PRESERVATION AND MIDI TRANSLATION OF THE PIANOCORDER MUSIC LIBRARY

A Thesis

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By

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ABSTRACT

Presented are computer-based methods for archiving the aging music library of the Marantz Pianocorder, a digital player piano system manufactured in the 1970s by Superscope, Inc. and controlled by digitally-encoded cassette tapes. Two techniques are described for capturing the binary data from production copies of the tapes and archiving the original frames in computer data files. Also implemented is conversion software for translating the musical performances to MIDI files, taking into account the physical response of the Pianocorder's solenoid-based playback system. Two methods of generating the Pianocorder control signal from the stored data files are presented, allowing Pianocorder cassettes to be remastered and adding new capabilities to existing Pianocorder systems. Finally, a conversion program is realized for encoding new Pianocorder music from MIDI files, expanding the available library of music for Pianocorder systems still in use.

Dedicated to my wife, Jessica,

and to my parents, Lou and Joyce Fontana

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

This thesis describes a project to preserve the aging digital music library of an electro-mechanical player piano system that was popular during the late 1970s and 1980s. Manufactured by Superscope, Inc. of Chatsworth, California, it was called the Pianocorder Reproducing System. Unlike traditional player pianos using vacuum-powered pneumatics to play music from paper rolls, the Pianocorder activates the piano mechanism using electro-magnetic solenoids controlled by digital data stored on cassette tapes.

1.1 Early solenoid-based player piano systems

The idea of electrically playing a piano is not new. As early as 1905, the Tel-Electric Company of New York produced a solenoid-based piano-playing system under the names "Tel-Electric" and "Telektra" (Roehl, 1961, p. 34). Designed by one of America's first college-trained electrical engineers, John Forrest Kelly, the Tel-Electric system could be installed into any existing piano, allowing it to play music stored on perforated music rolls made of ribbon-thin sheet brass. The console housing the music roll, connected to the piano by a cable, permitted the operator to add expression to the music by varying the voltages applied to the Tel-Electric's solenoids. The system became quite popular in the United States prior to World War I, and thousands of Tel-Electrics were sold (Holliday, 1989, p. 31). Promotional materials stressed the simplicity of its compact solenoids compared with the complex mechanisms of traditional pneumatic player pianos.

The Nystrøm Melograph, patented in 1909, was another early piano system employing electromagnets (Holliday, 1989, p. 29). It was designed by Carl Wilhelm Nystrøm of Karlstad, Sweden and was capable of recording and playing back a pianist's performance, complete with expression. The Melograph recorded performances using an ingenious mechanism that cut slots into a paper roll running over rotating cylinders. The velocity of each key was measured by two displaced electrical switches on moving shafts attached to each key, such that each switch closure caused a slot to be punched in the moving paper roll. Thus, the key velocity was recorded as the vertical distance between slots on the roll. The Melograph could immediately play back the resulting perforated rolls using a mechanism that read the pairs of slots and activated solenoids to produce variable degrees of force based on the distances between slots. The Melograph seems to have been the first system capable of recording true polyphonic expression, making it one of the first true "reproducing" pianos[1]. Despite the Melograph's technical sophistication, it was not a commercial success.

Other mechanical musical instruments of the early 1900's used electro-magnetic mechanisms as well, such as the Mills Violano-Virtuoso (a violin-playing machine accompanied by a 44-note piano) and the Mills Magnetic Expression Piano (Roehl,

[1] Player pianos capable of playing back prerecorded music with dynamic expression were called *reproducing* pianos; the term was derived from manufacturers' claims that their player systems could accurately reproduce the performances of live pianists.

1961, p. 183). However, very few electro-magnetic piano systems were produced after about 1920. Their demise came largely because pneumatic player pianos were cheaper to manufacture and offered more authentic reproduction of subtle expression.

The poor expression capabilities of early solenoid-based piano systems were due to the physics of solenoid response. As explained in (Holliday, 1989, p. 29), solenoids are, by nature, not well-suited for controlling a piano action. A piano action is best activated by a strong initial force that grows weaker once a note has sounded. The pneumatics[2] used in traditional vacuum-powered player pianos provide such a response. A solenoid, in comparison, produces a weak initial force that grows stronger as the solenoid pulls or pushes. The technology to compensate for the weak-to-strong behavior of solenoids was not developed until recently.

1.2 Solenoid-based player piano systems of the 1970s

In the early 1970s, advances in technology made possible the next generation of player piano systems. Not all were successful enough to be developed into products. In 1973, G. W. MacKennon, of a small company called Hathaway & Bowers Inc., demonstrated the prototype of a solenoid-based reproducing piano system. No technical details were revealed, but one observer of this demonstration remarked, “It was so bad that most of the time you couldn’t even tell the name of the tune that was being played.” (W. Stahnke, personal communication, November, 1997). McKinnen ultimately ceased development of the system and got out of the business.

[2] A pneumatic is a hinged bellows-like mechanism of airtight cloth and wood that activates a note in a player piano by collapsing when suction is applied.

In 1974, Raymond Vincent of Detroit patented his ideas for a player piano system that used solenoids to activate the notes and cassette tapes for data storage (Vincent, 1975). Vincent's patent did not present a particular implementation but rather described in considerable detail how such a player piano system could be constructed. Vincent also suggested storing lyric text and control data on the tape along with the musical performances.

1.2.1 Wayne Stahnke's reproducing system

By the mid-1970s, Wayne Stahnke of Los Angeles had developed a solenoid-based player piano system using high-speed magnetic tape for storage (W. Stahnke, personal communication, November, 1997). This system used optical switches and shutters on the hammer shanks of the recording piano to measure hammer velocities with 10 bits of resolution, providing 1024 levels of expression. The system recorded individual expression for each note, but pedal information was stored in a simple on/off fashion.

In the early 1980's, Stahnke developed a more sophisticated version of the system that can more accurately measure and reproduce variations in the positions of the pedals. It was marketed by Kimball International as the Bösendorfer SE Computer-Based Piano Performance Reproduction System, sold as a factory-installed option in three models of Bösendorfer grand pianos. The system uses either magnetic tape or a dedicated IBM-compatible computer and serial interface to control the recording and playback hardware, permitting easy editing of the performance data. The SE system scans the keyboard 800 times per second and is capable of reproducing the motion of keys, hammers, and pedals with great accuracy.

The Bösendorfer SE is believed by many to be the finest reproducing piano system ever constructed (Holliday, 1989, p. 141). Thirty-seven of these systems were built, and most are still in use at leading universities and conservatories worldwide. Production of the Bösendorfer system ceased around 1990, due to poor marketing and inflated pricing (pianos equipped with the recording system were priced at over $90,000). Stahnke is now a consultant to Yamaha Corporation, and his technology is utilized in Yamaha Disklavier player pianos (Yamaha acquires, 1991, p. 42).

1.2.2 The OrrTronic Piano Recorder/Player

Stahnke's Bösendorfer system was priced well beyond the means of the average consumer, but beginning in the mid-1970s, several companies began to market more affordable electronic player piano systems.

Among the first modern, commercial systems to successfully produce expressive performances using solenoids was the OrrTronic Piano Recorder/Player (Holliday, 1989, p. 132; New Piano Playorr, 1976, p. 52), sold by CV Corporation of Opelika, Alabama. First available in 1975 and eventually renamed the *OrrTronic Digital 88 Piano Playorr*), the system was developed by John Herbert Orr, a pioneer in the field of magnetic recording. Designed as a retrofit kit converting any piano into a player piano, the OrrTronic system was one of the first player piano systems to use cassette tapes for storage.[3] Equipped with sensitive switches under the keys, the Piano

[3]In the 1970s, a number of cassette-based systems were marketed that enabled traditional pneumatic reproducing pianos to play music rolls digitally stored on cassette tape. Wayne Stahnke's Cassette Converter system is an example of such a product; it enabled pianos with an Ampico reproducing system to be driven by digital scans of Ampico rolls stored on tape. A similar system called the Tape Converter was sold in Australia. While these systems used cassettes, they are different from solenoid piano systems in that they used the piano's existing pneumatic reproducing system to play the music.

Playorr was able to record live performances and play them back. Reproducing piano rolls of famous pianists were transcribed to cassette tape and sold to owners of the OrrTronic system (Holliday, 1989, p. 133). There is little evidence that the product was a commercial success, however, and available materials on the system are devoid of any technical details.

1.2.3 The Teledyne Piano Player

Another solenoid piano system was developed in the mid-1970s by Joseph Campbell, Larry Minyard, and other engineers at Teledyne Industries, Inc. of Lewisburg, Tennessee (Holliday, 1989, p. 133; Turner, 1978, p. 2). Using technology from the aerospace industry, they developed a reproducing system called *The Piano Player*. Teledyne promotional literature (see Appendix D) described the system as

> "...an electronic player and recorder attachment that is easily installed in almost any piano. Instead of a perforated paper roll, a special digital cassette tape recorder activates the keys through a brilliantly engineered data processing system. The Piano Player can do all the things a player piano can do... and much more. It has the capability of playing prerecorded tapes with full dynamic expression. In addition, the device can record and instantly play back anything played on its keyboard."

Like the OrrTronic Piano Playorr, Teledyne's Piano Player used solenoids to activate the keys.[4] The system used cassette tapes for storage, updating the piano approximately 35 times per second. Thirty-two levels of expression were supported. The device could also record performances played at the keyboard using a microphone and thin wire spring switches under the keys. The microphone signal was broken into

[4] The OrrTronic system closely resembles the Teledyne system visually, but it is unknown whether the systems were in any way related.

two frequency ranges using high and low-pass filters[5]; bass and treble expression levels were assigned according to the amplitude of the signal for each range.

One patent covering the Teledyne system describes a device by which reproducing piano rolls could be encoded into digital cassette tapes to be used with the Piano Player (Walker, 1979). However, few technical details are presented in this patent, and it appears that the system was never fully implemented.

Introduced at the June 1974 National Association of Music Merchants (NAMM) trade show in Houston, the Teledyne Piano Player was priced at $1,200 (in 1970s dollars). It apparently was not sold in great numbers, though a few piano technicians of the era recall working with the systems.

1.2.4 The Pianocorder Reproducing System

These new solenoid player piano systems attracted the interest of Joseph Tushinsky, chairman of the board of Superscope, Inc., a home audio equipment company specializing in tape recorder technology. In the mid-1970s, Tushinsky met with Wayne Stahnke to discuss the possibility of developing Stahnke's tape-based reproducing system into a commercial product. However, an agreement could not be reached, and Tushinsky began seeking to acquire Teledyne's system. In 1977, Superscope purchased the design rights from Teledyne and used the Piano Player technology as the basis for its Pianocorder Reproducing System, sold under the Marantz brand name. Figure 1.1 illustrates the basic mechanism used in the Pianocorder, and Figure 1.2 shows a piano with the Pianocorder system installed.

[5] The dividing frequency was approximately 330 Hz.

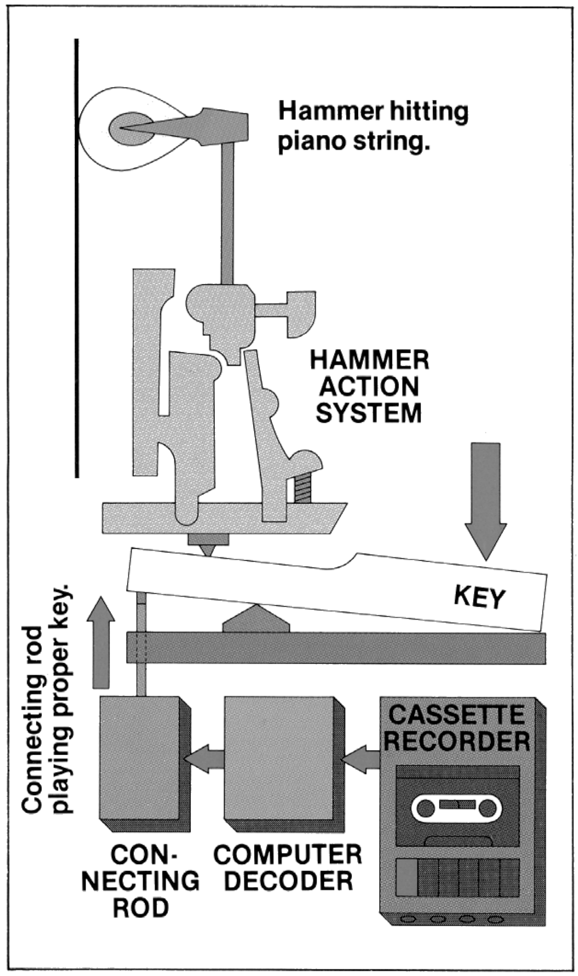
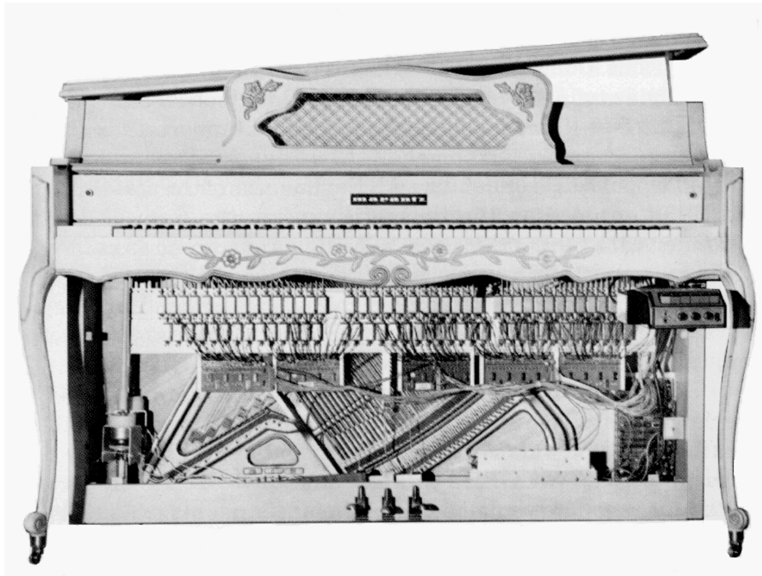


Figure 1.1: Simplified diagram of the Pianocorder mechanism



(Photo from *The Pianocorder Story*)

Figure 1.2: Piano with the Pianocorder system installed

The technical specifications of the Pianocorder closely follow those of the Teledyne system, and the tapes for both systems appear to use the same data format. Superscope contracted with Teledyne to manufacture the initial run of Pianocorder systems. In addition to the internally-installed model developed by Teledyne, Superscope also produced an external “Vorsetzer” model that could be pushed up to play a piano using rubber-tipped plungers above the keys and pedals.

Superscope introduced the Pianocorder in 1977 and immediately unleashed an aggressive marketing campaign; at the time, Marantz’s home audio division was experiencing flagging sales, and Tushinsky looked to the Pianocorder to save the company. (For examples of promotional literature, see Appendix B.)

Tushinsky had a diverse musical background. At one time, he played trumpet in NBC's Symphony of the Air under Arturo Toscanini. He also served as producer and conductor for the Carnegie Hall Light Opera and was a producer of Hollywood film musicals (Turner, 1978, p. iv; Pianocorder: The Potential, 1978, p. 74). While chairman of Superscope, he became fascinated by reproducing piano rolls— the lifelike paper-roll recordings made by eminent pianists earlier this century. Tushinsky quickly accumulated a collection of more than 18,000 piano rolls and in 1967 began playing them for the public in a popular series of radio broadcasts entitled *Keyboard Immortals Play Again— In Stereo.*

In 1972, Tushinsky commissioned Jim Miller of California to build him a custom "quad-format" Vorsetzer[6] on which to play his rolls (T. Steuer, personal communication, August, 1997). This one-of-a-kind pneumatic device was capable of accurately playing rolls for each of the four major reproducing systems (Ampico, Duo-Art, Welte, and Welte-Mignon) as well as standard 88-note (non-reproducing) piano rolls.

Once Tushinsky had acquired the Pianocorder technology, he realized that his vast collection of music rolls could form the basis of a music library for the new piano system if he could translate the rolls into the digital Pianocorder format. Since Superscope specialized in tape recorder technology, the cassette tape format adopted by Teledyne remained the logical choice of storage medium for the Pianocorder. Tushinsky knew that digital cassette tapes of reproducing rolls could be produced at a high profit margin, since they could be dubbed using standard equipment and using materials that were readily available at a fraction of the cost of the paper rolls he was replacing.

[6] A Vorsetzer (from the German "to sit in front of") is a mechanical device designed to sit before a piano and play its keyboard and pedals in place of a human pianist.

Figure 1.3: Sample Pianocorder cassette

To transfer piano rolls to computer format (and ultimately to cassette tapes for the Pianocorder), engineers at Superscope modified a German Vorsetzer. There were four major types of reproducing rolls to convert: Ampico, Duo-Art, Welte, and Welte-Mignon. The roll formats were similar in that they each divided the piano keyboard into treble and bass sections for expression purposes (thus allowing only two levels of intensity in notes struck at a given point in time). However, the split point between the treble and bass sections differed for each kind of roll, and each system employed a different method of encoding the expression. To facilitate accurate reproductions of music transferred from the various types of rolls, Superscope designed the Pianocorder with a variable split point controlled by two bits encoded in the music data.

(Photo from *The Pianocorder Story*)

Figure 1.4: Roll scanning equipment at Superscope

(Photo from *The Pianocorder Story*)

Figure 1.5: Superscope technician editing Pianocorder data

These bits are decoded upon playback, instructing the Pianocorder hardware to match the split point of the source material.

The Vorsetzer was equipped with switches to record the binary state information of the notes and pedals. The treble and bass dynamics were measured by attaching silver wire contacts to the expression pneumatics[7] in the Vorsetzer. The wires were placed in such a way that the opening and closing of the pneumatics caused the wires to contact a common buss bar in sequence. The outputs of the 32 switches formed a "walking code" that was transformed into a 5-bit value representing one of 32 levels of expression for playback on the Pianocorder (Stahnke, 1996b). The positions of the 32 wires were adjusted to achieve the best results upon playback.[8]

After converting many rolls using the modified Vorsetzer, Superscope contracted Joe Gaide at Cee-Jay Machine of Sun Valley, California to construct additional roll reading equipment to help meet demand for material (Stahnke, 1996b). One of these roll readers is shown in Figure 1.4.

With both transfer systems, the music data were recorded and edited on an Intel MDS-800 computer system using 8-inch floppy disks for storage. This equipment can be seen in Figure 1.5. The display on top of the monitor contains 128 light-emitting diodes showing the state of each note, pedal, and control bit in a given frame of Pianocorder data.

Figure 1.6: Ten-tape volume from the Pianocorder music library

1.3 The Pianocorder music library

Superscope produced approximately 350 tapes for the Pianocorder system, each holding about 40 minutes of music (20 minutes per tape side). These were organized into 30 ten-tape volumes, with the remaining cassettes sold separately. As a promotional incentive, Superscope offered 100 free cassettes to all new Pianocorder buyers.

[7] Expression pneumatics are bellows-like structures that control the strength of the vacuum available to the mechanisms striking the notes.

[8] It should be noted that this was a highly subjective method of performing the expression translation.

1.3.1 Music from piano rolls

Nineteen of the 30 volumes consist of piano rolls transferred to Pianocorder format using the roll scanning equipment at Superscope. Many of the rolls came from Joseph Tushinsky's personal collection. These tapes were touted as "Celebrated Performances Re-created from Noted Compositions and/or Reproducing Piano Rolls As Originally Performed by Distinguished Artists." Other rolls, featuring contemporary selections, were licensed from Q-R-S of Buffalo, New York.

1.3.2 Live performances

The Pianocorder volumes not derived from piano rolls contain material recorded live at Superscope in the late 1970s and early 1980s. These recordings are believed to have been made on a stock Pianocorder system equipped with the recording option sold by Superscope (the wire switch and microphone system originally designed by Teledyne). This recording system produced results of only mediocre quality. However, the Superscope engineers edited and cleaned up these recordings, marketing eleven volumes of tapes containing a variety of show tunes, jazz standards, romantic medleys, and popular hits of the 1970s.

1.3.3 The Contemporary Artists Series

In the early 1980s, Tushinsky wanted to produce a series of higher-quality recordings by popular pianists of the day. To achieve recordings of greater fidelity than the switch and microphone-based system could provide, Superscope developed a more sophisticated instrument called the Musically Expressive Recording Piano (MERP).

(Photo from *The Pianocorder Story*)

Figure 1.7: View of Tushinsky's vast collection of piano rolls

This recording piano was refined over a number of years, and it eventually employed optical switches and shutters on the hammer shanks to more accurately record a pianist's timing and dynamics.

Performances recorded by the MERP generally reproduced with poor fidelity on the Pianocorder, due to three fundamental limitations of the Pianocorder playback system: (a) the slow sample rate of only 35 frames per second; (b) the limited expression capabilities, allowing only two expression levels to be played at a time; and (c) the inability to record subtle variations in pedal position. Superscope was interested in marketing performances by world-class pianists, but before 1981, none would permit the release of their Pianocorder recordings— they did not feel that the Pianocorder could adequately reproduce their performances. Both Roger Williams and George Shearing made test recordings on the MERP but refused to participate in a commercial recording program.

Superscope engineer Jim Turner remedied the situation by developing a set of manual encoding tricks by which the quality of performances could be vastly improved. These techniques are based on a thorough understanding of the Pianocorder system's response and years of experience in editing Pianocorder performance data. Among Turner's tricks were methods for simulating half-pedaling effects, playing notes at more than two expression levels at once, and making notes strike at finer time resolution than the Pianocorder would seem to allow (by taking advantage of the inherent delay in the system's solenoid response). In this way, Turner was able to produce performances that transcended the Pianocorder's limitations and regained the confidence of the artists.

In 1981, Jim Turner created a Pianocorder rendition of Roger Williams' "September Song" for demonstration purposes. When Williams approved the performance, the *Contemporary Artists Series* was initiated. Between 1981 and 1987, twelve pianists recorded one-tape albums for the series: Roger Williams, George Shearing, Peter Nero, Steve Allen, Oscar Peterson, Liberace, Floyd Cramer, Anthony and Joseph Paratore, Teddy Wilson, Chick Corea, Johnny Guarnieri, and Dick Hyman. These tapes were sold individually, separate from the thirty main volumes of the Pianocorder music library.

Turner recalls that "by the time Roger Williams, Peter Nero, George Shearing, and Oscar Peterson had recorded, the program was so highly regarded technically and musically that other pianists accepted offers of engagement without any reluctance. In some cases, the artists even waived the rights of artistic approval because of their confidence in the music department's proven capacity for and standards of encoding quality." (Turner, 1985)

In 1985, after producing eleven of the twelve tapes in the Contemporary Artists Series, Turner documented his encoding techniques in an internal Superscope monograph entitled *The Theory of Pianocorder Tape Encoding*. In this treatise, Turner states that only four people were involved in the principal editing of the Contemporary Artists Series tapes: himself, Yabo Obien, John Horn, and Glenn Pickett. Other individuals were trained but "failed to attain satisfactory competence to contribute significantly to production." (Turner, 1985)

An incredible amount of effort was invested in manually editing the tapes in this series. Each tape required nearly six months of editing at a cost of over $47,000 per tape. Because the Marantz music department had only one studio with the appropriate equipment, the team of four editors worked in shifts, 24 hours per day. During each eight-hour shift, an editor typically produced only twenty seconds of finished music (J. Turner, personal communication, October, 1997). Turner's monograph was written with the intent of documenting the techniques involved so that the process could eventually be automated.

Superscope did take steps toward automating the procedure. Wayne Stahnke recalls that Superscope at one point had a Bösendorfer SE recording piano on site and had recorded a considerable number of performances on it, with plans to develop an automated processing system to simplify the highly-accurate performances recorded by the Bösendorfer for use on the Pianocorder (W. Stahnke, personal communication, November, 1997). There is no evidence that such an automated system was ever implemented, however. The Contemporary Artists Series concluded in 1987 with an album by Dick Hyman, released only months before the Pianocorder division was discontinued.

1.4 Demise of the Pianocorder system

The Pianocorder, despite the success of the Contemporary Artists Series, was ultimately ill-fated. According to industry press reports, Superscope chairman Joseph Tushinsky vastly overestimated the market for the Pianocorder. Tushinsky had anticipated sales of 60,000 units annually, hailing the Pianocorder as "the fourth most innovative home entertainment development of the twentieth century" (Pianocorder: the potential, 1978, p. 74). But over the product's ten-year lifetime, a total of some (estimated) 16,000 Pianocorder systems were sold (Tuttle, 1997; J. Alinsky, personal communication, March, 1997).

Marantz's Pianocorder division began to falter when Tushinsky purchased the Grand Piano Company of North Carolina and began manufacturing inexpensive pianos of relatively poor quality to house factory-installed Pianocorder systems. As one might expect, the idea of installing a $2000 reproducing system into a $1000 piano did not go over well with retailers, and sales began to decline.

Superscope subsequently underwent a number of corporate restructurings and later sold off the piano company. Tushinsky was eventually ousted in 1984, with total Pianocorder losses exceeding $20 million (Winners and losers, 1990, p. 144). Yamaha Corporation purchased the Pianocorder division of Marantz in late 1987 and terminated production of the system just three weeks later (Yamaha terminates, 1987, p. 24), very likely to eliminate competition for its new *Disklavier* line of electronic player piano technology.

Along with the patents to the electronic systems, Yamaha acquired the Pianocorder music library. Yamaha licensed Q-R-S Music of Buffalo, New York to sell duplicates of the Marantz Pianocorder cassettes. However, these have become increasingly poor in quality as the original reel-to-reel masters from which the tapes are duplicated have worn out (W. Dahlgren, personal communication, June, 1997).

With the exception of the celebrity recordings mentioned in the preceding section, Yamaha appears to have taken little action to preserve the music library or convert it for use with the Disklavier system. The original masters acquired from Marantz, in the form of 8-inch floppy disks, are now in storage at Yamaha's facility in Japan. It appears doubtful that Yamaha will do anything further with the material.

According to a spokesperson for Yamaha Corporation, "We have already gone through the library and selected the material that we legally could manufacture and that musically was suitable" (Macbride, 1996).

1.5 Preserving the Pianocorder music library

As of 1997, the Pianocorder system has been out of production for ten years, and many of the first original tapes manufactured by Superscope/Marantz are now twenty years old. Due to the finite lifetime of the cassette tape media, this extensive library of music is beginning to deteriorate and could be lost completely unless action is taken to preserve it. There are many reasons why this music should be saved.

First of all, the Pianocorder was a revolutionary product— one of the first commercial player piano systems utilizing magnetic storage media and digital electronics, and probably the most successful system of its kind. An impressive amount of engineering went into its design, including cleverly-designed playback circuitry built entirely from low-power Schottky TTL logic (i.e. no microprocessor).

The Pianocorder library also marked one of the first large-scale efforts at converting piano rolls to digital form. Although the conversions are not of archival quality, due to the low sample rate, the subjective method of translating the expression, and poor quality control, a sufficiently large quantity of rolls was transferred that it is worthwhile to preserve this collection for future generations. The data files may also be of interest to musicologists and those involved in studying the history of mechanical musical instruments. After the Pianocorder system was discontinued, Tushinsky's collection of piano rolls was reportedly purchased in Los Angeles by a Japanese collector by the name of Mr. Tsumura, president of a Japanese pharmacy, who brought them to Tokyo (Imai, 1997). In early 1997, the collection was returned to the U.S. and auctioned off in Los Angeles (Steuer, 1997). It is unknown whether or not the Tushinsky collection contained any rolls that were the last existing copies of a given selection. It is also uncertain whether all rolls transferred to tape are still extant. Although it is doubtful that the Superscope conversions are all that remain of some rolls, it is worth preserving the Pianocorder data just in case.

The Contemporary Artists Series recordings are the true gems of the Pianocorder library. These recordings of prominent pianists will surely be of interest to listeners and colleagues of these artists. Likewise, the portion of the thirty volume library recorded live at Superscope, despite its inferior quality, also merits preservation for its presentation of typical 1970s piano-playing styles.

An on-line search revealed that the U.S. Library of Congress has only five of the thirty ten-cassette volumes produced for the Pianocorder in its holdings. The condition of the library's tapes is unknown, but the collection is clearly far from complete. The Library of Congress is also missing the Contemporary Artists Series cassettes, the best examples of Pianocorder material. Fortunately, original copies of most Pianocorder cassettes are still available for loan from private collectors. But these tapes must be preserved quickly, because few collectors have taken any action to preserve their tapes.

Another reason for saving the Pianocorder library is the recent increased popularity of solenoid-based player piano systems. At least three vendors now offer disk and CDROM-based electronic player piano systems: Yamaha (Disklavier), Music Systems Research (PianoDisc), and Q-R-S (Pianomation). All of these systems are capable of playing material in Standard MIDI File format. The Pianocorder library, once converted to a collection of MIDI files, could continue to be enjoyed on these next-generation player systems.

Finally, there is a considerable number of Pianocorder systems still in use around the world. As the original tapes wear out, owners have begun to seek replacements. Q-R-S, the only supplier of cassettes, is experiencing an increasing amount of difficulty in producing dubs of adequate quality from the 20-year-old reel-to-reel masters. Therefore, a method of recreating new, clean copies of the original tapes is needed.

This thesis describes a two-year project designed to extract the raw digital data from Pianocorder tapes, archive it in computer data files, and translate the musical performances to the modern MIDI file format, making the music library more accessible to modern equipment. Also described are three sub-projects enabling (a) the remastering of original cassettes from files of archived data; (b) computer-based control of a Pianocorder system; and (c) the translation of MIDI files into Pianocorder format, which greatly expands the body of music available for Pianocorder systems still in use.

CHAPTER 2

TECHNICAL ISSUES AND PREVIOUS RESEARCH

The task of archiving the Pianocorder music library presents a number of technical challenges. Before describing the various approaches used in the final solution, it is necessary to become familiar with the details of the Pianocorder system's operation and how its data may be archived and converted to the modern MIDI[1] format. Along with the above topics, this chapter presents the technical goals to strive for and evaluates other individuals' attempts at doing these conversions.

2.1 Technical overview of the Pianocorder system

The Pianocorder system uses electro-magnetic solenoids to play digital music data stored on ordinary cassette tapes. The playback circuitry does not load the data into any kind of memory but instead plays directly from the tape using a decoding system of counters, shift registers, and other digital logic.[2] The playback tempo is changed simply by varying the speed of the tape player.

[1] Musical Instrument Digital Interface

[2] See Vincent (1975) for an excellent introduction to the general technologies used in systems such as the Pianocorder.

The data on the tape are stored as a stream of binary data in bi-phase, a self-clocking serial encoding (described in detail in Chapter 3). The bi-phase stream of the Pianocorder system runs at 4500 bits per second and consists of a stream of 128-bit data frames, each storing the full state (all notes and pedals) of the piano. This results in the Pianocorder having a nominal frame rate of $4500/128 = 35.15625$ frames per second. The bi-phase decoding circuitry of the Pianocorder is able to sync to rates of up to 15% faster or slower than the normal value of 4500 Hz, giving the user some freedom to adjust the tempo.

Each Pianocorder data frame stores the binary states of 80 notes along with the states of the soft and sustain pedals. Also encoded into each frame are two 5-bit expression values for the treble and bass sections of the keyboard, a 2-bit value indicating the appropriate keyboard split point for these treble/bass sections, and one byte of ASCII data for lyrics.[3] Finally, each data frame contains a sync byte (`FDh`, `11111101` in binary) that is used by the playback hardware to properly synchronize the decoding of logical frames to the binary data stream. The Pianocorder frame format is described in detail in Appendix A.

No error checking mechanism is present (not even simple parity), but the playback circuitry does require that two valid frames be received before accepting the data as valid. A frame is considered valid if two conditions are met: (a) the sync byte is correct, and (b) the sync byte appears at the correct point in the frame. At any time, if either condition is not satisfied, the Pianocorder will reset itself (turning off all notes and pedals) and wait for two frames that do meet these criteria.

[3] These lyrics were displayed on an optional scrolling LED display sold as an accessory to the Pianocorder, the Superscan Display Console.

For increased bandwidth and reliability, the Pianocorder's tape transport runs at 3.75 inches per second— twice the speed of normal cassettes.

Unlike more modern solenoid piano systems, the Pianocorder cannot reproduce polyphonic expression, the capability to assign different velocities to each individual key. Instead, the Pianocorder splits the keyboard into two halves, much like the pneumatic reproducing systems of the 1920s, using its 5-bit treble and bass intensity values to control the expression in each half. For a given frame, all treble notes and all bass notes receive the same respective intensities. However, the expression levels apply only to one data frame and can be entirely different for adjacent frames. In this way, notes in nearby frames can all receive different expression levels and still be played at about the same time. This can approximate the effect of polyphonic expression reasonably well, although the response time of the solenoids must be taken into account. This is especially true for notes struck at low velocities.

2.2 Modern player piano systems

In the late 1980s, Yamaha Corporation introduced the first of a new generation of diskette-based solenoid player systems that are now on the market. Yamaha's Disklavier system surpasses the Pianocorder's capabilities in several ways. Not only does it support all 88 notes of the piano (instead of the Pianocorder's 80) with up to 127 levels of expression (versus the Pianocorder's 32), it also supports half-pedaling (pedals may be depressed at any of 127 levels, whereas on the Pianocorder they are simply all the way down or all the way up). Most importantly, the Disklavier more closely permits polyphonic expression, which allows any note to be struck at any velocity at any time. In contrast, the Pianocorder allows only two velocities (treble and bass) at a given time. The Disklavier also allows much higher timing resolution than the Pianocorder: the playback system is accurate to 4 ms on the Disklavier (Litterst, 1997), whereas the Pianocorder updates the piano at coarser 28 ms intervals. The Disklavier system features the capability to record performances played by a live pianist, using a highly accurate system of optical shutters at the hammer shanks to measure note velocities. The Disklavier's performance is continually monitored by a feedback loop (the optical shutters measure the actual velocity achieved by each solenoid firing), allowing the on-board control software to compensate for any variations in the piano's physical response.

Music Systems Research markets a competing product called the PianoDisc system. Much like the Pianocorder, this is a solenoid player system that can be installed into virtually any existing piano. Its capabilities are similar to those of the Disklavier, though it lacks the Disklavier's sophisticated optical shutter recording mechanism, instead using a mechanical switch strip beneath the keys. Further information about the PianoDisc system is presented in (PianoDisc unveils, 1992; PianoDisc PDS-128, 1993; PianoDisc Story, 1993).

Q-R-S Music of New York markets a system called Pianomation. While seemingly not as popular as the Disklavier and PianoDisc systems, Pianomation has the advantage of Q-R-S' vast music library; Q-R-S has been in the business of producing music for player pianos since 1900 (Q-R-S Pianomation Center, 1996). Q-R-S is also the only manufacturer to offer an external version of its piano-playing mechanism; a Vorsetzer configuration called the Playola has been on the market since mid-1997 (Q-R-S Music, Inc., 1997).

Finally, one modern piano system, the Piano MIDI-Matic, employs a hybrid of old and new technology. Instead of the compact solenoids used in other modern systems, it uses digital electronics to activate a traditional pneumatic mechanism. Similar to the Pianocorder, the MIDI-Matic uses specially-encoded cassette tapes for storage but is also MIDI compatible. The system is not capable of reproducing expression, however (Thompson, 1991, p. 61).

The Disklavier, Pianomation, and PianoDisc systems can all play music from 3.5" floppy diskettes. The Pianomation and PianoDisc systems can also play from specially-encoded compact discs, using one audio channel to store an analog representation of the digital control data. These systems can also play music data in MIDI file format. Using the Pianocorder-to-MIDI conversions described in this thesis, the Pianocorder music library can be adapted to play on any of these modern systems, as well as on other types of MIDI equipment.

2.3 Using MIDI to store piano music

MIDI (Musical Instrument Digital Interface) is a communications protocol for digital music devices. Developed by several commercial synthesizer manufacturers in the early 1980s so that their products could exchange control information, it quickly became the industry standard and has become increasingly popular, especially with the rise of multimedia and Internet technology. Today, MIDI ports are found on almost every type of electronic musical instrument, including synthesizers, digital pianos, and tone modules. Most computer systems sold today come with MIDI interfaces as standard equipment, and MIDI interfaces are available for computers lacking built-in

MIDI ports. In addition to music applications, MIDI is also used to control light boards and sound equipment in theatrical performance applications.

As described in (Glatt, 1997b), MIDI consists of a unidirectional asynchronous 31.25 kbps serial link transmitted as an opto-isolated current loop between two devices. MIDI devices typically contain MIDI IN, OUT, and THRU ports, using standard 5-pin DIN connectors. In hooking up two devices, one device's IN is connected to the other device's OUT and vice versa. The THRU port on a device generally echoes all data received at the IN port, allowing multiple MIDI devices to be daisy-chained.

The actual data transmitted consists of a series of 8-bit command and data bytes, each with one start bit and one stop bit, no parity, for a total of 10 bits per byte. At MIDI's rate of 31.25 kbps, each byte requires 320 μs, and a maximum of 3125 bytes can be sent in one second. Command bytes are indicated by having their most significant bit set to 1 (no data bytes may have a MSB[4] of 1). There are separate command bytes for each possible type of event, such as a note on, a note off, and so on. Most commands are either 2 or 3 bytes in length.

To reduce the latency in transmitting a sequence of commands, MIDI employs a simple compression scheme called *running status* in which the last command byte remains in effect until it is replaced with another command byte. This allows a string of commands of the same type to be represented by transmitting the actual command byte just once, then sending the arguments for each individual instance of the command. Using running status typically reduces the amount of bandwidth required to transmit a string of messages by 30-50%.

[4] Most significant bit

A more complete description of MIDI and its history is presented in (Loy, 1985) and (Lehrman, 1993), and a full specification of the MIDI protocol, listing all available commands, is given in (Glatt, 1997b). Only a subset of the MIDI command set is needed to represent piano performances; the necessary commands are listed in Table 2.1.

Some researchers argue that MIDI cannot adequately represent piano performances. The author agrees with this claim in cases where a piano performance is to be stored as accurately as possible. MIDI permits only 127 levels (7 bits) of expression (key velocity) for notes, and only 127 positions of each pedal can be recorded. Truly accurate recordings of piano performances made on sophisticated equipment (such as the Bösendorfer SE recording piano, which measures hammer velocities to 10 bits of precision) cannot be represented in MIDI without reducing the accuracy of the expression and pedal data. (MIDI does provide adequate timing resolution, however.)

The author believes MIDI is suitable for representing Pianocorder performances, however. MIDI is entirely capable of representing the Pianocorder's timing and expression levels without any significant loss of accuracy. The Pianocorder's 32 expression levels are easily represented in MIDI's 127 expression levels. MIDI supports timing accuracy in excess of 1000 Hz, which is well above the Pianocorder's coarse 35 Hz update rate. MIDI is especially suitable for representing Pianocorder performances because all modern solenoid piano systems support the MIDI file format and internally utilize MIDI (or a proprietary variation of it; e.g. Yamaha's ESEQ format) to store music data.

Command byte	Argument byte 1	Argument byte 2	Function
90h	note (00h..7Fh)	vel (00h..7Fh)	Note on
80h	note (00h..7Fh)	vel (00h..7Fh) (usually 00h)	Note off
B0h	40h	40–7Fh	Sustain pedal on
B0h	40h	00–3Fh	Sustain pedal off
B0h	43h	40–7Fh	Soft pedal on
B0h	43h	00–3Fh	Soft pedal off

Table 2.1: MIDI commands used to represent piano music

MIDI supports sixteen channels of event data to handle multiple devices and multitimbral instruments. However, only one channel is needed to represent piano music, since a piano can produce just one kind of sound. In a MIDI data stream, the events for all sixteen channels are mixed together. The channel for a particular event is encoded into the low nybble[5] of the command byte; i.e. channel 1 is 0h, channel 2 is 1h and channel 15 is Fh. MIDI users have generally adopted the convention that piano music should be placed on channel 1, especially if no other instrumentation is present in a sequence. This explains why the command bytes in Table 2.1 all have 0 as the low nybble, indicating channel 1.

It is important to note that MIDI is an *event-based* method of encoding a performance. That is, a note is represented by sending a note-on event, waiting for the note's duration, then sending a note-off event. No data is transmitted while the note is held on. In contrast, the Pianocorder uses a *state-based* encoding of performance data. In this representation, the entire state of the piano is repeatedly transmitted

[5] A "nybble" is half (4 bits) of a "byte."

as a continuous stream of samples, regardless of whether or not any notes or pedals have changed state since the previous frame.

Each storage format has its advantages. The Pianocorder's event-based scheme transmits a lot of data (approximately 35 sixteen-byte frames (560 bytes) per second). However, since each frame is encoded exactly the same way (essentially containing a raw capture of the state of the piano), the circuitry to interpret this data stream was simple to implement using basic digital logic. This was an important consideration for the Pianocorder because microprocessor-controlled consumer equipment was not common in the mid-1970s when the Pianocorder was designed. Superscope kept the cost of the Pianocorder down by making the data complex but the hardware simple.

The disadvantage to the Pianocorder's format of streaming frames is that a large quantity of data is required to store relatively little information. Over the same period of time, the Pianocorder will use the same amount of data to store a simple one-finger melody as it will to store a complex Rachmaninoff concerto. MIDI is more economical about storage; simple pieces will use less space than complex ones because there will be fewer individual events representing the performance. However, the disadvantage of MIDI is that more sophisticated electronics are required to process a MIDI data stream. But with the explosion in MIDI's popularity in recent years, a number of single-chip MIDI processors have hit the market and virtually eliminated the difficulty in adding MIDI support to a device.

2.4 Pitfalls in translating from Pianocorder to MIDI

Translating the Pianocorder's state-based encoding to MIDI's event-based encoding is, on the surface, a straightforward process. The simplest approach involves comparing each Pianocorder frame with its predecessor and merely generating an appropriate MIDI event whenever any note or pedal changes state. This algorithm can be easily represented in a few dozen lines of code, once the Pianocorder data has been acquired from the tapes.

However, this method of conversion turns out to give poor results, because it fails to consider the physical response of the Pianocorder's solenoid-based playback system. Doing a straightforward literal conversion as described above is essentially making the assumption that the Pianocorder was capable of instantaneous response, regardless of the velocities at which notes were struck. This is physically impossible. In reality, a piano note actuated by a solenoid requires a variable amount of time to strike once the solenoid has been energized. The response time is a function of the desired acceleration of the piano action and the physical response of the solenoid when energized to produce a particular note velocity.[6] Response times of notes struck in a solenoid piano system are generally in the tens to hundreds of milliseconds, with shorter response times for notes struck with greater force and longer response times for notes struck with less force.

The engineers who edited the Pianocorder material were aware of the Pianocorder's limitations, and they encoded some Pianocorder material with the system's physical response in mind. Some performances received more attention than others.

[6]In the case of the Pianocorder, the drive circuitry energizes the solenoids at 170 VDC with a varying duty cycle to achieve various levels of expression.

The most carefully-edited tapes were those comprising the Contemporary Artists Series. Using encoding methods developed by Superscope engineer Jim Turner, these performances were painstakingly edited to closely approximate live performances. Turner's staff used coding tricks derived from a solid understanding of the Pianocorder's behavior. When converted without taking this behavior into account, the tapes produce bland results that fall short of what the editors intended.

MIDI commands are assumed to be processed immediately upon receipt; i.e. if a MIDI "note on" command is received by a MIDI device, the device is expected to sound the note immediately. Therefore, to produce accurate MIDI representations of Pianocorder performances, it is necessary to simulate the behavior of an optimally-adjusted Pianocorder (and piano) exposed to a stream of control data, then create a stream of MIDI events representing the notes and pedals actuated by the *simulated* Pianocorder.

This approach is developed in Chapter 4, and it has been found to produce superior results compared to the more simplistic method described above. Unfortunately, that algorithm seems to be the only method others have considered when converting Pianocorder performances to MIDI.

2.5 Previous research involving Pianocorder technology

The Pianocorder was a reasonably open system, and Superscope readily provided the schematics and other technical documentation required for experimentation. This made it attractive to a number of researchers in the field of computer music who wanted to experiment with programmable pianos, for example, in the style of Conlon

Nancarrow, a composer who created complex and unconventional performances for player piano by hand-punching paper rolls. In the early 1980s, Yamaha had not yet introduced its Disklavier system, and the Bösendorfer SE system was beyond the means of most experimenters. Consequently, several individuals designed their own programmable piano systems by adapting Pianocorder hardware to be driven by a computer. In (Hopkin, Bernstein & Riddell, 1991), Bart Hopkin describes several of these projects in detail.

Among the first to interface the Pianocorder to a computer were composer Richard Teitelbaum and computer systems designer Mark Bernard. In 1982, they developed a system controlling three interlocked Pianocorders playing three grand pianos. Using digital electronics, the system recorded performance information from one piano, manipulated it according to various parameters, and sent the modified data to either or both of the other pianos for playback.

In the early 1980s, Peter Zinovieff developed various projects with Pianocorders. One of the more interesting ones was a system designed to transcribe arbitrary noises into "patterns of notes amounting to a pianistic analog of the original" (Hopkin et al., 1991, p. 9). At one performance, Zinovieff's system monitored a radio broadcast and produced an interpretation of the analysis on the piano (Riddell, 1989).

Also in the 1980s, Alec Bernstein and Daniel Carney of the Aesthetic Research Ensemble (Baltimore, Maryland) created several varieties of computer-controlled devices for playing conventional instruments, all using Pianocorder technology (Hopkin et al., 1991, p. 9). As part of their work, Bernstein built a computer interface to replace the Pianocorder's tape cassette system, and Dan Carney wrote software to control it. The program featured a score editor with full control of tempo, dynamics, pitches, and durations. It could be used to either program a piece step-wise in advance or used live to modify a real-time performance.

In 1989, Australian composer and computer scientist Alistair Riddell completed a Master's thesis covering a variety of experimental electronic music projects employing Pianocorder technology. In his thesis, Riddell describes how he overcame the limitations of the Pianocorder by constructing a computer-based system and interface as a replacement to the Pianocorder's cassette deck. After discussing the history and application of the programmable piano in music theory, Riddell describes how he used the computer interface to realize a number of artistic ideas using a musical control language of his own design (Riddell, 1989).

2.6 Others' attempts to archive Pianocorder music

All of the projects described in the preceding section were conducted with the intent of expanding the artistic boundaries of performer-instrument interaction. Several of these interfacing projects could likely have facilitated the transfer and archival of existing Pianocorder performances to computer format. However, there is no evidence that the interfaces were used for this purpose. There are two explanations for this: (a) the task of preservation did not fall within the artistic goals of these projects, and (b) at the time the projects were conducted, the Pianocorder cassette media was not sufficiently deteriorated that there was an immediate need to preserve it. However, several individuals have recently made attempts to preserve the material. Their methods are described in the following sections.

2.6.1 Method using the Piano Automation MC-2

In the late 1980s, Will Dahlgren of Piano Automation, Inc. designed and marketed an electronic adapter called the MC-1 that added MIDI input and output capabilities to the Pianocorder. Dahlgren later sold the design rights to Bob Baker of Electric Orchestra, Inc., who continues to sell the device as the MC-2. The MC-2 translates incoming MIDI performance data to the Pianocorder's bi-phase frame-based representation. It also produces MIDI output from tapes played on the Pianocorder's cassette deck.

Using MIDI sequencing software on a computer to record the MIDI output of a Pianocorder equipped with an MC-2, it is possible to transfer Pianocorder performances to MIDI files. Through the Internet, the author has learned of several individuals who have done exactly that (R. Chapman, personal communication, June 11, 1996; G. Livingston, personal communication, October 1, 1996). Both have indicated intentions to preserve some or all of the Pianocorder library in this fashion. There are reasons why this approach is not ideal.

One problem is that this method does not capture the original data in its native format (the stream of 16-byte frames); the only thing being preserved is a MIDI interpretation of the Pianocorder performance. Since the original data are not stored, once the Pianocorder tapes deteriorate beyond playability, only a collection of MIDI files will remain.

The MIDI data stream produced by the MC-2, while useful for interactive applications, does not optimally represent the performance produced by the actual Pianocorder. The MC-2 implements the basic conversion scheme described in Section 2.4 and does not fully simulate the Pianocorder system's physical response (though it does support a single delay parameter to compensate for the Pianocorder's delayed response when driving the instrument via MIDI). Thus, tapes encoded with compensation for the system's physical response will not be properly translated.

Timing skew is another source of error. If one records the MIDI stream from the MC-2 in real time using sequencing software on a computer, the timing of events is skewed by the serialization process; i.e. consecutive Pianocorder frames are converted by the MC-2 into a serial stream of MIDI events that is transmitted to the receiving computer. Each event is timestamped according to its arrival time, which is used to calculate the elapsed "delta" time between events. As described in Section 2.3, MIDI requires 320 μs per byte. Typical MIDI sequencing software is accurate to around 1 or 2 ms. The difference in arrival times is often substantial enough to be recorded by the sequencer.

Note number	Size of MIDI event in bytes	Elapsed time at arrival in ms
1	3	0.960
2	2	1.600
3	2	2.240
4	2	2.880
5	2	3.520

Table 2.2: Timing skew of a five-note chord

For example, if a five-note chord is played on the Pianocorder, with all notes sounding simultaneously, the MC-2 will transmit five note-on events to the sequencing software. At best, their arrival times will be, in theory, as shown in Table 2.2.

(Notice that the MC-2 employs running status compression; the command byte is included only for the first note-on event. Thus, three bytes are needed for the first note-on event, and only two bytes are required for the remaining four events.) As the table shows, in the data recorded by the sequencer, the five notes will not appear to have been played simultaneously; their arrival times have been skewed by MIDI's serial nature and its limited transmission speed. A small amount of additional timing skew may be added when the recorded sequence is played back, for it must again be transmitted over a physical link in sending the data to a MIDI device for playback.[7]

The effects of this timing skew are subtle and may not impact the performance enough to concern the average listener. Holliday states (1989, p. 140) that an untrained human ear can detect two tones being played 10 ms apart, and a trained musical ear can discern differences of less than 5 ms. Thus, it is conceivable that a musician could detect the timing inaccuracy of the five-note chord example presented in the preceding paragraph. Since chords larger than five notes are common in piano music, especially in music arranged specifically for player pianos, the effects of timing skew can become quite pronounced.[8]

This effects of timing skew can be reduced by eliminating the serialization process; i.e. by using a computer to produce MIDI files directly from the original Pianocorder frames. Chapter 4 describes a method of producing MIDI files on the computer directly from the digital Pianocorder frames such that simultaneous chords are truly represented as such in the MIDI file, with no erroneous time recorded between the

[7]The increase is somewhat smaller than the initial skew effect since the data stream has already been temporally spaced to fit better into the available bandwidth.

[8]The quantity of time involved is quite small, however, compared to the 28.4 ms duration of each Pianocorder frame.

individual notes. This will reduce the amount of editing required when converting material derived from Pianocorder pieces into musical notation using scoring software.

When individual events in a MIDI file are played back over a MIDI link, they will be spread out over time as the result of transmission delay, even if chords are represented with no time between individual notes. This is an inevitable consequence of MIDI's limited bandwidth (3125 bytes per second). Although MIDI cannot truly play such notes simultaneously when a hardware link is involved, it is beneficial to store chords with no time between individual notes. This not only facilitates importing MIDI files into scoring software, but also enables better simultaneous playback of notes on devices that do not actually transmit the MIDI data before playback (e.g. a sound module playing from a built-in floppy diskette drive).

Another problem with the MC-2 approach is that the frame rate on Pianocorder tapes sometimes varies slightly over time due to poor duplication, stretching of the tape, interference between the tape spool and cassette shell, etc. The MC-2 method captures these speed variations in the recorded MIDI data, while the approaches in this thesis eliminate them (under the assumption that the frame rate should *not* vary over the course of a song, as was likely intended by the Superscope engineers).

Furthermore, users of the MC-2 have reported difficulty in obtaining acceptable results with the expression translation of the MC-2; i.e. the manner in which it translates the Pianocorder's 5-bit expression levels into MIDI's 7-bit velocity scale (of which only a portion is useful for playback on most MIDI-capable piano equipment, both acoustic and electronic). The device allows the expression translation to be adjusted using several user-configurable parameters, but much experimentation with these settings is required to achieve good results. The MIDI expression generated could be corrected by post-processing the MIDI file after recording the music into a sequencer, but the other problems described above would remain. Although the MC-2 is a useful and well-designed product, it is not optimal for preserving Pianocorder material.

2.6.2 Method using audio sampling

One researcher, David Dunthorn, has developed a Pianocorder-to-computer transfer system that does preserve the original frame data and that could allow for the proper conversion to produce correct MIDI expression. His method involves sampling an entire Pianocorder cassette into a digital audio file, then having a computer extract the binary Pianocorder frames from the recording to convert the performances to MIDI files (D. Dunthorn, personal communication, March 4, 1997). Dunthorn also saves the raw Pianocorder frame data into binary files. This approach solves many of the problems described above, and happens to be one of the methods described in Chapter 3 of this thesis; as Dunthorn's work is unpublished, the author was not aware of this work until attracting Dunthorn's interest by documenting this thesis work on the Internet. Correspondence with Mr. Dunthorn has revealed several similarities in approach; the technique will be described in detail in the following chapter.

Although it works surprisingly well, the method of processing audio files is time-consuming and error-prone, and so the author has implemented a faster, more reliable method. The alternate solution involves the interfacing of original Pianocorder hardware to a computer through the parallel port, and it will be described in Chapter 3.

A shortcoming in Dunthorn's approach is that his MIDI conversion routines do not take into account the solenoid response of the Pianocorder system. This results in MIDI files that do not accurately reflect the performance of an actual Pianocorder system. Dunthorn could add this functionality to his software in the future, however, and in all other respects, Dunthorn's approach is well-conceived.

In email correspondence, Dunthorn did not indicate whether or not he intends to convert the entire Pianocorder library. However, it seemed doubtful. It sounded as if Dunthorn will concentrate his efforts on comparing the accuracy of his resulting MIDI files with audio recordings of the original reproducing rolls from which the Pianocorder performances were derived, played on original pneumatic instruments.

2.7 Desirable goals in archiving Pianocorder data

The techniques described in this thesis are designed to produce a definitive archive of the Pianocorder music library. To this end, the following technical considerations will ensure that the music is accurately preserved with maximum flexibility.

Original frame data should be preserved.

A Pianocorder performance consists of a stream of 16-byte (128 bit) frames. Although the data representation is extremely wasteful, storing performances in plain, open frames makes the music data easy to work with on a computer. For example, the 16-byte width of each frame happens to align nicely with many hexadecimal file editors so that a performance can be conveniently edited with one frame per line. Disk space is now sufficiently inexpensive that the extra space used is not problematic. Also, because of its high coherency and sparseness, Pianocorder data may be compressed by over 90% with gzip and similar file compression utilities. Although some bits of the 16-byte frame are unused or used only rarely, it is worthwhile to store the entire frame intact.

Data rate should be preserved.

Production copies of Pianocorder tapes exhibit a variety of data rates, and these vary not only from tape to tape but among individual songs on one tape (for a given song, the data rate is generally constant). The data rates for Pianocorder material typically range from 4375 to 5100 Hz; the nominal data rate is 4500 Hz. Slight variances in tape duplication equipment probably account for some of the difference. However, it is also possible that the rates were adjusted by Superscope when recording the master tapes, as a means of correcting the tempo without having to resample the data. Because of this, the average data rate of each song should be measured and stored along with the frame data.

The default tempi of some Pianocorder material have been criticized by Pianocorder owners as being unreasonably slow or fast, and so it would be desirable to allow a means of indicating both the original tempo (data rate) as read from the tape and also a user-defined tempo that is more appropriate. This can be achieved by maintaining two fields in the file header, one preserving the original rate, and another storing the preferred rate.

Some irregularities in tape speed may be attributed to the hardware. Electrical engineer and Pianocorder enthusiast Jim Alinsky has determined that the speed of a typical Pianocorder cassette deck varies slightly as a function of playing time when a calibration tape is played. This may be due to thermal factors affecting the motor or mechanical drag within the mechanism. Such speed variations will not be captured during the conversion process; a single measurement of the average frame rate over the course of a song will be stored along with the song data. The data rate varies so little during a single song that storing the average rate is sufficiently accurate.

Blank leader frames should be removed.

Individual songs on Pianocorder tapes typically have a variable amount of quiet (empty) frames at the head and tail of the song. These are frames in which no notes are being played, no pedals are depressed, and no control codes are being sent to the Superscan Display console (external display for lyrics). The purpose of these frames is to allow some time for the hardware to sync to the bi-phase before playback begins, analogous to leader on a reel of movie film. The actual number of leader frames varies quite a bit among Pianocorder tapes. Although there are typically 10 to 20 blank frames, some songs contain over 80 frames of leader and some contain none at all.

Regardless of the number of blank frames present, such frames contain no data that is unique to a song, and there is no need for leader material when Pianocorder data are stored as disk files on a computer. Therefore, these extra frames should be removed and replaced with just a number indicating the number of head and tail frames that were there, in case this will be useful to know at a later date. There are two primary advantages to removing the leader frames as described above: (a) the start frame of a song is consistently the first frame in the data file, and (b) in the long run, a considerable amount of disk space will be conserved.

Glitches should be corrected.

Although the bi-phase signal on Pianocorder tapes is quite robust, one occasionally encounters glitches and quality control problems. Typically, a glitch consists of a very brief dropout in the bi-phase signal, probably due to a problem with the master tape from which the cassettes were duplicated. When listening to the bi-phase data on a conventional cassette deck, sometimes a low "thud" can be heard, as if the master tape had been spliced. When played on the Pianocorder system, such glitches cause the playback circuitry to fall out of sync and reset itself, waiting for two valid frames before continuing playback.

It is unfortunate that Superscope allowed such problems to exist on their tapes, but it is not difficult to smooth over the blemishes during the archival process. Such glitches can be eliminated by simply inserting an appropriate number of valid frames into any dropout gaps, ensuring that there is always a continuous stream of valid frames. A gap can usually be adequately filled by simply repeating the last valid frame received before the glitch occurred. This may cause some notes to be held slightly longer than intended, but it prevents the glitch from causing an abrupt interruption in the music or a jump in the rhythm. It is the author's opinion that archival copies of the tapes should be completely free of glitches, if at all possible. If several attempts have been made to transfer multiple copies of a given tape and the glitches persist, the computer should be allowed to fill in the gap as described above. In cases where the glitches exist at exactly the same point in all available copies of the tape, there is strong evidence of a problem with the master.

Stray sync bytes should be eliminated.

One other type of glitch is sometimes found in the material. During very complex musical passages, the Pianocorder sync byte (`11111101`) that is usually at the very end of each frame sometimes happens to appear in the middle of the note and expression data. When the Pianocorder receives the sync byte at the improper point in the frame, its circuitry believes an invalid frame has been received and obediently resets the system. This causes a dropout for two frames before playback resumes, even though the signal from the tape deck was otherwise valid. It is surprising that Superscope did not anticipate this problem and use a longer, more complex sync byte. Alternatively, the engineers could have edited the music data slightly to eliminate any occurrences of the sync byte in the middle of a frame. Apparently, either technical limitations or time constraints prevented them from doing so. In any case, it is easy to correct this problem during the archival process by slightly modifying any improperly-located instances of the sync byte (e.g. by replacing the byte `11111101` with `11111100`).

Source of material should be noted.

The performances comprising the Pianocorder music library were derived from several sources. Some were derived from piano rolls (both reproducing and non-reproducing), some were recorded live at Superscope on a stock Pianocorder recording system, and others were recorded live on a more sophisticated system (Superscope's Musically Expressive Recording Piano) and specially edited to produce optimal results on the Pianocorder. When storing Pianocorder material as computer files, it is desirable to store a code for the source of the material. This will be useful as a historical record and also in the process of converting the various kinds of Pianocorder material to MIDI format. Each type of source material requires a particular conversion algorithm for best results, and having the source encoded into the files enables the software to apply the correct algorithm automatically.

2.8 An archival file format for Pianocorder data

The author has designed a file format to use for archiving Pianocorder material as computer files. Each file stores an individual song or medley and consists of a 32-byte header followed by all of the 16-byte data frames for the song (with any blank head or tail frames removed). The format of the 32-byte header is shown in Table 2.3. The author has adopted the file extension ".PC" to distinguish these Pianocorder data files. It is not a great concern if this extension clashes with that of another file format, since files of Pianocorder data will not be widely distributed. They are also easily identifiable to both human and computer viewers by examining the ASCII string "PIANOCORDER" at the beginning of each file.

The 32-byte header facilitates all of the technical goals described in the preceding section. The original data rate is preserved, but provisions are made for a more appropriate rate to be stored as well. Blank leader frames are not stored, but a count of them is preserved. The original source of the musical performance is preserved as well. Finally, treble and bass expression offsets are provided. These are for future use and will allow the user to raise or lower the overall volume level of each piece.

Bytes	Description
0-10	File type identifier; ASCII string "PIANOCORDER" (In hex: `50 49 41 4E 4F 43 4F 52 44 45 52`)
11-14	Number of frames in file (32-bit unsigned integer, MSB first)
15-16	User's preferred data rate in bits per second (16-bit unsigned integer, MSB first; nominal rate is 4500 bits per second)
17-18	Original data rate in bits per second (16-bit unsigned integer, MSB first; nominal rate is 4500 bits per second)
19	Source of material: 0: reproducing piano roll (expression derived from piano roll) 1: non-reproducing piano roll (expression added synthetically) 2: stock Pianocorder recording system (microphone and wire switch mechanism) 3: specially-edited performance (e.g. "Contemporary Artists Series" performances) 4: Piano Automation MC-1 / MC-2 (Pianocorder MIDI adapter)
20	User's treble expression offset (-32 to 32) 00h = -32, 20h = 0, 40h = 32
21	User's bass expression offset (-32 to 32) 00h = -32, 20h = 0, 40h = 32
22	Number of quiet frames originally at the head of the song
23	Number of quiet frames originally at the tail of the song
24	Number of losses of sync that were corrected when transferring the data from tape
25-31	Reserved for future use

Table 2.3: Archival 32-byte file header for Pianocorder data

CHAPTER 3

DATA ACQUISITION FROM PIANOCORDER TAPES

This chapter will discuss the problem of capturing the original binary data from production copies of the Pianocorder cassettes, making it possible to archive and manipulate the data frames on a computer. Two solutions are presented for acquiring the data. The first method is "software-based", extracting Pianocorder data from audio samples of the tapes. The "hardware-based" method utilizes part of an actual Pianocorder system, interfaced with a PC, to transfer music data to the computer. Before describing the two solutions, several issues are addressed concerning the tapes themselves.

3.1 Present condition of the Pianocorder tapes

The original Pianocorder cassettes sold in the late 1970s are nearing the end of their useful life. Although the plastic cassette housings are typically in good condition, the tape media itself is often quite deteriorated, leaving a considerable amount of oxide residue along the tape path and in the cassette player after use. In many cases, the tapes are still playable and their data can be successfully captured.

Some tapes exhibit a more severe degree of deterioration in which a great deal of oxide rubs off on the playback head, quickly accumulating and causing the tape to stick and squeal as it passes over the head. This severely distorts the signal and renders the tape unusable. It is common knowledge in the recording industry that tapes in this condition can be temporarily rejuvenated by removing the tape media from its housing and baking it at 150 degrees Fahrenheit for approximately 30 hours. This chemically rejoins the oxide and binder, making the tape playable without squealing for a short time afterward (D. Blue, personal communication, February 11, 1996). In working with Pianocorder cassettes, the author has found the owners of borrowed tapes to be reluctant to permit their tapes to be subjected to this procedure, so it has not been used in the course of this project. Instead, the author has located multiple copies of each tape for transfer, and has usually been successful in finding at least one copy that is still in usable condition.

Tape media deterioration is the most serious problem encountered, but several other problems are frequently found as well. For example, the felt pressure pads that keep the tape traveling firmly and smoothly over the playback head often fall off (or are already missing), due to poor condition of the adhesive. When working with Pianocorder tapes, it is not uncommon to open a volume of tapes and find the pressure pads already loose in the bottom of the box. The pressure pads are easily reattached using fresh adhesive.

Other tapes have the mechanical problem of the tape spools not turning freely within their shells. This is usually caused by warped shells or cassettes containing unusually long lengths of tape. It appears that the tape media has expanded slightly as it aged, causing full spools of tape to rub against the cassette housing.

This condition can usually be remedied by loosening the screws of the housing slightly, or by temporarily moving the tape media to an alternate cassette shell for transfer.

3.2 Software-based data capture

This thesis work was started with only a single Pianocorder cassette, a copy of the Pianocorder system schematics, and a personal computer. As the author had more experience in writing software than in constructing specialized electronics hardware, the first approach at extracting the binary data from Pianocorder tapes was software-based. The general idea was that a Pianocorder cassette could be sampled by a personal computer's sound card into a digital audio file that could then be processed to extract the binary data.

3.2.1 Playback hardware

The first step in developing this approach was to find a cassette tape transport that would run at the Pianocorder's rate of 3.75 inches per second (standard cassette decks run at half this speed, 1.875 inches per second). Although a standard deck could have been used, resulting in the Pianocorder data being played at half speed, the author rejected this speed as impractically slow, considering that the Pianocorder library contains over 230 hours of music. Instead, the author located a portable stereo system containing a cassette deck that was capable of playing cassettes at 3.75 inches per second (as part of a high-speed dubbing feature). This deck allowed transferring the Pianocorder music in real time.

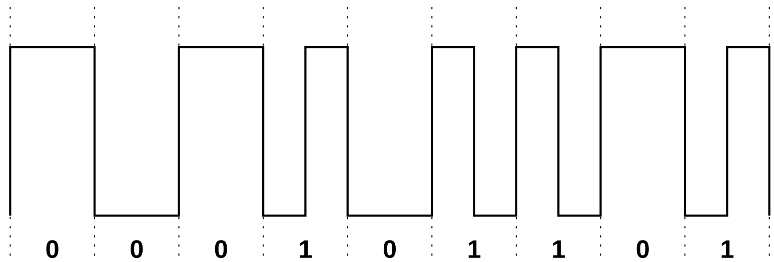


Figure 3.1: Example of Harvard bi-phase encoding

3.2.2 The Pianocorder's bi-phase data signal

Pianocorder data consists of a continuous stream of 16-byte data frames encoded into a bi-phase signal stored on cassette tape. Bi-phase (also known as *double frequency* coding) is a self-clocking serial encoding in which a zero or one is represented in a square wave signal by the number of zero crossings occurring in a given time period. Bi-phase and its variations are commonly used in the recording of digital data on magnetic media.

Bi-phase is based on a square wave whose zero crossings define the temporal boundaries of *bit cells*. Within the time period of each bit cell, an extra zero crossing can be inserted to indicate that the cell defines a binary one; a bit cell without the extra transition represents a binary zero.[1] Thus, a binary data stream is encoded as the presence or absence of extra zero crossings in a sequence of bit cells (see Figure 3.1). The Pianocorder's bi-phase signal runs at 4500 bits per second, giving it a bit cell frequency of 4.5 kHz.

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[1]This variation is called *Harvard bi-phase mark;* "mark" stemming from historical computer terminology, indicating that an extra zero crossing is given to binary ones instead of zeroes.

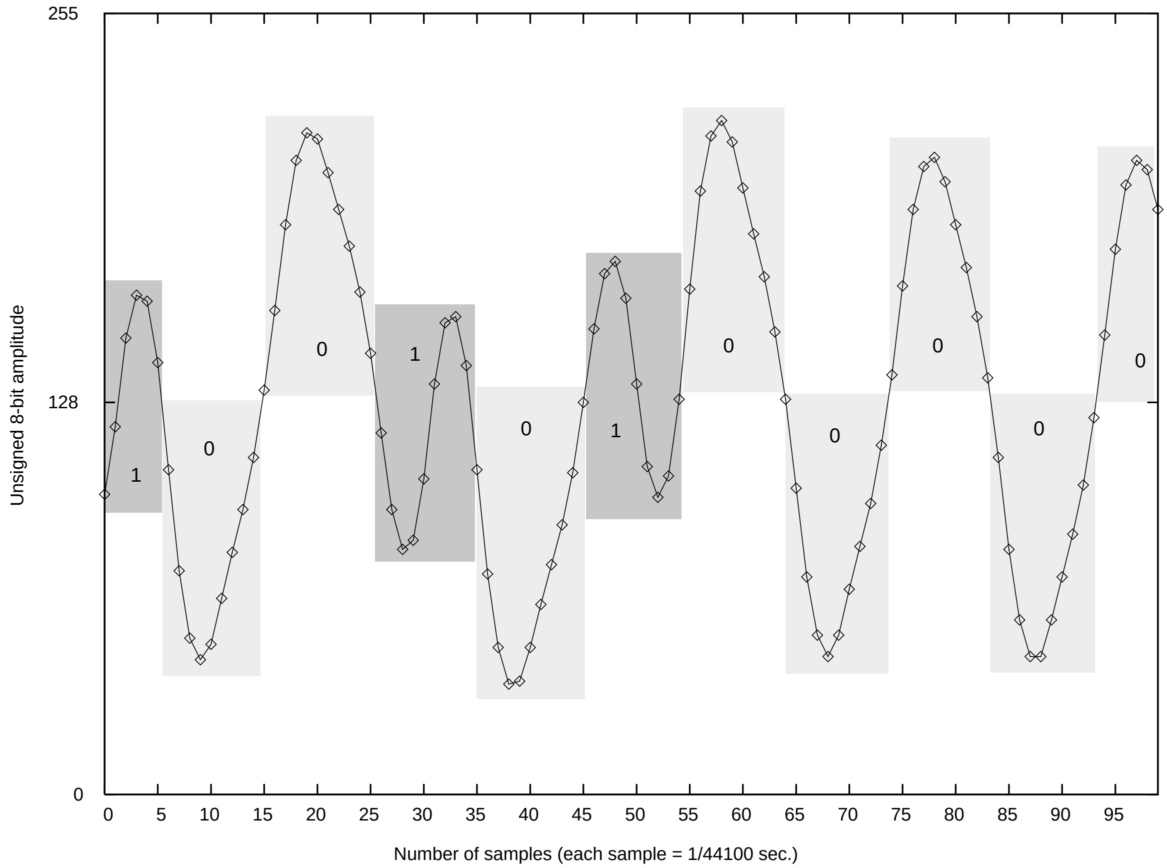


Figure 3.2: Bit cells in the Pianocorder's bi-phase signal

3.2.3 Choosing audio file parameters

The next step was to determine the appropriate digital audio file parameters for sampling the signal from the tapes. The Pianocorder's bi-phase signal runs at 4500 bits per second, with each bit cell having a duration of 1/4500 of a second. A binary zero is represented as one zero crossing in a bit cell, and a binary one is represented as two zero crossings in a bit cell (Figure 3.2 shows a graph of an actual Pianocorder signal with the bit cells highlighted).

Note that two binary zeros are required to form a complete cycle, whereas a single binary one itself forms a complete cycle. Therefore, the bi-phase signal may be considered a sequence of either half cycles of 2.25 kHz (the zeroes) or full cycles of 4.5 kHz (the ones). To capture this signal, Nyquist theory requires a sample rate of at least twice the highest frequency in the source signal, or in this case, 9 kHz. For greater reliability and to facilitate easier processing of the data, a sample rate of 44.1 kHz was selected. (This rate is frequently used in digital audio applications because it is the sample rate used on compact discs.) At 44.1 kHz, each bit in the Pianocorder's bi-phase lasts 9.8 samples, making it easy to distinguish between binary ones and zeroes. Because the bi-phase signal employs frequency modulation rather than amplitude modulation, a sample depth of 8 bits provided adequate resolution for capturing the amplitude of the signal. The sound card used was a standard consumer-grade MediaVision Proaudio Spectrum 16. Although the sound card was capable of stereo recording, this application required only one track of 44.1 kHz 8-bit audio.

3.2.4 Recording Pianocorder tapes

The Pianocorder tapes were recorded, one side at a time, into digital audio files under the Linux operating system using a software utility specially written for the purpose by the author ("recpc"). This software streamlined the task by automatically adjusting the gain of the sound card to ensure that the bi-phase signal would never clip, and by automatically terminating the recording process at the end of a tape (this was done simply by detecting an extended period of silence longer than the typical gap between songs). The digital samples were stored in files of raw unsigned 8-bit data, with each 22-minute side of a Pianocorder cassette producing a file 57 Mb in size. After the data frames were extracted from a given audio file, the audio file could be deleted and the space used for storing the next audio file.

3.2.5 Extracting data from the audio files

To extract the binary data from the sampled bi-phase data, the author wrote a command-line utility called "pc2mid." This program processed the large files of audio data, simultaneously extracting the digital Pianocorder frames, saving them to disk and converting the musical performances to MIDI format. (The MIDI conversion issues will be discussed in Chapter 4.) The raw frame data were saved in the ".PC" file format specified at the end of Chapter 2.

The algorithm to recognize and extract the binary data was designed under several constraints. The most important consideration was that the algorithm must be very fast, because of the large volume of Pianocorder material to convert and its rapid rate of deterioration. Large audio files (57 Mb in this case) are cumbersome to work with, and a considerable amount of time is expended simply reading them from disk. Therefore, preference was given to an algorithm that could process them in a single pass, as quickly as possible.

A second constraint was that the algorithm work very accurately, because a stream of Pianocorder data frames contains no means of error correction. Data errors may be detected only by recognizing an incorrect or misplaced sync byte at the end of each frame. This mechanism is similar to the concept of *parity* used in serial data transmission, in that an incidence of error can be detected but not corrected. It is also similar to parity in that it is easy to create a case that contains errors but still passes the validity check.

Extraction of the binary data from a bi-phase signal is typically done with a phase-locked-loop on the zero crossings defining bit cells. With the bit cell boundaries known, the binary data bits are determined by looking for a zero crossing between bit cell edges; the presence of an extra zero crossing within the bit cell indicates a binary one; the absence of an extra zero crossing indicates a binary zero. This method of data extraction is easily implemented in hardware (J. Kravitz, personal communication, February 4, 1996).

The algorithm implemented by the author differs from the usual method. It was conceived by visually examining the sampled waveform and looking for easily-recognizable characteristics. Graphing the raw sampled data from a Pianocorder tape reveals that the signal is not a square wave but rather is a distorted sine wave. This is an artifact of magnetic tape recording and occurs because magnetic recorders behave as low-pass filters at short wavelengths (Mallinson, 1975, p. 1166). One also notices that the point of zero crossing varies or "floats around" somewhat, particularly in portions of the signal alternating between zeroes and ones. This phenomenon has been documented in (e.g. Mallinson, 1975, p. 1167); it is caused by the poor low-frequency response of magnetic recording, and researchers frequently refer to the effect as "staircasing" or "wandering baseline." In addition, the effects of wow and flutter[2] were probably not insignificant.

[2]Distortion from fine tape speed variation due to mechanical limitations of the cassette transport.

These effects complicated the development of a software bi-phase decoding algorithm in that it was not possible to simply use the zero level of the samples (level 128 on a scale of 0 to 255) when finding zero crossings, because doing so would not locate the true point of zero crossing. Therefore, an algorithm to locate the bit cell boundaries at their points of zero crossing would be difficult to implement. An algorithm was devised that attempted to follow the floating zero level, extracting the binary data by looking for the extra zero crossing within bit cells. Although the author experienced moderate success, the algorithm was not consistently reliable.

Jacoby (1968) and Mallinson (1975) described how equalization can be applied to the signal read from a magnetic playback head to help eliminate the wandering baseline effect. Following equalization, several stages of amplification and limiting can be applied to recover the original square wave signal. At that point, it is easy to decode the bi-phase by simply observing the pattern of zero crossings (see White, 1985, for a detailed treatment of these topics). While this solution could have been implemented in software, the author continued, in the interest of speed, to pursue a solution requiring no processing of the sampled data.

The next attempt involved making use of the fact that, through the losses of magnetic reproduction, the square wave had become a distorted sine wave. By considering one sample point at a time and comparing its amplitude with the amplitudes of adjacent points, it is possible to determine whether the sample point is a local minimum or maximum; i.e. a peak in the sine wave. Then, by counting the number of samples between peaks, it can be determined whether the peak is part of a binary zero or a binary one. Thus, a long period between peaks represents a binary zero, and two short periods represent a binary one. An algorithm based on this approach

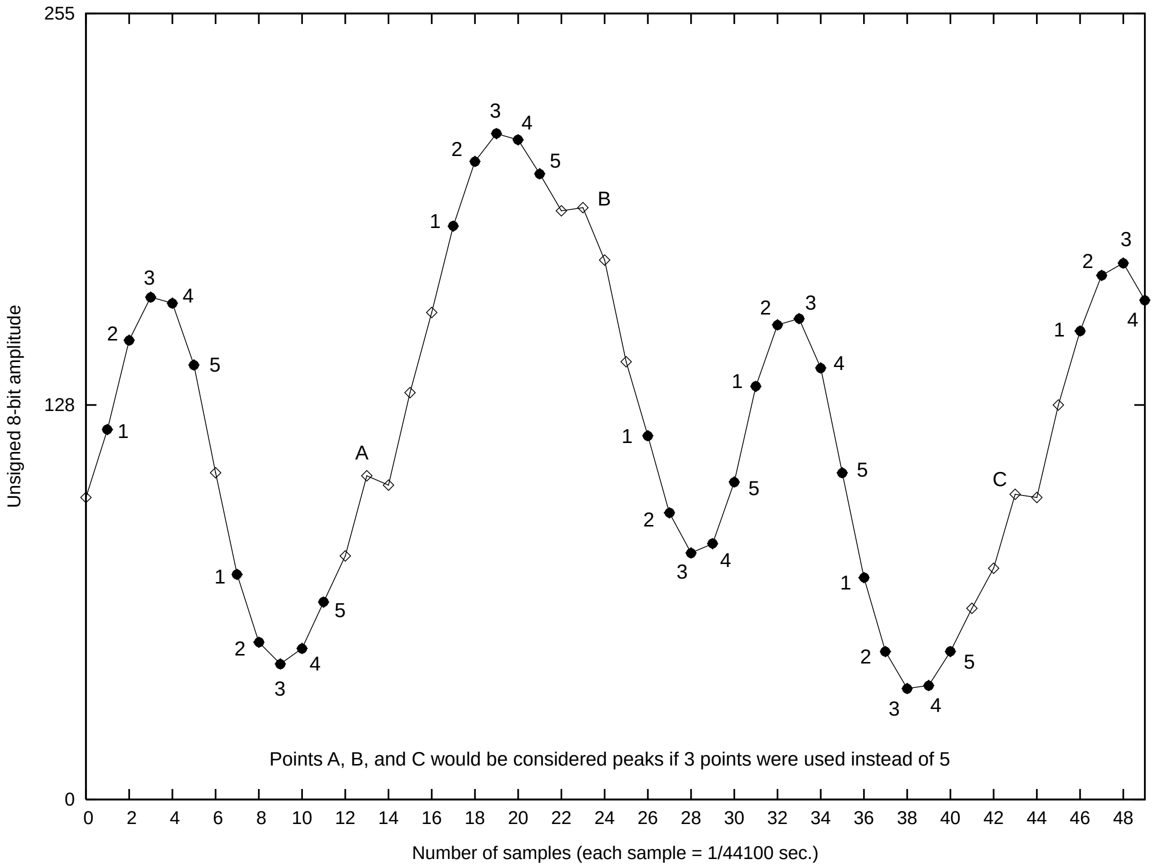


Figure 3.3: Peak detection in a bi-phase signal using five consecutive samples

was constructed, and it turned out to work well, completely eliminating the floating baseline problem and requiring no processing to equalize and restore the signal in advance of performing the bi-phase decoding.

At first, the peaks in the waveform were detected using just three sample points: the amplitude of the point under consideration was compared with its predecessor and successor. This peak detection algorithm worked accurately on Pianocorder data about 90% of the time. The errors occurring were believed to be caused by tape hiss and other distortion, causing a slight high frequency ripple in the basic bi-phase waveform. A few attempts were made at reducing the distortion by applying a software implementation of a low-pass Butterworth filter to the audio file as a preprocessing step before data extraction. However, the processing time for these large audio files was prohibitively high, and the filter was not completely effective at eliminating the distortion.

After some experimentation, it was found that the decoding errors caused by hiss and distortion could be almost entirely eliminated by increasing the number of points considered in detecting a peak from three to five; for a peak to be valid, there had to be two consecutive ascending (or zero) slopes to its left and two consecutive descending (or zero) slopes to its right. This essentially caused the algorithm to ignore the high frequency components, avoiding the need for time-consuming preprocessing of the audio file. Figure 3.3 shows a Pianocorder bi-phase waveform with several peaks detected; point number 3 of 5 in each group is the central data point under consideration.

It should be noted that the use of five data points is dependent upon both the choice of sample rate (44.1 kHz) and the bi-phase data rate (4500 bits per second). If either of these parameters were to change, the number of sample points to consider would likely be different. However, the simplicity of this method and its excellent performance outweigh its lack of generality. It would not be difficult to find suitable parameters for processing a different variety of bi-phase data with this method.

It should also be noted that this algorithm could fail to detect a peak in some cases (e.g. when point 3 of the 5-point group is lower than 2 or 4). However, no attempt was made to handle these cases, as they did not occur in the course of processing nearly 100 tapes. The low 8-bit resolution of the audio samples is believed to be a factor, along with the relatively low amplitude of the noise component in the signal and the brief (5–10 samples) duration of each peak in the waveform.

This algorithm for peak detection is very fast because it involves no arithmetic computation, only a handful of integer comparisons at each sample point. Note that the algorithm's speed can be increased by skipping ahead by several samples after finding a peak, since the next peak will not be expected until several samples later. To further improve the effectiveness of this algorithm, an additional trick was employed: the portable stereo containing the cassette deck used for playing Pianocorder tapes was equipped with a five-band graphic equalizer; the trick was to set the equalizer to boost frequencies between 1.0 kHz and 6.0 kHz and to attenuate frequencies outside that range. This improved the clarity of the bi-phase signal with no impact on the processing time.

3.2.6 Decoding data bits

After measuring the time between adjacent peaks in the bi-phase signal, the decoding algorithm must determine whether the peak represents a binary zero or whether it is one of two peaks representing a one. This was done by comparing the measured amount of time between peaks (in samples) with a threshold value; if the measured time was greater than the threshold (i.e. a longer time period), the peak represented a zero. If the measured time was less than the threshold (a shorter time period), the peak represented half of a binary one.[3] The threshold value was computed in advance

[3] This threshold value is analogous to the "3/4 bit" circuitry in the Pianocorder's bi-phase decoding hardware. Note that the threshold value described above is exactly 3/4 the duration of a bi-phase bit cell.

on a song-by-song basis by examining several hundred consecutive peaks and taking the average of the shortest and longest durations encountered between them.

The threshold value for almost all Pianocorder tapes was very frequently found to be 7 samples, with each sample representing 1/44100 of a second. The value of 7 is consistent with what one would expect; Section 3.2.3 predicted that each binary zero (spanning an entire bit cell) would occupy 9.8 samples. Each half of a binary one (spanning half of a bit cell) would thus occupy 4.9 samples. The average of 9.8 and 4.9 is 7.35, resulting in an optimal integer threshold value of 7.

3.2.7 Frame segmentation

The algorithm presented in Section 3.2.5 produces a stream of binary ones and zeroes. In order to do anything useful with these bits, it is necessary to arrange them into logical 16-byte (128-bit) Pianocorder frames. This was done using the same method implemented in the Pianocorder's hardware, summarized as follows: maintain a bit counter that counts upward from 0 to 127; when each bit is received, store it into an array indexed by the bit counter and increment the bit counter; if this bit and the previous seven bits received form the sync byte `11111101`, reset the bit counter to 0 and process the array containing the previous 128 bits as a valid frame. If the sync byte is recognized before 128 bits have been received, then an error must have occurred (a bit was lost somewhere) and that frame should be discarded. Likewise, if more than 128 bits are received without recognizing the sync byte, the received frame should be discarded. A frame should only be accepted as valid if the sync byte is correct and located at the proper point in the frame. Valid frames are processed

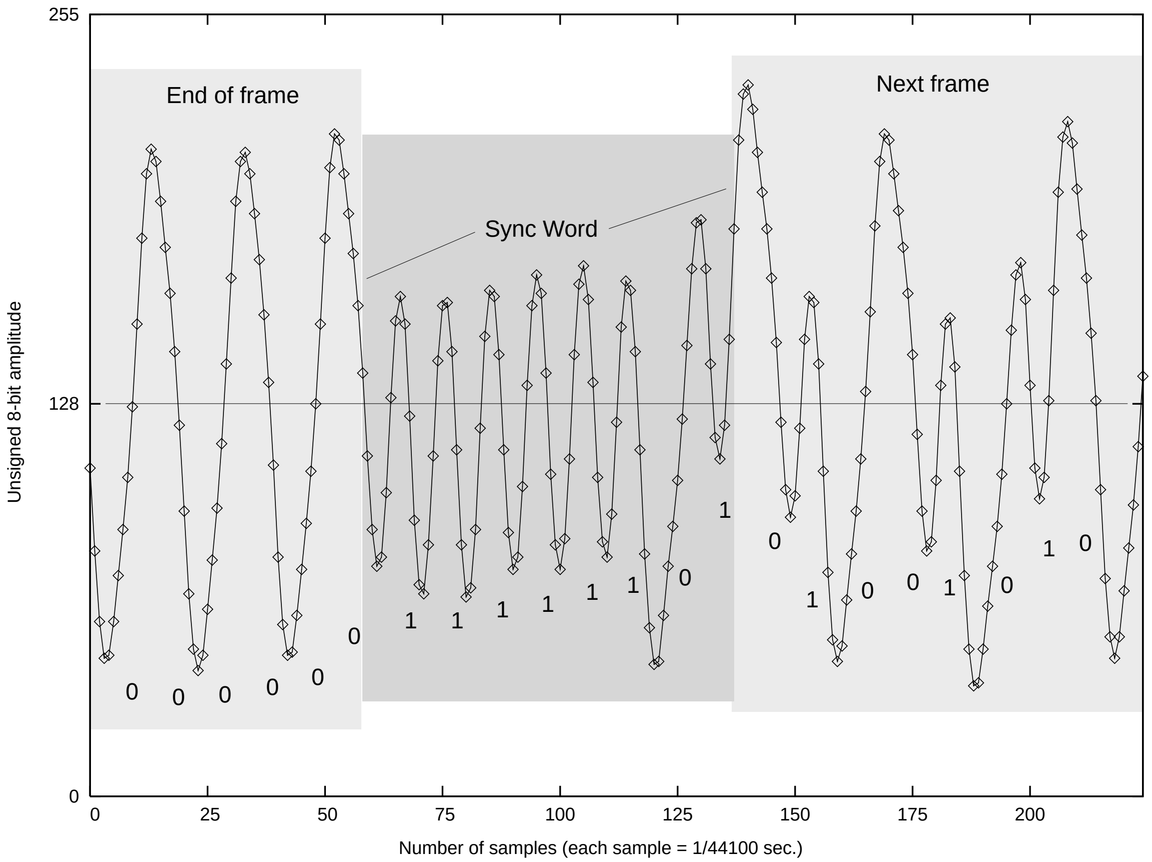


Figure 3.4: Example of bi-phase signal at frame boundary

by the software and saved to disk as a chunk of sixteen bytes. Figure 3.4 shows the boundary between two Pianocorder frames. The 8-bit sync byte `11111101` is visible at the center of the graph, and the decoded data bits are also shown.

3.2.8 Song segmentation

The bi-phase decoding algorithm also had to handle the problem of song segmentation, since it was desirable to store each piece of music in a separate file. Pianocorder cassettes usually have between three and eight songs on each side of a cassette. Before the first song begins, there is usually a human voice announcing the tape identification number and the tape side; e.g. "T-887 A." The chunks of song data on a tape are usually separated by a few seconds of silence, but this is not always true. Occasionally, songs are separated by a few seconds of all-zero bi-phase. This is interpreted as invalid data (i.e. silence) by the Pianocorder circuitry because of the absence of the sync byte. In some instances, songs are separated by a stream of valid Pianocorder frames that simply contain no music (sync bytes present, but no notes or pedals activated). This kind of song break usually occurs as part of a medley of songs transferred from a piano roll. The decoding routines had to properly handle each kind of song break.

A major problem in processing the data for a song was that of locating the exact beginning of a song. The bi-phase decoding algorithm described in Section 3.2.5 was designed to try to recover in the event of a fault; i.e. if it found an unusually long or short time between peaks. In these cases, the algorithm tries to recover by advancing ahead one peak at a time, trying to lock back on to the bi-phase. The recovery mechanism could potentially waste a lot of time futilely trying to find valid bi-phase in a complex waveform, such as the brief distortion at the start of a recording or the voice announcing the tape information at the beginning of a tape. If allowed to proceed, the recovery algorithm eventually finds the start of a song, but only after wasting a considerable amount of time.

This problem was solved by having the algorithm jump past the uncertain beginning of a song into what would likely be valid bi-phase. Once there, the software examines several hundred consecutive peaks to calculate a suitable threshold value for decoding the bi-phase. After doing that, the software simply backs up its data pointer peak-by-peak to the beginning of the song, counting the number of samples between peaks and stopping as soon as it finds an unreasonable value. Using this method, the beginning of a song can be found quickly and accurately, with minimal time spent trying to recover. In practice, it was found that jumping ahead by around 440,000 samples (10 seconds) before backing up worked consistently well.

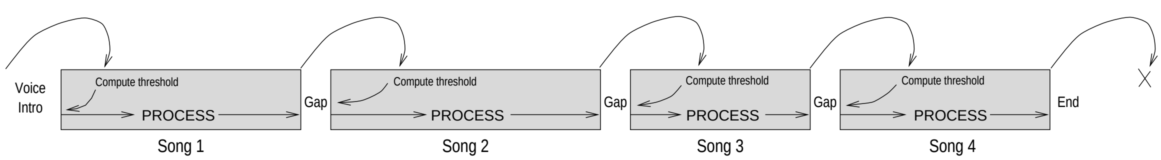


Figure 3.5: Graphical example of song segmentation technique

After backing up to the beginning of a song, the bi-phase decoding routines process the complete data for the song, assembling 16-byte Pianocorder frames and saving them to disk. The routines detect the end of a song when either (a) an unreasonably long or short time between peaks is found in the waveform, or (b) the decoded

Pianocorder frames no longer contain the proper sync byte. At this point, the software jumps ahead in the sampled data by 10 seconds, trying to find the next song. If valid bi-phase is found, it advances its song counter, calculates the threshold value, and backs up to the beginning of the song to process it. If no valid bi-phase is found after jumping ahead 10 seconds, then the software assumes the end of the tape has been reached and terminates. Figure 3.5 illustrates how the segmentation routines would handle a typical tape of four songs.

3.2.9 Performance of the software-based solution

Using the methods described above, the PC2MID software utility achieved reasonably good performance on a 66 MHz 486 DX2 system running Linux 2.0.30. Naturally, the recording of each cassette side into an audio file required an amount of time equal to the tape's duration, typically about 22 minutes. After recording, the audio files for a tape were processed by the PC2MID software utility. Due to the large size of these files, the data were processed in sections using a 20 Mb buffer in memory (songs straddling the boundaries of the buffer did not present a problem, and the software ensured that a sufficient quantity of data was loaded to properly handle song segmentation). The PC2MID software required an average of 1 minute and 40 seconds to extract the binary data from a 57 Mb audio file (one side of a cassette tape).

3.2.10 Problems with the software-based approach

This software-based data acquisition solution was used and improved upon for several months. Over 60 hours of material were successfully transferred to computer format. In this regard, the method of extracting Pianocorder data from sampled audio files was a success. However, a number of difficulties were encountered that made the method tedious.

First, when playing the tapes for sampling, it was not easy to ensure that an optimal signal was being recorded. Although the recording software was able to automatically set the gain of the sound card, the playback head azimuth of the cassette player had to be adjusted manually. This involved turning a small screw at one side of the playback head to properly align the head with the data track on the tape. An oscilloscope would have helped in this process, but lacking one, the author learned to make the adjustment by ear.[4] The azimuth adjustment was especially tricky because a stereo tape head was being used to read a mono data track on the cassette (all Pianocorder cassettes were mono). Consequently, the azimuth setting was very temperamental and would occasionally go out of adjustment during the course of a twenty-minute tape. The resulting distortions in the signal usually caused the bi-phase decoding algorithm to fail.

Another problem with this method was that there was no way to monitor the music while sampling the tapes. This became an increasingly important consideration when developing the routines for MIDI conversion discussed in the next chapter. Although it would have been possible to monitor the music by combining the recording software and the bi-phase decoding routines, this would not solve the azimuth problem mentioned earlier.

[4] Properly adjusted, the signal sounded clear and even in volume, without any high-frequency components above the bi-phase. With the azimuth slightly out of alignment, the signal sounded "brighter" and somewhat "abrasive." With the azimuth grossly misaligned, the signal sounded "boxed in," muddy and uneven in volume.

The author did make several attempts to solve the azimuth problem. The first attempt involved replacing the stereo playback head with a mono head. This failed due to mechanical difficulties in mounting the replacement head. The author also tried using a mono tape player to play the tapes. This gave moderate improvements but had the disadvantage that the tapes were transferred at half speed (since the mono tape deck had no high-speed dubbing mode). The mono deck also seemed to introduce some new distortion to the signal, probably due to the generally poor construction of the consumer-grade mono cassette deck employed. For this reason, it did not seem worthwhile to adapt the mono deck to run at double speed. It occurred to the author that a better-engineered mono deck (of the type used for home computer data storage) might provide better reliability. Another idea was to add some external circuitry between the tape deck and sound card to clean up the bi-phase signal.

These ideas gradually led the author to conclude that the best solution would be simply to find a working Pianocorder system and interface its cassette player and decoding circuitry to the computer. A major step towards this solution came when Richard Joaquim of the Scottsdale Conference Resort donated to the author a complete Pianocorder system that had been removed from service.

3.3 Hardware-based data capture

A description of the Pianocorder playback system will facilitate discussion of the second, "hardware-based," method of data capture.

3.3.1 Playback system overview and circuit description

The Pianocorder playback system consists of a power supply, a cassette tape deck, a playback logic board, solenoid driver boards, a solenoid rail, and two pedal solenoids. Only the tape deck and playback board are needed for data capture. Instead of using the Pianocorder's power supply to drive the playback board and cassette deck, power can be provided using a small 5 VDC / 12 VDC regulated supply.

Figure 3.6 shows the schematic of the cassette deck. Although similar in appearance to a conventional tape deck, the Pianocorder deck contains circuitry to recover a clean bi-phase square wave from the distorted sine wave read by the tape head. The square wave is passed to the playback board over a multi-conductor cable terminating in a 12-pin Molex connector.

It is beyond the scope of this document to fully describe the operation of the Pianocorder playback board (it is covered thoroughly in the *Pianocorder Circuit Description and Schematic Package* issued by Superscope).[5] Sufficient detail will be given to present a general understanding of the playback board's operation and to illustrate how the board may be interfaced to a computer.

The playback board is designed to receive a clean square wave 0–10 VDC bi-phase data signal from the tape deck, decode the binary note, pedal, and expression data, and distribute the bits sequentially to the appropriate solenoid driver boards. The playback board also implements the restriction that two valid data frames must be received before the solenoids will be enabled; this prevents the system from playing garbage data.

[5] Additional information may be found in U.S. patents 3,905,267; 3,604,299; 4,031,706; 4,104,950; 4,121,491; 4,132,141; 4,132,142; 4,135,428; and 4,161,901.

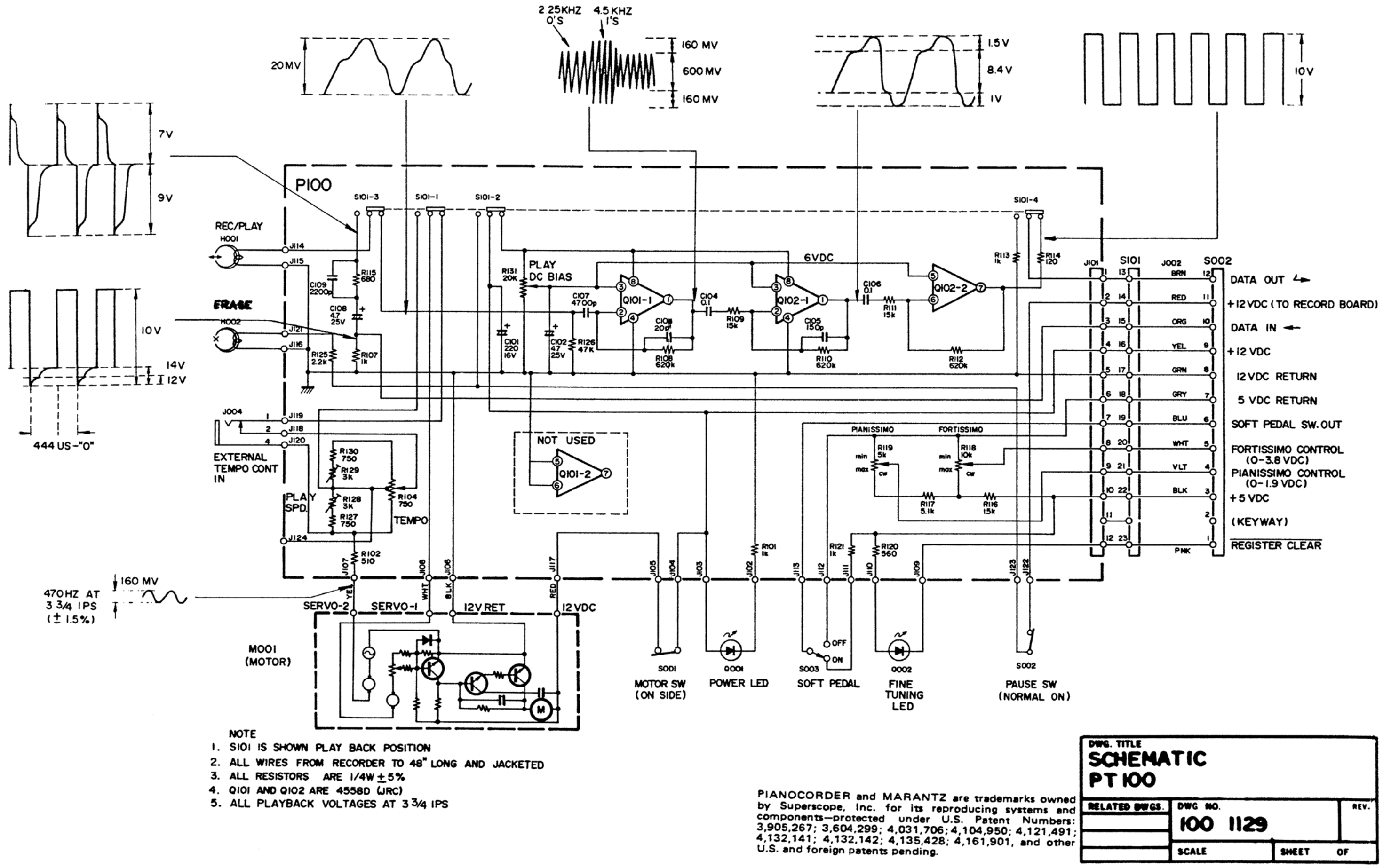


Figure 3.6: Pianocorder PT-100 cassette deck schematic

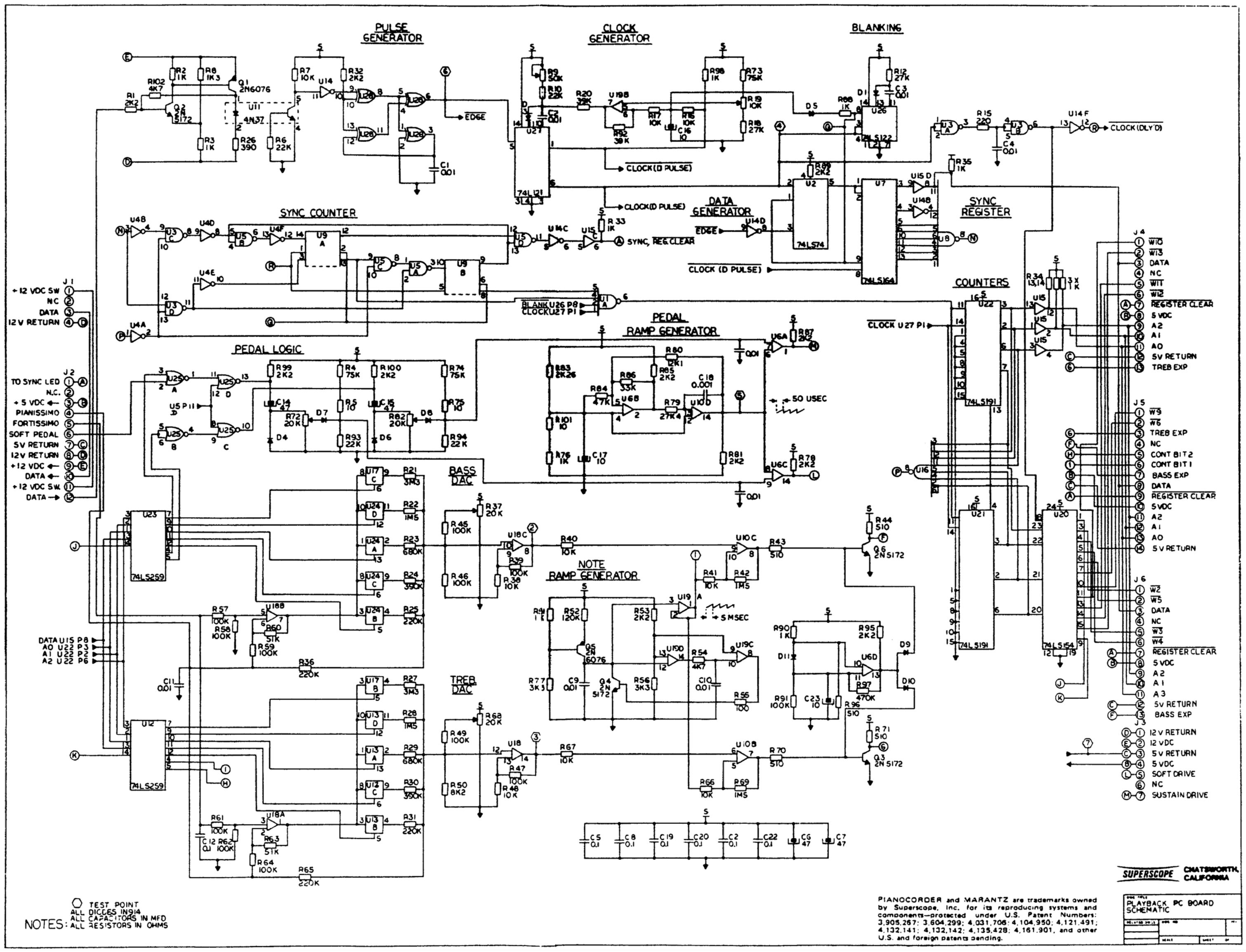


Figure 3.7: Pianocorder playback board schematic

Figure 3.7 shows the schematic of the playback board. The tape deck connects to jumper J2 at the far left side. The bi-phase decoding circuitry is located in the upper third of the board. In the section marked PULSE GENERATOR, the bi-phase square wave is converted into a normally high $\overline{EDGE}$ signal with a 0.5 μs low pulse at each zero crossing. From the $\overline{EDGE}$ signal, the circuitry in the CLOCK GENERATOR section derives a master CLOCK signal that is used to synchronize the data distribution throughout the rest of the system. In the DATA GENERATOR section, the CLOCK and EDGE signals are compared to produce decoded binary data.

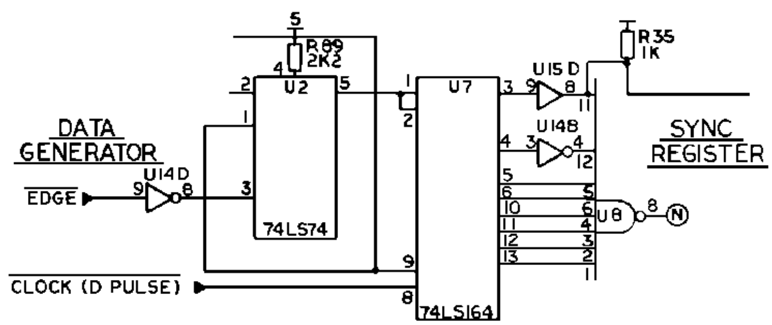


Figure 3.8: Pianocorder sync detector shift register

In the SYNC REGISTER section in the upper right corner, the binary data is shifted into U7, a 74LS164 8-stage serial-in, parallel-out shift register (see Figure 3.8). This shift register is used in recognizing the 8-bit sync byte `11111101`. The pattern of this sync byte can be clearly seen in the parallel output lines of U7 presented to the 8-input NAND gate of U8. Pin 4, the zero of the sync byte, is inverted so that all inputs to the NAND gate are high when the sync byte is present. Thus, the signal at point N is low when the shift register contains the valid sync byte and is high otherwise.

Notice that in the process of detecting the sync byte, the shift register will run through, in order, every bit in the Pianocorder's 16-byte frame. Therefore, this shift register provides a convenient place to grab the frame data one byte at a time and send it to the computer capturing the data. The data may be captured by tapping into the shift register output pins 3, 4, 5, 6, 10, 11, 12 and 13 and providing a cue to the computer to capture a byte after each group of 8 bits has been shifted in.

3.3.2 Jim Alinsky's capture system

Shortly after completing the software-based capture method in Section 3.2 and receiving the donation of Pianocorder hardware, the author was contacted by an Indiana electronics engineer, Jim Alinsky. Alinsky explained that he had been experimenting with Pianocorder hardware for over a decade, and that he had devised a hardware-based method for capturing Pianocorder data from cassette tapes into his computer. His method is based on the idea of letting the Pianocorder hardware handle decoding the bi-phase signal from the tapes using its own circuitry, tapping into the decoded binary data at an appropriate point, and sending the data as parallel 8-bit bytes to the computer.

Alinsky's capture system consisted of an original Pianocorder playback board plus an additional custom circuit board to drive the parallel input of an off-the-shelf parallel-to-serial converter. The converter's RS232 serial output was connected to the serial port of an IBM XT computer, and the data were saved to a disk file using the capture feature of a terminal program, as if the external hardware were a modem. The captured data were saved on the computer in raw binary files.

In order to play back the captured files, Alinsky developed a parallel-to-bi-phase converter circuit. This circuit receives parallel 8-bit data characters from the computer's printer port and recreates the original bi-phase signal. The bi-phase output of this circuit was connected to the Pianocorder playback board in place of the cassette deck's square wave data signal, and the input of the board was connected to an IBM-compatible computer's printer port, using standard parallel port handshaking signals. This permitted captured songs stored on the computer to be played back on the Pianocorder by simply "printing" them.

3.3.3 Collaboration

The system Alinsky devised was very clever, and after some discussion it was clear that Alinsky's hardware interface would be useful towards an effort to archive the Pianocorder music library. Alinsky agreed to collaborate with the author to develop a reliable and accurate way of accomplishing this goal. The final solution would utilize the hardware interface developed by Alinsky under the control of custom software written by the author, thus taking advantage of each person's skills.

The need for custom capture software arose from the desire to automate the data capture process (due to the large volume of material to convert) and the requirement that the music data be stored in a logical and consistent format. This will maximize the usefulness of the library for future applications.

Although the Pianocorder data could be captured from the interface in the raw fashion that Alinsky was using previously, that approach would have several limitations. It would preserve the original data in cases where the signal was without fault, but it would also preserve any glitches in the tapes or deficiencies in the encoding. When dropouts occur in Pianocorder tapes, the playback board produces large amounts of garbage data that are passed to the computer as the board tries to resynchronize to the data signal. Without custom software interpreting the stream of bytes and determining the presence or absence of valid frames, such garbage would be unconditionally stored, cluttering the data files.

Custom software is also required to measure and preserve the tempo (data rate) for each song. (A file of raw Pianocorder frames would not reveal anything about the rate at which the frames were received from the playback board.) A stored record of the tempo is useful in remastering tapes and in converting the music to MIDI format.

Custom capture software would also be useful to produce statistics about the capture operation and to monitor its progress. With the addition of MIDI conversion capabilities, the software could also enable the operator to monitor the musical performances as they are transferred.

Finally, custom software is needed to perform song segmentation, i.e. storing the data for each logical song on a tape in its own file. Without such software, the operator would have to continually supervise the capture process, starting and stopping the low-level capture operation manually, keying in filenames for each and every song, etc. The tape deck would have to be repeatedly stopped and started between songs, resulting in wear and tear on the mechanism and lengthening the overall time required to capture a given tape. With automatic song segmentation, an entire tape side can be captured without interruption.

The author began working with Alinsky on the hardware-based capture system in early 1997. By June 1997, their teamwork had produced a fast, reliable system for transferring Pianocorder material to a computer.

3.3.4 The bidirectional parallel port

As described previously, Jim Alinsky's capture system originally employed a parallel-to-serial converter. This device was necessary due to a lack of available computer software to capture data in parallel. Using the parallel-to-serial converter allowed Alinsky to capture the data with an off-the-shelf commercial terminal program. This approach proved to be unnecessary once the custom software was developed.

The problem of reading eight TTL data lines on a personal computer could have been solved using one of the many data acquisition boards presently on the market. However, most modern IBM-compatible computers are capable of handling this data capture task without additional hardware by using the bidirectional capability of their parallel printer ports.

The bidirectional parallel port is typically used to allow peripherals such as tape backup devices, removable cartridge drives and some kinds of printers to exchange data with a PC in both directions. However, the parallel port can also support custom devices. The technical documentation needed to interface devices and control the parallel port is readily available (an excellent on-line reference is Stewart, 1994).

Using the parallel port to capture Pianocorder data is ideal for two reasons. First of all, its eight data lines are easily interfaced to the parallel output of the Pianocorder's shift register. Secondly, the computer's parallel port is capable of generating a hardware interrupt in response to a transition on one of its control lines. This is a perfect way to cue the computer to read a byte from the Pianocorder playback board.

The Pianocorder's bi-phase data stream runs at 4500 bits per second. This means that with 8 bits per byte, 562.5 bytes per second will be sent to the parallel port, each triggering a hardware interrupt. This interrupt rate does not present a problem, particularly since the code to receive a byte is very short. If the playback board had not conveniently had a shift register available, it would have been necessary to add one externally. The computer could not have handled receiving the data one bit at a time, responding to 4500 interrupts per second.

3.3.5 Interface circuitry

The schematic for the Pianocorder-to-parallel-port interface is shown in Figure 3.9. The capture hardware circuitry used in this thesis project was designed and assembled by Jim Alinsky, incorporating the Pianocorder playback board donated to the author.

Providing the 8-bit byte to the parallel port basically involved tapping into the eight data lines on the playback board shift register. Because the shift register is an LS (Low-power Schottky) device with limited current drive, the data lines were routed through a 74LS244 octal line driver. The gate enable lines of the driver were tied low, allowing the output lines to continuously reflect the data on the shift register. To provide additional pull-up drive, 3.3 KΩ resistors tied to +5V were added to

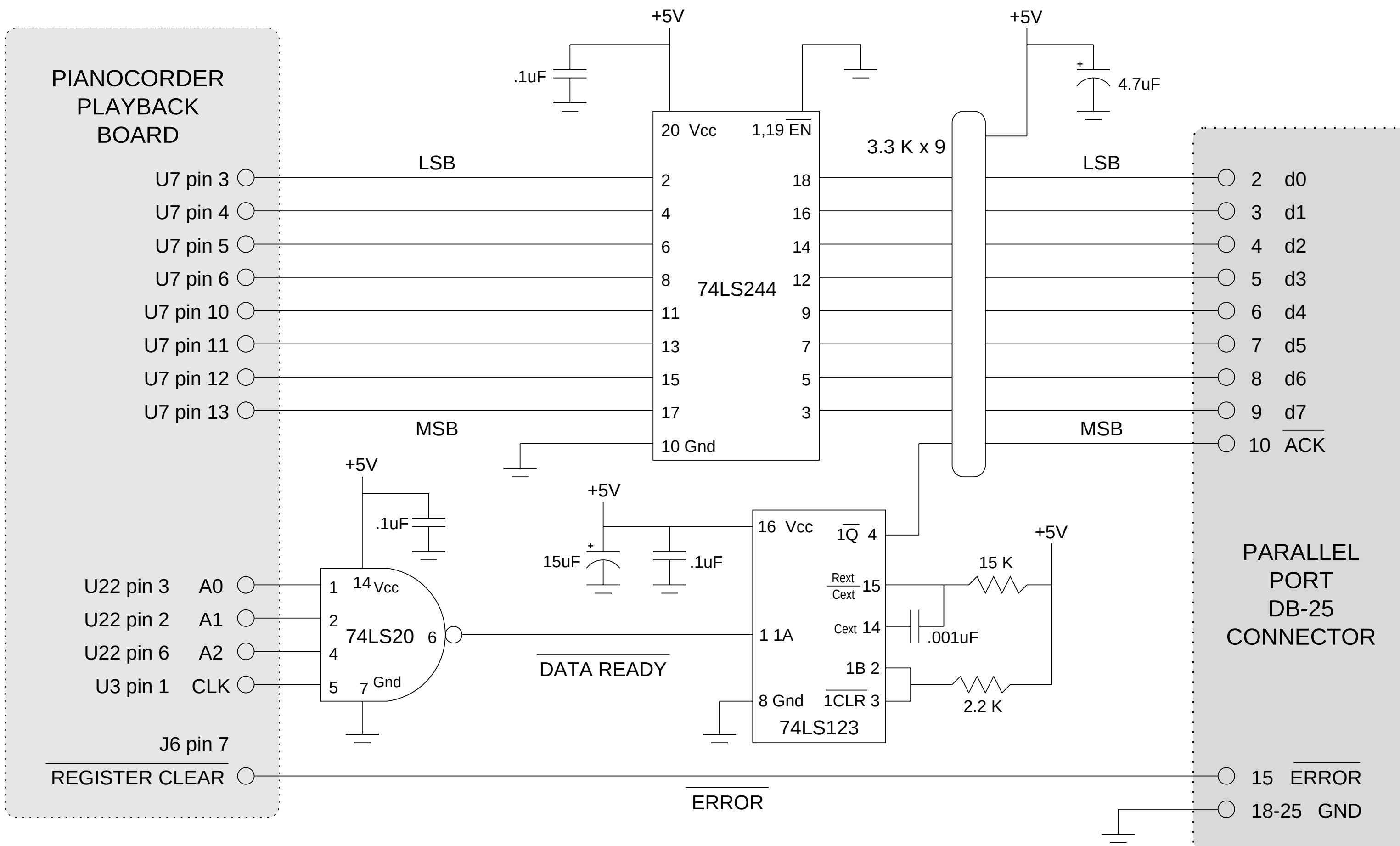


Figure 3.9: Playback board to parallel port interface schematic

the outputs. This helped to ensure that a sufficiently high pull-up voltage would be achieved on the receiving end (i.e. at the computer's parallel port).

The next problem was to find a way to signal the computer to read a byte. This cue was derived from the address lines A0, A1, and A2 which are present on jumpers J4, J5 and J6. In normal operation, the playback board distributes the binary data to the solenoid driver boards in a serial fashion, one bit at a time. The purpose of the address lines is to specify into which bit of a byte the current bit should be loaded. Thus, A0, A1 and A2 are all low during the first bit (MSB) of a byte, and they are all high during the last bit (LSB[6]) of a byte. At any time, the shift register U7 will hold the last eight bits received. Therefore, the computer should be cued to grab a byte after each complete byte has been loaded into the shift register; i.e. when A0, A1 and A2 are all high. This will occur exactly 16 times per frame, once after every 8 bits. This results in a very clean data stream (byte-aligned with the start of the frame) being sent to the computer.

It is important to ensure that the shift register will be in a stable state when the computer reads the output lines. The data from the shift register will be stable for at most 1/4500 of a second (222 μs) before the next bit is shifted in. Depending on the playback tempo, the maximum stable period could be as short as 200 μs.

The solution was to derive the cue signal by NAND'ing together the CLOCK line and the three address lines A0, A1 and A2. A0, A1 and A2 will all be high if and only if a complete byte is available to be read. The CLOCK signal is a square wave that is high 3/4 of the time and low 1/4 of the time. $\overline{CLOCK}$ is the inverse of CLOCK. Each bit is shifted into the shift register on the rising edge of $\overline{CLOCK}$. Using the rising

[6]Least significant bit

edge of CLOCK (as opposed to $\overline{CLOCK}$) as the fourth input to the NAND gate results in the cue occurring about 55 μs after the shift register has shifted. The data should then be stable for about 160 μs, giving the computer some time to respond to the cue and read the data. The output of the NAND gate, $\overline{DATA\ READY}$, will be low when data is available and high otherwise. The signal to the computer should thus occur on the falling edge of $\overline{DATA\ READY}$.

Signaling the computer to read a byte was achieved by strobing the $\overline{ACK}$ line (pin 10) of the parallel port, which is normally used by a printer to acknowledge that it has received a byte from the computer. (In this case, $\overline{ACK}$ is being used as a strobe instead of as an acknowledgment.) The $\overline{DATA\ READY}$ cue signal derived in the preceding paragraph will last about 150 μs, but the parallel port specifications require that the $\overline{ACK}$ line be strobed low for a much shorter period, approximately 0.5 μs. This was achieved in the interface circuit using an 74LS123 retriggerable monostable multivibrator. The 74LS123 was configured to trigger once on each high-to-low transition of $\overline{DATA\ READY}$, generating the appropriate 0.5 μs strobe pulse. The computer's parallel port controller responds to this strobe pulse by generating a hardware interrupt that can be associated with a software interrupt service routine on the computer to read the data byte.

A timing diagram of the important signals in the interface circuit is shown in Figure 3.10. The diagram shows the signal transitions occurring in the course of handling one data byte; subsequent bytes in the data stream are processed in an identical fashion. The duration of each bit is 1/4500 of a second, or 222.2 μs. The graph of the $\overline{ACK}$ line shows that the computer is being cued to read the byte at a point when the shift register is stable; the downward-going pulse occurs 25% (55 μs)

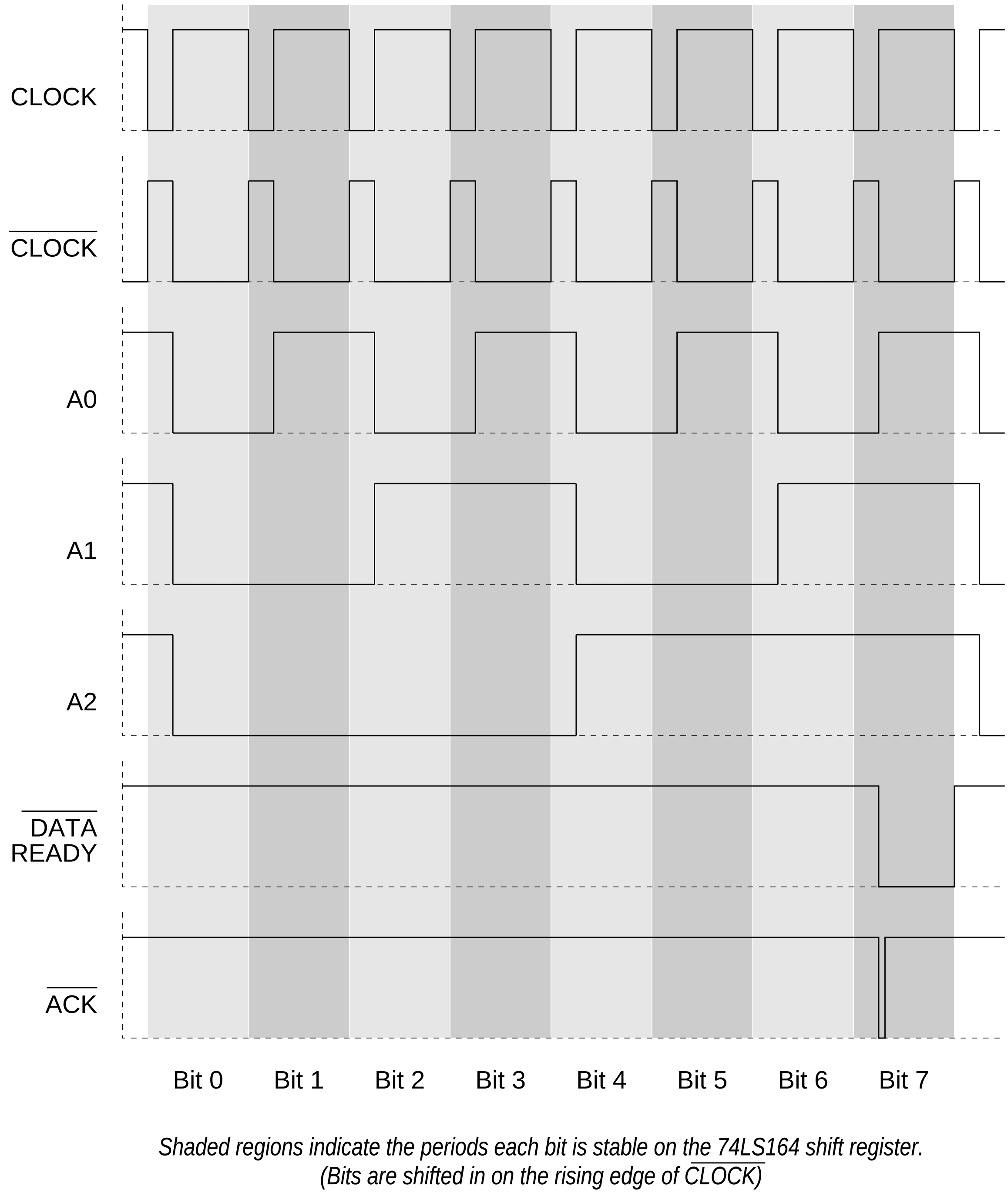
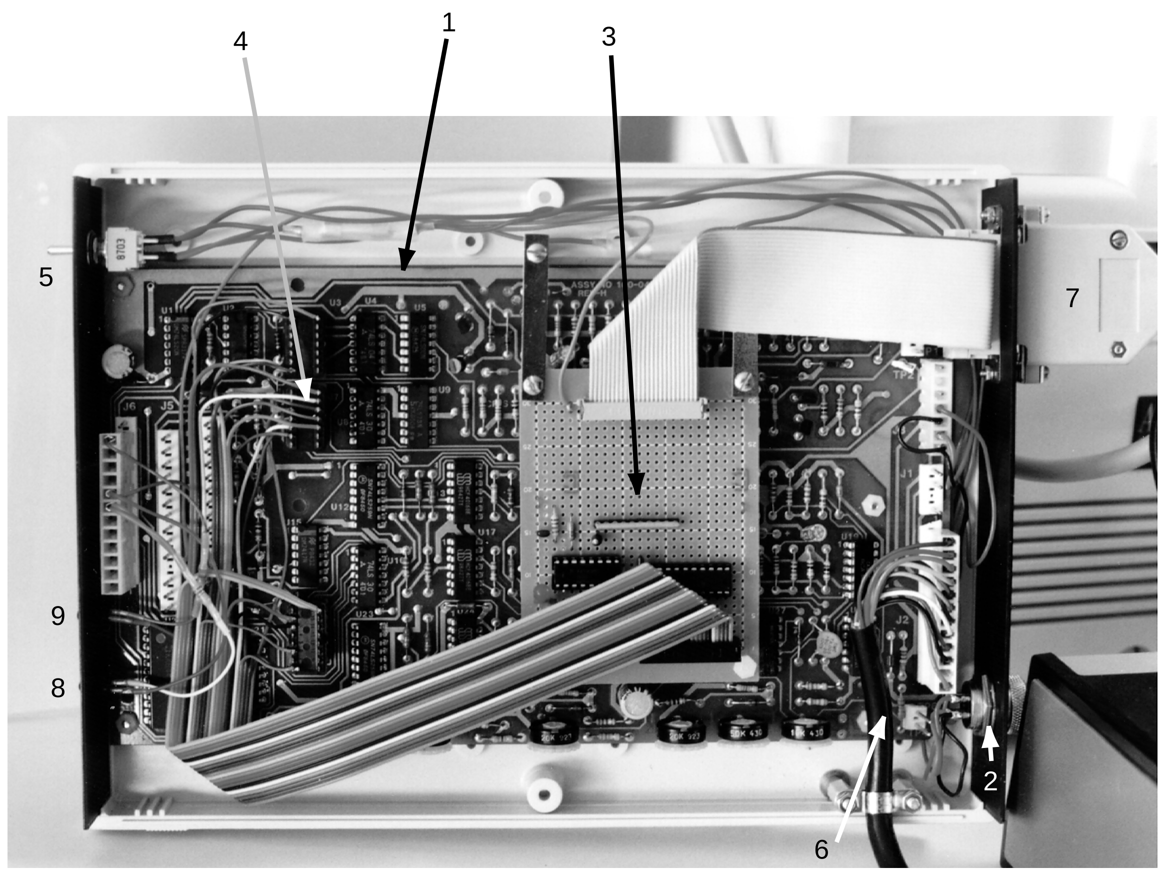


Figure 3.10: Interface circuit timing diagram

into the total duration of bit 7. This location of the pulse allows a reasonable time period (about 160 μs) for the computer to actually read the data.

Note that this data capture process could have been implemented by routing the $\overline{DATA\ READY}$ line to one of the parallel port control lines and having the computer poll this line instead of using hardware interrupts. However, that approach would result in the data bytes being read at an inconsistent and uncertain time after becoming ready. If the computer delayed too long for whatever reason (e.g. handling hardware interrupts for disk access), it could erroneously read the data after the shift register had already shifted in the next bit. That approach would also result in a considerable amount of the computer's CPU time being wasted on busy-waiting. Using hardware interrupts ensures consistently precise timing accuracy and also frees up the CPU to perform other tasks (disk access, real-time monitoring of the music via MIDI, etc.) during data acquisition.

In addition to the data lines and strobe signal, it is also desirable to give the computer some indication of whether or not the playback board is receiving valid data. The $\overline{REGISTER\ CLEAR}$ signal on the playback board is suitable for this purpose; it is used to clear the note registers in the case of a fault, preventing garbage data from being played. This line is high when valid data is being received and goes low when there is a fault. In the interface circuit, $\overline{REGISTER\ CLEAR}$ is connected to the parallel port's $\overline{ERROR}$ line (pin 15). This is an appropriate choice since the signals have the same polarity and semantics.



1 Pianocorder playback board
2 External 12 VDC / 5VDC power source
3 Data line driver and strobe generator
4 Shift register
5 Power switch
6 Cable from PT-100 cassette deck
7 Cable to parallel port
8 Loss-of-sync LED
9 Power LED

Figure 3.11: Pianocorder data capture box

Figure 3.12: Pianocorder data capture box and cassette deck

3.3.6 Hardware enclosure

Figure 3.11 shows the Pianocorder playback board mounted in a custom enclosure with Alinsky's parallel port interface board mounted directly above it. The major components are labeled. Figure 3.12 presents an external view of the enclosure paired up with the Pianocorder PT-100 cassette deck. The system is connected to the host computer's parallel port using a six foot male-to-male DB25 cable. A front panel switch controls power to the playback board, interface circuitry and cassette deck (which draws power through its 12-pin cable). A green LED on the front panel indicates that the system is turned on, and a red LED glows in the absence of valid data.

3.3.7 Calibrating the cassette deck transport speed

The data rate on some Pianocorder tapes can vary by up to 600 Hz from the nominal rate of 4500 bits per second. When archiving tapes, it is desirable to measure and record the data rate as a record of the musical tempo. To accomplish this, it was necessary to calibrate the cassette deck's tape speed, which is adjustable using both internal and external potentiometers. The calibration was done by playing a measured length of tape over a timed interval.

Once the tape deck was known to be running at the proper speed, a particular Pianocorder tape was played and its measured data rate recorded. This permitted playing the tape again later to quickly recalibrate the motor speed without the need to actually measure the tape speed again. This was done by simply adjusting the tape speed, while the tape was running, to match the previously-measured data rate.

3.3.8 Capture software

The software to handle the data acquisition process is largely based on the PC2MID software described in Section 3.2, with the bi-phase decoding code replaced by routines to control the external interface hardware. In addition, the user interface was upgraded from a simple command-line interface to an interactive full-screen application with numerous displays updated in real time, providing useful information about the capture operation.

Instead of continuing to use the Linux operating system, the data capture software was developed for MS-DOS, because it is considerably easier to develop critical real-time applications in a non-multitasking environment. Using MS-DOS also simplified the code for handling hardware interrupts (in Linux, a kernel-level driver would have been required). A specialized version of Linux for real-time applications exists (Real-Time Linux; see Barabanov, 1997), and the PC2MID software may eventually be ported to this platform. Presently, the Pianocorder data files are captured under MS-DOS and then transferred to a Linux machine for storage and backup on a DAT drive. All further processing of the data files is done under Linux.

Interrupt handling

At the core of the capture software are the low-level routines to set up the parallel port and receive data from it. Initialization consists of finding the I/O port address of the parallel port and setting bits in the port's control register to enable bidirectional mode and to enable generation of interrupts in response to low-going $\overline{ACK}$ pulses. The software then installs an interrupt handler on the port's interrupt line.

At each interrupt, the handler simply reads the current data and status bytes from the parallel port, enqueuing them into a circular buffer. The main application thread removes data bytes from this buffer as they become available, executing independently of the interrupt-driven data capture.

Measuring the data rate

The individual songs on Pianocorder cassettes are frequently recorded at slightly different data rates. These rates should be measured and stored along with the music data as a record of the original tempo. The capture software measures the data rate by counting how many bytes are received over time. For accuracy, the timing routines use a high-resolution 1.193180 MHz clock in the computer's programmable interrupt timer (PIT) chip. This permits measuring the elapsed time in units of 1/1193180 of a second (using assembly language routines written by the author). The measured data rate is converted to bits per second and stored as a 16-bit unsigned integer in the header of each file of captured data. The nominal data rate is 4500 bits per second (562.5 bytes per second).

Frame segmentation

Determining the boundaries of the 16-byte frames was tricky in the software-based data acquisition method of Section 3.2, but it is very easy to do in the hardware-based method. In this method, the data are processed as a string of bytes (as opposed to a string of bits, as in the software method). Since the 128-bit frames are guaranteed to be properly aligned on byte boundaries, the frame boundaries are easily determined by watching for the special sync byte `FDh` (`11111101` in binary) that occupies the last byte of each frame.

D8	00	20	00	00	00	08	00	90	00	00	02	C4	28	00	FD
D8	00	20	00	00	00	08	00	90	00	00	02	C4	28	00	FD
D8	00	20	00	00	00	08	00	98	00	00	02	00	20	00	FD
D8	00	20	00	00	00	08	00	98	00	00	02	00	20	00	FD
D8	00	20	00	00	00	08	00	98	00	00	02	00	20	00	FD
D8	00	20	00	00	00	08	00	98	44	A0	0A	40	A0	00	FD
D8	00	20	00	00	00	08	00	98	44	A0	0A	40	A0	00	FD

Figure 3.13: Sample Pianocorder data stream segmented into frames

The algorithm to extract frames simply maintains a byte counter counting from 0 to 15, incrementing as each byte is received. The incoming bytes are stored in a 16-byte array indexed by the byte counter. Whenever the sync byte is encountered, the byte counter is reset to 0. If the sync byte is read when the byte counter is exactly 15, the sixteen bytes in the buffer are saved as a valid frame. A portion of a Pianocorder data stream, segmented into frames, is shown in Figure 3.13.

To prevent garbage data from being played during a fault, the Pianocorder playback board does not permit the solenoids to be activated until two valid frames have been received. This effect is simulated in the capture software using a frame counter that is reset to zero at each loss of sync. The software throws out all received frames until this counter increments to a preset value (usually 2). Once this value has been reached, the software begins to process incoming frames. This ensures that the capture software handles the frame data exactly as the actual Pianocorder hardware does.

Song segmentation

Song segmentation under the hardware solution was also much easier to implement. Whenever the Pianocorder playback board is not reading valid data, nothing valid is received by the parallel port. Due to random behavior in the absence of valid bi-phase, the playback board usually transmits garbage bytes at a rapid pace during the breaks between songs. This garbage is easily ignored since it lacks the proper sync byte. If such garbage lasts longer than a large dropout in the tape might last (0.5 seconds), the software interprets the break as the end of a song. If the break lasts longer than 12 seconds, the software assumes that the end of the tape has been reached and stops waiting for data.

Error recovery

There are occasional glitches on Pianocorder tapes, resulting in one or more frames being corrupted. The capture software interprets the corrupted frames as invalid because their sync bytes are missing or improperly located. It will not store any data to disk until the valid data stream resumes and two consecutive valid frames have been read.

This action would normally produce a temporal skip in the music as stored on disk, since there is no indication of elapsed time other than the presence of the frames themselves. (The effect is the musical analog of what one observes when frames are spliced out of a strip of motion picture film.) To remedy this situation, the software measures the amount of time that elapses during the loss of sync. Until the data stream resumes, the software fills in the gap by adding one or more instances of the

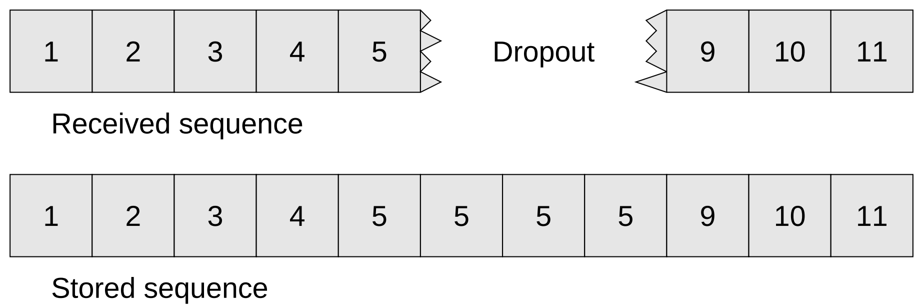


Figure 3.14: Example of frame padding filling a dropout

last valid frame received before the glitch occurred. This prevents a disruption in the timing and rhythm of a song. In some cases, such frame padding may cause notes to be held longer than usual, but this effect is less objectionable than filling the gap with momentary silence. The author has observed this same recovery technique being used by television networks to cover glitches in video transmission.

Stray sync byte correction

In the course of capturing data from many Pianocorder tapes, the author has found several instances in which the sync byte `11111101` appears in the body of a frame as part of the musical note data. This causes the Pianocorder playback board to momentarily lose sync, since it believes the end of a frame has been reached. Although one would rarely expect a chromatic pattern of notes in the sequence `11111101` to occur in a musical performance, the author found several pieces in which it does indeed happen[7], usually in the context of chords sliding upwards or downwards chromatically.

[7] e.g. "Scheherezade Fox Trot" in Volume 23, Tape 1, Side B.

The Superscope engineers editing the music data should have removed these stray sync bytes but apparently failed to do so.[8] However, the capture software written for this thesis project has the capability to remove stray sync bytes automatically during the capture process. This is done by modifying the bytes slightly, e.g. `11111101` becomes `11111100`. The software attempts to apply the change that causes the least degradation to the musical performance.

Naturally, the detection of stray sync bytes affects the frame segmentation routines by making it more difficult to tell whether invalid data has been received; if a sync byte appears within the body of a frame when stray sync byte correction is turned on, the sync byte is modified instead of the frame being discarded as invalid. For this reason, the stray sync byte correction feature is disabled by default, but may be temporarily enabled by the operator as required.

Archival files

The 16-byte Pianocorder frames captured by PC2MID are written to disk, one file per song, in the .PC file format specified in Table 2.3. The software automatically assigns an appropriate filename, adding a two-digit song number to a six-character template. All files have the extension ".PC".

Section 2.7 in Chapter 2 described several goals in archiving Pianocorder music data, and PC2MID fulfills each of them by recording appropriate values in each file's 32-byte header. Included are the number of frames received, the measured data rate, the musical source of the song, and the number of errors encountered. In accordance

[8]The stray sync bytes occur only in music data derived from piano rolls. According to anecdotes from individuals who either worked at or visited the Marantz facility, the rolls were transferred under severe time constraints and very little editing was performed.

with the stated goals, PC2MID also conserves disk space by trimming blank head and tail frames from songs, removes misplaced sync bytes, and pads gaps in the stream of frames when glitches occur. These considerations make the data files more consistent and maximize their usefulness for future users.

User interface

The capture software was designed to archive Pianocorder tapes in a highly automated fashion requiring minimal user intervention. The capture procedure is often as simple as inserting a tape into the player, starting the software, starting the tape, and letting the process run for twenty minutes. Song breaks are automatically detected, each song is automatically written to its own data file, and the capture process automatically stops at the end of the tape.

As data is captured, the screen display presents an array of useful information to the operator (see Figure 3.15). The upper third of the screen shows the current song number, filenames, and title/catalog information for the current song (used in generating MIDI files). The middle section of the screen gives a summary of the number of frames processed, the elapsed time, the data rate, the number of times sync was lost, and some statistics about the MIDI velocity levels involved in MIDI conversion.[9] The lower part of the screen gives a live display of all 80 notes, the status of the pedals, the expression levels (in both numerical and bar graph formats), the keyboard split point, and the contents of the unused parts of the Pianocorder frame (see Appendix A). Also shown is a rectangular window presenting an emulation of

[9]The note and pedal *Early Off, Off Skipped,* and *Too Short Skipped* fields in this section are currently unused; they were part of an attempt to modify the music data for better playback on modern solenoid piano systems.

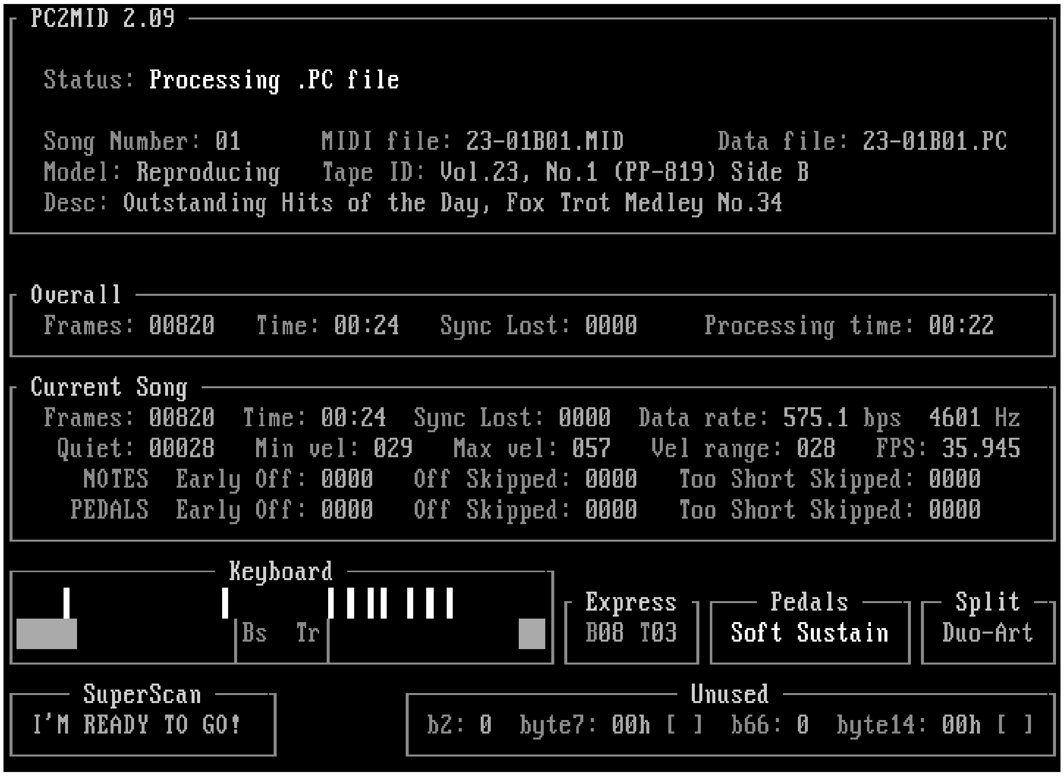


Figure 3.15: PC2MID capture/conversion software screen display

the Superscan Display Console, an external scrolling LED display that was sold as an accessory to the Pianocorder for singalong applications (only a subset of the music library contains control data to drive this display).

During data capture, the operator may override PC2MID's automated processing using a number of keyboard commands. For example, pressing the space bar will force a song break, pressing "S" will toggle PC2MID's stray sync byte correction, and pressing "I" will toggle whether PC2MID immediately gives up or tries to recover in the event of a fault. The capture process can be aborted by pressing ESC at any time.

Audible feedback

The capture software facilitates unattended operation by providing a number of audible warnings in response to various events that occur during capture. For example, PC2MID makes a high-pitched beep in the event of a high-level data error (i.e. there was no dropout on the tape, but a frame was received with an invalid sync byte). High-level data errors are caught in the frame segmentation routines. The software makes a low-pitched beep in the event of a low-level data error (i.e. the hardware is not receiving a valid bi-phase signal). Low-level errors are detected by monitoring the printer port's $\overline{ERROR}$ line, which is connected to the playback board's $\overline{REGISTER\,CLEAR}$ signal. These audio feedback functions allow the operator to archive tapes without the need to constantly watch the on-screen display.

3.3.9 Performance of the hardware-based solution

Implementation of the hardware interface was completed in the spring of 1997. Development of the PC2MID capture software occurred simultaneously with Jim Alinsky's fabrication of the external electronics. System integration and testing began in June 1997. The design was found to be sound and very reliable.

Only one major problem was encountered: the parallel port interrupt handler would occasionally take too long to respond to its interrupt while disk access was occurring. As a result, data bytes read from the parallel port would occasionally be shifted left by one or two bits, due to the shift register on the Pianocorder playback board having already shifted in some new bits. Since each bit is stable on the shift register for about 222.2 μs, the incorrect data bytes were apparently being read up to 450 μs late.

The author tried a number of things (altering the code and the PC's configuration) to eliminate the interrupt latency caused by disk access, but with no success. The problem could probably be solved by eliminating disk access; the music data would then have to be stored in memory and written to disk at the end of the capture process. But before implementing this solution in the software, the author found that the latency problem could be completely eliminated by simply using a ramdisk for all file input and output during capture. MS-DOS comes with a suitable ramdisk utility for this purpose (RAMDRIVE.SYS). The author decided to continue to use the ramdisk solution while continuing with the Pianocorder-to-MIDI conversion issues. These will be discussed in the next chapter.

3.4 Applications of Pianocorder data in .PC format

The preceding sections described two methods for transferring the binary data from Pianocorder tapes to a computer for storage. Once the original Pianocorder frames are available as .PC files, a number of operations may be conveniently performed.

3.4.1 Remastering Pianocorder tapes

One desirable operation is the capability to remaster Pianocorder tapes from the files of digital data. This is done by reading the data files and producing a clean bi-phase signal that can be recorded to fresh tape media. New copies of the tapes can be created in this manner once the originals are no longer playable.

The author and Jim Alinsky developed two methods of regenerating the bi-phase signal from the data files. The first method makes use of the sound card that is available in most modern personal computers. The author implemented a software utility to read one or more Pianocorder data files and encode them into an 8-bit 9 kHz .WAV-format audio file containing a pure square wave bi-phase representation of the digital data. The bi-phase signal is represented in digital audio samples by generating a square wave of fairly strong amplitude, with zeroes represented by two samples of the same amplitude and ones represented by two samples of opposite amplitude about the zero line. After each zero, the phase is reversed. A .PC file is converted to bi-phase by reading the frame data, byte by byte, from the .PC file and writing the appropriate bi-phase square wave to the .WAV file. When the .WAV file is played back on the computer's sound card (using existing sound file playback software), the bi-phase signal is produced in real time on the sound card's audio output.

These .WAV files can be used to digitally remaster Pianocorder tapes by recording the audio from the sound card to cassette tape. Because Pianocorder tapes run at twice the speed of a normal cassette deck, the audio files are set up to play the bi-phase at half speed. When recorded on a conventional cassette recorder (which is also at half speed), the data rate will be correct for playback on the Pianocorder system.

Since these digital audio files contain only three different values— positive amplitude, negative amplitude, and zero amplitude (during silence between songs)— and patterns that are highly repetitive, these audio files compress extremely well using utilities like gzip.

A second method of reproducing the bi-phase signal requires an external piece of circuitry connected to the computer's parallel port. This circuit, using standard parallel port handshaking, reads bytes in sequence from the parallel port and generates a 0–10 V bi-phase square wave at exactly 4500 bits per second. Section 3.3.2 described how Jim Alinsky constructed such a circuit, connected in place of the Pianocorder cassette deck, to permit playing computer data files of Pianocorder music on the actual Pianocorder system. Alinsky's circuit can also be used for remastering tapes; the bi-phase signal can be adjusted to an appropriate level and recorded to tape. The author wrote a command-line utility to dump .PC files to Alinsky's parallel-to-bi-phase converter. Although the present circuit design has a fixed output data rate of 4500 bits per second, future revisions will allow the rate to be set by the computer. This will allow the software to make the circuit reproduce the bi-phase at the same data rate that was observed when the data were captured.

Remastered Pianocorder tapes produced using the above methods are of much better quality than tapes recorded by dubbing the signal from original cassettes. The error recovery performed during the capture process also ensures that these tapes will be free of glitches.

3.4.2 Controlling a Pianocorder by computer

The above solutions for remastering tapes also permit the Pianocorder to be operated under computer control. Instead of recording the bi-phase signal to tape, it can be connected to the Pianocorder's playback circuitry[10] and used to drive the Pianocorder directly. Thus, the Pianocorder PT-100 cassette deck is no longer required.

[10] Opto-isolation is imperative, due to the Pianocorder's "hot chassis" design.

This can give new life to aging Pianocorder systems that are still in use, since the cassette decks are one of the first components to fail, becoming increasingly temperamental as they wear out. Replacing the cassette deck with a hardwired connection to a host computer results in much more reliable operation.

In cases where Pianocorder owners are unwilling to disconnect the cassette deck, the method employing .WAV files can still be used. Instead of connecting the computer's sound card output to the Pianocorder's playback board, the signal can be played into the PT-100 tape deck by means of a commercial "CD-to-cassette adapter" of the type sold for playing portable CD players in automobiles. The author has demonstrated that this approach is effective, though considerably more awkward than using a direct connection.

Computer control of a Pianocorder system permits features that were never possible using the tape deck. With the linear nature of the cassette media removed, random access to songs (or parts of songs) becomes possible. Also, the original Pianocorder system was never capable of transposing performances, but transposition can be done on the computer by modifying the original frames (shifting note bits left or right) prior to generating the bi-phase signal. Using the computer interface, a Pianocorder can also be made to play performance data generated in real time, facilitating the development of interactive applications employing an acoustic piano under computer control.

Finally, computer-based control ensures that Pianocorder systems still in operation may continue to be enjoyed long into the future, even if the cassette format becomes obsolete. With the Pianocorder library archived on a computer and the capability to send the data directly to a Pianocorder system, the Pianocorder music library is no longer in danger of being lost. As long as the computer archive is protected and converted to future digital storage formats, the music data will be safely preserved for generations to come.

CHAPTER 4

CONVERSION OF PIANOCORDER PERFORMANCES TO MIDI FORMAT

Chapter 3 described two methods of capturing the data from Pianocorder tapes and presented some applications for these .PC data files. A further application is the translation of the Pianocorder music library to MIDI format. This chapter will present a solution for accurately converting the captured Pianocorder data to MIDI files, permitting the Pianocorder music library to be used on modern player piano systems and other musical equipment.

4.1 Data distribution in the Pianocorder

As discussed in Chapters 2 and 3, a Pianocorder performance consists of a stream of 16-byte data frames at a nominal rate of 35.15625 frames per second. Each frame stores the entire state of the piano. Ten of the sixteen bytes are used to store the states of the 80 playing notes; two bytes are used to store the bass and treble expression levels, keyboard split point, and pedal states; one byte is used to store a character of ASCII lyrics; one byte is reserved for the sync pattern `FDh`; and two bytes are unused. A sample stream of Pianocorder frames is shown in Figure 4.1. Notes can be seen turning on and off under the bass and treble note sections, very much like perforations in a paper piano roll.

In the Pianocorder hardware, each frame is processed serially as a stream of 128 bits. The incoming data bits are immediately distributed to latched registers holding the individual states of notes and pedals. As a result, the state of the piano is updated not all at once, every 1/35.15625 of a second (28.4 ms), but rather in a sweeping fashion over a period of 28.4 ms. For example, the states of two adjacent notes on the piano are *not* updated at the same time, but rather offset by one bit interval (1/4500 of a second). Figure 4.1 shows that the pedals are updated first, then the bass notes (sequentially from lowest to highest), followed by the treble notes (from lowest to highest). The elapsed time between the updating of the bass notes and treble notes is even greater due to the "unused" and "treble expression" bytes between the bass and treble note sections. This time difference is significant; the highest note on the piano is updated 21.1 ms later than the lowest note.

This sequential updating complicated the creation of music data for the Pianocorder in that it was difficult to make two notes strike simultaneously. The Superscope music editors developed a number of encoding tricks to get around the system's limitations, but applying these tricks was a time-consuming process and only the Contemporary Artist Series recordings were edited to perfection. (The encoding tricks will be discussed later in this chapter.)

The bulk of the Pianocorder music library minimized the effects of the sequential update problem by having the music *encoded* sequentially as well. Most of the music was recorded by either (a) scanning player piano rolls into digital format, or (b) recording a live pianist on the stock Pianocorder recording system. The player

Bexp	SS	Bass Notes					uu	Texp	Treble Notes					uu	Sync
D8	00	20	00	00	00	08	00	90	00	00	02	C4	28	00	FD
D8	00	20	00	00	00	08	00	90	00	00	02	C4	28	00	FD
D8	00	20	00	00	00	08	00	98	00	00	02	00	20	00	FD
D8	00	20	00	00	00	08	00	98	00	00	02	00	20	00	FD
D8	00	20	00	00	00	08	00	98	00	00	02	00	20	00	FD
D8	00	20	00	00	00	08	00	98	44	A0	0A	40	A0	00	FD
D8	00	20	00	00	00	08	00	98	44	A0	0A	40	A0	00	FD
D8	00	20	00	00	00	08	00	98	44	A0	0A	40	A0	00	FD
D8	00	20	00	00	00	08	00	98	44	A0	08	40	80	00	FD
D8	00	20	00	00	00	08	00	98	00	00	48	44	80	00	FD
D8	00	20	00	00	00	08	00	98	00	00	48	04	80	00	FD
D8	00	20	00	00	00	08	00	98	00	00	48	04	80	00	FD
D4	00	20	00	00	00	08	00	98	00	00	48	04	80	00	FD
D4	00	20	00	00	00	08	00	98	00	04	40	44	00	00	FD
D4	00	20	00	00	00	08	00	98	00	04	40	44	00	00	FD
D4	00	20	00	00	00	08	00	98	00	04	40	44	00	00	FD
D4	00	20	00	00	00	08	00	98	00	04	00	40	00	00	FD
D4	00	00	00	00	00	08	00	98	00	04	00	40	00	00	FD
D4	00	00	00	00	00	08	00	98	00	24	02	40	00	00	FD
94	00	00	00	00	00	08	00	98	00	24	02	40	00	00	FD
94	00	00	00	10	00	08	00	98	00	24	02	40	00	00	FD
96	00	00	00	10	00	08	00	98	00	00	02	00	00	00	FD
96	00	00	00	10	00	48	00	98	04	24	42	00	00	00	FD
96	00	00	00	10	00	40	00	98	04	24	42	00	00	00	FD
D4	00	00	00	10	00	40	00	98	04	24	40	00	00	00	FD
D4	00	00	00	10	00	40	00	98	04	24	40	00	00	00	FD
D4	00	00	00	10	00	40	00	98	04	24	40	00	00	00	FD
D4	00	00	00	10	00	40	00	98	04	24	40	00	00	00	FD
D4	00	00	00	10	00	40	00	98	04	24	40	00	00	00	FD
D6	00	00	00	10	00	40	00	98	00	20	00	00	00	00	FD
D6	00	00	00	10	00	40	00	98	00	00	00	00	00	00	FD

Bexp = Bass expression and pedals
Texp = Treble expression and keyboard split point
SS = Superscan data (one byte of ASCII lyrics or control codes)
Sync = Sync byte
uu = Unused

Figure 4.1: Sample stream of Pianocorder frames

piano rolls were scanned in such a way that each note was sampled at the moment when the corresponding bit in the Pianocorder frame was recorded.[1] In the case of the live recordings, the Pianocorder recording hardware sequentially sampled the note states from wire spring switches under the keys, again in synchronization with the corresponding bits in the data frame.[2] Thus, the Pianocorder's internal data distribution timing must be considered to accurately convert the performances to MIDI format.

4.2 Standard MIDI File parameters

In the mid-1980s, the International MIDI Association, based in Los Angeles, California, developed a portable file format called "Standard MIDI File" (SMF) to store musical performances in the form of MIDI events. MIDI files are analogous to a printed musical score; they represent the notes, timing, instrumentation and expression of a musical piece. A computer or MIDI device interprets the stream of events in a MIDI file to reproduce a performance much as a human musician plays from sheet music. Because of MIDI's event-based structure, it is very compact, and MIDI has recently become very popular due to rapid growth in multimedia applications. It would be beneficial to convert Pianocorder performances to MIDI files so that they can be enjoyed on modern equipment.

[1] The author has been unable to verify that the Superscope engineers made certain of this detail, but it appears to be the case, based on comparing Pianocorder frame data with what one would expect musically.

[2] This is known for certain, as the schematics for this circuitry are available in (Superscope, Inc., 1979).

4.2.1 Timing parameters

The MIDI file format is not overly complicated, but there are a number of parameters that must be carefully chosen to maximize efficiency and accuracy. One of the most important issues is timing. MIDI files represent time in ticks, such that the number of ticks per minute is the product of a *time division*, representing the number of ticks per quarter note (TPQN), and the current *tempo* in beats (quarter notes) per minute (BPM). The time division is usually a multiple of 24, although the MIDI file specifications do not explicitly require this. For maximum compatibility, manufacturers of MIDI equipment recommend using the time division values 24, 48, 96, 120, 192, 240, 384, or 480 (Roland Corporation, 1994, p. 10). The tempo can generally range from 10 to 300 BPM (again, this is convention and there are no defined limits in the specifications).

Various degrees of timing resolution can be achieved by making suitable choices of time division and tempo. In a MIDI file, each event is preceded by a *delta time* (in ticks) that specifies how much time must elapse before the event is transmitted. The delta times are stored in a variable length format, using as many bytes as necessary to represent a given delta time.

In choosing suitable parameters for representing Pianocorder timing, several issues were considered. First of all, it was crucial to select one of the recommended time divisions so that the files would be compatible with all existing equipment. Secondly, the default tempo value should leave the user some room for adjustment. Thirdly, it is desirable to closely match the Pianocorder's frame rate of 35.15625 frames per second while simulating the sequential data distribution of the Pianocorder. A final consideration was that the choice of parameters result in the bits of the Pianocorder frame each playing for exactly the same duration.

The author eventually settled on a time division of 384 TPQN and tempo of 176 BPM. This results in timing that is accurate to (384 TPQN * 176 BPM) / 60 seconds per minute = 1126.4 ticks per second, or better than 1 ms resolution. Each 16-byte Pianocorder frame is divided into 32 ticks, or one tick per 4-bit nybble; four of the 80 notes are updated at each tick. With this choice of parameters, the effective frame rate is 1126.4 ticks per minute / 32 ticks per frame = 35.2 frames per second (0.12% error from the nominal value). These parameters seemed to provide the best compromise in producing accurate timing while using reasonable parameter values. Using lower values would sacrifice timing resolution unnecessarily. Subdividing each frame further (e.g. breaking each frame into 64 ticks instead of 32) would require unreasonably high values (at time division 480, a tempo of 281 BPM would be required, leaving little freedom for the user to increase the tempo).

4.2.2 Other parameters

Another MIDI file parameter to consider was the file type parameter. There are three types of MIDI files: Type 0 indicates a single-song file with one track of music data; Type 1 indicates a single-song file with multiple tracks of music data played in parallel (typically, each track contains data for a different musical instrument); Type 2 indicates a multi-song file with multiple tracks, each containing a complete song. Because Pianocorder music involves only one instrument, Type 0 MIDI files are appropriate for files derived from Pianocorder performances. This choice has the advantage that Type 0 MIDI files are supported by a slightly broader array of equipment than Type 1 files. (Type 2 files are rarely used.)

MIDI files typically contain events identifying the key signature and time signature of the piece. These events are not needed to represent Pianocorder music, but some MIDI devices expect to find these events in a MIDI file. To ensure compatibility with these devices, default values (key signature = C major, time signature = 4/4) were included in Pianocorder-derived files.

4.3 Interpreting the variable split point

Pianocorder material is encoded with any of three different split points to accommodate music data transferred from Ampico, Welte, and Duo-Art reproducing piano rolls. The split point is stored in bits 64 and 65 of the Pianocorder frame and can vary instantaneously from frame to frame. Table A.2 shows the various split points achieved by each combination of bits and the reproducing roll formats to which they correspond. In converting Pianocorder performances to MIDI events, it is important to take the split point into consideration, using the appropriate expression level (treble or bass) to compute the MIDI velocities for notes in each half of the keyboard.

In examining the Pianocorder data of material derived from reproducing rolls, the author found evidence that Superscope mistakenly exchanged the split points of the Ampico and Duo-Art systems. Thus, data encoded with what is known to be the Ampico split point were really captured from a Duo-Art roll and vice versa. This conclusion was reached by observing the encoded split points for various Pianocorder songs and looking up the roll documentation in published catalogs of reproducing rolls (Smith, 1987; Obenchain, 1977; Smith & Howe, 1994) based on information from the description sheets accompanying the Pianocorder tapes. Although there is some overlap between the music produced for the Ampico and Duo-Art systems, there are many cases in which a title was available only for the opposite format indicated by the observed split point. Having confirmed the true split points of each system and having verified the interpretation of encoded split points by the Pianocorder hardware, the only explanation the author can conceive is that Superscope must have mixed up the split points.

This is especially plausible considering that Teledyne, in designing the Piano Player system that ultimately became the Pianocorder, apparently got the split points wrong as well. In (Walker, 1979), Teledyne's patent covering a piano roll conversion approach, a completely incorrect understanding of the split points for each type of reproducing roll is presented. Oddly, Teledyne's split points are different from those adopted by Superscope. The source of Teledyne's error is unknown, and Superscope apparently failed to fully investigate the situation before initiating their piano roll transfer operations.

Superscope's Ampico/Duo-Art confusion results in an erroneous split point being specified to the Pianocorder playback system. In converting the performances to MIDI files, it is desirable to reverse the two split points, thereby restoring the correct split points are used in assigning MIDI expression. The author has applied this correction only to Pianocorder music derived from reproducing piano rolls. The correction can also be optionally performed in the software that digitally remasters Pianocorder tapes (discussed at the end of Chapter 3).

4.4 The Pianocorder's expression circuitry

The Pianocorder system strikes individual notes on the piano using solenoids operated at 170 VDC. Multiple levels of expression are achieved using pulse width modulation, i.e. by varying the duty cycle of the applied voltage. The keyboard is divided into bass and treble sections, and each section can assume any of 32 expression levels. The expression levels are updated once per frame, stored as two 5-bit integers in bytes 0 and 8 of each frame. Thus, the expression levels for each section are updated just before the notes to which they apply. Level 0 represents the softest intensity, and level 31 represents the loudest intensity.

4.4.1 The Pianocorder's DACs

The treble and bass solenoid duty cycles are controlled by two 5-bit digital-to-analog converters (DACs) on the Pianocorder playback board, shown in Figure 4.2. Notice the resistance values of 3.3 MΩ, 1.5 MΩ, 680 KΩ, 390 KΩ, and 220 KΩ. These values do not quite follow the ideal 1, 2, 4, 8, 16 weighting for a 5-bit linear DAC, and this causes the output function to be not exactly linear. In fact, there are some significant irregularities in the output function; most notably, that expression levels 16 and 17 are actually *lower* in volume than level 15.

Figure 4.3 shows the DAC output function graphically, and Table 4.1 compares normalized expression levels generated by the Pianocorder DAC with the corresponding levels that would be generated by a true linear DAC. The normalized DAC values in this table were computed using the parallel resistance formula to compute the

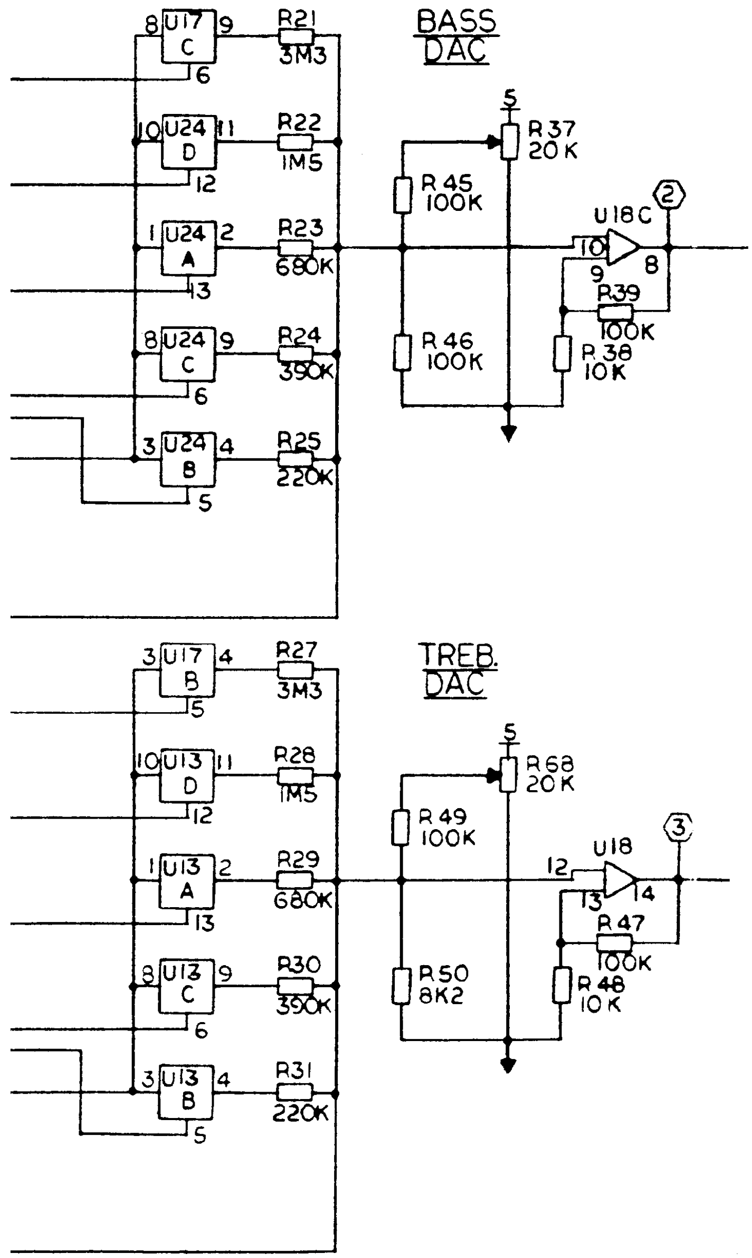


Figure 4.2: Expression DACs of Pianocorder playback circuitry

Expression level	Normalized intensity	
	Linear weighting	Pianocorder DAC
0	0.000000	0.000000
1	0.032258	0.031731
2	0.064516	0.069809
3	0.096774	0.101541
4	0.129032	0.153991
5	0.161290	0.185722
6	0.193548	0.223800
7	0.225807	0.255532
8	0.258065	0.268497
9	0.290323	0.300228
10	0.322581	0.338306
11	0.354839	0.370038
12	0.387097	0.422488
13	0.419355	0.454219
14	0.451613	0.492297
15	0.483871	0.524028
16	0.516129	0.475972
17	0.548387	0.507703
18	0.580645	0.545781
19	0.612903	0.577512
20	0.645161	0.629963
21	0.677419	0.661694
22	0.709677	0.699772
23	0.741936	0.731503
24	0.774194	0.744469
25	0.806452	0.776200
26	0.838710	0.814278
27	0.870968	0.846009
28	0.903226	0.898459
29	0.935484	0.930191
30	0.967742	0.968269
31	1.000000	1.000000

Table 4.1: Expression level intensities (Pianocorder DAC vs. linear weighting)

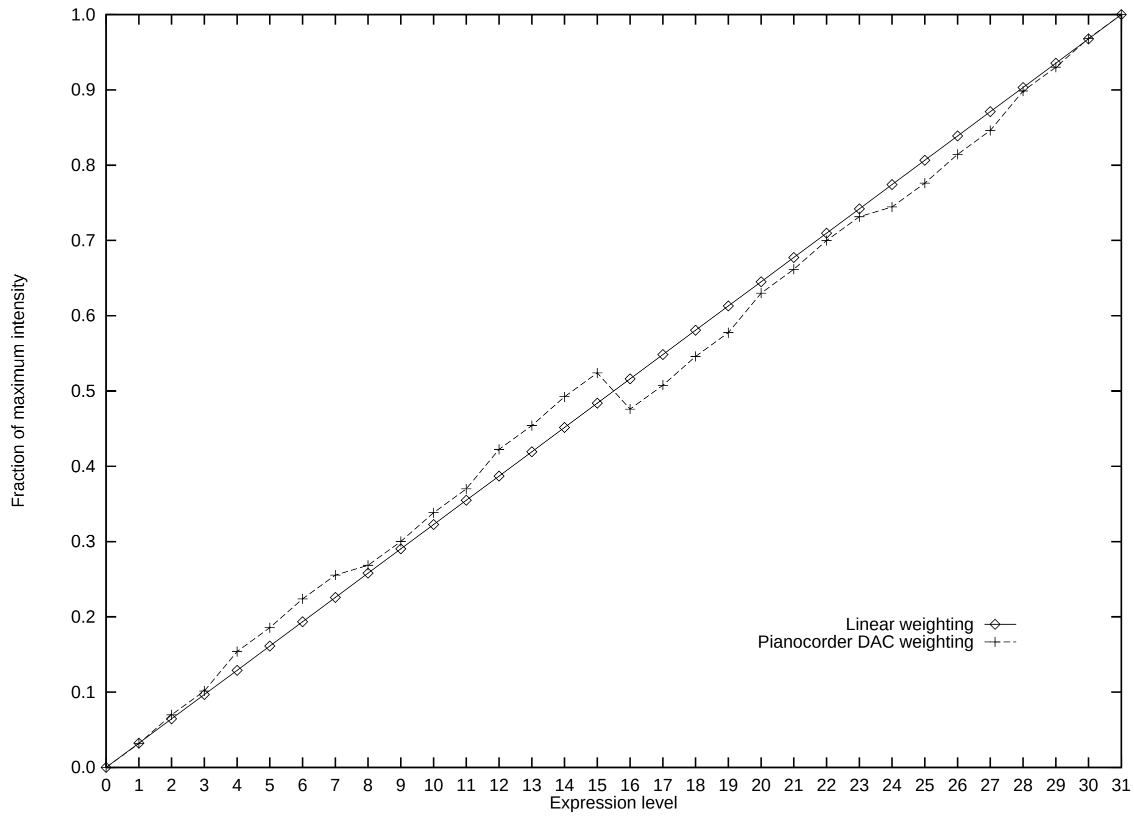


Figure 4.3: Comparison of linear and Pianocorder DAC expression functions

voltage output at each expression level. The range of output voltages was then normalized. The linear values were computed by dividing the range [0..1] into 32 divisions.

4.4.2 Irregularities in the transfer function

The irregularities in the Pianocorder expression function have an interesting history. They are apparently the result of some last-minute changes made late in the final design of the Pianocorder. The situation is explained in an anecdote by Wayne Stahnke, developer of the Bösendorfer SE reproducing system and perhaps the foremost authority on the development and history of electronic reproducing piano systems.

Apparently, the DAC was designed with simple linear voltage output in mind, but using 5% resistors. One late night, one of the engineers, Merlyn Morgan, stayed up late with Superscope chairman Joseph Tushinsky, listening to the infant Pianocorder, just before its introduction to the public. Between the two of them, they adjusted the values of the DAC resistors in an attempt to improve the sound. Eventually, they agreed on the values listed above, and these remained forever.

Later, when professional musicians were hired to create new music for the Pianocorder, it was belatedly discovered that there is a "notch" in the D/A output between levels 15 and 16. Apparently, no one at Superscope had ever plotted the output function of the DAC. Although subsequent musical performances were encoded with the DAC's irregularities in mind, the engineers who built the translators to read rolls had no knowledge of the notch (W. Stahnke, personal communication, November 6, 1996).

Thus, the majority of the Pianocorder library was encoded assuming the playback system had a linear expression function. Other performances were specifically designed for the irregular DAC function. In converting the material to MIDI format, the appropriate function should be applied according to the source of the Pianocorder data.

There were four basic sources of Pianocorder music: (1) songs derived from reproducing piano rolls, (2) songs derived from non-reproducing (88-note) piano rolls,

(3) songs recorded on a stock Pianocorder recording system (using wire switches under the keys and a microphone), and (4) songs recorded on Superscope's Musically Expressive Recording Piano and specially edited for playback on the Pianocorder. Stahnke's anecdote above suggests that the linear expression weighting should be used for case 1.

The author believes linear weighting should also be used for case 2, since expression was artificially added to these roll transfers at Superscope using a console with analog sliders for the bass and treble expression[3]. This console allowed the technicians to synthesize expression for 88-note piano rolls (this type of roll does not contain expression information). It is unreasonable to assume that the Superscope technicians were able to move a linear slider with the irregular transfer curve in mind. Thus, it is best to assume expression levels created in this manner did not take the DAC function into account.

Case 3 requires the linear weighting as well, since the Pianocorder's recording circuitry does not appear to take the irregular DAC function into account when calculating expression values (Superscope, Inc., 1979).[4]

Only case 4 material requires the use of the Pianocorder DAC weightings when converting expression levels. The material in case 4 consists of the 12-cassette Contemporary Artists Series, while the material of cases 1, 2, and 3 is mixed throughout the 30-volume music library. The proper source can usually be determined by examining the song description sheets accompanying each volume of tapes.

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[3]The author's PC2MID software displays instantaneous bar graphs of the expression levels, and one can clearly see the levels being adjusted manually.

[4]The circuitry measures expression by incrementing a 5-bit counter according to amplitude variations in the signal from a microphone.

4.5 Relation of timing and expression

There are two basic issues in creating a sequence of MIDI events from a stream of Pianocorder frames: timing of the notes and expression of the notes. These quantities are related to one another in that a solenoid-driven piano takes longer to strike a note softly than it does to strike a note loudly. The difference in time is not insignificant, as Section 4.7 will show. To compensate for the time difference, modern player piano systems such as Yamaha's Disklavier advance the strike times of softer notes. By giving the softer notes a "head start," loud and soft notes can be made to sound simultaneously. By optically measuring hammer velocities, the Disklavier can monitor the performance of each note and adjust its compensation for best results.

The Pianocorder lacks such a compensation mechanism. Data from the cassette tapes are decoded and immediately sent sequentially to the solenoids. For example, if a sequence of Pianocorder frames has a loud note striking in the bass section and a soft note striking in the treble section, the notes will not sound at the same time. Not only are the solenoids turned on up to 21 ms apart (due to sequential decoding of the data), but also the physical response of the solenoids and piano action will add a variable delay. To compensate for the delay, the softer note would have to be turned on a few frames early. Excellent results can be achieved by manually editing a Pianocorder performance to apply this compensation. However, it can be very difficult when many notes are striking in a short period of time at multiple levels of expression. Changing the expression level to fix one note will affect the intensities and response times of all other notes striking in a section.

Due to the complexity of manually adjusting the performances for best results, the twelve Contemporary Artist Series tapes, introduced in Chapter 1, were the only recordings to receive this treatment. For this series, performances were made of popular pianists such as Liberace, Oscar Peterson and Roger Williams. A rough digital performance was recorded in synchronization with a traditional analog audio tape recording. Then, under the supervision of Jim Turner (Superscope's head of artists and recording), the Pianocorder encodings were repeatedly tweaked and compared with the audio recordings until the Pianocorder renditions were as close as possible to the live performance. The end results are very good, and the Contemporary Artists Series tapes are the best recordings ever produced for the Pianocorder.

The rest of the Pianocorder library did not receive such treatment, at least not to the degree the celebrity recordings did. The remainder of the music library consists of material either recorded live on a stock Pianocorder system or transferred from pneumatic piano rolls. In both cases, a lot of material had to be produced in a very short time. Superscope chairman Joseph Tushinsky, who is frequently described by those who knew him as a particularly bombastic and overbearing person, worked his staff very hard to create a large library of music for new Pianocorder owners quickly after the product's release. There was no time for major editing and only the most objectionable problems were corrected. Based on examining a sizable portion of the Pianocorder library, the author believes it is safe to assume that little or no compensation for solenoid response was performed on any material outside of the Contemporary Artists Series. As expected, these performances exhibit minor timing irregularities when played on the Pianocorder.[5]

[5]It would be an interesting project to develop software for automatically adjusting this material (once transferred to a computer) to compensate for solenoid response. The task is not as straightforward as it might seem, however, and the author has not yet attempted to develop such a tool.

A stream of MIDI events does not require any kind of timing compensation, since MIDI events are assumed to be processed instantaneously upon receipt. Thus, for Pianocorder material lacking solenoid response compensation, it is possible to create MIDI versions of the performances that sound better than they did on the actual Pianocorder. Likewise, to create MIDI versions of Pianocorder performances that did have solenoid response compensation, i.e. the Contemporary Artists Series recordings, it is necessary to simulate the physical response of the Pianocorder's solenoid-based playback system in order to produce an accurate MIDI translation. The following sections describe how to properly translate source material of each type into MIDI format. These routines were implemented in the author's PC2MID conversion software, introduced in Chapter 3.

4.6 Simple approach: direct translation

This section describes a method of converting Pianocorder performances to MIDI format for source material that lacks solenoid response compensation. This method is applicable to all tapes in the Pianocorder music library except the twelve Contemporary Artist Series tapes.

The first step in converting from Pianocorder to MIDI format is to examine the sequence of Pianocorder frames and determine when notes change state. In cases where a note transitions from ON to OFF, a MIDI note-off is generated for the appropriate note number. When a note transitions from OFF to ON, a MIDI note-on for that note number is generated.

4.6.1 Computing MIDI velocity levels

In the case of note-on's, the "key velocity" (or expression level) of the note must be specified. MIDI supports 127 levels of expression, but only a subset of this range produces reasonable results on modern solenoid-based pianos; through experimentation, the author found that the MIDI velocity range 30–82 works well for the Yamaha Disklavier and MSR PianoDisc systems. (This range also produces reasonable results with most MIDI piano modules, including the Kurzweil Micropiano used by the author in the development of the conversion software.)

To compute a MIDI velocity level for a Pianocorder note transitioning from OFF to ON, the average of the two Pianocorder expression levels occurring in the first two frames of the note's duration are averaged and linearly mapped into the MIDI range 30–82. The reason for averaging two consecutive expression levels instead of simply using the first one is that on the Pianocorder, notes at most expression levels take at least two frames to actually strike. During this two-frame period in which a note is striking, the acceleration of the note's solenoid is affected by the expression level applied. Averaging the first two expression levels applied to the note thus produces a more accurate indication of the note's intensity. In the case of softer notes, i.e. those having Pianocorder expression levels of less than 12, it might be worthwhile to consider more than two consecutive expression levels in determining a note's MIDI velocity. The author may eventually implement this, but using two expression levels has been found to produce satisfactory results for most of the material in the Pianocorder library.

4.6.2 Emulating the Pianocorder's sequential updates

All note-on and note-off events are synchronized with the Pianocorder's sequential data distribution. To accomplish this, each 16-byte Pianocorder frame is divided into 32 MIDI ticks (see Section 4.2.1), accumulating one MIDI tick every 4-bit nybble. By processing the 128-bit frame in the same order as the Pianocorder hardware, adding one MIDI tick every 4 bits, the timing of the original performance is adequately preserved.

The conversion software processes each 16-byte frame in 4-bit chunks, updating the appropriate notes, pedals, control bits and expression levels at the proper points in time, according to the bit layout of the Pianocorder frame (see Table A.1 in Appendix A). As each note or pedal is updated, a MIDI event is produced if the note or pedal has changed state. The soft and sustain pedals are handled strictly in an on/off fashion, according to their current states in the Pianocorder frame. Note that this implies the pedals can respond instantaneously; the pedals actually require 100 ms or longer to activate on a real Pianocorder. However, the assumption of instantaneous response is consistent with the way notes are handled in this conversion method (i.e. generating a MIDI event immediately when notes turn on, regardless of their expression level).

4.7 Advanced approach: solenoid piano simulation

This section describes a method of converting Pianocorder music to MIDI format for source material incorporating solenoid response compensation. This method is applicable only to a small subset of the Pianocorder music library, the Contemporary Artist Series tapes.[6]

In the previous section, it was mentioned that the Pianocorder applies the current expression level to the solenoids continuously while a note is striking, and that notes can require more than one frame to strike. Thus, adjusting the expression level *while a note is striking* makes it possible to produce levels of intensity beyond the Pianocorder's 32 basic expression levels. Doing so also affects the response times of notes, making it possible to cause notes to sound with finer timing resolution than the Pianocorder's relatively coarse 35 Hz update rate would seem to allow. Such tricks were employed by Jim Turner and his staff when editing performances for the Contemporary Artists Series tapes.

4.7.1 A computer simulation of the Pianocorder

The author succeeded in producing excellent MIDI conversions of these specially-edited performances by simulating the physical response of the Pianocorder system. The idea was to create a simulation that would compute how the Pianocorder's 80 note solenoids would respond to a given stream of data frames over time. The simulation would generate MIDI events at the exact times that the notes would have sounded on an actual piano. MIDI velocity levels would be calculated from the terminal velocities of the solenoid plungers (an approximation of key velocity).

[6] One additional tape with solenoid response compensation was produced by Jim Turner at Joseph Tushinsky's request; the tape contains a performance by Vladimir Horowitz of "Stars and Stripes Forever," painstakingly transcribed from an audio recording. This tape was not sold to the public, but the author has located a copy and preserved it.

Because of the complex kinematic interactions between the Pianocorder's solenoids and the piano action, the author found it impractical to try to develop an accurate theoretical model of the Pianocorder (or any other solenoid-based piano, for that matter). The development of a theoretical model was further complicated by the non-trivial physics involved in calculating the force the Pianocorder solenoids might exert at each point in their travel and at each expression level.

For these reasons, the author decided to develop a model based not on the Pianocorder's theoretical response, but on its observed performance. To accomplish this, the response times of notes at each fundamental expression level were measured on an actual Pianocorder system and the measurements were used to drive the computer simulation.

4.7.2 Measuring the Pianocorder's physical response

To develop a model of the Pianocorder, it was necessary to accurately measure the response times of notes played at each of the Pianocorder's 32 expression levels. Lacking local access to an installed and functional Pianocorder system, a method of making the measurements on remote instruments was developed.

The first step was to create a special test sequence of Pianocorder frames that would permit measuring the response times at each expression level. These tests consisted of playing two notes simultaneously, one in the bass expression section and one in the treble expression section. One note in each pair was always played at full expression (level 31) and the other note's expression level was varied from 0 to 31. Because differences in hammer mass between notes could affect this measurement, pairs of notes in close proximity to the bass/treble split point were chosen. For greater accuracy, several trials were made at each expression level using three pairs of notes, and each pair was played with the control level (31) played in both the bass and treble sections. Using multiple pairs of notes (one pair at a time) also reduced the possibility of the solenoid performance being affected by accumulation of heat (due to being activated too frequently).

Pianocorder cassettes of the test sequence were produced (using the software described in Section 3.4.1) and mailed to several Pianocorder owners. The owners played the cassettes on their pianos and made audio recordings of the performances. Each owner set up their Pianocorder system identically, adjusting the expression controls for maximum dynamic range (i.e. "Pianissimo" level set to minimum, "Fortissimo" level set to maximum, soft pedal pedal override switch turned off). After running the tests, the owners mailed the audio recordings to the author for analysis.

To measure the timings, the author sampled the audio recordings into 8-bit 44.1 kHz digital audio files on a personal computer and examined them with a shareware software audio tool called "CoolEdit." This software is easily configured to count the number of samples in a highlighted region of the audio waveform. In examining the waveform of two notes struck at different velocities, one can see the initial attacks of the notes separated by a period of time proportional to the difference in the notes' velocities. This time was measured by highlighting the region between attacks and reading the number of samples highlighted. This produced a measurement of the *difference* in note strike times in units of 1/44100 of a second. The time delays were measured for multiple trials at each expression level and converted to milliseconds.

As expected, there was a considerable separation between notes struck at each end of the expression range; the greatest difference was approximately 162 ms. The time difference gradually reduced to zero as the experimental expression level grew closer to the reference expression level (level 31). As the time periods became shorter, it became increasingly difficult to determine exactly where the peaks in the second attacks occurred, due to overlap in the attacks. In some cases, it was necessary to look for subtle differences in the frequency of the waveform, since the amplitudes of the two notes were nearly identical. The author was not able to measure the time difference with much certainty beyond expression level 20 of 32. However, the values beyond 20 turned out to be very close together, and their values can be extrapolated with a high level of confidence.

The author notes that while the point of the first note's attack was always very clear, the process of determining the second note's point of attack was rather subjective. The measurements obtained are believed to be accurate to 1.5 ms. In the future, the author intends to repeat the experiment using a high-resolution clock started by the activation of a solenoid and stopped when the corresponding hammer activates an optical sensor, just before hitting the string. This will remove the subjective element and provide more accurate measurements.

The experiment described above measured the time difference between attacks of notes struck at various expression levels, but it did not produce a measurement of the elapsed time between the energizing of the first solenoid and the sounding of the first note. Assistance in measuring this quantity was provided by Jim Alinsky, who assisted the author in developing the hardware-based data acquisition solution presented in Chapter 3.

To measure this time period, a piezoelectric beeper was connected to an output line on one of the registers driving one of the note solenoids, such that the beeper would sound whenever drive current was applied to the solenoid. The note was then made to strike at full velocity several times while an audio recording was made of the piano and beeper. The recording was sampled as in the other tests, and the elapsed time was measured by recording the number of samples between the start of the beeper and the attack of the piano note. This time was consistently measured to be 45 ms. By adding this value to the time difference between notes struck at different expression levels, the author was able to compute total response times for notes struck at each expression level on a Pianocorder system.

Table 4.2 presents the averaged results of running the tests on three Pianocorder systems, with six trials per expression level on each piano. Figure 4.4 presents the results graphically, showing the response time as a function of the expression level. Note that the irregularity at levels 15–17 is not an error but rather was expected and is consistent with the irregularities in the Pianocorder DAC described in Section 4.4.

4.7.3 Simulating solenoid response

The measurements taken in the previous section were incorporated into the conversion software and used to drive the simulation of the Pianocorder system. The simulation works as follows.

First, each solenoid plunger in the simulated Pianocorder system is assigned a position in units of 0..1,000,000,000, where 0 represents the resting position of the solenoid (plunger fully extended below the coil) and 1,000,000,000 represents the

Expression level	Strike time difference between this level and level 31		Total strike time for this expression level in ms
	in samples	in ms	
0	7143.5	161.98	206.98
1	5266.0	119.41	164.41
2	4285.2	97.17	142.17
3	3586.5	81.33	126.33
4	3076.5	69.76	114.76
5	2813.0	63.79	108.79
6	2441.2	55.36	100.36
7	2086.8	47.32	92.32
8	2030.2	46.04	91.04
9	1764.0	40.00	85.00
10	1523.8	34.55	79.55
11	1377.2	31.23	76.23
12	1208.5	27.40	72.40
13	1016.7	23.05	68.05
14	826.0	18.73	63.73
15	637.8	14.46	59.46
16	746.5	16.93	61.93
17	657.0	14.90	59.90
18	623.7	14.14	59.14
19	536.2	12.16	57.16
20	519.8	11.79	56.79
21	472.6	10.72	55.72
22	425.3	9.64	54.64
23	378.1	8.57	53.57
24	330.8	7.50	52.50
25	283.5	6.43	51.43
26	236.3	5.36	50.36
27	189.0	4.29	49.29
28	141.8	3.21	48.21
29	94.5	2.14	47.14
30	47.3	1.07	46.07
31	0.0	0.00	45.00

Note: Data for levels 21-31 are extrapolated

Table 4.2: Observed response times of Pianocorder expression levels

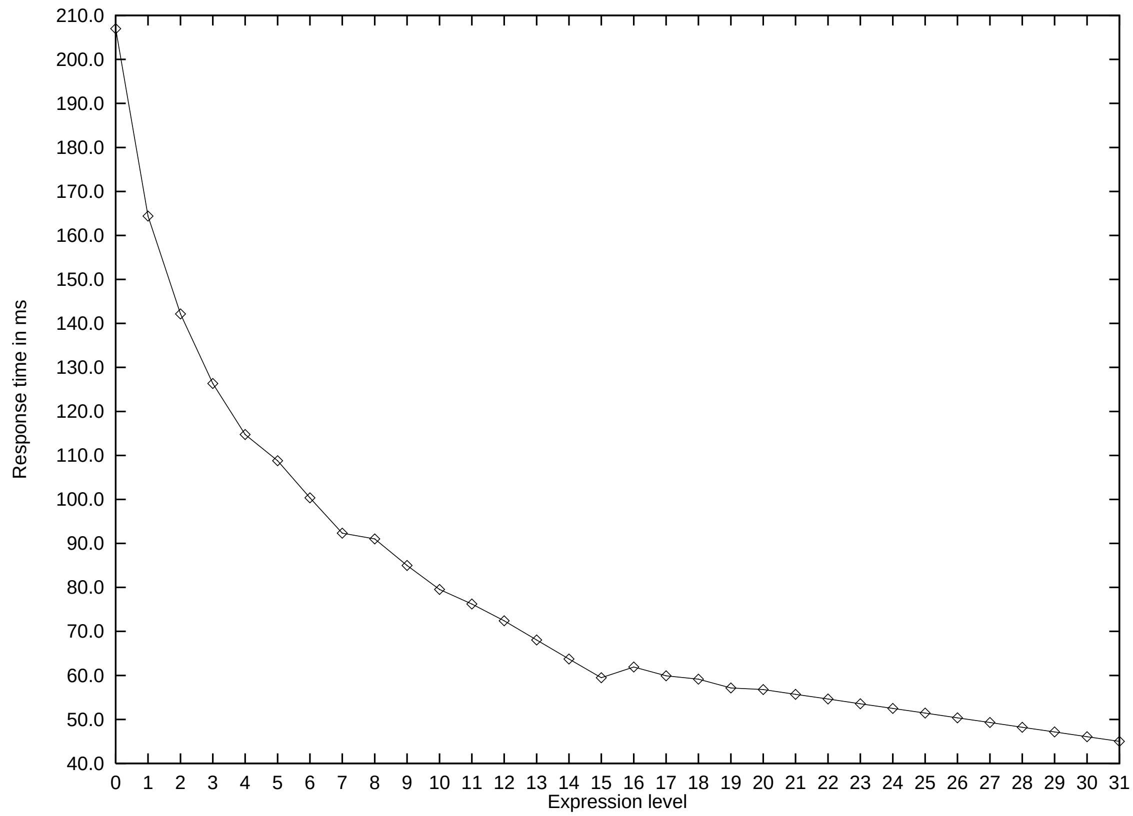


Figure 4.4: Observed response times of Pianocorder expression levels

fully-activated position of the solenoid (plunger pulled into the coil).[7] Each solenoid is also assigned a velocity. The initial positions and velocities of the solenoids are both 0.

From the total response times in Table 4.2, the software computes the acceleration produced by the solenoid when activated at particular expression level. The accelerations are computed in units of difference in solenoid position per MIDI tick (1/1126.4th of a second). Also computed is the acceleration at which the mechanism returns to its resting state due to gravity (in the same units).

[7]In an actual Pianocorder, the solenoid plunger travels a distance of approximately 42 mm.

At each tick in the MIDI file (32 ticks per frame), the software updates the velocity of the solenoids by adding the appropriate acceleration level according to the current expression level and whether or not the solenoid is turned on. (If a solenoid is turned off, the gravitational acceleration towards the resting state is used instead.) The software then updates the instantaneous position of each solenoid according to its velocity. If a solenoid reaches its full strike travel, the note is turned on with a MIDI velocity proportional to the final velocity of the solenoid. If a solenoid then falls below a certain threshold (representing the point at which the note's damper would contact the strings in the piano), its note is turned off. The software must also handle special cases. For example, solenoids are sometimes reactivated while still falling back from an earlier strike, before reaching the note-off threshold point; this case requires a MIDI note-off event to be generated to allow for the MIDI note-on event that will occur when the solenoid reaches its full travel again. The soft and sustain pedals are handled like the note solenoids, except that they have a fixed acceleration corresponding to a response time of approximately 100 ms.

As in the more simplistic MIDI translation method described in Section 4.6, this method processes the frame data sequentially using a close approximation to the timing of the Pianocorder hardware. Coupled with the simulation above, this enables very accurate MIDI reproductions of Pianocorder performances to be produced. The final MIDI conversions of the Contemporary Artist Series recordings sound quite good, and there is a great difference between MIDI files generated with and without the solenoid simulation enabled.

4.7.4 Topics for future work

The simulation software does not yet take into account several important factors. Failure to consider these factors has likely affected the quality of the music in a subtle manner.

Effect of hammer mass on response time

One of these factors is hammer mass; the response times of notes at different points on the keyboard will vary due to differences in the masses of their hammers. The present simulation allows only one response time profile covering all notes on the keyboard. However, the error in this simplification is likely reduced by measuring the single response profile using notes near the middle of the keyboard. It would not be hard to add individual per-key response profiles to the software once these are determined (through measurement or theoretical means).

Physical differences between notes

Another factor is that the relation of sound volume produced versus the final velocity of the solenoid plunger is not taken into account. The relationship is expected to vary at different points on the keyboard as the result of physical differences in string length, hammer mass, the number of strings per note, etc. The current simulation does not take any of these factors into account when assigning MIDI velocities to notes, although an approximation is made using a heuristic developed by Wayne Stahnke: after computing the MIDI velocity (0..127) of a note, the velocity is increased by one unit for each octave the note is located below middle C, and the velocity is decreased by one unit for each octave the note is located above middle C (Stahnke, 1996a). This compensation is based on the fact that a low note will produce a sound of greater amplitude than a high note when both notes are struck at equal velocities (Campbell & Minyard, 1979b).

Solenoid heating

During the course of a twenty-minute tape side, the solenoids in an actual Pianocorder system gradually accumulate heat through normal operation. The rise in temperature alters the resistance of the copper windings in the solenoid coils, affecting their performance; when the solenoids are hot, they strike with less force at a given expression level. According to Wayne Stahnke (personal communication, November, 1997), some performances in the Contemporary Artists Series were indeed edited at Superscope to compensate for this effect. Thus, in order to recreate the performances intended by the music editors, the simulation routines in PC2MID should take solenoid heating into account.

As of this writing, the author has not yet incorporated the aspect of solenoid heating into the simulation. Simulating the effect with reasonable accuracy will require measurement of an operating Pianocorder system to determine the rates of heat accumulation and dissipation and the temperatures involved. Information on the procedure by which performances were compensated would be useful as well. Once these details are known, the author will implement solenoid heating simulation in a future update of the conversion software.

Features and irregularities of the Marantz studio piano

Wayne Stahnke made occasional visits to the Marantz facility at the time the Contemporary Artists Series performances were being recorded. During one of these visits, Stahnke noticed some irregularities regarding the grand piano Superscope was using to play back the Contemporary Artists Series performances for editing purposes.

One observation was that this piano was equipped with not one but *two* solenoid plunger rails beneath the keys, operating in tandem. According to Stahnke, it was felt that a single Pianocorder solenoid rail did not provide adequate fortissimo response when installed on a grand piano. Using two rails in tandem strengthened the response, and this helped Superscope to satisfy the artists who recorded for the series.

The use of two solenoid rails would surely affect the response time of the system. Thus, it appears that Superscope edited the performances to play optimally on a non-standard Pianocorder installation that was different from the system sold to consumers. The degree of variation in response time is unknown, but the author noticed an improvement in the MIDI expression produced by the simulation when the response times in Table 4.2 were shortened by approximately 20 ms.

In examining Marantz's playback piano, Stahnke also noticed that one of the treble notes was softer in tone, due to the hammer felts having been ironed in an attempt to improve the sound of the instrument. The hammer felt of this problem note had been ironed too long, making the note more subdued in tone than its neighbors. Stahnke recalls Superscope engineers explaining to him that they compensated for this by increasing the intensity for this particular note whenever it occurred in a song. If this is true, this would have the effect of making the note play too loudly on all other pianos. If the author is eventually able to determine (by observation or from former Marantz employees) which note was involved, the MIDI velocity of the problem note could be lowered proportionately to simulate Marantz's studio piano.

4.8 Additional features of the conversion software

In addition to supporting both types of MIDI conversion presented in this chapter, the author's PC2MID conversion software also contains a number of unique features.

Real-time monitoring of Pianocorder music via MIDI

The software is able to perform the solenoid simulation and MIDI conversion in real time while the data frames are being captured from Pianocorder tapes. The MIDI events generated by the conversion routines are not only saved to a MIDI file but also transmitted to an external MIDI sound module. This is very useful, for it enables the operator to monitor the music and listen for problems without having to wait until all of the data has been captured. The real-time monitoring is also very useful for locating songs on a cassette, as the cassette deck may be operated in the same fashion as if the tape contained a conventional analog recording. The fast-forward and rewind buttons may be used as needed, and monitoring of the music data begins immediately when the operator presses PLAY.

Automatic tempo setting of MIDI files

The data capture system described in Chapter 3 measures the data rate of the digital signal for each song on a Pianocorder. This provides a measure of the music's tempo. Naturally, it is desirable to have the default tempo of a MIDI files match this tempo, and so the PC2MID software automatically adjusts the tempo of each MIDI file from its nominal value of 176 BPM (see Section 4.2.1) to the value that most closely matches the tempo on the tape.

Automatic annotation of MIDI files

Each volume of Pianocorder cassettes comes with a printed program sheet providing a track listing for each tape. Listed are each song's title, composer, lyricist (if applicable), and pianist. It is desirable to embed this text information into the MIDI files produced from Pianocorder material. This will permit MIDI file playback software to display the information when the songs are played. To facilitate this, PC2MID reads a text file from disk that contains the song information for each side of a tape (this information must be typed in manually). As each song is processed, PC2MID adds the appropriate text events to the MIDI file in a logical and consistent manner.

4.9 MIDI-to-Pianocorder conversions

The author has also written some software to encode new Pianocorder material from MIDI files. Performing this task accurately is a difficult problem because of the limited timing accuracy and expression capabilities of the Pianocorder system compared to what is possible in MIDI. Typically, MIDI files are accurate to around 200 ticks per second, while the Pianocorder is updated only 35 times per second. The considerable quantization required in reducing MIDI timing to 35 Hz results in terrible aliasing of trills and other complex ornamentation. In addition, the problem of assigning expression levels to notes while also compensating for their solenoid response times is fairly complex.

Part of the solution to these problems is the concept of “least objectionable degradation,” a term coined by Wayne Stahnke while Jim Turner was working on the Pianocorder Contemporary Artists Series. This is basically the idea of taking a musical phrase that is known to be beyond the capabilities of the playback hardware and replacing it with a phrase that is similar in style but simplified enough to be played reliably. This type of editing must be done by someone with a musical background and considerable training; developing computer software to perform this work is a challenging (but probably not impossible) task.

The author has developed a preliminary software package for playing MIDI files on the Pianocorder. The software runs on an IBM-compatible personal computer, using the computer’s sound card to produce the bi-phase signal to control the Pianocorder in real time. This allows interactive control of all aspects of music playback on the piano, including standard functions such as tempo and volume adjustments, transposition, and random access to a collection of music files.

At this point, the MIDI encodings produced by the software are not optimal. However, the solenoid response simulation described in this chapter is one of the latest developments in the project, and the author believes that similar techniques can be applied to produce optimal Pianocorder encodings of MIDI files. A successful algorithm to perform this task could also be adapted to translate MIDI files into optimal encodings for the traditional split-stack pneumatic reproducing systems.

CHAPTER 5

CONTRIBUTIONS AND FUTURE WORK

This thesis has presented a method for archiving and preserving the music library of the Superscope/Marantz Pianocorder Reproducing System.

Chapter 3 described software and hardware-based methods of capturing data from production copies of Pianocorder cassettes and explained how the music data can be optimally stored as computer files. Chapter 3 also described the implementation of a software tool that allows any of the original cassette tapes to be digitally remastered from the archive of master data files. This will ensure that Pianocorder tapes can always be regenerated, even after the originals have deteriorated beyond playability. These perfect reproductions will be useful to individuals studying the history of mechanical musical instruments, to museums, and to people who still own Pianocorder systems.

Chapter 4 described two methods of translating the performances to MIDI file format, permitting Pianocorder music to be played on modern computerized player piano systems. Chapter 4 also described some preliminary work involving the encoding new Pianocorder material from MIDI files. This will greatly expand the library of music available for Pianocorder systems still in use.

5.1 Future work

At the time of this writing, copies of about 325 of the 350 available Pianocorder cassettes have been obtained from private collectors for transfer. To date, over 100 of these tapes have been successfully captured to computer files. The remainder of the library will be transferred in the coming months.

The thirty main volumes of material have been located, but a handful of additional tapes are still being sought. Most of these are in Superscope's "Sing-A-Long" series, a selection of tapes intended for use with the Superscan Display Console. Pianocorder systems equipped with the Superscan option (a scrolling LED display) provided music and lyrics in bars and clubs as a sort of predecessor to the karaoke entertainment that is popular today.

In addition, several Pianocorder owners have reported that third-party companies produced tapes for the Pianocorder system, especially in foreign markets. These tapes will be located and preserved as discovered.

To locate Pianocorder tapes, a web site has been set up explaining the goals of the project and soliciting collectors to loan tapes for preservation. The site has been quite effective; it resulted in contacts with every one of the collectors who has loaned tapes so far.

5.1.1 Correction of song documentation

As the body of music transferred has continued to grow, many mistakes and omissions have been found in the printed documentation accompanying each tape. In some cases, the song titles or names of pianists are incorrect. Sometimes there are obvious errors in the composer and lyricist information. It is desirable to have this information be as accurate as possible, but during the development of this project, there has been little time to consult the necessary databases and correct the errors. (The most important consideration has been to capture the data from the tapes before they deteriorate any further.) As the stage of transferring tapes nears completion, the song descriptions for each tape in the archive will be verified for accuracy whenever possible.

5.1.2 Determination of piano rolls transferred

As explained in Chapter 1, nineteen of the thirty Pianocorder volumes were derived from reproducing piano rolls. Unfortunately, in the text descriptions accompanying the tapes, the Superscope technicians did not document any information about the actual rolls they used, such as the type of roll, catalog number, date of issue, etc. However, most of this information can be determined with the help of clues provided in the text descriptions, song ordering, and actual Pianocorder data.

For example, in the Pianocorder data frames, each song has a clearly-defined split point encoded into two of the control bits. Since the split point was different for each type of piano roll, the encoded split point can be used to make an educated guess about which type of roll Superscope used (however, it may be possible that the technicians occasionally failed to set the split point properly). The choice of split point will identify the probable roll type as Ampico, Duo-Art, or Welte. Roll catalogs are available for each of these systems (see Smith, 1987; Obenchain, 1977; Smith & Howe, 1994), listing roll numbers by song title, pianist, or composer.

Looking up roll numbers can be a time-consuming process, but the additional details found are often quite interesting, providing information about the pianists and arrangers or about the musical shows of the day from which the selections came. The cross-referencing process is also very helpful in verifying the accuracy of the song information (described in the previous section).

5.2 Preservation of the archive

Over the course of this project, the Pianocorder material has been stored on ordinary computer hard disk drives. For backup purposes, the archive has been written to DAT tape periodically. The author is currently in the process of determining the best long-term media to use for preserving the full archive of the Pianocorder library, once it is finished.

The original data for all 350 Pianocorder tapes could easily fit on a single CDROM (capacity 650 Mb), as each tape contains about 1.5 Mb of data files. However, limited funds prohibit the mastering of actual compact discs, and the expected lifetime of current CD-R media varies wildly according to various sources. For now, the best solution will probably be to burn CD-R's of the material periodically and maintain multiple geographically-separated copies of the archive.

Copies of the archive will contain detailed descriptions of the file formats and Pianocorder encoding techniques. Also included will be source code for software to access and manipulate the data files. These materials will permit future generations to more easily make use of the data.

5.3 Other tape-driven piano systems

The work presented in this thesis could readily be adapted to the capture and conversion of musical performance data created for other cassette-driven player piano systems. These systems (discussed in Chapters 1 and 2) include Wayne Stahnke's Cassette Converter system, the Australian-made Tape Converter, the Piano MIDI-Matic, the Teledyne Piano Player, and the OrrTronic Digital 88 Piano Playorr.

In the cases where original examples of the systems can be found, a hardware-based solution similar to the one presented in Section 3.3 would be practical. In cases where the tapes survive but the original hardware is lost or non-functional, a software-based solution like the one presented in Section 3.2 would be appropriate. The software utilities developed for this thesis provide an ideal framework for similar conversion projects, as most of the aforementioned systems used frame-based encoding schemes not unlike the Pianocorder's.

The author welcomes collaboration while continuing to explore the history and technology of solenoid-based player piano systems. Please address correspondence to Mark Fontana via email: mark.fontana@acm.org.

APPENDIX A

DETAILS OF PIANOCORDER FRAME FORMAT

This appendix describes the format of the 128-bit frames used by the Pianocorder Reproducing System.

In the bits of Table A.1, bits that are on (1) indicate that the note/pedal is activated. Bits that are off (0) indicate that the note/pedal is not activated. The *Superscan byte* is used to provide a stream of ASCII data and formatting codes to an external scrolling LED display sold as an accessory to the Pianocorder, the Superscan Display Console. Tables A.3, A.4 and A.5 describe the possible control codes for the Superscan control byte.

The *Song Counter* bits are not documented in any of the Superscope schematic diagrams. They were used in a small portion of the Pianocorder library to maintain an ascending count of the logical song number on the tape, typically with the high nybble set to F and the low nybble representing the song number (0, 1, 2, . . .). The author suspects that the song number was used to start and stop the tape at the end of each song in coin-operated commercial installations of the Pianocorder system.

Table A.2 details the function of the control bits (frame bits 64 and 65), used to set the split point between the treble and bass expression ranges of the keyboard.

Pianocorder Data Frame Bit Descriptions					
0.	Soft pedal	43.	Note 32 E	86.	Note 59 G
1.	Sustain pedal	44.	Note 33 F	87.	Note 60 G#
2.	not used	45.	Note 34 F#	88.	Note 61 A
3.	Bass intensity (LSB)	46.	Note 35 G	89.	Note 62 A#
4.	Bass intensity	47.	Note 36 G#	90.	Note 63 B
5.	Bass intensity	48.	Note 37 A	91.	Note 64 C
6.	Bass intensity	49.	Note 38 A#	92.	Note 65 C#
7.	Bass intensity (MSB)	50.	Note 39 B	93.	Note 66 D
8.	Superscan byte (MSB)	51.	Note 40 C	94.	Note 67 D#
9.	Superscan byte	52.	Note 41 C#	95.	Note 68 E
10.	Superscan byte	53.	Note 42 D	96.	Note 69 F
11.	Superscan byte	54.	Note 43 D#	97.	Note 70 F#
12.	Superscan byte	55.	Note 44 E	98.	Note 71 G
13.	Superscan byte	56.	not used	99.	Note 72 G#
14.	Superscan byte	57.	not used	100.	Note 73 A
15.	Superscan byte (LSB)	58.	not used	101.	Note 74 A#
16.	Note 5 C#	59.	not used	102.	Note 75 B
17.	Note 6 D	60.	not used	103.	Note 76 C
18.	Note 7 D#	61.	not used	104.	Note 77 C#
19.	Note 8 E	62.	not used	105.	Note 78 D
20.	Note 9 F	63.	not used	106.	Note 79 D#
21.	Note 10 F#	64.	Control bit 1	107.	Note 80 E
22.	Note 11 G	65.	Control bit 2	108.	Note 81 F
23.	Note 12 G#	66.	not used	109.	Note 82 F#
24.	Note 13 A	67.	Treble intensity (LSB)	110.	Note 83 G
25.	Note 14 A#	68.	Treble intensity	111.	Note 84 G#
26.	Note 15 B	69.	Treble intensity	112.	Song counter (MSB)
27.	Note 16 C	70.	Treble intensity	113.	Song counter
28.	Note 17 C#	71.	Treble intensity (MSB)	114.	Song counter
29.	Note 18 D	72.	Note 45 F	115.	Song counter
30.	Note 19 D#	73.	Note 46 F#	116.	Song counter
31.	Note 20 E	74.	Note 47 G	117.	Song counter
32.	Note 21 F	75.	Note 48 G#	118.	Song counter
33.	Note 22 F#	76.	Note 49 A	119.	Song counter (LSB)
34.	Note 23 G	77.	Note 50 A#	120.	Sync byte (1)
35.	Note 24 G#	78.	Note 51 B	121.	Sync byte (1)
36.	Note 25 A	79.	Note 52 C	122.	Sync byte (1)
37.	Note 26 A#	80.	Note 53 C#	123.	Sync byte (1)
38.	Note 27 B	81.	Note 54 D	124.	Sync byte (1)
39.	Note 28 C	82.	Note 55 D#	125.	Sync byte (1)
40.	Note 29 C#	83.	Note 56 E	126.	Sync byte (0)
41.	Note 30 D	84.	Note 57 F	127.	Sync byte (1)
42.	Note 31 D#	85.	Note 58 F#		

Table A.1: Pianocorder data frame bit description

Pianocorder Split Points				
Ctrl bit 1	Ctrl bit 2	Split point on piano keyboard	Roll type	Description
0	0	E / F	Ampico	Note 44 gets bass expression; notes 45 and 46 get treble expression. This split point was also used for all of the live performances recorded on Superscope's master recording piano.
0	1	F# / G	Welte	Notes 44, 45, and 46 get bass expression
1	0	D# / E	Duo-Art	Notes 44, 45 and 46 get treble expression
1	1	—	—	Not used (Note 44 gets treble expression; notes 45 and 46 get bass expression.)

Table A.2: Truth table for Pianocorder split-point control bits

Superscan General Commands		
Ctrl byte	*Arg byte*	*Function description*
00h		No operation; causes system to wait one time period before continuing. The time period duration is determined by the time set with command `19h`.
02h		Completely resets the display system. The graphics memory is not affected.
04h		Scrolls the display down one line if in single mode or 7 lines if in multiple mode. The scroll rate is set using command `19h`.
06h		Makes the whole display non-highlighted (not inverted).
09h		Toggles highlighting (inverse) mode.
0Ah		Activates the Venetian blind effect from the right. Shifts once in single mode or six times in multiple mode.
0Ch		Produces a two-second delay.
0Dh		Activates the Venetian blind effect from the left. Shifts once in single mode, or six times in multiple mode.
0Eh		Sets the scroll and Venetian blind effects to multiple mode.
0Fh		Makes the whole display highlighted (inverted).
10h		Sets the scroll and Venetian blind effects to single mode.
12h		Clears the screen, makes Venetian blind and scrolling features visible, sets the text mode to normal (not inverted), turns off blinking, and positions the cursor at the leftmost position on the display.
13h		Initializes the Venetian blind feature in an invisible state. Commands `0Ah` or `0Dh` will cause the text to Venetian blind into place.
14h		Initializes the scroll feature in an invisible state. Commands `15h` or `04h` will cause the screen to scroll into place.
15h		Causes the display to scroll upwards one row in single mode or seven rows in multiple mode.
16h		Causes any partially-completed scrolling or Venetian blind operation to become fully visible and centered on the display. (May be used in combination with commands `13h` and `14h` to cause the entire screen to flash.)
17h		Toggles the text blinking attribute on and off.
18h	pos	Sets the cursor position where the next character will be placed on the screen. The argument `pos` should be an ASCII character `0-9` or `A-I`, specifying a cursor location from 0 to 18.
19h	rate	Sets the clock rate at which the message is displayed. The argument `rate` should be an ASCII character of `1-9` or `A-Z`, with `1` giving the shortest delay and `Z` giving the longest delay. Each delay increment is 1/40 of a second.

Table A.3: Superscan Display Console general commands

Superscan Graphics Mode Commands		
Ctrl byte	*Arg byte*	*Function description*
07h	gchar	Inserts custom graphics character `gchar` at this point in the text.
0Bh	gchar	Edits graphics character `gchar`, entering graphics mode. `gchar` is any ASCII character from 0–127. The edit cursor is initially placed in the upper left corner.
44h		Moves cursor up one row
45h		Stores changes and leaves graphics mode.
4Ch		Moves cursor left one column
52h		Moves cursor right one column
30h		Turns current pixel off
31h		Turns current pixel on

Table A.4: Superscan Display Console graphics commands

Superscan Miscellaneous Commands	
Ctrl byte	*Function description*
05h	End-of-message marker (not used in continuous Pianocorder data)
03h	Inserts customization message (factory-programmed) into the text.
11h	Enables cassette output mode (for dumping programs in memory to cassette tape).

Note: The Superscan commands in this table are recognized by the Superscan Display Console but are not used in the Pianocorder lyric data.

Table A.5: Superscan Display Console miscellaneous commands

APPENDIX B

PIANOCORDER CONSUMER PRODUCT LITERATURE

This appendix presents scans of the consumer-targeted Pianocorder promotional literature to provide the reader with a feeling for how the system was marketed (courtesy of Jim Alinsky).


Pianocorder
reproducing system.
Your lonesome piano
will come alive with music.
Pianocorder
All by itself.

Your piano will come alive with hours and hours of home entertainment.

Imagine you and your family enjoying all your favorite piano music. Played by all your favorite pianists. Right in your own home. Right on your own piano.

That's exactly what it's like when your piano is equipped with a PIANOCORDER reproducing system. It can reproduce the world's greatest pianists performing all your favorite music. With their touch and their interpretation. For hours on end.

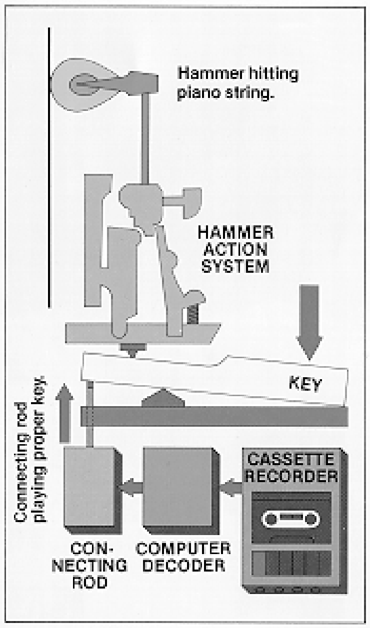
You won't believe your eyes, or your ears, as your lonesome silent piano comes alive with music. Anytime you want. And neither will your friends. Just slip in an encoded cassette tape and push the button. Your piano will turn any friendly gathering into a gala event.

And with a PIANOCORDER reproducing system, your piano can record you playing. Or any of your guests. Then it will play their music back. With their touch and their interpretation.

If you should have a small person (or big one) in your home who is learning to play the piano, the PIANOCORDER reproducing system becomes a valuable teaching aid. The record and playback features can greatly accelerate learning. And listening to and watching the fingering of the great pianists as they perform can be a real inspiration.

So there's no reason for your ordinary piano to sit idle anymore. Due to modern technology, it can now be an active part of your family entertainment by coming alive with music. All by itself.

What makes your piano come alive.

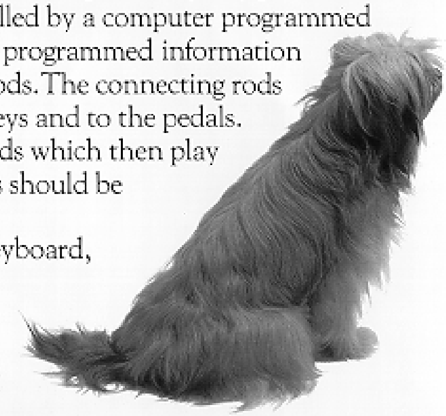


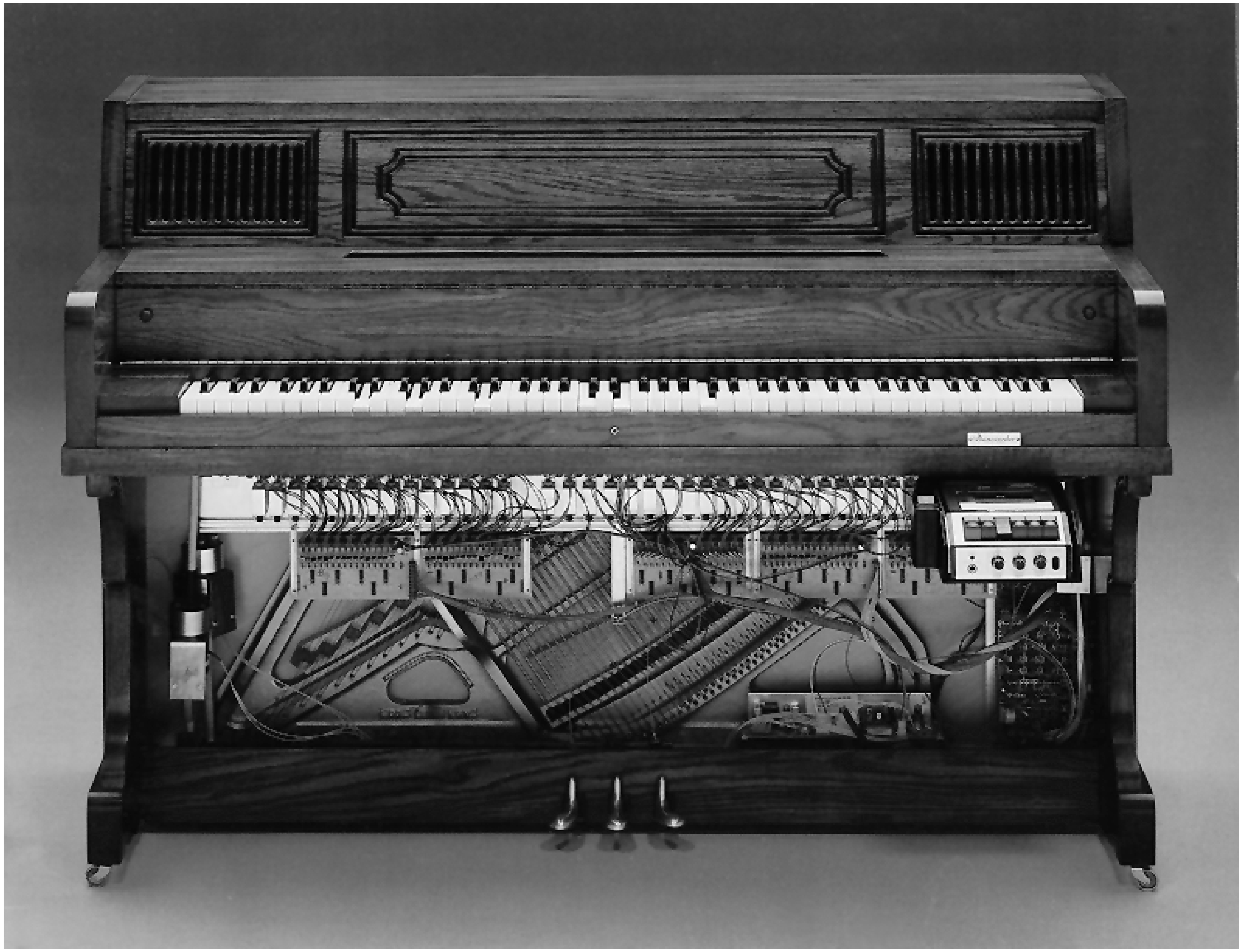
The PIANOCORDER reproducing system is a sophisticated electronic computer mechanism. It is mounted across the open space behind the knee board. And it can be installed by a factory-trained technician in practically any piano.

The playback of the performance is controlled by a computer programmed cassette tape. The cassette recorder transfers the programmed information through the computer to a bank of connecting rods. The connecting rods extend to just under the back of the individual keys and to the pedals.

When you play a tape, the computer sends signals to the right connecting rods which then play the correct keys and operate the pedals. It tells them how soft or how hard the keys should be played. How slow or how fast. And it tells them how long to hold the keys.

When ready to use, simply swing the cassette recorder out from under the keyboard, insert a tape and play. The PIANOCORDER reproducing system reproduces the performance of the pianist. With his or her touch and interpretation.





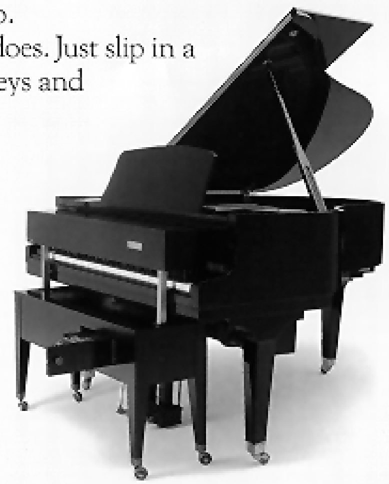
Your Grand Piano will come alive in grand style.

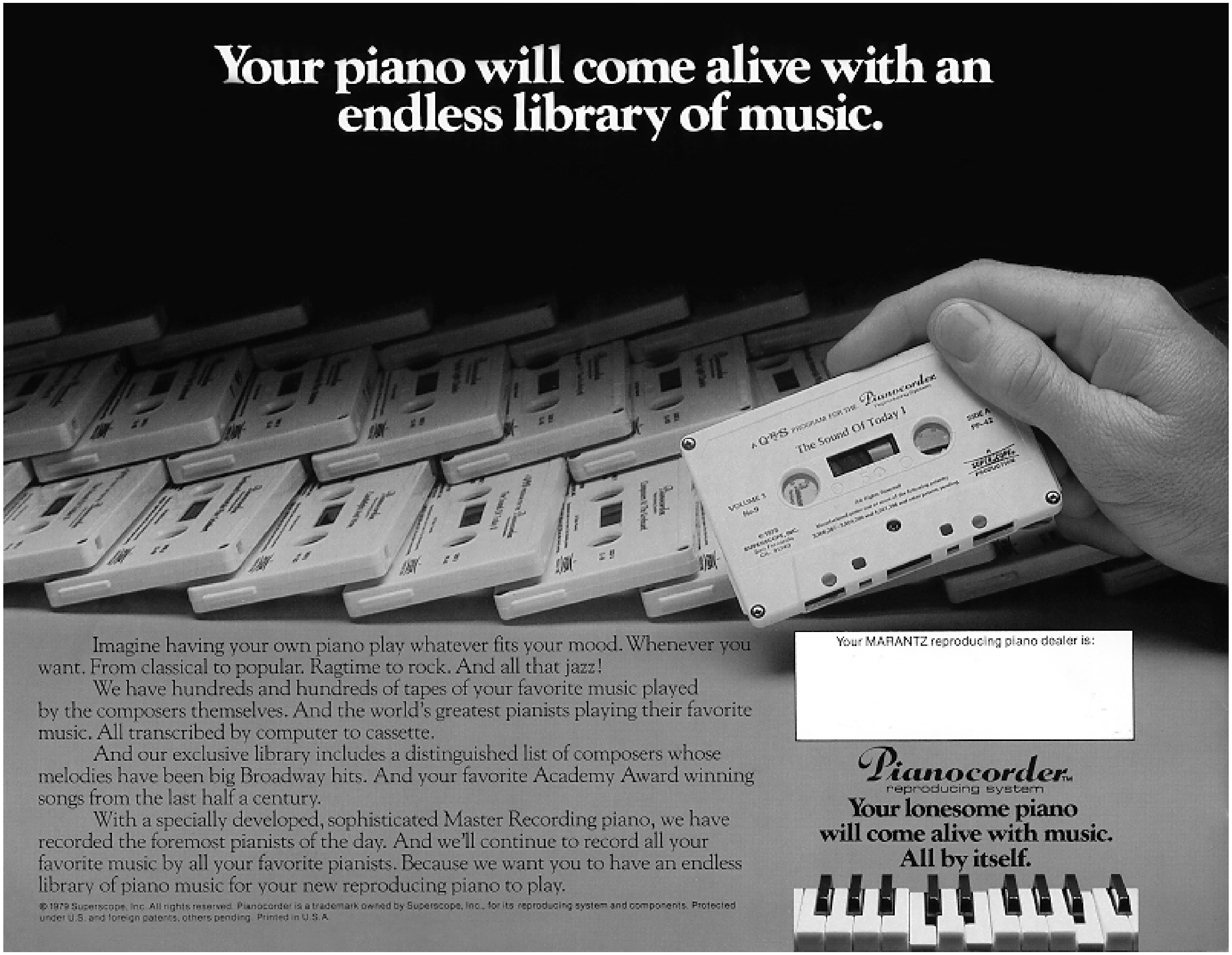
Imagine the world's greatest pianists playing in the manner in which they are accustomed. Right in your own home. Right on your own Grand Piano.

That's exactly what it's like when your Grand Piano is equipped with the PIANOCORDER reproducing system. It can reproduce many of your favorite composers and pianists, playing all your favorite music. With their touch and their interpretation.

Or you might prefer the PIANOCORDER Vorsetzer Reproducer. It's a completely self-contained version of the PIANOCORDER reproducing system and requires no installation in your piano.

Vorsetzer is the German word for "sitter-in-front." And that's exactly what it does. Just slip in a computer encoded cassette tape. And with cushioned "fingers" positioned over the keys and connecting "feet" over the pedals, your piano will come alive with music.

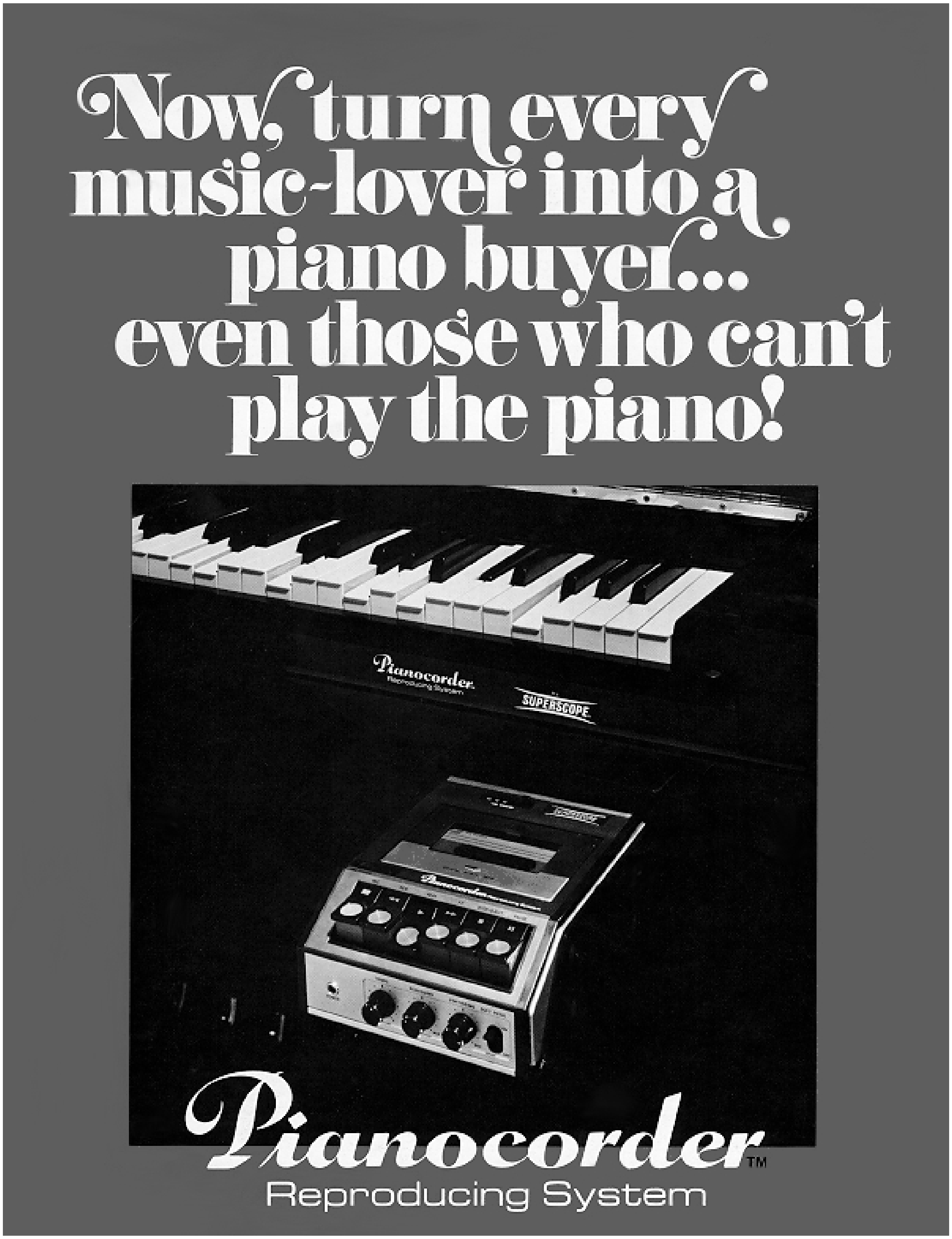



Your piano will come alive with an endless library of music.
The Sound Of Today 1
Imagine having your own piano play whatever fits your mood. Whenever you want. From classical to popular. Ragtime to rock. And all that jazz!
We have hundreds and hundreds of tapes of your favorite music played by the composers themselves. And the world's greatest pianists playing their favorite music. All transcribed by computer to cassette.
And our exclusive library includes a distinguished list of composers whose melodies have been big Broadway hits. And your favorite Academy Award winning songs from the last half a century.
With a specially developed, sophisticated Master Recording piano, we have recorded the foremost pianists of the day. And we'll continue to record all your favorite music by all your favorite pianists. Because we want you to have an endless library of piano music for your new reproducing piano to play.
© 1979 Superscope, Inc. All rights reserved. Pianocorder is a trademark owned by Superscope, Inc., for its reproducing system and components. Protected under U.S. and foreign patents, others pending. Printed in U.S.A.
Your MARANTZ reproducing piano dealer is:
Pianocorder™
reproducing system
Your lonesome piano will come alive with music. All by itself.

APPENDIX C

PIANOCORDER DEALER PRODUCT LITERATURE

This appendix presents scans of the dealer-targeted Pianocorder promotional literature to provide the reader with a feeling for how the Pianocorder system was marketed (courtesy of Jim Alinsky).


Now, turn every music-lover into a piano buyer... even those who can't play the piano!
Pianocorder
Reproducing System
SUPERSCOPE
Pianocorder™
Reproducing System


Pianocorder
YAMAHA

INTRODUCING THE WORLD'S FIRST RECORDING AND REPRODUCING PIANO COMPLETELY CONTROLLED BY COMPUTER PROGRAMMED CASSETTE TAPE.

Pianocorder™
Reproducing System

Hearing the piano at its best.

Anyone who has ever longed for the unique pleasure that only a piano in the hands of an artist can provide, will want the PIANOCORDER Reproducing System for their very own.

Just imagine a piano that can transport your customers to the very edge of the concert stage. Imagine a piano that can play a Debussy prelude *as Debussy himself played it!* Not as he *may* have played it. Or, *should* have played it. But as he actually *did* play it! With all of his dynamics and pedaling. His exact interpretation. His exact touch. Or, a piano that can play a Gershwin tune with Gershwin himself at the keyboard! Imagine a piano that can perform "live"—by itself—the immortal and uplifting artistry of the world's greatest pianists exactly as they played it. From classical to popular, jazz, ragtime and rock. A piano that can reproduce anyone's performance immediately after they have performed with all the expression (and even the mistakes, if you will) of the original.

That's the miracle of the PIANOCORDER Reproducing System. A sophisticated electronic recording and reproducing system that actually puts the artists' fingers on any piano.

A revolution in piano merchandising

For the first time, space age technology converts the piano from a limited, part-time educational tool* into a versatile, full-time home entertainment system every music-lover can enjoy owning... *even those who can't play the piano or don't care to learn.*

No longer does a piano have to sit idle. No longer will a piano purchase be for just one member of a household. The PIANOCORDER Reproducing System gives the piano owner full enjoyment of his piano investment. Thus, the piano becomes a "wanted" purchase instead of a "needed" purchase.

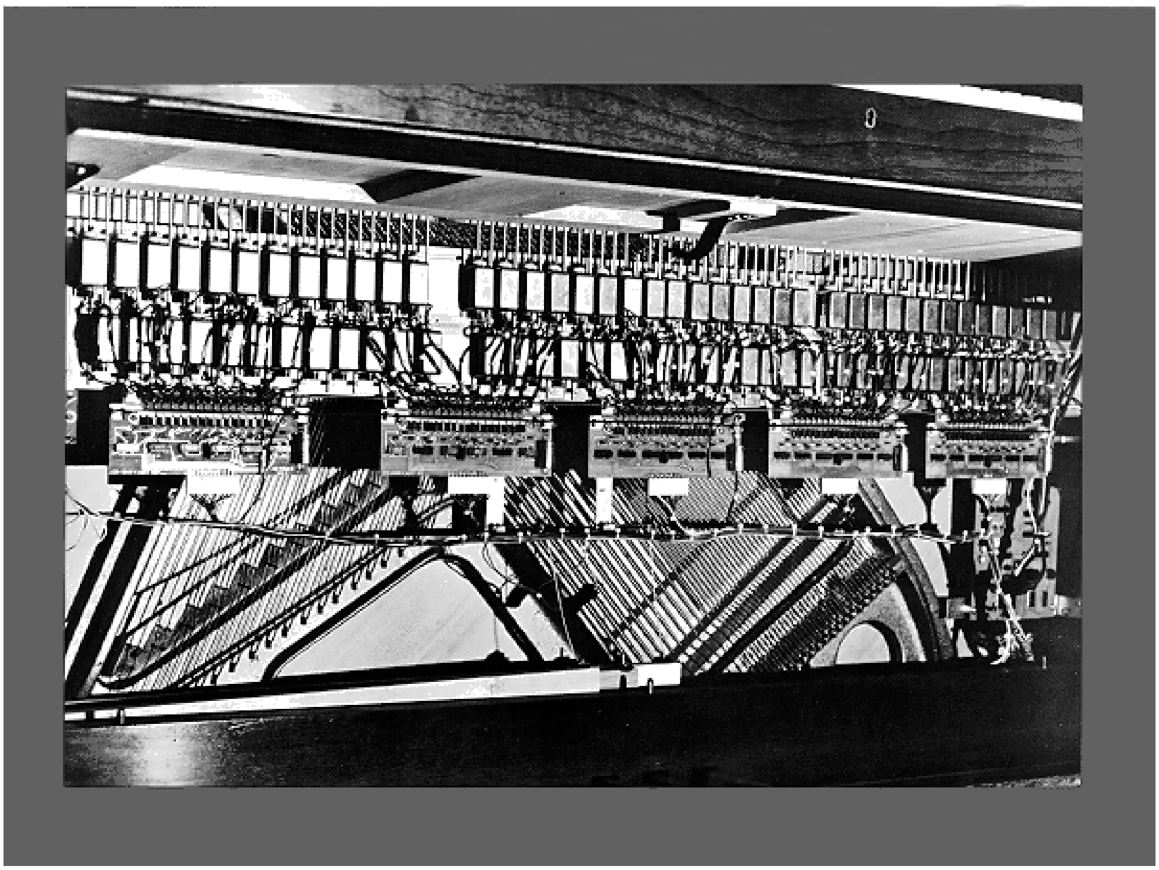
* Eighty percent of all pianos sold are for educational purposes. The typical piano is purchased for just one member of a household, usually a child, who practices just a few hours each week. For the rest of the time the piano sits idle.

How it works.

BUILT-IN SYSTEM

The heart of the PIANOCORDER Reproducing System is a sophisticated electronically controlled keyboard mechanism built into a standard piano.

Playback performance is controlled by a computer programmed cassette tape that commands which keys to play, and how fast and hard they should be struck. Computer logic circuitry in the cassette recorder transfers the programmed information to a bank of solenoids that completely controls the piano keys and pedals, virtually simulating an exact human performance.

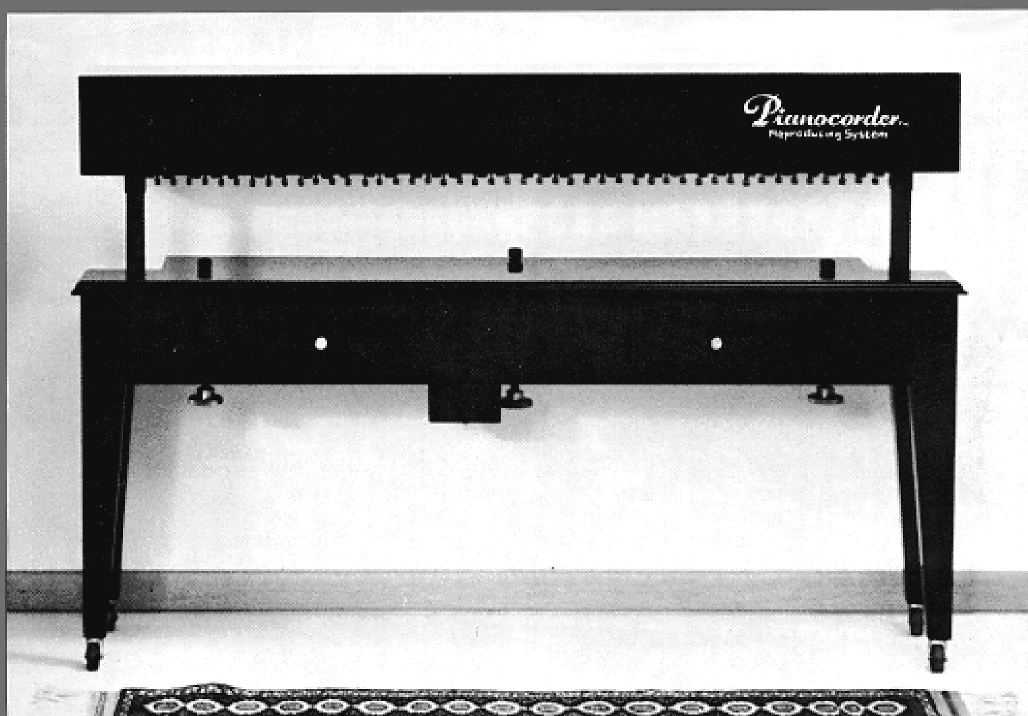


VORSETZER* SYSTEM: a "sitter-in-front"

The PIANOCORDER Vorsetzer Reproducer is a completely self-contained unit that requires no modification to the piano. The customer simply slides the Vorsetzer up to his piano and inserts the cassette tape of a PIANOCORDER performance album into the cassette recorder. The Vorsetzer then plays much as a human pianist would, with cushioned fingers for the keys and two feet for the pedals. Each finger plays with the same dexterity and subtlety of expression as does a human pianist. (Just imagine how helpful the Vorsetzer can be on your floor demonstrating any piano you sell!)

When not performing, the Vorsetzer can easily be placed against a wall to serve as a handsomely crafted console-table. Finishes are available to match most pianos.

* In 1904, a German inventor unveiled a music reproduction system that was used and applauded by nearly every great pianist of the day. The ingenious key to the system was a robot piano player called a "vorsetzer" (the German word for "sitter-in-front") that could reproduce the tempo, touch, tone quality — the exact expression of a pianist's performance. Now the Vorsetzer is with us again. The PIANOCORDER Vorsetzer Reproducing System is a modernized, dramatically improved version that can perform on any piano.



Wherever there's a piano...Whenever a piano is sold...There's a market for the *Pianocorder*™ reproducing system.

The piano is the most popular musical instrument in the world. Now the PIANOCORDER Reproducing System is destined to increase the piano's popularity even more.

A small indication of the vast market potential of the PIANOCORDER Reproducing System comes from the sales figures for the reproducing pianos of old. Even though they were considerably inferior to the PIANOCORDER Reproducing System, and had only a limited market, over 5 million were sold in the United States between the turn of the century and 1929. A remarkable performance!

Today, there are literally dozens of markets for the PIANOCORDER Reproducing System.

If there was ever a product with guaranteed success, that product is a piano with a built-in PIANOCORDER Reproducing System.

THE EXTENSIVE IN-HOME MARKET:

There are already more than ten million pianos in U.S. homes, and more than 30 million pianos in homes throughout the world. All these present owners are potential customers for the PIANOCORDER Reproducing System.

THE NEW PIANO MARKET:

A piano with a factory-installed PIANOCORDER Reproducing System adds new feature-excitement to the sale of a new piano and stimulates higher profits for the Dealer. It converts a piano from a "needed" purchase to a "wanted" purchase.

THE USED PIANO MARKET:

The installed assembly PIANOCORDER Reproducing System transforms your inventory of used pianos into the newest product on the market. It's like finding the fountain of youth for used pianos.

THE COMMERCIAL MARKET:

This market consists of about one million hotels, restaurants, cocktail lounges and bars world-wide. It's a known fact that these establishments enhance their business by offering "live" musical entertainment. Now, with the PIANOCORDER Reproducing System, even those establishments that could not afford it in the past, can now offer their customers "live" piano music—the type of music their customers prefer most.

THE EDUCATIONAL MARKET:

Because the PIANOCORDER Reproducing System is an excellent learning aid, it will be an important educational tool. It records and plays back a student's piano lesson note for note on the piano. This provides a unique opportunity for the student to actually hear and chart his own progress. And the PIANOCORDER Reproducing System also serves as an excellent accompanist for singers, dancers, or students of other musical instruments. This will prove invaluable for those who can not afford a professional accompanist or where none are available. Hand-held and foot-operated remote controls are available for students who wish to vary the tempo of the PIANOCORDER Reproducing System to suit their style of playing, singing or dancing. In the future there will be specially prepared accompanist tapes for the PIANOCORDER Reproducing System.

THE RELIGIOUS MARKET:

The PIANOCORDER Reproducing System is perfect for weddings, services and all other occasions where "live" piano music is used in houses of worship.

THE FRATERNAL, SOCIAL AND MILITARY MARKETS:

These organizations will find that the PIANOCORDER Reproducing System is the ideal entertainment medium for meetings and social gatherings.

HOW IT'S SOLD.

The PIANOCORDER Reproducing System begins a totally new era in piano merchandising.

The essence of our merchandising program is creative selling—exposure and demonstration—in and out of the store—on an active, aggressive basis.

The PIANOCORDER Reproducing System will be demonstrated at shopping centers, banks, new business openings, country fairs and flower shows. All are prime avenues for this exciting new product.

WHO WILL SELL IT.

The PIANOCORDER Reproducing System will only be sold through authorized, franchised dealers. All PIANOCORDER Reproducing System dealers will receive thorough product training and comprehensive advertising and merchandising support.

Each Pianocorder™ reproducing system comes with an extensive collection of great piano performances computer programmed on cassette tape.

Thousands of computer programmed cassette albums will be available for exclusive use with the PIANOCORDER Reproducing System. Many of these albums are genuine collector's items, transcribed from Joseph S. Tushinsky's personal collection of 18,000 rare and valuable expression music rolls which include performances by some of history's greatest pianists. In their original form, which feature performances of only three to fifteen minutes duration, the rolls would be worth as much as $18.00 apiece—if they could be purchased. A good pneumatic reproducing piano required to play these paper rolls would cost upwards of $10,000!

SPECIAL INTRODUCTORY OFFER OF 100 FREE PRE-PROGRAMMED CASSETTES

Every music-lover who buys a PIANOCORDER Reproducing System will also receive, at no additional cost, his selection of one hundred computer programmed 45-minute PIANOCORDER performance tapes—worth $795.00! Additonal tapes can be ordered from the vast PIANOCORDER Performance Album Library.

CLASSICAL MUSIC

PIANOCORDER performance albums include the great classical pianists of music's romantic era, playing the works of hundreds of composers from the baroque, classical, romantic and impressionist periods. Many can be heard performing their own compositions.

CONTEMPORARY MUSIC

Popular and jazz recordings include George Shearing, Liberace, Roger Williams, Fats Waller, Scott Joplin, Eubie Blake, George Gershwin and hundreds of others.

Other albums feature popular hits of every decade from the '20s through the '70s, much-loved standards from Tin Pan Alley and the big bands, the best of Broadway and Hollywood, rhythm and blues, plus the most dynamic rock. In the future, albums of the greatest modern pianists will also be available. All brought to you "live" through the medium of the PIANOCORDER Reproducing System.

The future will also bring special PIANOCORDER performance accompaniment albums for use in teaching piano, voice and other instruments, as well as special albums for commercial establishments.

Artists and composers include:

Some of the truly immortal classical pianists included will be:

Clarence Adler
Lubo D'Alexandrovsko
Wilhelm Bachaus
Harold Bauer
Emanuel Bay
Andre Benoist
Carrie Jacobs Bond
Alexander Brailowsky
Dei Buell
Richard Buhlig
Ferruccio Busoni
Charles Wakefield Cadman
John Alden Carpenter
Theresa Carreno
Maria Carreras
Alfredo Casella
*Cecile Chaminade
Wilbur Chenoweth
Shura Cherkassy
Jan Chiapusso
Aaron Copland
George Copeland
Alfred Cortot
*Eugene D'Albert
Walter Damrosch
Fanny Davies
*Claude Debussy
*Reginald De Koven
Louis Diemer
*Ernst Von Dohnanyi
*Georges Enesco
Anetta Esipoff
Geraldine Farrar
*Gabriel Faure
Edwin Fischer
Karl Friedberg
Arthur Friedman
*Ignaz Friedman
*Rudolf Friml
Robert Fryer
Ossip Gabrilowitsch
Rudolph Ganz
*Walter Gieseking
*Alexander Glazunow
Leopold Godowsky
Katherine Goodson
Gitta Gradova
*Percy Grainger
*Enrique Granados
*Edvard Grieg
*Charles Griffes
Alfred Grunfeld
Henry Hadley
Mark Hambourg
Alfred Hertz
Joseph Hofmann
Vladimir Horowitz
Edwin Hughes
Ernest Hutcheson
McNair Ilgenfritz
Jose Iturbi
Werner Janssen
Alberto Jonas
Clotilde Kleeberg
Wilhelm Kienzl
Raoul von Koczalski
*Fritz Kreisler
Frederic Lamond
Wanda Landowska
Ernesto Lecuona
*Ethel Leginska
*Ruggiero Leoncavallo
Tina Lerner
*Theodore Leschetizky
Mischa Levitzki
Josef Lhevinne
*Serge Liapounoff
Thurlow Lieurance
*Arthur Loesser
*Gustav Mahler
*Pietro Mascagni
*Nicholas Medtner
Yolanda Mero
Alfred Mirovitch
Benno Moiseivitch
Felix Mottl
Mieczyslaw Munz
Otto Neitzel
Elly Ney
Erwin Nyiregyhazi
*Walter Niemann
Arthur Nikisch
Guiomar Novaes
Nikolai Orloff
Leo Ornstein
*Ignace Paderewski
*Selim Palmgren
Emil Paur
Max Pauer
Leff Pouishnoff
Serge Prokofieff
Raoul Pugno
*Sergei Rachmaninoff
Maurice Rauch
Carl Reinecke
Alfred Reisenauer
Nadia Reisenberg
Max Reger
Carol Robinson
Moriz Rosenthal
Artur Rubinstein
Beryl Rubinstein
*Camille Saint-Saens
Carlos Salzedo
Olga Samaroff
Harold Samuel
Emil Sauer
Irene Scharer
*Xaver Scharwenka
Ernst Schelling
E. Robert Schmitz
Artur Schnabel
*Cyril Scott
Alexander Scriabin
Rudolf Serkin
Arthur Shattuck
Frank Sheridan
Alexander Siloti
Richard Singer
Emil Sjoegren
Joseph Slivinski
Enrique Soro
Constantin Sternberg
Albert Stoessel
*Richard Strauss
*Igor Stravinsky
Vera Timinoff
Marguerite Volavy
Wladimer von Pachmann
*Fanny Weiland
*Felix Weingartner
Victor Wittengenstein
Michael Zadora
Fannie Bloomfield Zeisler

*Great composer-pianists playing their own works.

The most comprehensive list of great composers ever assembled, including:

Isaac Albeniz
Eugen d'Albert
Anthony Stepanovich Arensky
Johann Sebastian Bach
Mili Balakirew
Ludwig von Beethoven
Georges Bizet
Luigi Boccherini
Johannes Brahms
Charles Wakefield Cadman
John Alden Carpenter
Cecile Chaminade
Francois Frederic Chopin
Samuel Coleridge-Taylor
Cesar Cui
Leo Delibes
Erno Dohnanyi
Gaetano Donizetti
R. Drigo
Anton Dvorak
Gabriel Faure
Friedrich von Flotow
Stephen Collins Foster
Rudolph Friml
Alexandre Glazounow
Michael Ivanovich Glinka
Benjamin Louis Paul Godard
Charles Francois Gounod
Percy Grainger
Enrique Granados
Edvard Hagerup Grieg
George Frederick Handel
Franz Joseph Hayden
Emmerich Kalman
Erich Wolfgang Korngold
Fritz Kreisler
Ernesto Lecuona
Franz Lehar
Ruggiero Leoncavallo
Theodore Leschetizky
Thurlow Lieurance
Franz Liszt
Edward A. MacDowell
Gustav Mahler
Pietro Mascagni
Jules Massenet
Flex Mendelssohn-Bartholdi
Giacomo Meyerbeer
Modest Petrovich Moussorgsky
Wolfgang Amadeus Mozart
Ethelbert Nevin
Jacques Offenbach
Paganini-Liszt
Selim Palmgren
Giacomo Puccini
Sergei Rachmaninoff
Maurice Ravel
Max Reger
Nicholas Rimsky-Korsakoff
Sigmund Romberg
Gioacchino Antonio Rossini
Anton Gregor Rubinstein
Camille Saint-Saens
Pablo de Sarasate
Domenico Scarlatti
Franz Peter Schubert
Robert Alexander Schumann
Cyril Scott
Alexander Scriabine
Giovanni Sgambati
Christian Sinding
John Philip Sousa
Oscar Straus
Johann Strauss
Richard Strauss
Igor Stravinsky
Franz von Suppe
Karl Tausig
Ambroise Thomas
Peter Ilich Tschaikowsky
Giuseppe Verdi
Wilhelm Richard Wagner
Emil Waldteufel
Carl Maria von Weber
Henri Wieniawski
Wolf-Ferrari

A dazzling selection of Jazz and Popular Pianists, including:

Ralph Addison
Harold Arlen
Felix Arndt
Frank Barth
Rubin Beckwith
Frank Black
Eubie Blake
Adam Carroll
Zez Confrey
Corrine DeBert
J. Milton Delcamp
Walter Donaldson
Peter Duchin
Bob Edgeworth
Edgar Fairchild
George Gershwin
Morton Gould
Ford Gray
Stuart Gregory
Gerde Grofe
Earl "Father" Hines
James P. Johnston
Johnny Johnston
Scott Joplin
George Kerry
Holbrook King
Victor Lane
Enrico Lauarro
Lee Lawnhurst
Liberace
Harvey Linderman
Vincent Lopez
Leslie Loth
Howard Lutter
Frank Milne
Jelly Roll Morton
Peter Nero
Phil Ohman
Ray Perkins
Harry Perrella
Muriel Pollack
Ralph Rainger
Richard Rodgers
Julian Rodney
Charles Rosoff
Domenico Savino
Frank Serli
George Shearing
Harry Shipman
Lee Sims
Walter Sturgis
Fats Waller
Roger Williams
Allie Wrubel

PIANOCORDER PERFORMANCE ALBUMS ...A VAST LIBRARY OF TWO-THOUSAND 45-MINUTE CASSETTE ALBUMS WILL BE AVAILABLE TO YOU.

THE COMPANY BEHIND THE

Pianocorder™
Reproducing System

The PIANOCORDER Reproducing System is manufactured, marketed and sold exclusively by Superscope, Inc., the largest American-owned manufacturer of audio home entertainment products.

Superscope, Inc., is the worldwide manufacturer and distributor of Marantz stereo high fidelity components and Superscope home entertainment products. The company is also the sole United States distributor for those Sony model tape recorders that include stereo cartridge, reel-to-reel and stereo cassette decks.

SUPERSCOPE, INC.

20525 Nordhoff Street, Chatsworth, California 91311

Protected under U.S. Patent Numbers 3,604,299, 3,905,267, and 4,031,796 and other U.S. and foreign patents.

APPENDIX D

TELEDYNE PIANO PLAYER PRODUCT LITERATURE

This appendix presents scans of some Teledyne Piano Player promotional literature (circa 1975) to provide the reader with a feeling for how that system was marketed (courtesy of Wayne Stahnke). The Piano Player technology was acquired by Superscope/Marantz in 1977 and ultimately became the Pianocorder Reproducing System.

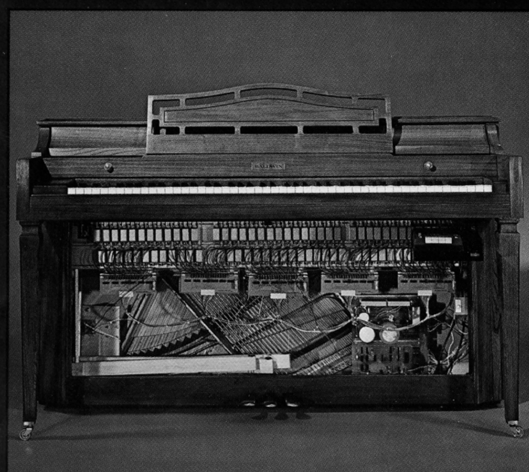
From the photographs in the following brochures, it is clear that the systems were very similar. Examination of the Teledyne patents revealed that the Piano Player system also used the same frame rate and data format as the Pianocorder (e.g., Campbell & Minyard, 1979a).

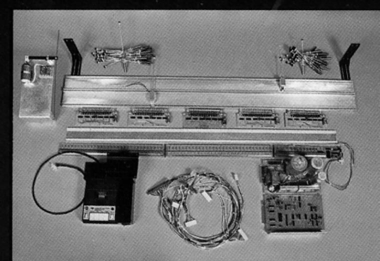
The Piano Player®

It's the first new development for the piano since grandpa fed the paper into his player piano. Now you can have all the advantages of a player piano...and much more.

The Piano Player® is an electronic player and recorder attachment that is easily installed in almost any piano. Instead of a perforated paper roll, a special digital cassette tape recorder activates the keys through a brilliantly engineered data processing system.

The Piano Player® can do all the things a player piano can do...and much more. It has the capability of playing pre-recorded tapes with full dynamic expression. In addition the device can record and instantly play back anything played on its keyboard.



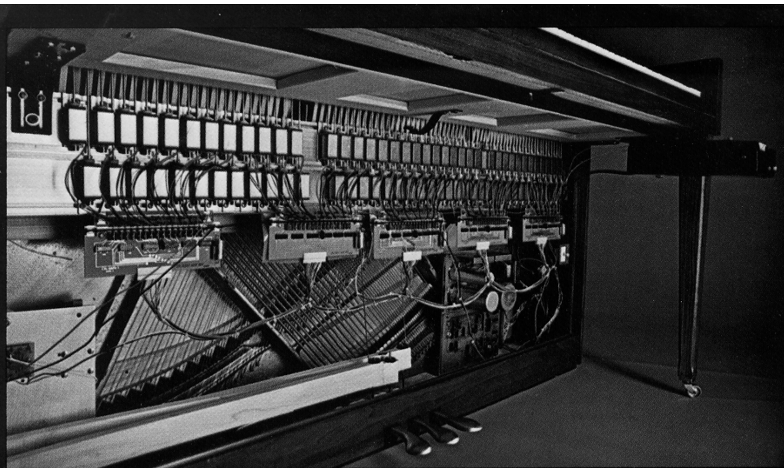


Technical information:

1. Operates on 110 v. household current drawing between 150 and 300 watts when in use and 21 watts when not in use.
2. All electronics parts operate below normal level of rated stress for durability.
3. Special high performance solenoids and unique precision key switches have passed millions of operation cycles during life tests.
4. With a digital processing system developed from Teledyne's space research, The Piano Player's® microcircuitry contains the equivalent of 8000 transistors.
5. The special tape recorder, while similar to the popular audio versions, is a heavy-duty model designed specifically to play digital tapes.
6. All controls to operate The Piano Player® are on the tape recorder.
7. Electrical interlock turns off power automatically when lower panel of piano is removed.

Compare Teledyne's The Piano Player® to a player piano.

	THE PIANO PLAYER®	A PLAYER PIANO
Physical Characteristics:	Small unit easily installed in any piano	A large, original equipment unit requiring special installation
	Inexpensive electronic tape with near-indefinite playback life	Pneumatically operated fragile paper rolls, hard-to-find and expensive
Capabilities:	Record/playback	Playback only
Piano Quality:	Standard	Impaired
Reproduction Quality:	Excellent in every shading of tone and tempo...full expression	Characteristically mechanical monotone... no expression
Market:	Original equipment and conversion on new or used	Original equipment only
Library:	Ready available compact library, easy to use	Bulky library, hard to handle and store
Servicing:	Dealer serviceable in the home because of modular design	Difficult to repair because of non-modular complex pneumatic system...sometimes requires factory representative
Cost to retail customer:	Cost of piano plus approximately $1200 for reproducer and recorder	Approximately $2000 for player piano without expression



TELEDYNE
LEWISBURG

TELEDYNE
LEWISBURG
Industrial Park
Lewisburg, Tennessee 37091
(615) 359-4531

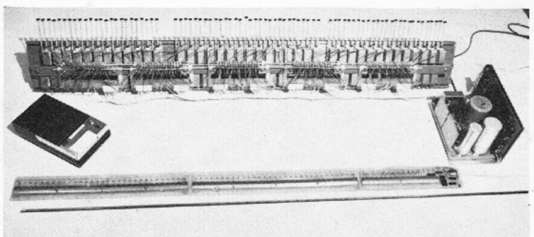
INTRODUCING...

The Piano Player®

From
TELEDYNE
LEWISBURG

TELEDYNE LEWISBURG

Electronic Piano Recorder/Player Kit



"Revolutionary!"

"Amazing!"

"The first really new innovation to come to the piano industry in years!"

"It really converts a standard to a player?"

"Boy! I can sell those!"

"Are they available now?"

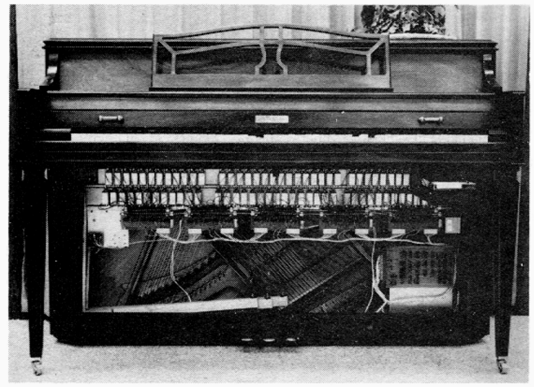
"I want a dealership!"

These were comments from the Houston NAMM show about Teledyne's new Electronic Piano Recorder/Player Kits. The unit is both a Recorder and a Player operating through a tape cassette recorder. It is adaptable to most pianos. Come see for yourself and become a franschised Dealer selling these unique systems from:

Teledyne Lewisburg
Industrial Park
Lewisburg, Tennessee 37091

Call Reese Davis (615) 359-4531

ELECTRONIC PIANO
RECORDER/PLAYER SYSTEM
Installed in a Typical Piano



Nothing visible except the Tape Recorder

See in Chicago Room
or Suite 1729
of the
Los Angeles Marriott.
Dealership
appointments
being made during
the show.

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