the number of sets of 64 all-zero nibbles. The second set is then encoded according to the previously described rules.

These rules may be illustrated by way of the examples of FIG. 2. In Example 1, the first string comprises 31 all-zero nibbles and a terminating nibble of 1000. $X \epsilon A$ and $26 \leqq Y \leqq 63$ so a Type 3A output word is called for. In this case, 11,nnnnnn,bbbb=11,011111 (31 all-zero nibbles), 1000 (the actual bit pattern).

The next input word is 00100. Y=0 and $X \epsilon A$ so a Type 1 word is required. In this case 10##=1010.

The last input word is a 1000 which is also in the set of A so the Type 1 output word, 10##, becomes 1000 as shown.

In Example 2 of FIG. 2, the first input string has 94 zero nibbles and a terminating nibble of 0001 making a total of 96 nibbles. First the multiples of 64 zero nibbles are separated out. Here there is one group of 64 zero nibbles, so a Type 3B word is called for. 11nnnnnn0000=11,000001 (one set of 64 zero nibbles), 0000. Next, the remainder is encoded using the above described rules. There are 31 zero nibbles in the remainder and the termination nibble is of the set of A so a Type 3A output word will be produced. 11,nnnnnn,bbbb=11,011111 (31 zero nibbles), 0001.

The next input word is 1100 which is in the set of B, and Y=0. A Type 2C word is required. 011,bbbb,Z=011,1100 (the actual pattern), 0 (Y=0).

The final input word is 0000 1011. Here, Y=1 and the terminator is the set of the set of B so a Type 2C word is again required. 011,bbbb,Z=011,1011 (the actual pattern), 1 (Y=1).

FIG. 3 is a simplified block diagram of a typical image processing system for reading an image in binary form into and back from a communication channel or memory storage device 33.

The document is scanned by a raster input scanner 30 which transforms each scanned line of image into a series of binary bits representing black and white pixels. The majority of bits output are white or 0 bits since the scanned document usually is text. Next, the predictor 31 operates on the bit string, usually reducing further the number of 1 bits. Finally, the bit string is encoded using the results stated above to compress the data prior to transmission or storage.

To read from the communication channel or memory 33 and print on paper, the reverse process is called for. A decoder 34 expands the coded words into bit strings, an image recovery circuit 35 or depredictor recreates the original bit string as it was produced by the raster input scanner 30, and the image is printed by the raster output printer 36.

FIG. 4 is a detailed block diagram of the circuit. The incoming image data, in the form of four bit nibbles, are input to the eleven bit run length counter 40 which increments for each all-zero nibble received. An eleven bit counter was chosen to accommodate the count of a complete scan line of all-zero nibbles corresponding to an all-white scan. The input is also received at the terminating register 41 which controls the remaining circuitry if the received nibble is a terminating nibble. An additional input is the error valid (EV) bit input to data valid flip-flop 42. The error valid line going high indicates that the accompanying data word is a non-zero terminating nibble from the predictor.

During scan line operation, if the predictor correctly predicted all four bits of the nibble, the error valid signal will be low and the counter 40 is incremented. If the predictor failed to predict one or more of the four bits correctly, the error valid signal will be high. In either case, the circuit will address 1K×4 bit PROMs 44 and 45 with the contents of register 41 and the least significant six bits of counter 40. The result is that if a four bit output word is appropriate it will be contained in register A0; if an eight bit word is appropriate, it will be contained in registers A0 and A1; and if a twelve bit output word is appropriate, it will be contained in registers A0, A1 and A2.

In fact, registers A0, A1 and A2 will be loaded from PROMs 44 and 45 and register 41 whether the data is valid or not. The data will be valid if it was received with a high error valid bit. As the error data is shifted to "Level A", the error valid (EV) bit is shifted also, to flip-flop Ta, thus indicating that the Level A data is valid.

The control codes are also generated at Level A. For example, two control codes representing a normal end of line (NOL) and a predition break (PBK) may be multiplexed into registers A0 and A1 through tri-state devices 46 as shown.

During the same cycle, if there is a non-zero terminator and the count is more than sixty-four, the five most significant bits of the counter 40 and some leading code bits (110) may be coupled through the tri-state devices 47 and multiplexers 49, 50 and 51 into registers C0, C1, D0 and D1. Thus, the code words produced as the result of the reception of one terminating nibble may be clocked into various registers at Levels A, C and D. During succeeding clock times, this data is then shifted down through the four level pipeline to emerge as eight bit output words.

The process is controlled by PROM 48 which receives input bits indicating the size and location of the various code word segments and controls the multiplexers 40, 50 and 51 so that these segments are shifted through the pipeline properly.

The function of the pipeline elements is most easily demonstrated by a discussion of the worst case where register D0 contains data from a previous cycle, the instant input nibble produces a twelve bit Type 3B run length and a twelve bit Type 3A1 or 3A2 terminating code word, and where the subsequent code word produced is an eight bit Type 2 word. The circuit must produce and output these code words in the correct sequence, compacted into eight bit output words, without the loss of data.

During the first clock period the five most significant bits of the counter 40 and three leading code bits (110) are coupled through the tri-state devices 47 and multiplexer 49 and loaded into registers D1 and C0, and register C1 is zeroed, to produce a twelve bit Type 3B code word at Levels C and D.

At the same time a twelve bit Type 3A1 or 3A2 word is produced by the encoders 44, 45 and loaded into the A0, A1 and A2 registers.

During the second clock period the data in registers D0 and D1 is output, the C0 and C1 data is shifted into

registers D0 and D1, the A0, A1 and A2 data is shifted into B0, B1 and B2 and a new code word is loaded into Level A. At this point, Levels A, B and D contain data.

During the third clock period the data in registers D0 and D1 is output, the data in B0 and B1 is shifted directly into D0 and D1, and thereafter data is shifted down the pipeline in a straight forward manner.

The control of this process is provided by the PROM 48 which receives data information from the Ta and Tb flip-flops and is coupled by control lines to registers C0, C1, D0 and D1 and to multiplexers 40, 50 and 51.

FIGS. 6, 7, 8 and 9 are detailed schematics of the circuit. In FIG. 6, counter devices f07, f06 and f05 comprise the eleven bit counter 40. The six least significant bits are connected as address inputs to ROM devices g07 and g06 which are the encoder PROMs 44, 45.

The terminator register 41 is the lower half of register device e07, and receives the four error inputs Err0–3 from the predictor, said inputs constituting the predicted image data word inputs to this circuit. The error valid signal, EV, is also buffered through this device e07. The error valid signal, EV, which is buffered through this device e07 represents the difference between the predicted and actual scanned data. The presence of predicted data at the input causes the "Data Valid" flip flop to be set.

FIG. 6 tri-state devices g04a through g04h are the tri-state devices 46 of FIG. 4 that may be used to inject control codes into the data stream. In the case shown, there is a capability for generating four control codes using the Term 0 and Term 1 lines.

As shown in FIG. 7, the A0, A1 and A2 registers implemented from a multiplexer h06 and a register h05 receive twelve parallel bits of data on the ROM 00 through ROM 07 lines from ROM 1, 44 and ROM 2, 45 memory devices and on lines Term 0 through Term 3 from the terminating register 41. As described above, the next clock pulse will then transfer these twelve bits on lines A00 through A11 to the B0 and B1 registers i07 and B2 register i06.

The tri-state devices 47 of FIG. 4 are shown as devices h08a through h08h and couple the three leading bits (110) of the Type 3B code word and the five most significant counter 40 bits from lines NibCntr0 through NibCntr4 to the B0, B1 and B2 register output lines B00 through B11.

The C0 register, a multiplexing latch g10, is shown in FIG. 8 as receiving data from either the B0 register on lines B00 through B03 or through multiplexer 50 from either the B1 register on lines B04 through B07 or the B2 register on lines B08 through B11. The multiplexer 51 of FIG. 4 and the C0 register are combined into multiplexer/latch device h11 which is labeled as the D0 register, and which receives four bits of data from the B0 register on lines B00 through B03 or from the C0 register on lines C00 through C03.

The C1 register h09 is also a multiplexing latch receiving data from the B1 and B2 registers. Finally, the D1 register h10 receives either C1 register data through lines C04 through C07 or B0 and B1 register data through the M1 multiplexer 49 on lines B00 through B07.

FIG. 9 is a schematic of the encoder PROM 48 circuit of FIG. 4. The NibCntro-4 signal line is driven by the output of gate e06b which monitors the five most significant bits of the counter 40 to signify whether more than 64 all-zero nibbles have been received and therefore whether a Type 3B code word need be produced. The Valid Term input is a result of the exclusive ORing of the four bits of the latest data input nibble and signifies whether the last nibble is all-zero. ValidCode-b is a function of the bit in the Ta register of FIG. 4 and signifies whether the data in the A Level registers during the previous clock period, and in the B Level registers during the current clock period, are valid. These inputs are used as inputs to the encoder control PROM 48 which drives a decoder f12 to produce control signals C-0, C-1, D-0 and D-1 which are used to control the M1 multiplexer 49, the M2 multiplexer 50 and the C0, C1, D0 and D1 registers of FIG. 8.

The invention is not limited to any of the embodiments described above, but all changes and modifications thereof not constituting departures from the spirit and scope of the invention are intended to be covered by the following claims.

I claim:

1. A method for the compression of serial binary data comprising the steps of:
   - separating said serial data into bit nibbles,
   - counting the run length of all-zero nibbles received prior to receiving a terminating nibble,
   - converting the run length of all-zero nibbles into a first code word portion,
   - converting the terminating nibble data pattern into a second code word portion, the more common terminating nibble data patterns being compressed into second code words of shorter length than the original data,
   - generating a plurality of flag bits to identify the format of said code word, and
   - combining the first and second code word portions and said flag bits into a code word a multiple of n bits long.

2. The method of claim 1 where n=4 and x=4.

3. The method of claim 2 wherein said more common terminating nibble data patterns are 1000, 0100, 0010 and 0001, and are compressed into 2 bit second code words.

4. The method of claim 2 wherein the more frequently occurring run lengths are assigned to shorter code words.

5. The method of claim 4 wherein any all-zero count which is too large to be convertable into a first code word portion is separated into a first run length which is convertable, and a second run length which is the remainder,
   - said first run length being converted into a code word which contains only run length information, and
   - said second run length and the terminating nibble being converted into an additional code word as described in claim 4.

6. The method of claim 5 wherein the first run length is 64, all code words are 4, 8 or 12 bits, and code word prefixes of one, two or three bits identify the length of the word.

7. The method of claim 6 wherein code word prefixes of 10, 0 and 11 identify code word lengths of 4, 8 and 12 bits, respectively.

8. The method of claim 6 wherein the four more common terminating nibble bit patterns are coded into 2 bit code word portions, and the remaining eleven patterns are embedded directly into an 8 or 12 bit code word to enable simple decoding.

9. The method of claim 5 wherein otherwise unused codes are used as control codes.

10. The method of claim 9 wherein six control codes are converted into 8 bit code words.

11. A method of run-length encoding and compression for converting input data into output code words, each a multiple of n bits in length, for use in an image processing system including means to raster scan a document to form raster scan lines of black and white pixels, each line represented as a series of n binary bit nibbles, the method of converting strings of said input data into a series of encoded words having a run-length and data pattern format, said conversion comprising the steps of:

determining the run length of zero nibbles prior to receiving a terminating nibble,

generating a first code word portion representative of said run length,

generating a second code word portion representative of said terminating nibble, wherein said second code word portion may be a compressed representation of said terminating nibble,

generating a plurality of flag bits to specify the format of said code word, and

combining said first and second code word portions and said flag bits into composite code words, the bit lengths of which are multiple integers of n thereby permitting high data conversion rates of said input data.

12. The method of claim 11 including the step of compressing second code word portions comprising terminating nibbles of common occurrence by generating two bit second code word portions thereby producing shorter code words upon combining said first and second code word portions.

13. The method of claim 11 wherein n=4 and said multiple integers are 1, 2 and 3.

14. The method of claim 11 including the steps of separating out run lengths of said zero nibbles that are multiples of m, and

generating a second type of code word indicative only of the run length thereof.

15. The method of claim 11 including the step of providing one, two or three bit code word prefixes indicative of the code word length.

16. The method of claim 14 including the step of providing code word prefixes indicative of the code word length, said code prefixes being 10, 0 and 11, identifying code word lengths of 4, 8 and 12 bits, respectively, where n is equal to 4 and m is equal to 64.

17. A method of compressing serial binary data into code words comprising the steps of:

separating said serial data into 4 bit nibbles,

incrementing the count of all-zero nibbles if the current nibble is all zeros,

transmitting a code word if the current nibble is not all zeros, said code word being one of three types,

a first type 4 bits in length wherein the leading two bits are code word identifiers and the second two bits identify four of sixteen possible nibble bit patterns,

a second type 8 bits in length wherein the leading two or three bits are code word identifiers, two bits identify said four nibble patterns and the remaining bits are the all-zero nibble count, and

a third type 8 or 12 bits in length wherein the leading two or three bits are code word identifiers, four bits are an exact representation of the current nibble bit pattern and the remaining bits are the all-zero nibble count, and

zeroing the all-zero nibble count.

18. The method of claim 17 wherein said four identified bit patterns are 1000, 0100, 0010 and 0001.

19. The method of claim 17 further comprising a fourth type of code word 12 bits in length wherein the first one or several bits are code word identifiers and the remaining bits contain a representation of the all-zero nibble count, for use when the count is too large to be contained in any of the first three types of code words.

20. The method of claim 17 wherein a number of 8 bit codes are reserved as control codes.

* * * * *

EXHIBIT C

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UPPER BOUND, LOWER BOUND AND RUN-LENGTH SUBSTITUTION CODING

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Abstract

In this paper, several bounds of bandwidth compression for run-length coding are defined and discussed. First, a Maximum Entropy Bound is introduced as a lower bound for run-length coding. The Practical Coding Bound is an achievable bound employing independent run-length coding techniques, which provides us a useful guideline for compression performance. The Markov source bound is only an ideal case which does not usually agree with image statistics. Finally, we introduce a run-length substitution technique. The technique aims to achieve the Practical Coding Bound using only a subset of all run-lengths. The experimental results have shown that using as few as 1% of the message set, we can achieve compression ratios as high as 90% of the Practical Upper Bound.

Introduction

A number of run-length coding techniques has been reported in the literature. In the simplest form, the facsimile signal is quantized into a sequence of binary digits (1's and 0's) which directly represent black and white picture elements. Each sequence of digits of the same value is called a run. The basic idea is to encode only the length of the runs. In more advanced forms of run-length coding, the image data (after one or two dimensional prediction) is run-length coded.

A common problem that exists in each run-length coding technique is the selection of the proper message set. For a relatively low resolution (say, 120 lpi), there may be thousands of types of runs (1's and 0's) for encoding. It is observed that if one attempts to encode every possible run-length statistically, the complexity of hardware becomes unacceptable. Therefore, in each statistical run-length coding technique reported, there is a strategy for restricting the number of runs to be encoded. Those not selected for encoding can be represented by two or more other selected runs. The encoding message set thus becomes the major characteristic of run-length coding. After the set is chosen, each message can be assigned a unique code. The best code assignment will be the set of codes with the shortest average length; i.e., the minimum redundancy code. Huffman's coding[1] is a systematic procedure for constructing such a code with minimum redundancy.

The probability distribution of black and white runs in a binary facsimile signal has been investigated in literature[2,3]. It was constantly concluded that the run-length distribution has a strong exponential trend. However, the results discussed are strictly without predictive coding. In recent years, area prediction has been employed successfully to remove the inherent correlation between black elements that exists in the text structure.

Prediction and Compression Ratio

A portion of raster scanned data is depicted in Figure 1. In area prediction, the present element y is predicted by the previous elements $x_1, x_2, \ldots, x_n$.

$$\hat{y} = f(x_1, x_2, \ldots, x_n) \qquad (1)$$

The prediction function is usually nonlinear since binary data is used. A new binary sample e is generated by taking the modulo 2 sum of the prediction $\hat{y}$ and the actual y.

$$e = \hat{y} \oplus y \qquad (2)$$

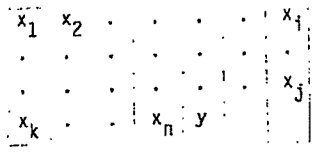


Figure 1 Area Predictor

It is found that area prediction would effectively remove most of the two dimensional correlation for a class of documents and thus improve the compression.

As more and more previous elements are involved in prediction, the prediction error becomes more and more independent of previous error. At an indefinitely high resolution, if the probability of independent occurrence of an error in a small interval Δt is $\lambda \Delta t$, where λ is the mean number of prediction errors. The probability that an error bit does not occur in Δt is $1 - \lambda \Delta t$. The arrival pattern of error bits in a scan becomes a Poisson Point process. The distribution of white runs is exponential.

$$P(t) = \lambda e^{-\lambda t} \quad \text{for } t \geq 0,$$

$$P(t) = 0 \quad \text{for } t < 0 \qquad (3)$$

Where t is the continuous run-length. The average run-length α for the exponential distribution is $1/\lambda$.

Now suppose that the continous run-length variable t is quantized to obtain discrete run-length r_i, the run-length distribution is found to be geometric[4,5].

$$P_i = \frac{1}{(\alpha - 1)} \left(\frac{\alpha - 1}{\alpha} \right)^i \quad i = 1, 2, \ldots \qquad (4)$$

The corresponding entropy for this distribution is:

$$Hg(P) = \alpha \log_2 \alpha - (\alpha - 1) \log_2 (\alpha - 1) \qquad (5)$$

The entropy is proved to be the upper bound for a given mean run-length, α.

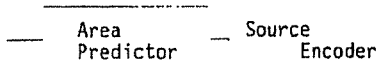


Figure 2. A General Bandwidth Compressor

A general functional block diagram of bandwidth compressor is depicted in Figure 2. The bandwidth compression ratio CR is defined as the total input bits to the compressor divided by the total output bits. If run-length coding is used in the Source Encoder, the total input bits to the compressor becomes the sum of the product of the run-length and corresponding frequencies. The total output bits from the compressor is the sum of the product of the coded lengths and corresponding frequencies, i.e.

$$CR = \frac{\sum_{i=1}^{n} f_i r_i}{\sum_{i=1}^{n} f_i l_i} = \frac{\sum_{i=1}^{n} P_i r_i}{\sum_{i=1}^{n} P_i l_i} = \frac{\alpha}{L}$$

Where f_i is defined as the frequency of i^{th} run; r_i, l_i are defined as the run-length and code length respectively of i^{th} run and P_i is the probability of i^{th} run. From Information Theory[6], if the successive runs are independent, the average length of minimum redundancy code is approximated to, and lower bounded by H(P), the memoryless entropy of run-length. Thus,

$$CR \leq \frac{\alpha}{H(P)} \qquad (7)$$

Where

$$H(P) = -\sum_{i=1}^{n} P_i \log_2 P_i$$

Maximum Entropy Lower Bound

For a given document with a fixed area predictor, the number of prediction error is uniquely determined. The prediction errors are reported to be nearly independent of each other. The run-lengths of prediction errors constitute a majority of single bit runs and a few other short runs. Let the prediction error be recorded as "B" and correct prediction be recorded as "W". We define the message set as shown on Table 1.

Table 1. Message Set

B	run-length 1
W+B	run-length 2
2W+B	run-length 3
.	.
.	.
.	.
1535 W+B	run-length 1536 (I)
1536 W	run-length 1536 (II)

If the last run of a scan is white, it is intentionally terminated by a "B". We further define n as sum of total prediction count, total end of line count, and N the total number of elements in a document. It is observed that only a prediction error "B" or an end of line could terminate a run. The total number of runs in a document is equivalent to the frequency n, thus the average run-length is

$$\alpha = \frac{N}{n} = \frac{1}{\lambda_1} \qquad (8)$$

where λ_1 is called the adjusted prediction error.

In order to be able to compute the entropy, the run-length distribution must be known. Most of the experimental evidence shown in the literature claimed that the successive run-lengths are nearly independent. Indeed, if the structural redundancy of an image is totally removed, the prediction errors occur independently. The run-length distribution becomes geometrical, which achieves the upper bound of entropy as shown in (5). Unfortunately, the occurrence of an error pattern usually is not a purely independent process. There is no known analytical approach to compute the data compression ratio for a given prediction error. However, since the geometric distribution achieves the maximum entropy, it provides the lower bound.

$$CR_L \equiv \frac{\alpha}{\alpha \log \alpha - (\alpha - 1) \log (\alpha - 1)}$$

Practical Coding Upper Bound

Since the geometric distribution is simply an assumption for analytical convenience and since the practical run-length distribution is usually not geometric, the practical data compression could easily exceed the lower bound. Using the run-length message set defined previously, the actual run-length distribution can be measured. For practical reasons, the run-lengths are usually coded as independent runs. The entropy of a memoryless run-length distribution can be achieved closely using the Huffman coding procedure (provided a fairly large message is defined). Since this technique of run-length encoding of the entire message set usually achieves the maximum practical bandwidth compression, the Practical Coding Upper Bound is defined as:

$$CR_U = \frac{\alpha_{max}}{H(P)_{max}} = \frac{1}{\lambda_1 H(P)_{max}}$$

Where α_{max} is the average run-length without substitution and $H(P)_{max}$ is the corresponding entropy for memoryless run-length coding.

Markov Source Bound

As discussed previously, the assumption of independent runs which resulted in Maximum Entropy Bound is usually not true in practice. There is interdependence between successive runs and the runs between successive scans even after area prediction. Nevertheless, it is not easy to identify the statistical model of interdependence of run-lengths. If we assume that a two dimensional image structure fits an nth order Markov source; the present element y is assumed to be statistically dependent only on n previous elements from the same and previous scanlines. The dependence is expressed by the state transition probabilities $P(\hat{y}/x_1,x_2,\ldots,x_n)$. The entropy of the Markov source is expressed as

$$H_M(P) = -\Sigma P(\hat{y}\, x_1,x_2,\ldots,x_n) \log_2 P(\hat{y}/x_1,x_2,\ldots,x_n)$$

The assumption of a Markov source model is simply an ideal case. The actual image structure is non-stationary and could be a Markov Chain of indefinite number of states. The compression ratio obtained by this assumption is expressed as:

$$CR_M = \frac{1}{H_M(P)} \qquad (12)$$

It is noticed that if the order of the Markov source is reduced to zero, it becomes a memoryless source. The entropy is denoted as Ho(P) for a given probability of error. Since the geometric distribution is an extension of memoryless source, it can be shown that the entropy Hg(P) is simply the product of the memoryless entropy Ho(P) and average run-length α

$$Hg(P) = \alpha\, Ho(P) \qquad (13)$$

It is observed that the technique of independent run-length coding addressed so far is a practical means of encoding the source with memory which exceeds the memoryless bound.

Run-Length Substitution

For the run-length codes used in achieving the practical coding bound, the possible run-lengths could range from one sample up to the whole scan length. The sampling rate required is more than a thousand samples per scan if legible reproduction of regular office documents is desired. Therefore, there will be more than a thousand runs to be encoded which is not at all acceptable in practice. It is more practical to limit the number of runs to be encoded. In the run-length substitution technique addressed, a fixed number of runs is picked from the entire message set. Runs without codes can be represented by two or more shorter runs with codes. For example, in Table 2, the run-length 4W is selected and 5W+B is not selected, the run 5W+B is substituted by 4W + (W+B).

Given a fixed number of substituting runs, there exists an optimum selection for a set of messages which achieve the maximum compression. If the runlength distribution is known, such as geometric distribution, the problem can be solved analytically. In the example of Golomb code[5] shown on Table 2, a small set of messages can be used to substitute the entire message set.

Table 2. Golomb Code Table m = 4

Message	Run-Length	Code words
B	0	000
W+B	1	001
2W+B	2	010
3W+B	3	011
4W+B	4	1000
5W+B	5	1001
6W+B	6	1010
7W+B	7	1011
8W+B	8	11000
9W+B	9	11001

Subs.Message	Code Words	Subs. Codes
B	000	000
W+B	001	001
2W+B	010	010
3W+B	011	011
4W	1	1 000
		1 001
		1 010
		1 011
		1 1 000
		1 1 001

The most direct criterion of optimization is to find the set of codes achieving optimum compression ratio given a number of substituting runs. In some applications, it is desired to limit the maximum Huffman code length for the purpose of using fixed size processor and storing codes in limited size of memory arrays. Then, the criterion of optimization is to find the set of runs achieving the highest compression ratio given the longest Huffman length allowable. The effect of run-length substitution is the increase in total number of run-length frequencies. Therefore, the average run-length " α " is decreased. On the other hand, the entropy H(P) is also decreased correspondingly, but to a lesser degree, however; due to lesser number of runs encoded and possibly due to the reshaping of the run-length histograms. The amount of compression lost by using this technique can be insignificant but it is not yet totally defined. From our past experience, the compression ratio seldom drops below the maximum entropy bound if over 5% of substituting runs are used.

Experimental Results

Ten standard documents were selected for our experiments. The contents of the documents and the percentage of usage is listed in Table 3. The resolution used is 192 x 192 pixel/inch which resulted in 1632 pixels per 8.5 inch scan. We have adopted a fixed seven elements predictor for our experiment as depicted in Figure 3.

X_1 X_2 X_3 X_4 X_5

X_6 X_7 Y

FIGURE 3. 7 Elements Predictor

In Figure 4, the Maximum Entropy Bound (Memoryless Source Bound), Practical Upper Bound and Markov source Bound of 128 states are plotted. The Practical Coding bound is always greater than the Maximum Entropy Bound in all 10 cases. Therefore, we can define the region between the Practical Coding Bound and Maximum Entropy Bound as the run-length substitution region. The degree of success of run-length substitution depends on the number of substituting runs and the optimum choice of encoding set. It is noted that the Maximum Entropy Bound is the lowest compression ratio obtained using the entire message set defined. If poor run-length substitution takes place or very few runs are selected, the compression ratio could fall below the lower bound. However, it is the goal that the compression ratio after substitution will approach the upper bound.

The measure of average compression ratio over the set of standard documents has been a controversial topic. If the compression ratio of document i is C_i with corresponding weighting factor W_i. Generally, the weighted average compression ratio over a set of documents is defined as:

$$C_w = \sum_{i=1}^{n} W_i C_i \qquad (14)$$

It is observed that the average compression ratio is not inversely proportional to the average time of transmission as it is for each individual document. However, if we define the time average compression ratio C_t in the following way:

$$C_t = \frac{1}{\sum_{i=1}^{n} \frac{W_i}{C_i}} \qquad (15)$$

Then it follows that C_t is inversely proportional to the time of transmission. Furthermore, using the general inequality of arithmetic and geometric means, it can be shown that:

$$C_w \geq C_t \qquad (16)$$

The results of run-length substitution are summarized in Table 4. The time average and weighted compression ratios are compared in the last column. Because of computing time limitation, the maximum substituting run was limited to 32. Figure 5 illustrates the effect of increasing the number of substituting runs on the compression ratio for the standard documents. It is seen that all the compression ratios using more than 15 substituting runs fall between the upper bound and lower bound. The improvement of time average compression ratio C_t as a function of substituting runs is depicted in Figure 6. In general, the data compression ratio increases with increasing number of substituting runs. The abnormal decrease of compression at 17, 28 and 29 runs are believed to be the effect of improper choice of initial substituting set. It is also observed that the improvement of compression ratio is faster with a smaller number of runs. As soon as the number reaches 20, the improvement becomes insignificant and almost linear with increasing number of runs. The time average compression ratio exceeds 80% of the upper bound with more than 10 substituting runs. It exceeds 90% of the upper bound with more than 15 substituting runs. A typical run-length substitution code with 16 runs is shown on Table 5. The maximum Huffman code length required is 8 bits, which would be suitable for implementation using an 8 bit processor.

Concluding Remarks

The combination of area-prediction and run-length coding is a practical means for bandwidth compression of two level images. However, the implementation of a statistical matched code to encode the entire message set can be very complicated. The common characteristic in each run-length coding technique is either to define a smaller run-length message set for statistical coding or to design an easily implementable run-length code for practical realization. The experiment of optimum run-length substitution is intended to maximize the bandwidth compression efficiency with given implementation constraints. In other words, the optimum substitution is one way to minimize the implementation cost for a given performance requirement. The maximum number of substituting run in the experiement was limited to 32. The substitution between 32 and the entire scan was not investigated. However, the compression performance at this range could be approximated by linear interpolation with fairly good accuracy since there is not much room for improvement. The major result of this experiment is that by using as few as 1% of the entire message set, as much as 90% of the upper bound compression ratio could be achieved.

Acknowledgement

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References

1. D.A. Huffman, "A Method for the Construction of Minimum Redundancy Codes", Proc. of IRE. Sep. 1952, PD 1098-1101

2. J.Capon, "A Probabilistic Model for Run-Length Coding of Pictures", IRE Trans. of IT, December, 1959, P. 157

3. S. Deutch, "Some Statistics Concerning Typewritten or Printed Material", Microwave Res. Inst. PIB, Brooklyn, N.Y. Report No. R-526, 1956

4. T.S. Huang, "An Upper Bound on the Entropy of Run-Length Coding", IEEE Trans. on IT, Sep. 1974

5. H.Kobayashi and L.R. Bahl,"Image Data Compression by Predictive Coding", IBM Journal of Research and Development, 1974

6. C.E. Shannon, "A Mathematical Theory of Communication", BSTJ. Vol. 27, PD 398-403 July 1948.

7. S.W. Golomb, "Run-Length Coding", IEEE Trans of IT, PD 399-401, July 1966

8. T.S. Huang, "Easily Implementable Suboptimum Run-Length Codes", ICC, 1975 pp 7-8, 7-10

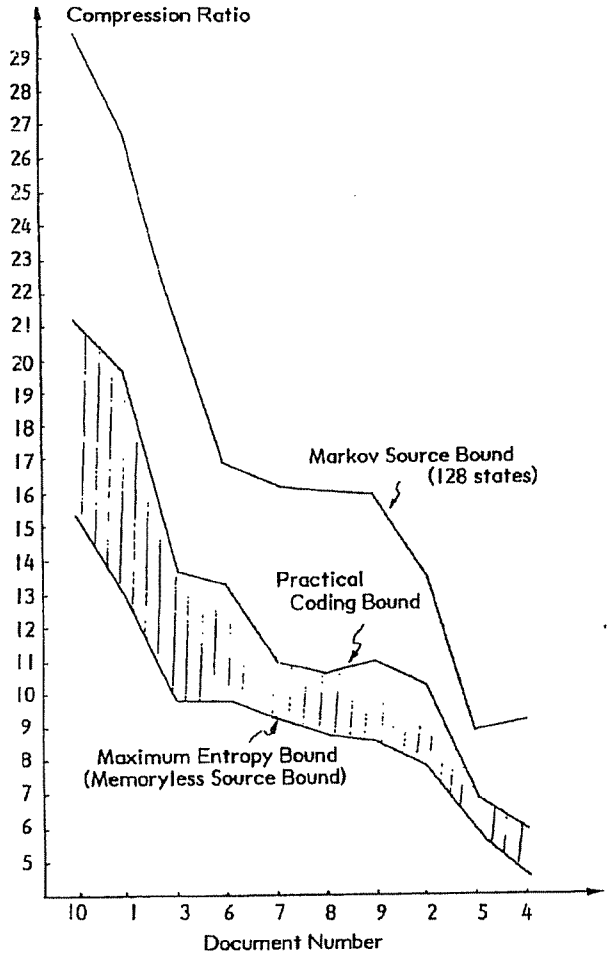


FIGURE 4. UPPER BOUNDS AND LOWER BOUND

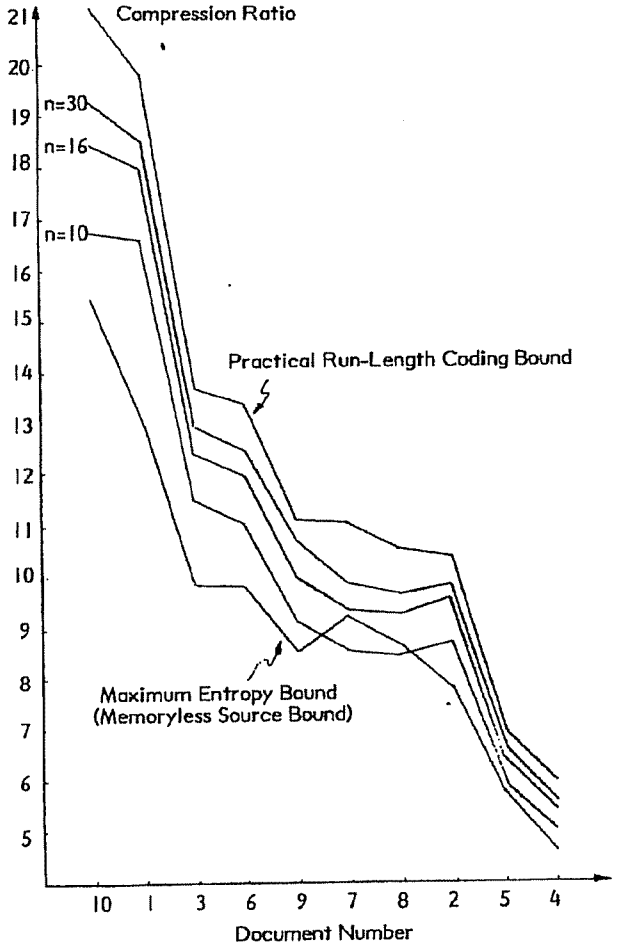


FIGURE 5. BOUNDED COMPRESSION OF RUN-LENGTH SUBSTITUTION

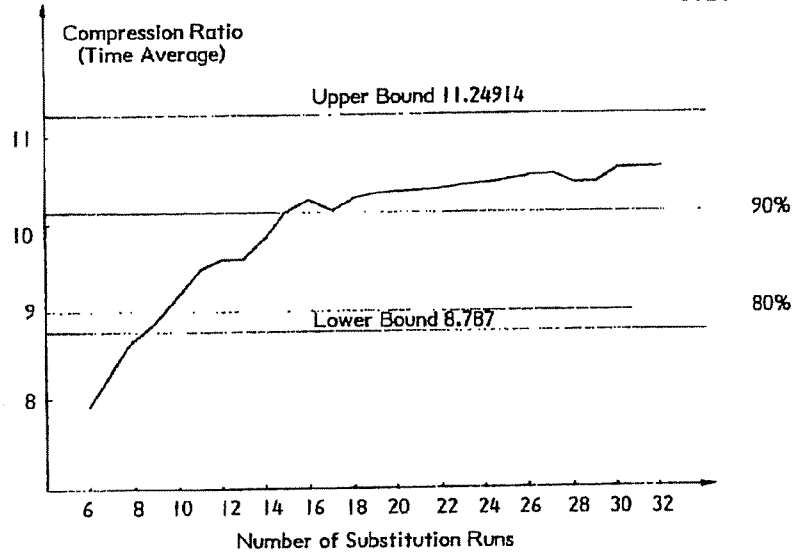


FIGURE 6. TIME AVERAGE COMPRESSION RATIO

TABLE 3 STANDARD DOCUMENTS

Document Number	1	2	3	4	5	6	7	8	9	10
Contents	Text	Text	Memo	Filled Form	Freight Waybill	Shipping Form	Purchase Order	Circuit Diagram	Comp. Prtg.	Test Pattern
Percent Usage	10%	15%	20%	4%	7%	7%	10%	9%	9%	9%

TABLE 4

	Document Number											
No. of Runs	1	2	3	4	5	6	7	8	9	10	Time Ave.	Weight Ave.
6	14.21	7.41	9.44	4.28	4.90	9.07	7.23	7.07	7.73	13.58	7.92	8.85
10	16.58	8.74	11.48	5.00	5.83	11.02	8.53	8.45	8.95	16.64	9.40	10.56
16	17.98	9.57	12.39	5.39	6.3[illegible]	11.96	9.33	9.26	[illegible]	18.42	10.26	11.53
25	18.04	9.53	12.54	5.50	6.36	12.09	9.54	9.34	10.1[illegible]	18.79	10.34	11.66
32	18.48	9.79	12.91	5.59	6.54	12.44	9.85	9.64	10.30	19.36	10.62	11.98
Upper Bound	19.98	10.34	13.70	5.91	6.92	13.34	11.00	10.59	11.08	21.19	11.24	12.88
Lower Bound	13.00	7.85	9.82	4.62	5.75	9.81	9.81	8.73	8.51	15.45	8.79	9.58

TABLE 5 RUN-LENGTH SUBSTITUTION CODE

Total Number of Bits = 3158103

RUN-LENGTH		FREQUENCY	PROBABILITY	HUFFMAN LENGTH
B	1	13970.	0.11827256	3
W	1 + B	6802.	0.05758697	4
W	2 + B	6664.	0.05641864	4
W	3 + B	6326.	0.05355707	4
W	4 + B	5493.	0.04650474	4
W	5 + B	4713.	0.03990112	5
W	6 + B	4333.	0.03668397	5
W	7	61216.	0.51826579	1
W	68	1765.	0.01494281	6
W	101	1124.	0.00951599	7
W	134	779.	0.00659516	8
W	170	1040.	0.00880483	7
W	220	2334.	0.01976007	6
W	520	641.	0.00542682	8
W	988	340.	0.00287850	8
W	1516	577.	0.00488499	8

Actual Compression = 10.26078 P = 26.75005 L = 2.60702
Compression Upper Bound = 11.24914 P = 64.64700 H = 5.74684
Ratio To Upper Bound = 0.91214
Number of Substituting Runs = 16