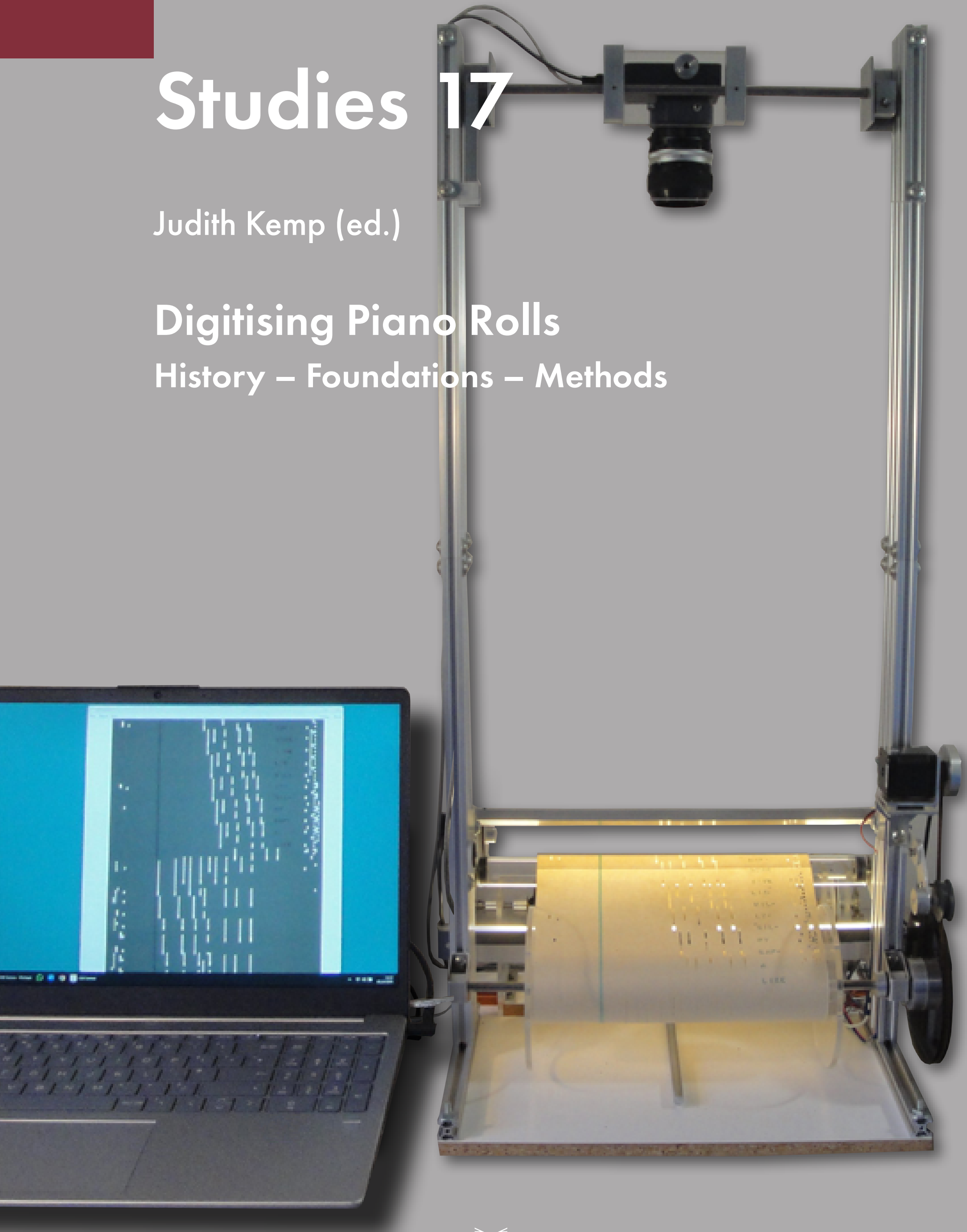
Studies 17

Judith Kemp (ed.)

Digitising Piano Rolls

History – Foundations – Methods



Deutsches Museum

Digitising Piano Rolls
History – Foundations – Methods

Deutsches Museum Studies

Edited by Eva Bunge, Frank Dittmann, Sarah Ehlers, Ulf Hashagen,
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Contents

Foreword

Judith Kemp

The digitisation of rolls for self-playing pianos has been attracting increasing interest for a good 50 years now.[1] Produced in their millions, the rolls provide information about the musical taste of the period around 1900 and the first decades of the 20th century, as well as the fashions for pianistic interpretation of that time. They therefore represent a valuable musical-historical heritage that is opening up an important field of musicological research.

However, the study of these items has some limiting factors: on the one hand, well-preserved and thus playable piano rolls and, on the other hand, playback devices in a suitable condition to produce satisfying results. In many instances, neither is available and, as time goes on, factors such as roll deterioration and the dwindling number of devices capable of playing the rolls with convincing musical results make access to this corpus ever more difficult. Another issue is the worldwide distribution of roll collections with limited lending opportunities, so that in many cases an on-site analysis of the roll is unavoidable. Even then, suitable on-site playback equipment is often not available. The preservation and care of this material heritage, i.e. the historical self-playing pianos and the music storage media produced for them (the rolls), is therefore of great urgency.

Fortunately, the development of conversion methods to digitise the information stored on the rolls over the last 50 years has led to the increased preservation of this intangible heritage, i.e. the music contained on the rolls, being ever more detached from the imperative need to preserve its tangible basis, i.e. the rolls themselves. The first attempts to digitise piano rolls, thus protecting them from loss and making them available for listening, re-punching and research, date back to the 1970s. Since then, interest in this field has grown steadily, especially among institutions such as museums and universities. Today, thanks to constantly evolving hardware and software, piano rolls can be completely digitised from scanning as image files and conversion to audio data, to enabling physical reproductions and access, whether online or otherwise.

In 2015, the Deutsches Museum – in whose "Studies" series this volume appears – asked itself the question of how its collection of around 3200 piano rolls could be catalogued and digitised in the future. The first step in this process, i.e. a project to develop an online database in which the museum's inventory was systematically catalogued, was initiated by Silke Berdux, curator of the Deutsches Museum's collection of musical instruments, together with Rebecca Wolf. This was met with great international acclaim upon its completion in 2015 and the database itself became a standard upon which later projects modelled themselves.[2]

1 Rolls for self-playing pianos constitute the majority of perforated paper music rolls, which have also been used to operate other instruments such as various types of organs and orchestrions. The processes described below also encompass, in part, the digitisation of other types of music rolls; however, the primary focus is on piano rolls.

2 https://digital.deutsches-museum.de/projekte/notenrollen/

However, a digitisation of the rolls themselves – including both image and audio files – is still pending. In order to investigate how to undertake this step, a research project entitled "Klingendes Papier. Aktuelle Digitalisierungsverfahren für Notenrollen" (Sounding paper. Current digitisation processes for piano rolls) was launched, in which the existing approaches were examined. This project led to an in-depth and extremely fruitful international exchange with private experts, institutions such as the Bern University of Applied Sciences, the University of Pavia and the Stanford University Library, as well as with forums such as the Mechanical Music Digest and the Global Piano Roll Meetings amongst others, all of which work in the field of piano roll digitisation.

In particular, the private experts were a great source of information whose sphere of knowledge-sharing had hitherto been largely restricted to their immediate circle of contacts (i.e. other enthusiasts or specialist forums such as the Mechanical Music Digest[3]) and had been only minimally tapped into by any established institutions. This meant that valuable information was thinly dispersed and could only be found through intensive research. One exception to this is Peter Phillips, who has published his findings and work steps in various widely-available publications, making them accessible to a much larger audience.[4] In the main, however, most information regarding digitisation approaches are published on the experts' private websites, which are often difficult to find. Sometimes, the demands of running such a website on their owners can result in that website being abandoned or even, in the worst-case scenario, being removed from the internet, resulting in a great loss of knowledge, as was the case with the two highly respected websites of Warren Trachtman and Terry Smythe. It is thanks to Michael Falco, the web manager of AMICA (Automatic Musical Instrument Collectors' Association), that Smythe's website is now once again accessible after several years offline,[5] but such an effort is likely to remain the exception.

As became apparent in the course of the research project, the restrictions on accessing existing knowledge means that those working on the complex topic of piano roll digitisation often have to begin their research from scratch. This can result in an otherwise avoidable expenditure of time and is a significant source of errors that could be circumvented if the existing knowledge in the field of piano roll digitisation were more readily available.

This observation gave rise to this book, a first anthology on the subject of piano roll digitisation, which aims to make it easier for interested parties to orient themselves. The volume sheds light on the fundamentals of piano roll digitisation and brings together important research findings that were previously either inaccessible or only available via painstaking research. For the first time, some of the leading experts in the field also provide their contribution.

3 https://www.mmdigest.com/

4 See here above all: Phillips, "History" and *Piano Rolls*.

5 https://www.amica.org/RollScanning.htm

The book opens with the article **"Preserving and Accessing a Musical Treasure: 50 Years of Digitising Piano Rolls"** by **Judith Kemp.** This outlines the results of the aforementioned research project at the Deutsches Museum, providing a history of piano roll digitisation while shedding light on the pioneers and leading personalities and institutions in this field. Focus areas include the devices developed, the visual and auditory digitisation output, as well as the forums and other mediums for the exchange of ideas from the beginning to the present day.

This is then followed by **Anthony Robinson's "Introduction to Piano Roll Scanning".** Today, Robinson is regarded as one of the leading players in the field of piano roll digitisation, who on the one hand has designed and built the most advanced, privately-owned piano roll scanner, and on the other has made significant developments in the field of piano roll digitisation software, and is therefore frequently consulted internationally by private and public institutions. Our extended communication over several years has proved to be crucial to this research project and we are extremely grateful that Robinson, who previously only published parts of his research on his private website,[6] agreed to provide such a comprehensive contribution to this book. Robinson's text explains the basics of the scanning process, from the characteristics of source material (the piano rolls) and the various scanning methods, to the processing of the output. The text is divided into short sections and offers a thorough yet easy-to-understand introduction to the subject, especially for newcomers to the field.

Scanning piano rolls with line scan cameras has established itself as the standard in recent years and today delivers high-quality images that contain all the visual details of the rolls. However, there is still a need for development in the conversion of this image data into audible music data. This applies in particular to piano rolls for player pianos. In this case, while the rolls play the notes, the pianolist acts as the interpreter of the piece by using levers and foot pressure to influence the dynamics and speed. If such a player piano roll is scanned and the resulting image file is transferred into music, in most cases the resultant sound is merely the pitches and durations stamped on the roll and is correspondingly mechanical. The necessary creative intervention for the artistic modelling of this source material is not possible and so far no workable hardware/software-based solution has been found to compensate for this shortcoming, although initial in-roads are currently being made.[7]

6 http://semitone440.co.uk/scanner/index.htm

7 See Kemp, "Preserving", 32–33. I would like to thank Werner Goebl, head of the Department of Music Acoustics – Wiener Klangstil (IWK) at the mdw – University of Music and Performing Arts Vienna, for his references to Carlos Cancino-Chacon's AI-based system that generates musical expression based on machine-learned models and a complex score, including dynamic and other interpretation instructions: http://carloscancinochacon.com/documents/online_extras/basis_mixer/basis_mixer.html, accessed 18th July 2025. See also https://www.frontiersin.org/journals/digital-humanities/articles/10.3389/fdigh.2018.00025/full, accessed 18th July 2025. However, this method has not yet been applied to player piano rolls.

The situation is different in the case of reproducing rolls, i.e. those rolls that contain all the interpretative details in the form of punchings and therefore deliver a more realistic sound result simply by being played on the reproducing pianos. Various experts have managed to digitally recreate and reproduce the information contained on the rolls for interpretation, a process known as emulation – although there is much debate in specialist circles about the extent to which the results of emulation can even come close to the original sound result. One of the experts in this field is **Peter Phillips,** a Sydney-based electronics engineer and musicologist who is one of the most active people in the international piano roll scene. For many decades, Phillips has been working with a roll reader he built, which enables him to convert the information stored on the rolls directly into MIDI data. He has also developed software for emulation, which has been and continues to be used in many institutional projects, particularly in German-speaking countries.[8] In his article **"Emulating MIDI Files of Reproducing Piano Rolls for Playing on Contemporary MIDI Instruments",** which was written for this book, Phillips describes how MIDI data is generated using a roll reader or pre-produced scans and how this is then emulated. He provides insights into the software-based emulator "Rollmidi", which he and software engineer David Gosden developed and which makes it possible to digitally reproduce the mechanical expression processes of a reproduction piano.

Another key figure in this field is **Wayne Stahnke,** who has long played a leading role thanks to the modern self-playing pianos he has developed in cooperation with Steinway, Bösendorfer and Yamaha. At our request, he kindly wrote the article **"Seven Steps to Emulating a Reproducing Piano Roll Performance"**, in which light is shed on the theoretical foundations of emulating piano rolls, separating the process into seven discrete steps. For several decades, Stahnke has investigated the highly complex process of emulating reproducing rolls and – as early as the late 1980s – began compiling his research findings into extensive essays that, until now, have never been published and thus appear here for the first time. While these essays – **"Skew, Scatter, and Pitch in Music Rolls"** (1999), **"Acceleration in Music Rolls"** (2019) and **"Windchest Pressure and Hammer Velocity"** (1989), which provide an extremely in-depth view of steps 2, 4, and 6, respectively, within the seven steps outlined in the first text above – have a highly complex, mathematical-theoretical orientation, it was a matter close to the editor's heart to save this important theoretical foundation of emulation from being lost by publishing it in this volume.

The above contributions are supplemented by a glossary that explains some of the most important terms from the world of piano roll digitisation, as it became apparent in the course of the research project that many terms were by no means used consistently, especially in the non-English-speaking circles of the research community.

In this sense, the present volume documents and consolidates a body of knowledge that has emerged independently of artificial intelligence. It thus captures a moment of

8 See Kemp, "Preserving", 31, 35, 37.

transition: a culmination of five decades of non-AI-based digitisation practice, at a point when AI-driven approaches are only beginning to enter the field.

This book is the outcome of my research project “Klingendes Papier”, which itself grew out of Silke Berdux’s previous work on the topic of piano rolls, and was carried out in 2023/24 as part of a scholar-in-residence fellowship at the Research Institute for the History of Science and Technology at the Deutsches Museum. The research project was first and foremost made possible by Silke Berdux, the curator of the musical instruments department. I would like to thank her for the thorough exchange of ideas, her suggestions and feedback as well as for our long and fruitful collaboration in the context of the new exhibition of musical instruments at the Deutsches Museum that preceded the research project.

I would also like to thank Helmuth Trischler, the former head of the Research Department (Bereich Forschung) of the Deutsches Museum, for kindly granting me the scholarship, Andrea Walther for welcoming me to the Research Institute (Forschungsinstitut), and Ulf Hashagen, director of the Research Institute and co-editor of the “Studies” series, who immediately signalled his great interest when the possibility of producing a volume on the subject of piano roll digitisation came up during the course of the project, subsequently enabling it to happen.

I am indebted to Anthony Robinson, Wayne Stahnke and Peter Phillips for honouring my request to contribute to this volume and to share their immense knowledge.

Markus Ehberger and Claudia Hellmann, responsible for editing and proofreading the “Deutsches Museum Studies” series, also greatly supported the creation of this book with their expert advice. My sincere thanks go to them and the staff at the publishing house. And last but not least, I would like to thank my copyreader Robert Jacobs, who provided a final linguistic polish.

Preserving and Accessing a Musical Treasure: 50 Years of Digitising Piano Rolls

Judith Kemp

Abstract

For more than 50 years, experts worldwide have been working on the digitisation of piano rolls in order to preserve this valuable music and cultural-historical resource from decay and to ensure continued research and reproduction. This paper shows the most important stages in the history of piano roll digitisation from its beginnings to the present day and sheds light on the various technical processes developed by numerous private experts and international institutions over the years and highlights important networks within this community. Thanks to the ever-advancing technical possibilities, this community is in a constant state of flux, continuously delivering new approaches and research results. This article has been updated to incorporate those developments up until summer 2025; subsequent changes to the time of going to press are not reflected.

Introduction

Piano roll digitisation has attracted great interest among experts over the past 50 years and increasingly also in academic circles. Although such statements are difficult to substantiate, Wayne Stahnke is said to be the first to attempt the digitisation of piano rolls in 1973.[1] He was followed by many who, using different approaches, tried to transfer piano rolls into computer data and make them accessible, thereby preventing the music stored on the rolls from being forgotten or lost. At first, it was private individuals who dedicated themselves to this task because of their enthusiasm for the music of self-playing pianos, but since around 2010, there has also been a growing interest in piano rolls and their digitisation amongst institutions and scholars.

In view of the many different initiatives and increased international interest, it now seems a matter of urgency to provide an overview of this wide and complex field of activity and research. To this end, the following article – covering the history of piano roll digitisation from its beginnings to the present day – has been prepared. It is intended as an initial orientation for all those who want to find out more about the subject, while highlighting the most important stages and people involved in the historical development of piano roll digitisation. Furthermore, the current state of piano digitisation technology as of summer 2025 is discussed.

Important texts, which served as a starting point and gave crucial impetus for this article are the two essays "In The Beginning … (Evolution of scanning music rolls into midi)" by Terry Smythe (2016) and "History of piano roll digitization" (2022) by Peter

1 Wayne Stahnke's email, 23rd March 2023.

Phillips.[2] Julian Dyer also devotes a passage to the history of piano roll digitisation in his essays "Perfect roll copying with the Mk3 BT roll scanner" (2003) and "Roll Scanning and Roll Replication" (2019).[3] Of course, not all the developments and characters covered in these texts can be mentioned here, as it is impossible to reflect the extraordinary number of people and events involved in the history of piano roll digitisation within the framework of an essay such as this. Therefore, only the most notable elements have been selected here, although some of these points have also been significantly expanded in part where relevant. As far as the technical details of the devices and computer programs used for piano roll digitisation are concerned, the numerous websites mentioned below enable a deeper insight into some topics which can only be touched upon lightly here.

A significant innovation with regards to this book, however, is that numerous experts from the field of piano roll digitisation get to have their say. Likewise, a detailed view of the various known institutional initiatives relating to piano roll digitisation is presented, something that has been completely lacking up until now. In academic and in museum circles in particular, there is a lot of activity in this regard, and new international projects around the topic of piano roll digitisation and the evaluation and use of the digitised data are constantly emerging. This means that the description of the current situation given here (i.e. up until summer 2025) is written in the knowledge that there is still much to be researched and worked on in the future, not least with the recent developments in the world of AI.

While much information given in this text is based on the publications mentioned above, an effort was made to prioritise information gathered via an intensive exchange with the many people working in the field. For this, a questionnaire was prepared – designed to obtain initial insights on the topic – which was sent primarily to the musicological departments of several universities, as well as to museums, archives and libraries that are active in the field. This questionnaire asked about the current status of the indexing and cataloguing of the respective piano roll collections, about the digitisation process and the number of rolls that have been digitised, about the possible uses of the digitisation results, as well as about the exchange of knowledge and publications in this area. The subsequent exchange with private experts, who willingly provided their knowledge, proved to be decisive. In this context, the contributions of Wayne Stahnke and Peter Phillips should be mentioned, as they were able to provide crucial information and answer various questions on the topic in detail. I would also like to thank Peter Phillips for the numerous pictures he provided. My sincere thanks also goes to Sebastian Bausch, Richard Brandle, Tim Baxter, Spencer Chase, Daniel Debrunner, Julian Dyer, Koos van Kruistum and Marcel Veel, Rex Lawson, Craig Sapp, Katsumasa Sasaki, Michael Swanson, Marc Widuch and Pietro Zappalà for providing important components for this

2 Smythe, "Beginning"; Phillips, "History".

3 Dyer, "Perfect roll copying" and "Roll Scanning". In Germany, Walter Tenten has reported several times on the various digitisation projects and associated technology in the journal *Das Mechanische Musikinstrument:* Tenten, "So einfach", "Unterschied zwischen e-MIDI und e-Roll", "Player-Piano-Projekt der Universität Stanford", "Neuigkeiten vom Player-Piano-Projekt", "Sie scannen noch immer!".

text and being available to discuss ideas. Finally, I would like to thank Anthony Robinson. Without his infinitely patient and readily-available advice, his enormous expertise and his open, encouraging manner, the following presentation would not have been possible.

Digitisation Steps

Before tracing the history of the digitisation of piano rolls, it would be worth briefly describing the individual steps of the digitisation process and to clarify some terminology. This seems all the more necessary as, during the research for this text, the impression arose that there is not always clarity about the various terms and their uniform use in the international community of piano roll research. For this reason, a glossary has been compiled for this volume, which provides a quick overview of the central terms from the field of piano roll digitisation and how they are used in the context of this book.

Digitisation is the process of converting information into a digital (i.e. computer-readable) format.[4] What is not meant here is the digital indexing of data to produce an (online) catalogue. Rather, digitisation means that all the information contained on a piano roll is transferred into a digital format which can then be further processed and used in different ways. The following three steps are regarded as the central ones:

1. Scanning:
The first step in the digitisation process consists of scanning the piano roll, i.e. creating an image file that contains all visible elements. These are the holes punched in the paper as well as some graphic elements. The graphic elements can be divided into two groups:
 a) Elements for musical interpretation, such as tempo, expression and volume markings, and sometimes song lyrics.
 a) Elements to identify the roll, often printed on the leader, such as roll manufacturer, song title, composer, pianist, etc.
Additionally, the scan captures the nature of the paper's texture and any visible damage. Devices with line scan cameras have proven to be the most suitable for this purpose and will be discussed in more detail below.

2. Processing scan data:
The production of the image file is followed by further processing. Initially, scans should be checked visually for accuracy. Minor corrections may sometimes be made by editing the image file but if any holes are obscured by folded-over edges then the roll should be physically repaired and rescanned. Once a satisfactory scan has been achieved, it can then be further processed and converted into other data formats.

4 https://en.wikipedia.org/wiki/Digitization, accessed 25th June 2025.

Anthony Robinson describes the different steps of this procedure in his text "An Introduction to Piano Roll Scanning", which will therefore not be discussed in detail here. In this text, however, the final processing step, i.e. the editing of sound files, is of particular interest, which is given here as the third step of digitisation.

3. Production of sound files:
One of the aims of the digitisation of piano rolls is to make the music stored on them audible independently of the pianos originally intended for it. To this end, the image data obtained during the scanning process is converted into musical data, which is typically converted into MIDI files, enabling electronic playback of the music stored on the rolls.[5] The steps required for this are explained in more detail in the sub-chapter "Emulation of reproducing rolls and devices for interpreting player piano rolls".

Today, this digitisation process, i.e. first producing an image file using a scanner and then processing and converting it – not least into data that can be used to re-punch new piano rolls – has become the standard. The following section sheds light on how this development took place.

As far as the defining of specialist terminology is concerned, it seems necessary to remain briefly with the primary focus of this text, namely the piano rolls and the instruments associated with them, and to clarify this point as well.

The English term "player piano" refers to all pneumatically operated pianos, i.e. both the earlier pedal-operated pianos such as the Pianola and the later reproducing pianos such as the Welte Mignon. While the term "reproducing piano" has become established for the latter and the term "reproducing roll" for the associated rolls, no separate term for pedal-operated pianos has become established in English and they are also referred to as "player pianos". Sometimes these instruments are also referred to as pianolas, a name derived from the most successful American player piano, the Pianola from the Aeolian company. The terms for the rolls used on these instruments also vary. Some authors use the term "player piano rolls", others speak of "88-note rolls". Neither is unproblematic, as "player piano rolls" can be interpreted as an overarching term that includes all types of rolls including those for reproducing pianos, and the term "88-note rolls" is sometimes also used as a shorthand term to include earlier roll formats that play fewer than 88 notes.

In order to achieve the greatest possible clarity in this text, the terms are used as follows:

The term "self-playing piano" is used in this text as an umbrella term for both pedal-operated player pianos and reproducing pianos – unless otherwise stated, this only refers to those instruments built around/after 1900.

The term "player piano" refers only to pedal-operated player pianos. The corresponding rolls are referred to here as "player piano rolls".

5 There are alternative proprietary file formats, however the most widespread is the industry standard MIDI file format, and so for simplicity the term MIDI will be used exclusively from now on when referring to musical digital data.

The terms "reproducing pianos" and "reproducing rolls" are simpler, as these terms are unambiguous and established and are therefore used accordingly.

The History of Digitising Piano Rolls I: Private Initiatives and Devices

From the definition of the digitisation process of piano rolls stated above, consisting of scanning (production of an image file) and processing (including the production of sound files), it follows that the history of piano roll digitisation only really began in the 1990s, when Wayne Stahnke developed the first optical scanner. Nevertheless, reference should be made here to two preceding attempts which succeeded in transferring parts of the information stored on piano rolls to other data formats using various methods.

Pneumatic-Electric Roll Readers

As early as the 1970s, various interested individuals attempted to convert the perforations stored on piano rolls to an electronic format. One of the most influential pioneers in this field, who has worked intensively on the subject and made key contributions to date, is Wayne Stahnke, who now lives in Reno, Nevada.[6] The graduate electrical engineer and mathematician distinguished himself, among other things, through the development of modern self-playing piano systems, which were created in cooperation with Steinway, Bösendorfer and Yamaha.[7] In 1973, Stahnke built the first pneumatic-electric roll reader. His equipment sensed the presence or absence of the holes in a piano roll every 1/100 of a second and converted the resulting data into a signal that could be recorded using conventional audio recorders, storing it on cassettes, a widely-used audio recording medium at the time. The recording controlled the operation of a pneumatic reproducing piano (Ampico A, Ampico B, and Duo-Art pianos) via electromagnets that opened and closed openings connected with the playing mechanism, which operated exactly as if holes in a roll had produced the same open-close pattern. The data obtained using the roll reader could therefore be used to trigger a self-playing piano, but no image file of the roll was created. Stahnke was followed in 1977 by Peter Phillips, a Sydney-based electronics engineer and musicologist who built another pneumatic-electric roll reader (Fig. 1).[8] Other similar devices were produced by the company Superscope, which used the same method as Stahnke and Phillips to store piano roll codes on cassettes. In the late 1970s, Superscope also developed the first new electronic instrument that could be played using these cassettes: the Pianocorder.[9]

6 http://www.live-performance.com/index.html. See also Phillips, "History", 6.

7 Fisher, "Ivories". To get an overview of Wayne Stahnke's patents, enter "Wayne Stahnke" in the search window of the webpage https://depatisnet.dpma.de/, accessed 25th June 2025.

8 For Stahnke's and Phillips' roll readers, see also Dyer, "Roll Scanning", 22.

9 See Phillips, "History," 7, and Fontana, *Pianocorder*.

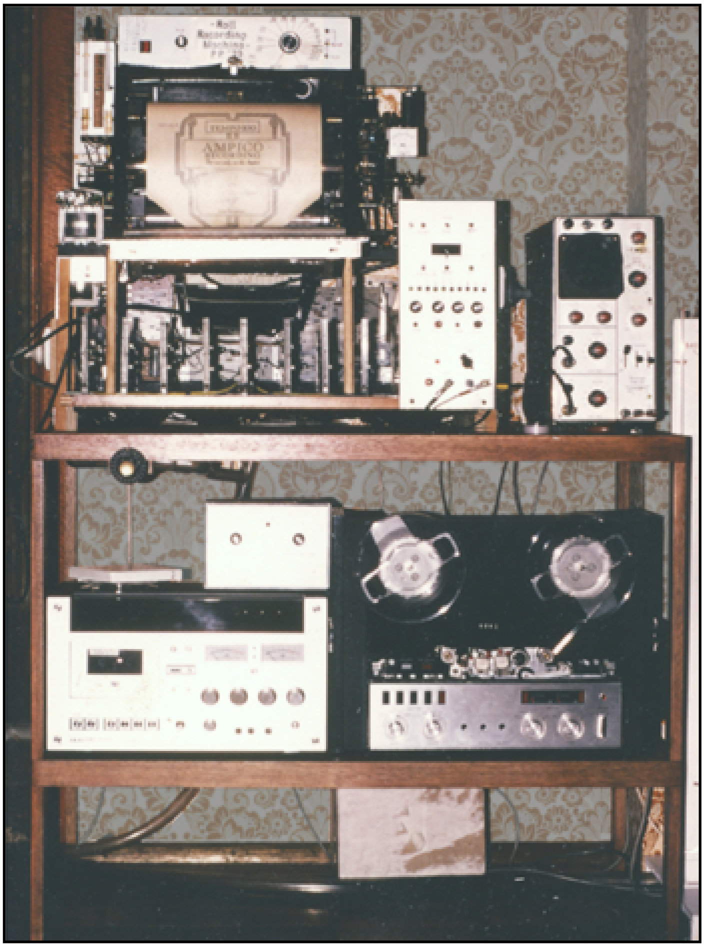

Fig. 1 The Phillips roll reader, circa 1979.
Peter Phillips: "This photo shows the roll reader and an oscilloscope to display the signal from the roll reader. This signal was recorded on the reel-to-reel tape recorder on the bottom shelf. The rotary control under the roll reader was used to set the air pressure in the roll reader spool box and was shown by the manometer on the left of the reader's spool box. The panel attached to the roll reader was used to check the operation of the 98 pneumatic switches. These were fitted in the bottom timber section of the reader, and were connected to the circuit boards beneath the spool box. The cassette deck was used to make cassette recordings of the roll reader data by feeding the output of the reel-to-reel tape deck to the cassette deck. The speed of the roll drive motor was adjusted by the control in the top panel. The reader was only suited to recording Ampico rolls, one of which is in the spool box."[10]

10 Peter Phillips' email, 7th March 2024.

While Stahnke later converted his roll reader into an optical scanner, which now also produces images and which will be discussed later, Phillips still works with his more-developed device. His present roll reader, like the previous one, converts piano roll perforations directly into MIDI data which can then be played back via computer on a suitably equipped reproducing piano, or after further processing (emulation) on a contemporary MIDI piano, such as a Disklavier or a virtual piano such as PianoTeq. Phillips goes into more detail about his method in his PhD thesis, published in 2016.[11]

Another pneumatic roll reader was developed by Richard Tonnesen, a physicist and programmer who ran the company Custom Music Rolls as a sideline and died in Texas in 2014.[12] His device, which went into operation in 1979, could read the perforations of the rolls and then transfer this information to a second device, which could use the data to make a copy of the original roll.[13]

The roll readers mentioned above represent an important stage on the way to modern piano roll digitisation. They made it possible to convert information stored on the rolls into other data formats, which could then be used to play back the music and/or re-punch rolls. However, these devices were not able to perform the actual scanning in the sense of creating an image file of the rolls.

Videotaping Piano Rolls

As far as we know today, the first attempt to create image data of the rolls in the form of video data was undertaken by David L. Quinlan, an employee of the RS Microwave Company, Inc. in Butler, New Jersey in 1989.[14] The initiative for this came from the American pianist and music historian Artis Wodehouse, who was looking for ways to convert early piano-roll recordings of George Gershwin to print scores. To this end, she and others developed a three-stage process: First, the rolls were filmed using equipment developed by Microwave Company/David Quinlan involving a 1984 National Saticon video camera (Fig. 2). This film data was then converted into MIDI information and finally to notation software.[15]

As the resulting print score was the intended output of the project, the film data gained in the process was not intended as documentation of the rolls, but rather a means to an end. As such, no further significance was accorded to them and nothing is known about their whereabouts.[16]

11 Phillips, *Piano Rolls*. See also https://www.petersmidi.com/.

12 https://www.mmdigest.com/Archives/Digests/201402/2014.02.05.01.html, accessed 27th June 2025.

13 Tonnesen, "Roll Reader" and "Roll Cutting."

14 See also Phillips, "History," 11.

15 Doerschuk, "Gershwin", 66. For Wodehouse's project see: https://www.youtube.com/watch?v=yC4v30gjEVc, accessed 25th June 2025.

16 Artis Wodehouse's email, 7th March 2024.

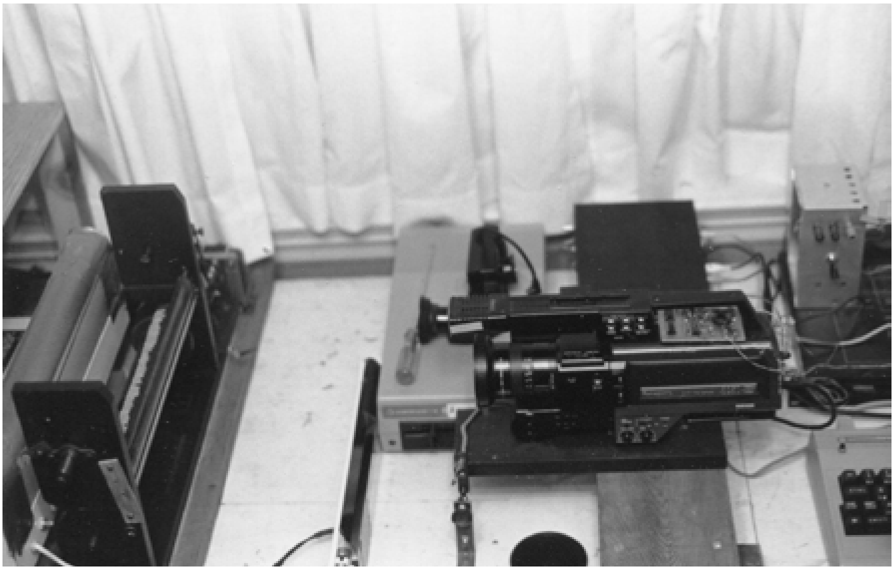

Fig. 2 David Quinlan's apparatus for filming the Gershwin rolls: On the left is the piano roll spool box on which the roll unwound, which was then filmed by the camera on the right, a 1984 National Saticon colour video camera, model WVP-200. The lighting required for this was provided by a fluorescent lamp sitting on the table to the left of the camera.

The filming of piano rolls has also subsequently been used on various occasions as a way of converting the codes stored on the rolls to computers. More recently, the Japanese computer programmer Katsumasa Sasaki pursued such an approach, who said he worked on this method between 2014 and 2020.[17] However, he was not primarily interested in creating image data and the subsequent digital archiving of the rolls. Instead, he used his video recordings to digitally play back the pieces stored on the rolls with the help of a program he created himself.[18] However, since the results obtained in this way proved to be inaccurate, he has since withdrawn the open-source software he developed for this purpose.

Overall, all attempts to digitise piano rolls with the aid of video cameras have proved unsatisfactory, which is why this procedure is not detailed further here.

17 Katsumasa Sasaki's email, 8th January 2024. See also https://www.youtube.com/watch?v=NpGtE7H6Z7o, accessed 25th June 2025.

18 Katsumasa Sasaki's email, 7th March 2024.

Optical Piano Roll Scanners

The First Optical Line Scanner by Wayne Stahnke

Wayne Stahnke chose a different way of producing image files from piano rolls when he began to convert his pneumatic-electric roll reader in the 1990s and put his new device with a line scan camera into operation in 1996.[19] Stahnke describes his scanner as follows (Fig. 3–7): "The scanner consists of two parts, mounted on a special table that I had built for the purpose, and separated by about 750 mm. The wooden-frame roll transport is in front, where the operator has access to it. The camera is behind it and stares at the roll, which is positioned between the camera (about 750 mm away from the paper) and a fluorescent light (about 100 mm away from the paper, toward the operator)."[20]

The heart of this arrangement is the line scan camera. Anthony Robinson – an engineer from Nomansland, Wiltshire, who worked at the BBC and later independently designed data logging equipment for British Telecom – is today one of the central figures in the field of piano roll digitisation. He writes about this device, which has now established itself as a standard, and explains the way it works: "Line scan cameras are more like conventional cameras, with the object placed at some distance from the camera and focussed onto a sensor by a lens." With this line scan camera, "individual one-dimensional scan lines are triggered at regular intervals along the roll, building up a two-dimensional image."[21]

Stahnke explains the process of image acquisition and the advantages of this method: "Previously, all roll digitization (except for a late modification of my pneumatic reader, for which I created the measuring roller) relied on having two unrelated processes advance perfectly in time. These are the triggering interval (time interval), and roll speed. Variations in the roll speed corrupt the scan, making it useless for anything other than casual listening. Accurate time intervals are easy to generate electronically, but accurate roll speed is a practical impossibility. Thus, triggering the line scan camera from the measuring roller eliminates a major source of inaccuracy in a single step."[22]

With this device, Stahnke succeeded for the first time in producing high-quality scans of a piano roll. He did not present his approach to a wider public for lack of interest, and so his scanner with line scan camera remained the only one for many years.

19 See also Dyer, "Roll scanning", 22.

20 Wayne Stahnke's email, 8th October 2023.

21 Robinson, "Introduction", 56.

22 Wayne Stahnke's email, 24th October 2023.

Fig. 3 The front of the camera. The lens and lens hood are clearly visible, as is the hand-made circuit board on the table.

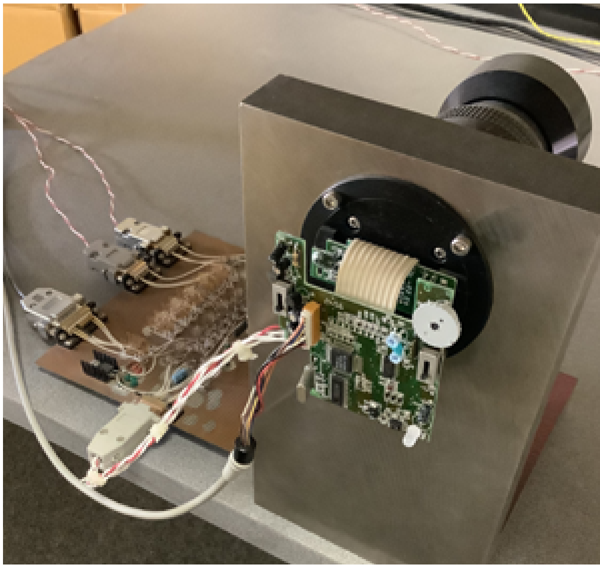

Fig. 4 The back of the camera that Stahnke built from the Logitech ScanMan 256 printed circuit board, which is in the centre of the picture. The lens and lens hood can be seen on the opposite side of the heavy L-shaped frame. The small circuit board lying on the table serves as the interface between the ScanMan circuitry and the computer.

Fig. 5 The whole scanner with the left side of the roll transport in the front and the camera in the background.

Fig. 6 Head-on view of the centre of the roll transport. Here, one can see the chucks for holding the roll, the copper-coloured tensioning bar, the aluminium measuring roller (125 mm in circumference) and the wooden take-up spool.

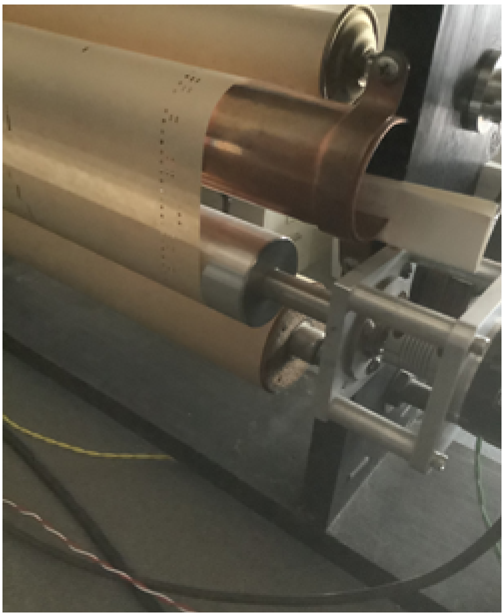

Fig. 7 This shows the roll passing from the feed spool over the tensioning bar, down to the measuring roller, and on to the take-up spool. The light path is between the tensioning bar and the measuring roller.

Optical Scanners with CIS

Another approach to the development of optical piano roll scanners was met with a greater response, which was significantly advanced in the early 2000s by BBC television engineer Richard Stibbons, who last lived in Lowestoft, UK, and died in 2022.[23] Stibbons promoted the use of a Contact Image Sensor (CIS), as used in flatbed scanners consisting of a row of sensors, a rod lens and a strip light.[24] As with Stahnke's device, these scanners also scan the roll line-by-line and then transfer this data into a two-dimensional image. Together with piano roll enthusiast Spencer Chase of Garberville, CA, Stibbons developed his Mk3 roll scanner (Fig. 8), described in detail by English physicist, IT professional and piano roll expert Julian Dyer.[25] The A3 CIS modules used are wide enough to handle standard 11¼ inch rolls, but for wider rolls it is necessary to use two modules in a staggered formation. This causes problems if the roll weaves as it then becomes impossible to recombine the two images accurately.

Fig. 8 Richard Stibbons with his Mk3 roll scanner built by Spencer Chase, which is sitting on top of a Yamaha Clavinova.

Decisive improvements were made in the successor model, the Mk4 roll scanner, designed by Larry Doe of Poughkeepsie, New York (Fig. 9–11). After Doe demonstrated his prototype scanner in 2005, a group of people subsequently joined forces to elaborate on it: the software to drive the scanner and process the roll scans came from Anthony

23 See the obituary for Stibbons: https://www.greshams.com/wp-content/uploads/2023/01/OGM_2022-updated-Jan-2023.pdf, 123, accessed 25th June 2025. See also Dyer, "Roll scanning," 22–23, Phillips, "History," 13, and Smythe, "Beginning," 25–26.

24 Stibbons published several contributions to piano roll digitisation on the website of the Mechanical Music Digest: https://www.mmdigest.com/Archives/Authors/Aut1197.html, accessed 25th June 2025. See also Stibbons, "PC Pianola" and "Roll Scanning."

25 Dyer, "Roll Scanning".

Robinson and Warren Trachtman. Trachtman, who died in 2017,[26] was an electrical engineer in Potomac, Maryland, who also did a lot of work on the subject, scanned thousands of rolls and was also important in the field of software development. Michael Swanson, a machinist and musician from San Diego, California, who has scanned countless piano rolls for many people, was responsible for the mechanical parts for the frames and transports. He describes the scanner as follows: "The Mk4 roll scanner was designed to be a true archival machine capable of capturing all details of the rolls including the graphics, i.e. anything written, drawn or printed on the roll. It was the first CIS-based scanner to capture the perforations and the graphics by using a clever bi-color scheme to split the images. One channel (green) would pick up the note field using the backlight and another channel (red) would pick up the graphics with the front light in the CIS module. The Mk4 has a capstan drive to pull the paper past the CIS at a constant speed. The scanner frame is made to extreme precision to minimize paper wander and skew. It produces excellent bi-color archival scans."[27]

In July 2006, the Mk4 roll scanner was presented at the AMICA Convention in Chicago to the public for the first time.[28] 10 of these scanners were built, which Rex Lawson, perhaps one of the last great masters of Pianola playing, praised at the time as "the most accurate scanning system."[29]

The Doe scanner ensures that the roll is held at a fixed distance from the CIS by wrapping it around a glass tube at the point of scanning. In common with all Mk3 and the following Mk3a scanners, the Mk4 was originally confined to running under MS-DOS using increasingly archaic hardware. However, Anthony Robinson has since updated some of these devices to run under Windows on modern hardware. Some of these updated scanners are in the possession of Robinson, Michael Swanson and the New Zealand-based piano roll enthusiast and airline cabin manager Robert Perry, who makes files obtained from his scans available for download free on his website.[30]

26 See obituary for Trachtman: https://www.mmdigest.com/Archives/Digests/201704/2017.04.03.02.html, accessed 18th July 2025.

27 Michael Swanson's email, 20th April 2023.

28 See Smythe, "Larry Doe's MK4 Roll Scanner."

29 Lawson, "Librarians," 361.

30 https://www.pianola.co.nz/public/index.php/wmidi/

Fig. 9–11 Impressions of Larry Doe's Mk4 roll scanner.

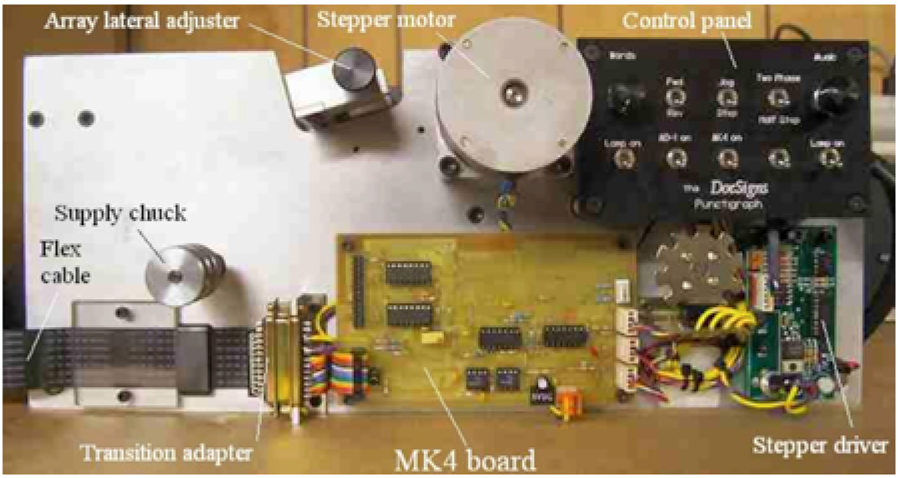

Fig. 10

Fig. 11

The Newest Model: Anthony Robinson's Scanner with Line Scan Camera

Anthony Robinson, who had been working on scanning piano rolls since the 2000s and also wrote software for this, began developing his own scanner with a line scan camera in 2014. He presented a video of his prototype scanner during a brief talk on roll scanning at Stanford University in 2015. The device has been in use ever since and is constantly being developed further (Fig. 12).[31]

In contrast to Stahnke's scanner, in which the camera is mounted on a table and sits opposite the roll to be scanned, the camera here is attached to a frame and points downwards at the roll. This design also corresponds to that of all the scanners from institutional contexts mentioned below and, with suitable adjustment of the camera height, rolls of any width may be scanned. As with the CIS scanners, two light sources are also used here: the backlight, which ensures the correct transmission of the perforations, and the front light, which is required to obtain a correct image of the front of the roll. However, Robinson's scanner is equipped with a black-and-white camera, meaning that the colours of the paper and printing are only captured in greyscale.

31 Robinson provides a detailed description of his optical scanner on his website: http://semitone440.co.uk/scanner/index.htm

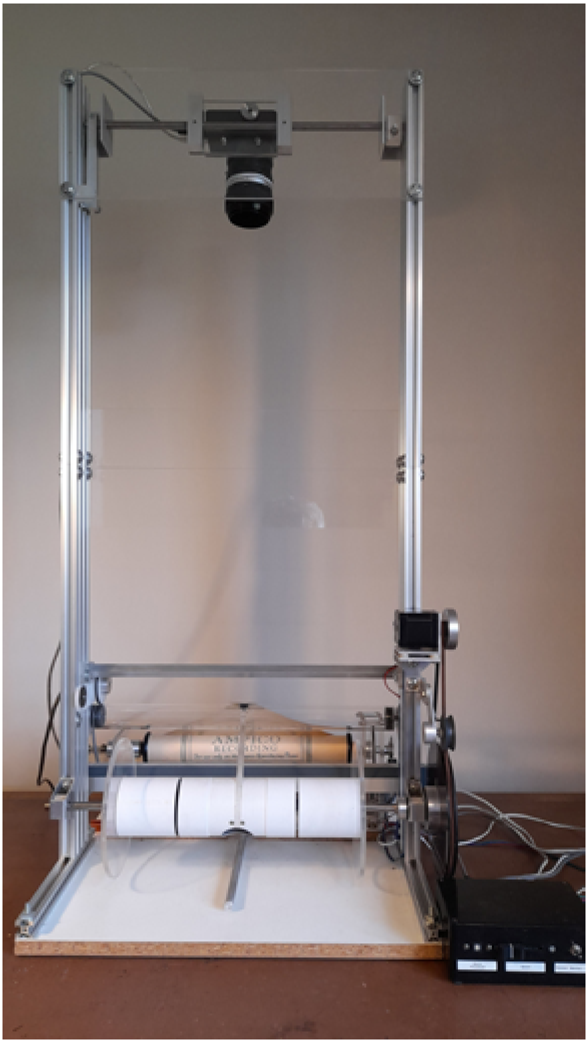

Fig. 12 Anthony Robinson's scanner in 2024.

At the point of scanning, the roll is wrapped around a glass tube which rotates with the roll. The roll is pulled through the scanner by the take-up spool whose rotational speed is slowly reduced during scanning to compensate for the paper build-up and so maintain an even scanning speed. An encoder wheel measures the rotation of the tube and triggers line scans at a rate of 150 scan lines per inch of roll to match the camera's default horizontal resolution. During scanning, scan lines are transferred by USB to the

PC where they are temporarily stored. A secondary optical encoder measures the rotational speed of the feed spool from which the diameter of the remaining paper on its core can be deduced. As the end of the roll approaches, a warning beep alerts the operator to stop scanning once the last perforations have passed. Completed scans can then be stored as standard greyscale TIFF image files with LZW lossless file compression.

Robinson names the following most important advantages of his scanner compared to the CIS scanners:

1. Rolls are more easily loaded.
2. Rolls can be scanned from the very start with the aid of a hook attached to a belt that extends from the take-up spool.
3. The speed of the scanner can be varied with a slider control, allowing delicate rolls to be scanned more cautiously.

Robinson's scanner has attracted a lot of attention in academic circles and its builder is still consulted for advice today.

Although scanners with line scan cameras are considered by many experts in the field to be the best, there do not appear to be more than the two aforementioned specimens, by Stahnke and Robinson, in private hands at this time.[32]

This is where the history of piano roll scanners developed by private experts ends. For a good ten years now, further development has shifted significantly to the institutional sector, which is examined in the section on "The History of Digitising Piano Rolls II: Institutions". Before that, however, it makes sense to take a look at the further processing of the scan data, and here in particular at the process of emulation, as this appears repeatedly in the following chapter on institutional initiatives and would otherwise remain incomprehensible.

Emulation of Reproducing Rolls and Devices and Software for Interpreting Player Piano Rolls

So far, we have described the devices that – apart from roll readers – have mostly been developed since the 2000s to produce image data from the rolls. However, this is only one part of a complete digitisation process, which should also enable the reproduction of the music stored on the rolls independently of the original instruments intended for this purpose. To achieve this, the scan data obtained must be further processed and converted into a format suitable for playback. The above-mentioned persons and other experts have also been working intensively in this field, as the following shows.

32 Robinson remembers another relatively simple scanner with a line scan camera owned by the collector Thomas Jansen mentioned below, but nothing is known about its whereabouts after Jansen's death in 2021.

Emulation of Reproducing Rolls

As is well known, there are two main categories of piano rolls: those for player pianos and those for reproducing pianos. Whereas the perforations of the rolls for player pianos mostly only contain information about pitch and rhythm, additional perforations in reproducing rolls contain information about the dynamics, encoded in a form that is specific to the particular system.

However, with these reproducing rolls, not all parameters contained on the rolls are accessible when the perforation information is converted into MIDI – this must be done by an emulator. This is used to subsequently interpret the expression coding on the rolls and convert it into MIDI velocities. Only through the emulation of digitised rolls is an audibly satisfying result achieved that more or less corresponds to playing the roll on an original instrument. Since the pneumatic systems of all pianos function differently, a separate emulation must also be produced for each system.

In addition to the development of scanning devices and the corresponding software, the development of emulation software thus proved to be crucial. Early emulation software was created in the early 1990s by Wayne Stahnke (Welte-Mignon, Ampico)[33] and Richard Brandle, a mathematician who worked in hardware/software design and now lives in Dallas, Texas.[34] His software WindSuite, developed in 1993 with emulations for Ampico A and B, Aeolian Duo-Art, all Welte-Mignon systems, and other less prominent American models, is still for sale today and enjoys significant popularity in the scene due to its good sound results. Brandle writes about the roll simulation in his WindSuite applications:

> The simulators in the WindSuite Roll Editor and Roll Player applications all use a common pneumatic/mechanical model. The model is written in C++ and is composed of about 150 classes corresponding to the elements in various pneumatic player systems.
> Each system's physical attributes are encoded into a set of tables that are used by the model. Examples of the attributes in the tables are maximum vacuum pressure, pneumatic response times, accuracy of the system's vacuum regulators, tracker bar port function assignment, pneumatic stack split, take up spool circumference and many, many more.
> When the roll is 'played', the data representing the holes in the roll are fed into the model. At each row time, the position of the vacuum regulators on each side of the pneumatic stack is calculated. Then, the number of open ports is determined (which indicate what notes are being played) and the vacuum is adjusted for the resulting 'load' imposed by the collapsing pneumatics and the speed of the pneumatics collapse. This determines how much force is being applied to the key which is directly related to the volume of each played key. The volume is

33 Available on demand from Wayne Stahnke.

34 See also Phillips, "History," 11–12.

> translated into a MIDI velocity value and sent to the output device. This process continues for each row of data contained in the roll image.
> Despite the maturity of the product set, it continues to undergo enhancement with new features and systems. At present about 20 different pneumatic instrument systems are simulated.[35]

Spencer Chase used the emulation programs of Stahnke and Brandle for the MIDI files of piano rolls scanned by him, which he sold via his website.[36]

Julian Dyer developed emulation software for all Welte-Mignon systems, Duo-Art, Triphonola and Themodist-Metrostyle Pianola, which can be downloaded freely, but is no longer supported.[37]

Peter Phillips has also developed emulation processes for all Welte-Mignon systems, Ampico, Duo-Art, Triphonola and Duca rolls and offers MIDI files of these types of rolls on his website, which can be played on modern self-playing pianos.[38] On the same website, he also sells CDs with recordings of a Bösendorfer CEUS Imperial grand piano operated with his emulations. Phillips has already made his emulation software available on several occasions and plans to license it to interested parties in the future.

The aforementioned programmer Katsumasa Sasaki developed emulation software as well. The most recent version "PlaySK ver3.7" supports Ampico A and B, Duo-Art and Welte-Mignon T-98 and T-100 and Licensee, Recordo B, ArtEcho and Aeolian Duo-Art Pipe Organ systems, using MIDI data he derived from scans by Michael Swanson and others. Examples of his attempts can be heard on Sasaki's YouTube channel.[39] He has also published his software on the open-source platform Github.[40] This software can be used with a variety of image file formats such as TIFF, PNG and CIS. It then emulates the roll and outputs a MIDI stream in real time, which can be played on electronic pianos like the Disklavier or on synthesized pianos on the PC.

In the Netherlands, the company Euterpe Rolls based in Voorhout near Leiden and led by Koos van Kruistum and Marcel Veel, whose activities will be discussed further below, has also developed emulation software for all Welte-Mignon systems, Ampico A and B, Duo-Art and Tri-Phonola. The acoustic results of their emulation of more than 4000 Welte rolls can be listened to on their website.[41]

35 Richard Brandle's email, 30th January 2024.

36 http://www.spencerserolls.com/. Spencer Chase died in June 2025 after a long illness. He is sorely missed in the piano roll community, as the various obituaries on the Mechanical Music Digest website prove: https://www.mmdigest.com/Archives/KWIC/C/chase.html, accessed 18th July 2025.

37 http://www.pianorolls.co.uk/roll_editor.html

38 https://www.petersmidi.com/

39 https://www.youtube.com/@kyokutyou2007/videos

40 https://github.com/nai-kon/PlaySK-Piano-Roll-Reader

41 https://www.euterperolls.com/

Devices and Software for Interpreting Player Piano Rolls

The MIDI files derived from emulated reproducing rolls can produce high-quality sound results when played back on modern self-playing pianos or virtual instruments such as Pianoteq. The situation is quite different, however, for MIDI files derived from player piano rolls: if such a MIDI file is played back on a modern self-playing piano or virtually, it only offers the musical material of the piece, but an intervention of a performer, which would be necessary in this case to make it a musical or non-mechanical listening experience, is not possible. While the process of emulation has become established for reproducing rolls – albeit with different sound results, as the term "emulation" only really refers to the processing of reproducing rolls – no comparable process has yet been able to establish itself for player piano rolls that could convincingly solve this problem.

Among private individuals, there have been various experiments to produce a device that makes it possible to intervene in musical events when the MIDI files of player piano rolls are played. As early as 1995, Rex Lawson described a "computer pianola" developed by him in an article in the Player Piano Group Bulletin: "My own hardware system […] has a real-time computer pianola, with speed, subduing, pedal and fast forward/play/re-roll levers, and a pianola pedal unit connected to a suction sensor in the Apple [Mac]. It is effectively a complete pianola system that plays out through MIDI."[42] As Rex Lawson explained further, he used this device mainly for listening to rolls that he was creating, "because it's much easier to hear wrong notes, or the exact length of staccato chords, rather than simply looking at a screen with dots on it."[43]

Another device (Fig. 13) was created by Peter Phillips, who describes it as follows: "I call this device 'Player roll to Disklavier'. It has sliders to create dynamics either for bass or treble side of the keyboard or, for rolls with theme perforations, accompaniment and theme. It also has buttons for soft and loud pedals. It accepts a MIDI file of a player roll."[44] Phillips also used his "Player roll to Disklavier"-device in a recent project with Bonn University,[45] which will be highlighted below.

In the field of software development, Spencer Chase is said to have created a program that allows a video-game controller to be used to influence tempo and dynamics, but nothing more could be found out about this.[46] More recently, Katsumasa Sasaki has also experimented with software that allows a manual intervention during the digital playback of a piano roll on the computer using the computer keyboard. His results can be viewed on YouTube, but as Sasaki reports, he did not subsequently publish his program because it was too difficult to operate.[47]

42 Lawson, "Rolling," 22.

43 Rex Lawson's email, 16th January 2024.

44 Peter Phillips' email, 12th May 2023.

45 Ibid.

46 Conversation with Julian Dyer, 7th July 2023.

47 Katsumasa Sasaki's email, 20th March 2024, and https://www.youtube.com/watch?v=QXwPkmI57gg, accessed 25th June 2025.

Fig. 13 Devised by Peter Phillips, this interface accepts a MIDI file of a player piano roll and has user-operated controls to add expression to the file when it is played on a MIDI piano, such as a Disklavier.

Another attempt by Katsumasa Sasaki to breathe life into the player piano rolls is based on the AI-tool midihum by Erich Grunewald, a programmer based in Berlin. On the Github platform, where the program can be downloaded, it says: "midihum […] is a command-line tool for humanizing MIDI – that is, for taking as input MIDI compositions and producing as output those same compositions with new velocity (loudness/dynamics) values for each of the contained notes. […] The model is trained on 2579 performances from the International Piano-e-Competition for pianists aged 35 and under."[48] Sasaki has further developed the program and uses it to add varying volumes to MIDI files obtained from scans of player piano rolls.[49] The basis for these volume changes is also formed by the performances at the competition previously mentioned and evaluated by AI, but not the actual source material, i.e. the piano rolls and the graphic lines applied to them to modify the volume and playback speed.

Various institutional initiatives have also experimented with programs for the subsequent sound processing of scanned player piano rolls, as will be discussed in more detail below.

48 https://github.com/erwald/midihum. This refers to the Minnesota International Piano-e-Competition: https://en.wikipedia.org/wiki/Minnesota_International_Piano-e-Competition, accessed 5th August 2025.

49 https://github.com/nai-kon/midihum_gui/releases/tag/Ver1.0.0

The History of Digitising Piano Rolls II: Institutions

It was not until sometime after private individuals had begun to engage in piano roll digitisation that various institutions also showed interest.[50] This may have to do with the fact that the music stored on the piano rolls was not readily accessible and therefore – and also due to the lack of catalogues and directories at that time – in many cases, rolls were stored unnoticed in institutions for years without anyone taking an interest in them. Often, the necessary instruments to play the rolls were also lacking, or the existing ones were in too poor a condition to put them into operation or generate convincing sound results. Although there is also a whole series of good recordings of pieces stored on piano rolls, others were often rather off-putting, as they were all too often played on poorly-adjusted instruments, as Peter Phillips points out.[51]

It was only around the turn of the millennium that an awareness of the music-historical value of piano rolls seemed to gradually emerge within institutions, and this awareness has grown steadily ever since, as the following account demonstrates. One reason for this was certainly the technical progress and the establishment of digital camera systems, which made it possible to approach the data saved on the piano rolls by transferring them to new media. Nearly all initiatives highlighted in the following relied on this new technology from the beginning and developed devices with line scan cameras, ignoring the older CIS-based approaches mentioned above.

The Scanner of the Berner Fachhochschule and its Further Use

A first approach to the creation of a universal roll scanner was made in 1999 by the Berner Fachhochschule (BFH; Bern University of Applied Sciences) at the suggestion and seed funding of Barnabé (Jean-Claude Pasche, 1940–2020, CH-1077 Servion). A "scan all roll types" system based on a line scan camera was developed in the context of various diploma/study projects, without recourse to prior knowledge by people mentioned above. Initial experience was gained with scanning private collections of rolls from Jean-Claude Pasche and André Scheurer. In 2007, the scanner (Fig. 14) was ready for use and was further refined with the help of Roger Tschanz and David Gräub until 2010. It is described in detail in an essay by Daniel Debrunner, professor emeritus in the field of computer science and technology at Berner Fachhochschule and head of the project from 1999 onwards.[52] It was used in 2008 and 2010 in the projects of the Hochschule der Künste Bern (HKB; Bern University of the Arts) "Wie von Geisterhand 1" and "Wie von Geisterhand 2" (As if by a ghost's hand 1 and 2), in which the whole Welte Philharmonie collection located in the Museum für Musikautomaten in Seewen,

50 Phillips shortly mentions some of the following approaches in Phillips, "History," 13–14.

51 See Phillips, *Piano Rolls*, 5–6.

52 Debrunner, "Musikrollenscanner," 35–36.

Solothurn, was scanned and examined – around 1500 rolls.[53] The following file formats can be automatically generated by the scanning and post-processing algorithms of the Bern device, which works with a transmitted-light monochrome and a reflected-light RGB colour camera:

a) camera stream data in raw format, unaffected (.mrs and .mrsc)
b) track data conversion as readable (and size-efficient) character file with length stamp (.dsp)
c) export for the Welte Philharmonic organ control (.rec)
d) export as lossless, compressed images of the roll surface (.png)
e) export as a MIDI file either as raw data (e.g. tracks 1–100 for MIDI piano prefixes) or audible piano data in correct pitch and separated control tracks in a 2nd track (.mid)
Input information is used from:
f) roll data type files, there is one file for each instrument variation (.mrt)
g) MIDI data can also be backward-imported to .rec, if errors of the roll digitisation have been edited and a CD recording of the original instrument with the digital control is to be made.[54]

Daniel Debrunner names important requirements for a roll scanner that this device fulfils: "The scanner should be able to read all common roll types. This poses the challenge of mechanical adaptation of roll ends, roll width, different paper qualities, track pitches, hole diameters and hole chains."[55] Debrunner also stresses the need for a transportable scanner that can be brought to the collections.

The scan counter of the Bern device records almost 9350 scan starts.[56] This figure is made up of all fully scanned rolls but also includes all aborted scans and multiple scans of the same roll. An index of the successfully digitised rolls with image and audio files is currently being compiled. The first results can be viewed on a webpage which was set up in 2021, with emulations by Peter Phillips.[57] In December 2021, Sebastian Bausch, who has established himself as a leading figure within the Bern piano roll digitisation project, and Manuel Bärtsch from HKB introduced an advent calendar on YouTube, which presented films and emulated sounds of the rolls digitised with the Bern scanner in 24 clips alongside short introductions.[58]

53 https://www.hkb-interpretation.ch/projekte/wie-von-geisterhand-1 and https://www.hkb-interpretation.ch/projekte/wie-von-geisterhand-2

54 Daniel Debrunner's emails, 29th March 2023 and 1st July 2024. Translation of the German original by J.K.

55 Debrunner, "Musikrollenscanner," 37. Translation of the German original by J.K.

56 Status as of June 2024. No later information was available.

57 https://www.magic-piano.ch/en/time-machine/roll-archive/

58 https://www.youtube.com/watch?v=LyAejySQOrw&list=PLfHAQbexxkeyeH0u9VQi-qlSvjZMvcaE3, accessed 25th June 2025.

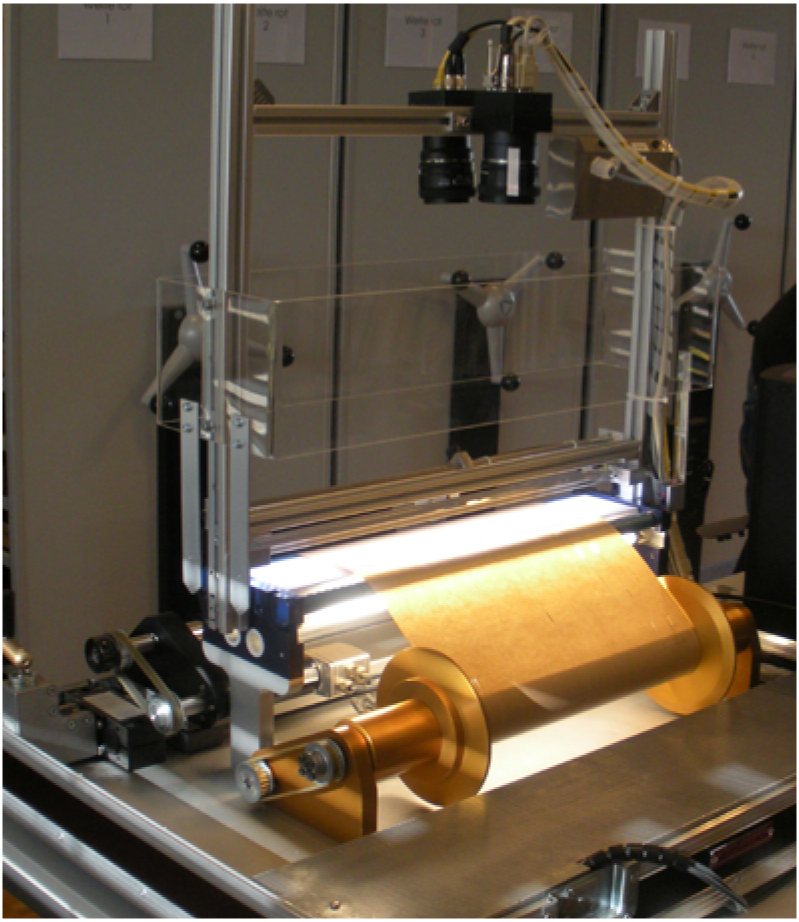

Fig. 14 The first scanner of Berner Fachhochschule.

HKB Interpretation Institute (Martin Skamletz, Manuel Bärtsch) initiated the development of the second generation of the scanner. This development was carried out by Michael Moll, engineering assistant at BFH-TI (Berner Fachhochschule, Technik und Informatik) and Daniel Debrunner. The second-generation scanner system has been operational since 2025. Its main additional features apart from technology upgrade are: interactive scan speed (down to zero) during scanning in case of bad rolls, automatic rewinding after scanning, reverse side scanning if needed, improved transportability, and full-length roll images using the JPEG2000 family of file formats.[59]

59 Daniel Debrunner's email, 17th May 2025.

The first Bern scanner has been loaned since 2021 to Marc Widuch, owner of Faszination Pianola (shop for golden era/self-playing pianos and rolls) and DMP (Daniel Heil's and Marc Widuch's Pianolarolls; digitisation and production of pianola rolls) near Munich,[60] initiator and organiser of the Global Piano Roll Meeting Conferences, a format that will be discussed in more detail below. Widuch uses the Bern scanner to digitise piano rolls for many private individuals and institutions. These include the Department of Musicology/Sound Studies at Bonn University with its project "Synkopierung und Volumen. Sondierungen einer sonischen Moderne, 1890–1945" (Syncopation and Volume. Probing Sonic Modernity, 1890–1945), which ran until 2025. Part of the project was a database containing images of the scanned rolls as well as MIDI files and emulated sound files – again by Peter Phillips – which is currently not available online.[61] The rolls are owned by the Deutsches Musikarchiv der Deutschen Nationalbibliothek (German Music Archive of the German National Library) in Leipzig and by private individuals. Another project currently being carried out by Marc Widuch with the Bern scanner is the digitisation of the unique collection of c. 950 Philipps DUCARTIST rolls held at the department of musicology at Goethe-Universität in Frankfurt am Main.[62]

Over the past few years, Marc Widuch has amassed an immense collection of data from scanned piano rolls, which he plans to make accessible to the public in the future. When asked, he explained: "We are currently talking to the Deutsche Nationalbibliothek and other institutions about archiving all the roll data in a central location and making it accessible (for non-commercial purposes). We currently share the data with the HKB and Peter Phillips, with whom we are working on the digitisation of the piano rolls. We have been responding to individual requests for digitised material for research projects for some time. A complete database of the thousands of scans is under construction. Until that is complete, we are working with internal work lists."[63] Daniel Heil and Marc Widuch are pursuing an ambitious plan with their company DMP, which they named in an article for the German magazine *Das Mechanische Musikinstrument* 2022: "Our goal, in collaboration with others, is to establish an online database that contains all titles ever issued, and more importantly, allows easy access to all piano roll titles still preserved today. Here, 'access' means the availability of all relevant roll information, listenability of audio files, and usability of digitised data (image data, etc.) for research and scholarship, for example."[64] An extremely daunting task, but its successful implementation would represent a real milestone for the preservation of piano rolls!

60 https://www.faszinationpianola.de/and https://pianolarollen.de/

61 https://sonic-modernity.net/2022/10/21/datenbank/, accessed 3rd January 2026.

62 Thomas Betzwieser's email, 10th January 2024.

63 Marc Widuch's email, 15th May 2023.

64 Widuch, "Wiederentdeckung," 67. Translation of the German original by J.K.

The SISAR project by AMMILAB and the Università degli studi di Pavia

In 2013, a few years after the completion of the first Bern scanner, the Department of Musicology and Cultural Heritage at the Università degli studi di Pavia (UniPV, University of Pavia) produced a scanner for piano rolls, also equipped with a black and white line scan camera (Fig. 15). It was developed by the staff of AMMILAB, the laboratory of the Italian Mechanical Music Association, without any prior knowledge from other sources. Within the framework of the SISAR project (Sistema integrato – Scannerizzazione – Ascolto – Registrazione / Integrated system – scanning – listening – alignment), Flavio Pedrazzini, Niccolò Perego and Matteo Malosio developed various devices for scanning music storage media between 2009 and 2013, such as a Pinned Barrel Scanner (PBS) to scan music of pinned storage media for instruments such as barrel pianos and barrel organs, including helicoidal barrels, as well as a Cardboard Scanner 2.0 and two scanners for rolls of self-playing pianos.[65]

Fig. 15 The "Sala rulli" in the Musicology Institute of the University of Pavia, based in Cremona. On the left an Aeolian Pianola, on the right the first piano roll scanner of AMMILAB. In the background, piano rolls from the Italian company F.I.R.S.T. from the institute's collection.

65 https://sites.google.com/view/ammi-lab/projects/sisar. A description of the project can also be found in Perretti, Perego and Pedrazzini, "'SISAR' Project."

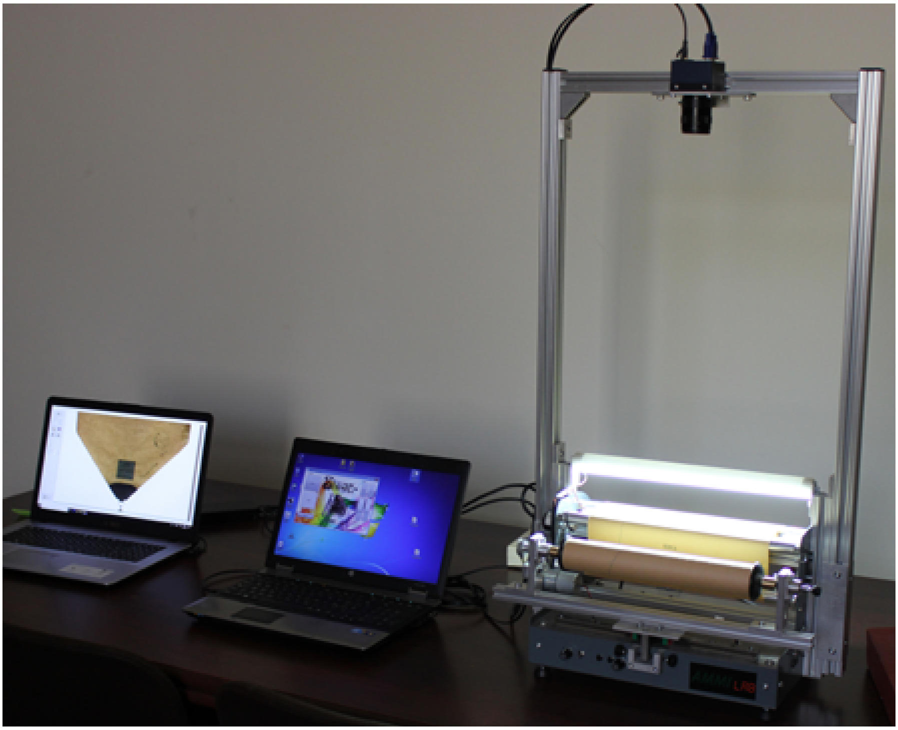

Fig. 16 The piano roll scanner 2.0 of AMMILAB in 2019.

The second, revised piano roll scanner 2.0, which is equipped with a colour camera, went into operation in 2019 and is described in detail on the webpage of the project (Fig. 16).[66] It is used by Prof. Pietro Zappalà of the University of Pavia , which has a stock of about 10 000 piano rolls, 10 % of which are reproducing rolls (mainly Duo-Art) and 90 % rolls for player pianos.[67]

To date, Zappalà has scanned over 1700 piano rolls, mostly for player pianos. Unfortunately, the university's server does not have sufficient storage space to upload the images of these scans to the internet, but they are made available on request. Thus, only the sound files generated by the scans are available on the university's website.[68]

66 https://sites.google.com/view/ammi-lab/projects/sisar/piano-roll-scanner-2-0, accessed 6th August 2025.

67 Provisional overview lists of the holdings can be viewed on the website and are updated approximately every six months: Zappalà, "Catalogo compositore", "Catalogo marca" and "Catalogo donatore."

68 Currently under construction, in future it will be: https://pianorolls.unipv.it/ An overview of the F.I.R.S.T. rolls of the University of Pavia can also be found on the website of the Musikinstrumentenmuseum der Universität Leipzig: https://musixplora.de/catalogus/search/?mxp=5001940&selected=5001940, accessed 18th July 2025.

The sound files available there are produced in a two-step process: When scanned, all information stored via the perforations, i.e. sound duration, pitch, pedal and – in the case of Aeolian Themodist rolls – small perforations that emphasise individual notes, are automatically recorded. As Zappalà explains, the (mostly dotted) line graphically applied to the rolls concerning dynamics is then added manually in a subsequent processing step with the help of software. This software, which was developed by AMMILAB, processes the manually stored information and implements it in the MIDI file. Similarly, the basic tempo of the roll and possible intervening tempo changes, both expressed via numeric values, are also manually added and then processed by the software. By contrast, the Metrostyle, another graphic line introduced by Aeolian to guide performance phrasing through subtle tempo variations, is not considered by the software. Zappalà describes his procedure as follows: "First and foremost, I want to copy the parameters I see on the roll. I do without personal interpretation, but strictly follow the instructions on the roll, although I know that the result is very flat and mechanical, like when you just step on the pedal and don't operate a lever. Which means that pitch, dynamic and basic tempo are correctly rendered, whereas minor tempo changes inspired by fermatas or 'accelerando', or 'ritardando' or the like are not performed."[69]

Thus, the sound files produced in this way at least give an impression of the pieces and enable the music stored on the rolls of the collection to be listened to. This would otherwise not be possible as the institute only owns one functioning player piano on which not all rolls can be played. Zappalà emphasises that the primary goal of digitising for him and his colleagues is to preserve the images and the code stored on the rolls, and not to produce flawless music, which – as mentioned before – is a difficult task, especially in the case of the rolls for player pianos. This difficulty is also evidenced by the research projects of doctoral student Pierluigi Bontempi and bachelor student Federico Frontini at the Centro di Sonologia Computazionale (CSC) of the Università degli studi di Padova (University of Padua), who worked together with Pietro Zappalà on the further development of the software used for the MIDI conversion of the scans. This was intended to automate the previously manual processes and thus achieve better results, but has not yielded any practical output.[70]

Digitising Piano Rolls at the Universitat Autònoma de Barcelona

Another piano roll scanner was developed for the Arts and Musicology Department of the Universitat Autònoma de Barcelona (UAB, Autonomous University of Barcelona) by the Barcelona-based Computer Vision Centre and presented in 2015.[71] This device was then used to digitise about 5000 rolls, most of which came from the Biblioteca nacional de España (Spanish National Library) and the Museu de la Música de Barcelona (Music

69 Conversation with Pietro Zappalà, 15th March 2023. See also: Frontini, "Enhancement".

70 Pierluigi Bontempi's emails, 14th April and 23rd May 2023. Pietro Zappalà's email, 9th July 2025.

71 https://www.youtube.com/watch?v=vmTryKCM_e8, accessed 25th June 2025.

Museum of Barcelona), except for a small number of rolls owned by the UAB (about 150).[72] Until recently, over 3500 of the results obtained could be viewed on the website of the Biblioteca digital hispánica (Hispanic Digital Library) of the Spanish National Library, however, they have since been removed. It could be seen from the pictures uploaded there that these were compiled from a series of still images – taken by a still image digital camera and not a line scan camera – that had been stitched together, a process that has proved inadequate in the past, as it is impossible to produce flawless transitions of the individual images. In addition, sound files of the rolls were also available on the website, however, these only played back the pitch and duration of the pieces. The scanning and data conversion process used did not allow the expression data stored on the rolls to be reproduced musically, as Jordi Roquer from the Department of Art and Musicology at the UAB explained – a problem already known about from the scenarios mentioned above. It can be assumed that dissatisfaction with the image and sound results achieved was the impetus for removing the files from the internet. According to their own statement, the staff of the Arts and Musicology Department plan to revise the output and present the results of this improvement in the near future. For this purpose, it is planned to build a new scanner based on Anthony Robinson's system.

The SUPRA and the Pianolatron Projects of Stanford University Libraries

Without doubt, the most impressive online presentation of a piano roll digitising project is provided by the Stanford University Libraries – containing more than 16 000 rolls – with its SUPRA (Stanford University Piano Roll Archive) website launched in 2019.[73] The project was preceded by a preparatory phase lasting several years, during which a scanner was developed. The then Head of the Music Library Jerry McBride sought inspiration for this from the aforementioned members of AMMILAB as well as from various experts previously spoken of. Stanford Libraries reported on the progress of the scanner's development in a blog that existed when work on this article began, but is no longer online. As could be seen from these blog entries, Monica Caravias, a graduate student at the Stanford Product Realization Lab, worked on the development of the scanner in collaboration with Anthony Robinson from 2015 onwards. In 2016, the scanner was built by the San Francisco-based company Swope Design Solutions and was then finalised by a team led by then Adjunct Professor of Music Craig Sapp[74] in spring 2018 (Fig. 17).

72 All information on the Spanish scanning project comes from an email by Jordi Roquer of the Arts and Musicology Department of the Autonomous University of Barcelona, 23rd February 2023.

73 https://supra.stanford.edu/

74 Craip Sapp runs the following informative website with various references that are also of interest in this context: http://pianoroll.sapp.org/

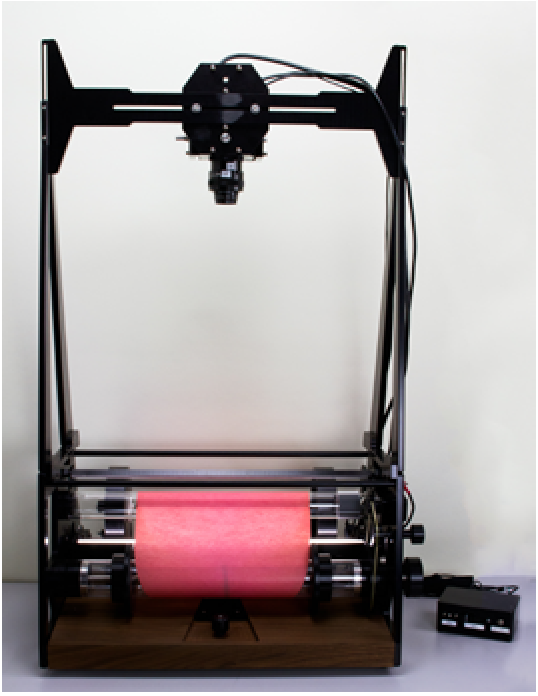

Fig. 17 The piano roll scanner of Stanford University Libraries.

In their first major scanning project, 456 Welte-Mignon T-100 rolls were digitised, achieving the following file formats:

a) Archival TIFF image at 300 DPI (dots per inch) and 24-bit color.
b) JPEG files derived from the archival TIFF.
c) Uncompressed grayscale TIFF file (that utilizes the green color channel of the original scan) allowing efficient access to high resolution detail of the holes.
d) Raw MIDI file that captures all hole data extracted from the grayscale TIFF file.
e) Expressive MIDI file that merges multiple holes into single musical notes, applies emulation algorithms to control for individual note dynamics, and adds pedaling. Metadata such as title and composer is also added to this file.
f) Audio files (WAV and M4A) rendered by running the expressive MIDI file through the Ivory Keys II software synthesizer.[75]

75 Shi and Sapp and Arul and McBride and Smith, "SUPRA," 518. See also the earlier publication on previous experiments of digitising and emulation piano rolls at Stanford: Shi and Arul and Smith, "Modeling".

Some of these file formats, as well as extensive documentary information on each individual roll, are available on the above-mentioned website. There is a tab for further, highly complex details on the production of the retrievable data, and the open source software "roll-image-perser" written by Craig Sapp to extract all holes on the roll to a "raw" MIDI file, as well as the emulation software "midi2exp" programmed by Shi Zhengshan (Kitty), PhD student at the Center for Computer Research in Music and Acoustics of Stanford University, can be downloaded from the site.[76] As for image files, very large ones are available on the central SUPRA webpage, which takes a lot of time to download/save.[77] Small image files, though not of all rolls, can be found on a second webpage.[78]

Stanford University Libraries is the only institution that makes the data of the rolls they digitise available to all interested parties, thus allowing for their more precise appraisal and evaluation. The SUPRA project has attracted a great deal of attention, but at the same time has also received a certain amount of criticism from the aforementioned experts in the field.[79] Among the critics are Peter Phillips, Anthony Robinson and Wayne Stahnke, who advised the project with varying degrees of intensity and criticise what they see as insufficient consideration of their knowledge and suggestions resulting from many years of work on the subject. The criticism refers, for example, to the quality of the images, which in many cases show very strong shifts and drifts that occurred during scanning. The Stanford team took the trouble to document and show all these errors on a separate page.[80] The emulation developed by Stanford is also the target of the experts' criticism. Phillips, for example, says that the emulation algorithms are not accurate enough and deliver dynamic values that don't always do justice to the sound of the rolls on a well-adjusted Welte-Mignon.[81] Robinson also confirms the "too simplistic approach"[82] of the developed algorithms for emulation.

The criticism expressed is known to the staff at Stanford and is also partly acknowledged, which has led to a reengineering of the scanner that is currently taking place. It may be the apparent problems of the digitising process or the fact that institutions like Stanford often do not have the spare capacity to permanently undertake digitisations – in any case, no further piano roll files have been uploaded since the SUPRA project page was published in 2019. However, the fact that Stanford continues to work on the emulation of piano rolls is also evident from the presentation by Peter Broadwell, the manager and technical lead of AI Modeling & Inference in Research Data Services at Stanford

76 https://github.com/pianoroll/roll-image-parser and https://github.com/pianoroll/midi2exp

77 https://supra.stanford.edu/

78 https://exhibits.stanford.edu/supra/browse/all-exhibit-items, accessed 25th June 2025.

79 See Chase, "Stanford," probably the only publicly voiced criticisms; the others are mostly more under the radar.

80 https://supra.stanford.edu/shifts/, accessed 6th August 2025. In addition, there are reports on the following page for each individual roll, some of which also show extreme shifts and drifts: https://supra.stanford.edu/stats/, accessed 25th June 2025.

81 Peter Phillips' email, 26th May 2023.

82 Conversation with Anthony Robinson, 26th May 2023.

University, at the 3rd Global Piano Roll meeting in Sydney.[83] The team around Kumaran Arul of the Department of Music at Stanford University is currently working on a new project, Pianolatron, which will attempt to enable the player interactions necessary in the context of player pianos through a virtual user interface.[84]

Digitisation at the Musikinstrumentenmuseum der Universität Leipzig

Among the institutions involved in the digitisation of piano rolls, the Musikinstrumentenmuseum der Universität Leipzig (MIMUL, Musical Instrument Museum at the University of Leipzig) also plays an important role. The "Digital Organology" research unit, established in 2021, is intensively dedicated to the digital indexing of various phenomena from the field of musical instruments.[85] This includes piano rolls, of which the museum owns over 3300.[86] In the context of the research project "Tasten" (Piano keys), held from 2018 to 2020, 2397 of these rolls were scanned, with an external service provider producing the scans using a line scan camera, as the museum did not have its own. The data uploaded so far can be viewed on the website musiXplora.[87] These are thumbnails of the rolls. As in other cases mentioned above, the museum does not have sufficient storage capacity to make the high-resolution image files available online, although they are made available on request for research purposes. The webpage of the "Tasten" project also contains about 300 sound files, which are not emulations but rather recordings of the museum's Tri-Phonola grand piano.[88] In the follow-up project "DISKOS"[89] from 2021 to 2023, a program was developed that generated MIDI data from the previously acquired image data. It focused on the various formats of the Hupfeld rolls, which make up the largest part of the Leipzig collection. The almost 1650 MIDI data files obtained in this way are available for download on the musiXplora website. Likewise, the website also makes so-called "auralisates" available, a term introduced by MIMUL to describe audio files that were created from the MIDI files, employing an instrument sample for the audio-conversion rather than the audio of the originally intended player piano.[90] The program developed by the team of the "DISKOS" project is also freely accessible on the internet.[91]

83 https://www.youtube.com/watch?v=fglZYgQTwTs&list=PLSFHNq95NCPlErgq9bFIes-OtJsfT22F0&index=8, accessed 25th June 2025.

84 https://pianolatron.stanford.edu/ and the presentation of the project at the 2nd Global Piano Roll Meeting 2022 in Bern https://www.youtube.com/watch?v=6ocKj8khWmo&list=PL5J-BZoNMhGIfDv8Vp6B9za4BeJnbWcD&index=11 and the 3rd Global Piano Roll Meeting 2024 in Sydney https://www.youtube.com/watch?v=fglZYgQTwTs&list=PLSFHNq95NCPlErgq9bFIes-OtJsfT22F0&index=8, accessed 25th June 2025.

85 https://organology.uni-leipzig.de/ accessed 25th June 2025.

86 All roll types owned by the MIMUL are listed on the musiXplora museum website: https://musixplora.de/res/search/?simple=Notenrolle&selected=2002522, accessed 18th July 2025.

87 https://musixplora.de/mxp/5060001 to https://musixplora.de/mxp/5060850, accessed 25th June 2025.

88 Heike Fricke's email, 5th June 2023. https://organology.uni-leipzig.de/index.php/forschung/tasten

89 https://organology.uni-leipzig.de/index.php/forschung/diskos

90 https://musixplora.de/catalogus/search/?simple=MIMUL%2520MIDI&selected=5501022, accessed 18th July 2025.

91 https://github.com/digital-organology/hmsm. An overview of the tested formats can be found here: https://github.com/digital-organology/hmsm/blob/main/docs/FORMATS.md, accessed 25th July 2025.

Forums for Exchange

An impressive testimony to the activities of people who have scanned many thousands of rolls since the early 2000s with CIS scanners – often home-made and varying in quality – can be found on the website of the International Association of Mechanical Music Preservationists (IAMMP), founded by Trachtman in 2001.[92] Julian Dyer writes about this association: "The aim of this group has been to focus and publicise scanning efforts worldwide, encouraging sharing of progress and knowledge, a radical shift from the earlier essentially private attempts."[93] On a subpage, a list of the scanned rolls can be seen as well as the names of the producers of the scans, many of whom have already been named:[94] Larry Doe, Julian Dyer, Michael Swanson and Warren Trachtman, as well as Maryland-based engineer Marshall Jose, and Terry Smythe in Winnipeg, Canada. This page also contains a large number of MIDI files, which, however, are generally not convincing in terms of accurate audio, as random samples have shown.

The Mechanical Music Digest portal, founded in 1995, has established itself as a further important forum for the exchange of ideas among people working in the field of piano rolls, as the countless contributions of many of the people mentioned here attest to.[95] The decisive impetus for the founding of this portal came from Terry Smythe,[96] a civil servant in charge of taxicabs for the city of Winnipeg. Smythe has contributed a great deal to the world of self-playing pianos over the years, including scanning more than 6000 piano rolls and making the thus gained CIS image files and the MIDI files generated from them accessible, which can be freely downloaded from the internet (Fig. 18).[97]

Fig. 18 Terry Smythe with his CIS scanner.

92 http://www.pianorollmusic.org/index.php

93 Dyer, "Perfect roll copying."

94 http://www.pianorollmusic.org/rolldatabase.php, accessed 25th June 2025.

95 See for instance the numerous contributions of Tim Baxter, Spencer Chase, Julian Dyer, Terry Smythe and others, which can be found via the author search https://www.mmdigest.com/Archives/Authors/index.html, accessed 25th June 2025.

96 Kravitz, "Automatic Music."

97 https://drive.google.com/u/0/uc?id=0B5IhVbYatt-XZVdIa2FzTGtrZzA&export=download&resourcekey=0-zGxwM4rOZPlOBaV4qTWZWQ. See also Smythe, "Free RollScan Files".

For a number of years, Smythe maintained a series of webpage resources related to automatic musical instruments and the digitisation of piano rolls, but these are no longer available. It is thanks to Michael Falco, the web manager of AMICA (the Automatic Musical Instrument Collectors' Association) who archived these pages, that, inspired by our exchange in the context of this publication, Smythe's web pages have been reconstructed on the AMICA website, thus making these important contributions accessible again.[98]

In recent years, the Global Piano Roll Meetings have established themselves as an important forum for exchange between institutions and private experts, which were initiated in 2018 by Marc Wilduch[99] – the originator of the idea – and Jerry McBride of Stanford Library. A first meeting in 2018 at the University of Leipzig was followed by the second and third conference in Bern/Seewen in 2022 and Sydney in 2024. The next meeting is planned for Stanford in 2026.[100] The conferences are preceded by regular virtual preludes, where participants exchange ideas in online meetings.

Production of New Piano Rolls

When it comes to the further processing and use of the image data obtained from the scanning of piano rolls, the topic of the production of new piano rolls should not be overlooked. We will therefore also take a brief look at this aspect here, although of the many people and companies involved in the re-punching and sale of piano rolls, only those who played a role in the research for this text will be mentioned.

Among those who use scan data for this purpose are Julian Dyer, who offers replica Duo-Art and 88-note Themodist rolls,[101] and Tim Baxter in Atlanta, Georgia, who sells reproducing rolls for Welte-Mignon Licensee, Welte-Mignon T-98, Ampico A & B, Duo-Art, and various player piano rolls through his online store Meliora Music Rolls, receiving the underlying scans from others.[102] In Germany, the music automaton collector and restorer Thomas Jansen, who lived in Monschau near Aachen and died in 2021, was for many years a leader in the production of new piano rolls.[103]

98 www.amica.org/RollScanning.htm

99 Widuch, "Convention."

100 https://www.hkb-interpretation.ch/global-piano-roll-meeting, accessed 6th August 2025. All contributions of the Bern and the Sydney conferences are available on YouTube: https://www.youtube.com/watch?v=VJewd6OBDy4&list=PL5J-BZoNMhGI-fDv8Vp6B9za4BeJnbWcD and https://youtube.com/playlist?list=PLSFHNq95NCPlErgq9bFIes-OtJsfT22F0&si=lgB3yuR5u0wMWXV7.

101 http://www.pianorolls.co.uk

102 http://www.melioramusicrolls.com/. See also Baxter's presentation at the 2nd Global Piano Roll Meeting 2022 in Bern: https://www.youtube.com/watch?v=vtVWWTzYvJg&list=PL5J-BZoNMhGI-fDv8Vp6B9za4BeJnbWcD&index=15, accessed 25th June 2025.

103 His collection of musical instruments and automata and piano rolls is now at the Musikmuseum Beeskow www.burg-beeskow.de/musikmuseum, accessed 25th June 2025.

More recently, Daniel Heil and Marc Widuch have joined forces to form the aforementioned DMP, which offers rolls for sale in all formats. Widuch explains: “Our punching machine works on the CNC principle and can punch all formats with different punching heads.”[104] They receive the image files used for this primarily from the scanner of the Berner Fachhochschule (Bern University of Applied Sciences) mentioned above. In addition, they use a pneumatic roll reader to produce their perforation data, which they developed themselves and which reads the perforation information pneumatically, converts it into digital information and generates MIDI data. For control purposes, the roll is filmed by a camera to make it easier to check for possible errors during transmission.[105] In addition to new piano rolls, DMP also offers digitisation of collections, roll restoration, and transcriptions (between formats) and new recordings (for pianists, or of sheet music).

The aforementioned company Euterpe Rolls in Voorhout specialises in the reproduction of Welte-Mignon T-100 rolls.[106] It has developed its own scanner, for which Anthony Robinson provided the image acquisition software. With this system, the original rolls are digitised and, after further processing steps, copies are punched by a perforation machine that was also developed in-house. The company also claims to have developed software to produce a roll from an existing MIDI file of piano pieces. They describe the process as follows: “We hire a pianist and play a piano piece on our recording grand piano. The piece is recorded in MIDI format. Using software we developed ourselves, the velocities are translated by an algorithm into holes that make the Welte play at the correct dynamic level.”[107] At present, it is even possible for them to create a roll from a clean audio-file containing only piano music. Euterpe Rolls is also experimenting with ways of transferring information from one roll system to another, for example converting a piece stored on a Welte-Mignon roll so that it can be played on an Ampico piano.[108] Furthermore, they make copies of Phonola, various Welte organ systems, Tri-Phonola rolls, Phonola rolls, Weber Unika, Pierre_Eich, Animatics-S, and standard 88-note rolls. All rolls with dynamics can easily be converted by them to the 88-note format.

104 Marc Widuch’s email, 15th May 2023.

105 https://pianolarollen.de/en/ and Marc Widuch’s email, 15th May 2023. Widuch also runs a company for the restoration and sale of (self-playing) pianos: https://www.faszinationpianola.de/#weglot_switcher, accessed 25th June 2025.

106 https://www.euterperolls.com/

107 Van Kruistum’s and Veel’s email, 11th May 2023.

108 A description of their approach can be seen here: https://www.youtube.com/watch?v=Y9k3Sl9kF7I, accessed 25th June 2025.

Conclusion

The initiatives taken over the last 50 years to digitise piano rolls testify to considerable progress in this field. As of today, the following results have been achieved:

a) The code and thus the music stored on the piano rolls is preserved.
b) The optical processes used today for this purpose produce high-quality images of the rolls, which reproduce information such as the perforation pattern, the colour of the paper, inscriptions on the roll, etc.
c) The conversion of the scanned data into digital musical data such as MIDI enables the audio reproduction of the music stored on the roll, independent of the instruments originally intended for it. Thus, the digital musical data can be transferred into any sampler sounds and then stored in audio formats such as MP3 and played back via computers. Alternatively, the digital musical data can be used to control modern self-playing pianos. However, it is still difficult to reproduce many of the musical parameters stored on the rolls satisfactorily, as explained in detail above.
d) Using the digital data, copies of the piano rolls can be punched, to be played on original instruments.
e) The data obtained in this way enables access to historical recordings and interpretations and can also help to identify pieces that cannot be assigned – due to missing inscriptions and low familiarity – by comparing them with other digital copies.

The fact that these results are available today is first and foremost thanks to numerous individuals who recognised the importance of piano rolls early on and sought ways to preserve this cultural asset and make it accessible. Only after some delay did institutions turn to the subject. Today, however, there is a consensus that piano rolls are a central source of music history that need to be conserved, made accessible and researched.

All that has been said so far about the history of piano roll digitisation and the current projects and initiatives is to be understood as documentation that aims to provide an overview and thus serve as orientation in this – at first glance – rather confusing field. However, an actual and objective evaluation of the different image and sound results achieved by the various processes mentioned is lacking and cannot be made in this article. To be able to do so, it would be necessary to obtain a relatively large number of the image and sound files of the respective persons and institutions and to compare them systematically in order to shed light on the respective strengths and weaknesses of the different approaches of image acquisition, conversion into MIDI and emulation. Such an elaborate investigation is not possible within the framework of this presentation, which is part of a time-limited research project, but would be highly desirable for future optimisation of the processes.

Whether and when further scanners will be built is questionable, as their production has proven to be a complex process that should not be underestimated, as has been shown. In any case, it would be a sensible approach to try not to reinvent the wheel every time, but to enter into an exchange with those who have already been active in this field, and to find out the known problems in advance and subsequently avoid them. It was one of the most surprising results of this research that projects were created without knowledge of or consultation with existing ones.

With regard to the further development of emulation software for reproducing rolls, it would also be advisable to enter into an exchange and evaluate the programs produced thus far. Most experts agree that there is still room for improvement in this area. Many of them see the emulated sound results produced so far as mere aids to working with the rolls, which convey a sound impression and at best approximate the sound of a real self-playing piano, but can hardly reproduce it completely.

Regarding the rolls for player pianos, it seems even more urgent to give more attention to them than has been the case hitherto. Among both private professionals and institutions, the main interest has been in the rolls for reproducing pianos, on which the supposedly more important musical heritage has survived, since great pianists and composers recorded on them. In fact, however, the rolls for player pianos prove to be an equally important source not only from a musical but also from a cultural-sociological point of view, since they had a much wider distribution and provide information about the musical taste of broad sections of the population at the beginning of the 20th century. The problem of an audibly convincing reproduction of the music stored on these rolls by computer software urgently needs clarification. This is because the lack of devices or software that could enable the musical interpretation of a pianolist on the computer has so far made it impossible to fully exploit the acoustic potential of the rolls.

In 2006, Rex Lawson made a visionary proposal at the IAML (International Association of Music Libraries) conference in Gothenburg: "I'd like to suggest [...] an international listing of such holdings [collections of piano rolls held by institutions, J.K.]. This is not to suggest a series of detailed catalogues, at least not yet. But a rough description of the types and quantity of rolls that you have, published in an international format, would begin to make sense of this resource."[109]

A lot has happened in this respect since then, as a considerable number of online piano roll catalogues have been created in recent years. The digitisation of piano rolls in the sense of digital indexing of data is therefore well advanced. And the digitisation of piano rolls, as defined here, i.e. the scanning and processing of scans with the aim of digital audio reproduction, has also made significant progress. One goal should now be to continue this process and to gradually solve the problems that still exist in this context. Another desirable aim would be the creation of an international piano roll portal that would make the digital data accessible, in addition to the information on the preserved rolls. This would be a real gain for all those who have set themselves the goal of maintaining this important music-historical resource in the future.

109 Lawson, "Librarians," 359.

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An Introduction to Piano Roll Scanning

Anthony Robinson

Abstract

The rise in popularity of the player piano coincided with the Roaring Twenties, a period of optimism and prosperity following World War 1, producing an outpouring of joyful music. Now, 100 years later, the rolls are fast deteriorating and very few player pianos remain that are capable of playing the rolls. However, with the aid of roll scanning and modern digital techniques, the music can live on to be rediscovered by future generations. This article discusses techniques for scanning the rolls and their subsequent interpretation in order to reproduce the music.

Introduction

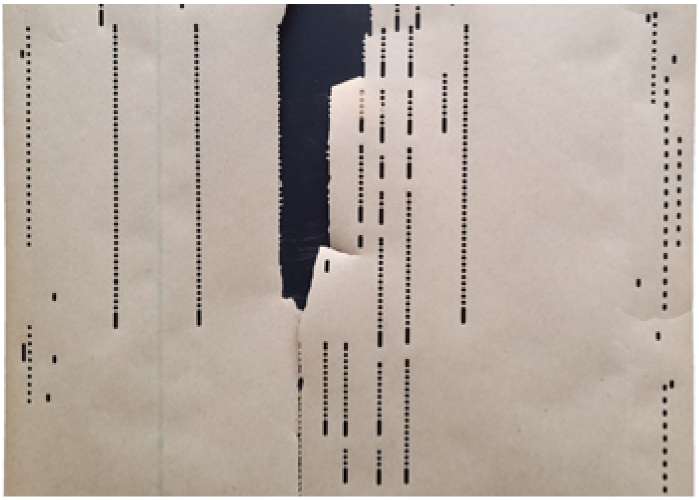

Fig. 1 This roll has become so brittle that it is now fast disintegrating.

Many of the 100-year-old rolls are now very brittle, particularly those made from acidic paper. Some, like this one, are already too far gone to be rescued (Fig. 1). The race is therefore on to preserve the rolls before it is too late. Meanwhile, the number of player pianos still capable of delivering a satisfactory rendition of the rolls is also dwindling. Scanning the rolls allows the historic recordings to live on and to reach a wider audience, with the scans being used either to play the music on modern digital pianos or to produce modern copies of the rolls on new paper.

There are two distinct stages involved in roll scanning: the first involves producing a digital image of the roll; the second involves processing the scans. These two stages need not take place at the same time and, indeed, techniques for processing the scans are likely to improve over time so that the scans can then be revisited.

Scanning the Rolls

Essentially, the roll is spooled through a custom-built scanning device to produce a digital representation of the roll (Fig. 2, 3). Various methods have been tried, but the most effective and accurate so far has proved to be optical scanning which produces a photographic image of the roll. A light source is placed behind the roll so that the holes appear white, while another light source may be placed in front of the roll to capture any printing on the roll or other important details such as damage or repair work that might be obscuring the holes. If the lighting balance is set with the paper at around mid-intensity then everything can be captured in a single pass, and the image contrast can later be manipulated either to extract just the notes or to enhance the printed image. Image scanning is not restricted to the roll's normal playing speed and can be considerably faster.

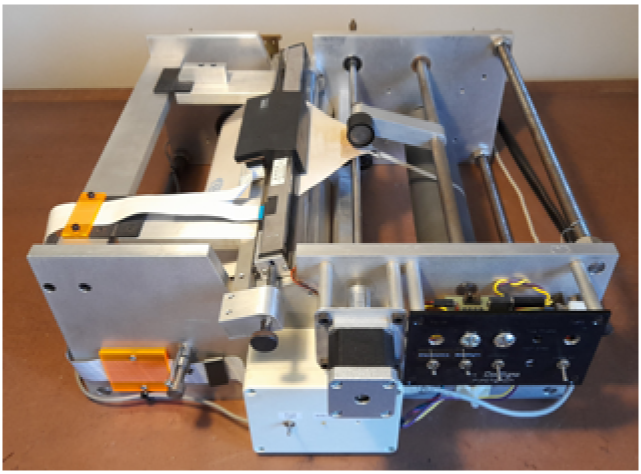

Fig. 2 A contact image sensor (CIS) based scanner. The scanner is shown sideways on, with the roll travelling from left to right, first wrapping around a toughened glass tube, underneath which is the backlight and above which is the CIS. The black housing above the CIS contains the inverter for the CCFL that provides the front lighting. The roll then passes over an 8mm diameter capstan connected directly to a stepper motor. Once loaded, a pinch roller is engaged that presses the roll firmly against the capstan. Finally, the roll winds onto the take-up spool. A thin band with a hook on the end, extending from the take-up spool, allows more of the roll's leader to be scanned. Not visible in the picture are two torque motors attached to the supply and take-up spools that provide appropriate roll tension for scanning and rewinding.

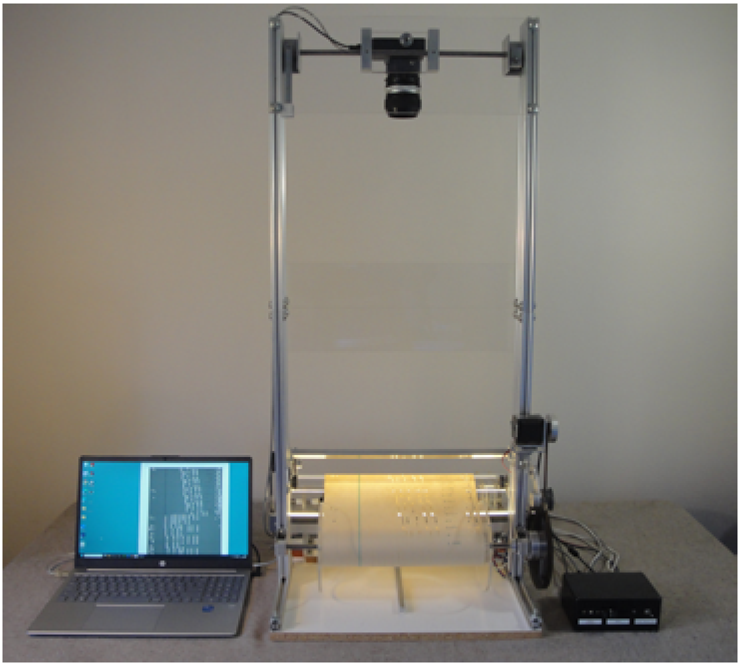

Fig. 3 Robinson's line scan camera scanner on which the Stanford scanner was based. The roll is pulled through the scanner by the take-up spool. It first wraps around a toughened glass tube mounted on axles which rotates with the roll. An encoder wheel resting on one end of the tube triggers scan lines at regular intervals along the roll. Below the tube is an LED backlight which shines through the tube to illuminate the holes. The roll is also lit from above by an LED strip mounted within an aluminium channel. The camera is mounted above the scanner, pointing downwards towards the lit area, with the camera's height set to achieve a horizontal resolution that matches the vertical resolution. The black box beside the scanner contains the control electronics, with a slider control allowing both the scanning and rewind speeds to be varied.

Image Sensors

The two types of image sensor commonly used are Contact Image Sensors and Line Scan Cameras.

Contact Image Sensors

Contact Image Sensor (CIS) modules house a row of sensors, a rod lens and a strip light (Fig. 4). They are usually found in flatbed scanners under the glass, just millimetres away from the object being scanned. One drawback is that the depth of focus is very narrow, so the rolls need to be carefully constrained as they pass through the scanning area. The scanned width is restricted to the width of the sensor array, with A3 modules catering for

Fig. 4 A contact image sensor. The white cold cathode fluorescent lamp (CCFL) and the rod lens are mounted within separate channels so that no direct light passes between them. A row of image sensors is mounted inside the sealed unit behind the rod lens.

anything up to standard 11¼ inch width rolls. The advantage of this fixed resolution and immunity from any lens distortion is that roll dimensions can be measured very accurately in the horizontal direction.

CIS modules suitable for roll scanning have mostly been salvaged from obsolete Mustek A3 flatbed scanners, though these are now becoming increasingly rare. Additionally, the rod lens in these modules was not always mounted straight, resulting in some bowing of the image, which can cause problems with punch matrix reconstruction. However, this particular model still has two main advantages: Firstly, it has a resolution of 300 DPI which is ideal for our purposes; modern CIS modules mostly have a far higher resolution. Secondly, we have the manufacturer's data sheet for it, which in itself is no mean feat.

Fig. 5 Line scan camera.

Line Scan Cameras

Line scan cameras are more like conventional film cameras, with the object placed at some distance from the camera and focussed onto a sensor by a lens (Fig. 5). The scanned width may be adjusted by moving and refocusing the camera, so wider rolls can be accommodated if needs be. Line scans are initiated by means of an external trigger.

In both cases, individual one-dimensional scan lines are triggered at regular intervals along the roll, building up a two-dimensional image. The distance travelled between one scan line and the next determines the scanner's **vertical resolution** which is typically measured in scan lines per inch. The image may be either full colour or greyscale. While colour images are undoubtedly more attractive, greyscale images contain all the important details and the resulting files are significantly smaller. The choice will ultimately depend on the budget and the intended use of the scans.

Roll Transport

Rolls may be pulled through the scanner either by a capstan or by a driven take-up spool.

A **capstan** driven by a stepper motor allows the roll to be pulled through at a steady rate which, combined with a steady scanning rate, ensures that the scan's vertical resolution remains constant. Many roll scanners adopt the simple approach of advancing one step per scan line, but this is neither necessary nor desirable. Rolls should ideally advance in a continuous smooth movement rather than as a series of discrete steps. Fortunately, this mostly happens anyway due to inertia, but micro-stepping can improve matters still further. With rolls now considered to be moving smoothly, the need to match scan and step rates no longer exists, and – by merely adjusting this ratio without changing the existing gearing – the scanner's vertical resolution may be set to match its horizontal resolution, making the image's aspect ratio correct.

With a **take-up spool** drive, the speed of the roll is less well defined, making it necessary to measure regular intervals along the length of the roll with an encoder wheel. **Line scan cameras** can be triggered by the encoder wheel pulses at varying speeds while still maintaining a constant exposure time, allowing fragile rolls to be scanned more slowly. **CIS scanners** do not include this level of sophistication, and the line scan rate must remain steady in order to maintain a consistent exposure time, while the roll speed is liable to vary. Interpolation is then needed to equalise the number of scan lines over a given roll length, however some image degradation is inevitable.

Image File Formats

CIS based scanners built by private individuals have mostly adopted the proprietary **CIS file format** devised by Richard Stibbons. Though easy to implement, it can only store binary black and white images; all the greyscale information is discarded and with it a great deal of valuable detail. It cannot therefore be recommended for future projects.

The industry standard **TIFF file format** embraces every conceivable image type from full colour downwards. It is well documented, widely supported, and is increasingly being adopted by the next generation of roll scanners. One particularly useful feature is the ability to specify the orientation of the displayed image as, contrary to the normal convention, most rolls need to be viewed from the bottom up, which would otherwise involve inverting the image in the file with the unfortunate consequence that the music would then be stored backwards.

Types of Roll

Rolls fall into two main categories: standard (88 note) rolls and reproducing rolls.

Standard (88 note) Rolls

The most common type of roll, just containing punched holes for the notes and perhaps a sustain pedal track. These rolls are often simple metronomic transcriptions of the score, with bars equally spaced throughout the roll. Depending on the type of music being played, a literal rendition of the roll – with no changes in tempo or dynamics – can sound excruciating. Some rolls include printed guidance as to the interpretation, while others do not. However, as with any pianist following a score, it is ultimately up to the pianolist to interpret the music as they see fit, using the pedals and hand controls to transform the mechanical representation into a human performance.

Song rolls also often include printed lyrics – the forerunner of modern-day karaoke machines. As most player systems scroll the rolls downwards, there is the added challenge of having to read the words backwards from bottom to top. The irony is that some rarer systems scroll in the normal reading direction, but few if any of these included printed lyrics.

In the early days, there were various incompatible standards, 65 note rolls being the most common, using 11¼ inch paper with the tracks spaced at six to the inch. After 1908, the now more familiar 88 note standard was adopted, again using 11¼ inch width paper but now with nine tracks to the inch spacing and a simpler clutch arrangement for mounting the rolls.

Reproducing Rolls

At the luxury end of the market were the rolls produced for reproducing pianos. These control the dynamics by means of extra perforations in the margins of the roll. The pianos normally included an electric pump so that they could, if one were to believe the publicity, reproduce the artists' original performances entirely unaided. In truth, none of the systems were physically capable of reproducing every nuance of an artist's performance, however with skilful editing they could produce a close approximation. There were numerous incompatible systems developed by different manufacturers, the most notable being Welte, Duo-Art and Ampico.

Roll Damage

In addition to the paper deteriorating with age, many rolls will by now have sustained some degree of damage through being played; typically most visible on the roll edges which become crumpled or folded over. As long as none of the holes are obscured, it should be possible to scan the rolls in this state; scanning is a far gentler process than playing them. However, if holes are obscured, then the roll will need some preliminary repair work.

Chaining

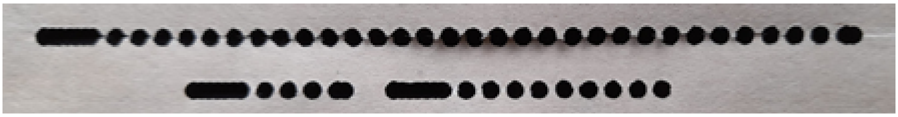

Fig. 6 Chaining with torn bridges.

Another area of vulnerability is the thin paper bridges between punches that are liable to tear (Fig. 6). These bridges, known as **chaining** or **webbing,** are often inserted into long slots to reinforce the rolls. The bridges are thin enough never to completely block the passage of air and so are effectively invisible to the tracker bar which perceives the chains as continuous slots.

MIDI (Musical Instrument Digital Interface)

A quick word about MIDI, which is a standard protocol for exchanging data in real time between instruments. Data is sent serially which inevitably means that no two events can ever be exactly coincident. The real-time constraint also makes it a slow means of communication. Serial MIDI is nevertheless well suited to the real-time playback of the music, but better alternatives exist for all the intermediate processes.

SMF (Standard MIDI Files)

Standard MIDI Files, by contrast, store MIDI data. The protocol is similar to serial MIDI but with the addition of timing data for each event, which provides two distinct advantages. Firstly, data exchange is not limited to real time and, secondly, the time difference between events can be zero, allowing for multiple simultaneous events. Standard MIDI Files are therefore well suited to storing all the intermediate processes outlined below.

Master Rolls

Most rolls were produced from master rolls, also known as stencils.

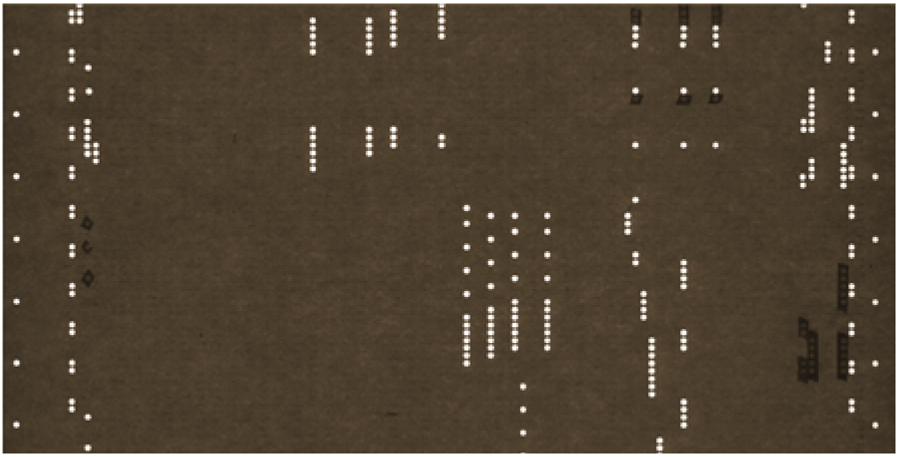

Fig. 7 Section of master for Ampico roll 68583, *Frühlingsstimmen*, by Johann Strauss, played by Alfred Grünfeld. This was a trial copy produced during the editing process, containing corrections.

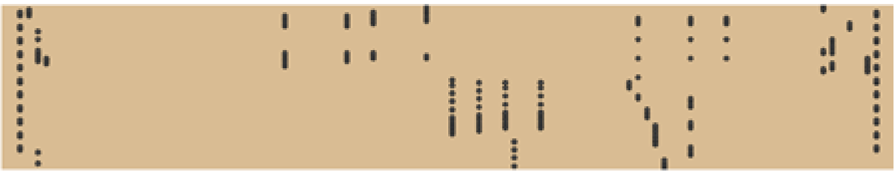

Fig. 8 The same section as it would appear in a production copy.

These masters contained the same punch patterns as the production rolls sold to the public, but spaced out over a considerably longer length into discrete, non-overlapping rows, allowing (in theory, at least) exact copies to be made using the technology available at the time (Fig. 7, 8). Made of cardboard or paper, with sprocket holes down the side, they were inevitably more bulky than the production rolls. Few of the masters still survive and those that do are now mostly very fragile.

Processing the Scans

The vast majority of rolls now available for scanning are therefore the production rolls. After the rolls have been scanned, the scans need to be suitably processed either to cut new rolls or to play the rolls electronically.

Raw Files

Production rolls contain exactly the same number of rows and columns of punches as the master rolls, however while the masters allow each punch row to be read in isolation, the rows here are more closely spaced to the extent that punches often overlap. While it is therefore still straightforward to sort punches into columns (tracks), sorting them into rows is more problematic and so no attempt is made to do so at this stage. Instead, the start and end coordinates of every note are recorded, including those for every individual punch in the chaining. Files in this form are often referred to as **Raw** or **Scan Image MIDI** files. Rolls may be re-cut from these files, although the copies will inevitably inherit any inaccuracies present in the original roll. Moreover, if the perforator runs at a different step rate from the original roll, timings will be further degraded by requantisation where the note timings are distorted to align with the new steps. This distortion can be reduced by using smaller steps but with consequently longer perforating times, and time is money, as the saying goes. Raw files still include the chaining and so are not yet suitable for playback.

Punch Matrix Reconstruction

The Holy Grail of roll scanning is to recreate the lost masters in electronic form from the production rolls, by assigning each punch to its correct row, even though the holes now often overlap one another, the rows may be slightly skewed, and the row spacing may not be entirely even. When performed accurately, it then becomes possible to produce roll copies with perfectly horizontal rows and evenly spaced steps that are potentially even more accurate than the original rolls. Often referred to as **Punch** or **Web** files, they can either be used to drive a perforator or further processed to produce playable MIDI files.

Two programs commonly used for punch matrix reconstruction are those by Wayne Stahnke and the late Warren Trachtman. The Trachtman software runs under Windows and is very alluring, but unfortunately not very accurate. The Stahnke software runs under MS-DOS and is more intimidating but produces far more accurate results, making it the clear winner.

Both programs work with **Raw** files, however this approach has a few limitations:

- The number of punches within a slot can only be estimated, even though the individual punches may be visible in the scanned image.
- There is no distinction between punches and tears in the roll.
- All rows within a slot are assumed to contain punches even where some are skipped. While this does not impair playback, the resulting punch pattern will not be entirely authentic.

A more sophisticated approach that should alleviate these problems might be to work directly with the image files and to detect punch shaped objects. Circle Hough Transforms,

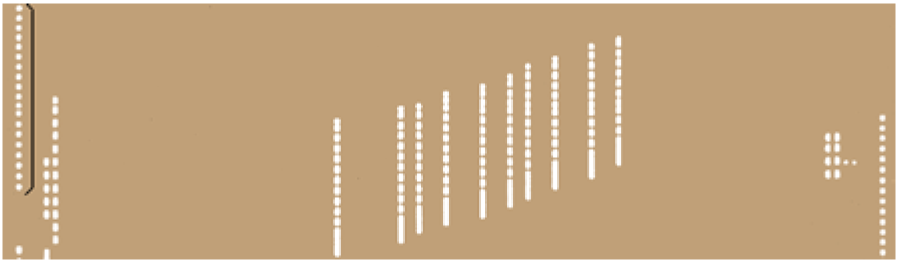

Fig. 9 Duo-Art roll with irregular row spacing. The punches in the sustain pedal track on the left should all be equally spaced. Similarly, the bridges in the note fields should all be of an equal size.

for instance, can detect the centres of circles, even if they are incomplete or imperfect. There are also alternative transforms for handling different shaped objects.

However, the row spacing in some rolls can be so erratic that any automated system will at times be fooled into adding or skipping rows; Duo-Art rolls are notorious for this (Fig. 9). At this point, a visual inspection is needed to track down and correct the errors. Unusual disruptions to the chaining pattern in the punch file may indicate row slips, and in the case of metrically arranged rolls, counting the number of rows per beat is another useful technique.

Not all rolls are suited to this treatment. Where punches were never aligned into rows in the first place (such as with early Red Welte rolls), or where the rows are too closely or too erratically spaced ever to be identified accurately, then this process is best avoided, as it is liable to make the situation worse rather than better.

Electronic Rolls

Not all the holes (ports) in tracker bars are necessarily in a straight line or the same size, and so the next stage involves offsetting and lengthening events in the raw or punch files to correspond with the periods when they would align with the tracker bar ports.

The bridges in the chaining never totally obscure the tracker bar ports and so these are stripped out at this stage to leave continuous slots. They are generally known as **E-Roll** or **Bar** files.

Any player pianos that have been retrofitted with solenoid valves may play files in this form as an alternative to playing the original rolls.

Emulation of the Reproducing Roll Dynamics

Reproducing pianos use the tracks down the sides of the roll to control the suction level and hence the velocities with which the hammers hit the strings, i.e. the note dynamics. An emulator's task is to mimic this process to produce comparable note velocities in the

MIDI file. All the reproducing piano manufacturers used their own incompatible systems, with each needing a different approach to emulation. A number of attempts have been made at emulation, some more successful than others.

Acceleration

With the paper being pulled through the piano by the take-up spool, the speed of the paper inevitably increases as the roll builds up on it. The degree of acceleration depends on the diameter of the spool, but also on the tendency for wind motors to slow down under load, whereas electric motor drives maintain a reasonably constant speed. However, the acceleration characteristics of the roll may not match those of the piano. Some rolls provided an appropriate level of compensation to maintain a steady music tempo; some provided an inappropriate level of compensation, while many provided none whatsoever, resulting in a steadily increasing music tempo. Ironically, the strict tempo dance rolls are amongst the worst offenders for this.

It is not always possible to predict which of these categories rolls will fall into. Player pianos do at least include a tempo control that can be nudged down if needs be. MIDI players are unlikely to include an equivalent tempo control so it is important that the MIDI files match the acceleration characteristics of the roll, and sometimes this may only become apparent after repeated listening.

Introducing acceleration into the MIDI file rather than at the scanning stage allows unlimited adjustments to be made without needing to rescan the roll each time. If it is implemented as a series of MIDI tempo changes, it can be repeatedly modified without progressively degrading the note timing accuracy.

Errors in Rolls

Although many rolls sustain damage during their lifetime, they may also have contained errors from the outset. Perforators were liable to malfunction and it is not unusual to find punches that were added manually by the manufacturers to make the rolls saleable. However, many errors still slipped through the net.

Examining the roll's punch matrix is a useful means of finding errors. Clear violations of the rules (such as excessively wide bridges) can be detected automatically, while other errors can be spotted by eye or, ultimately, by ear.

With metrically arranged rolls, a number of additional checks are possible. The musical beats will normally be a fixed number of punch rows apart with the chords lining up. It is quite common to find particular notes consistently starting or finishing a row or more late due to a perforator malfunction.

Different copies of a roll often contain different errors, and comparing their punch matrices will quickly reveal these differences. It is usually obvious which version is correct, allowing the final result to be an amalgamation of the best bits of each, and potentially a more accurate representation of the intended punch pattern than any of the original rolls. Further refinements can then be made as more copies of the roll become available.

Examples of Errors

Here are two copies of the same roll containing different errors, identified as follows:

1. Missing punches
2. Spurious punches introduced by the perforator
3. Punches added manually to fill the gaps left by missing punches

The first example is unusual in having vast numbers of missing punches that have somehow evaded quality checking. Normally, such rolls would have been patched up manually before being sold. Unlike regular punches, the manually added punches are often slightly misaligned.

Spurious punches are a common feature in Ampico rolls, thought to be caused by a slight misalignment of the master roll during the perforating process. Unless they fall at the start or end of a chain of holes, they don't affect the performance, but they do weaken the roll and so are best eliminated from the recreated punch matrix. (Fig. 10, 11)

Playing Reproducing Rolls on Modern Pianos

Re-cut rolls may be played on the original instruments. The emulated MIDI files may be played on digital synthesised pianos or modern solenoid operated pianos such as the Yamaha Disklavier.

Playing Standard 88 Note Rolls on Modern Pianos

The re-cut rolls may be played on the old player pianos, but beyond this there is a problem. Without the interpretation of a pianolist, the lack of any expression makes the rolls sound tedious. The dance rolls that were arranged for the player piano may be considered tolerable, but the classical rolls most definitely are not. It is possible to imagine a modern electronic equivalent to the pianola that allows pianolists to inject some musicality into the rolls, but as of yet no satisfactory contrivance appears to exist.

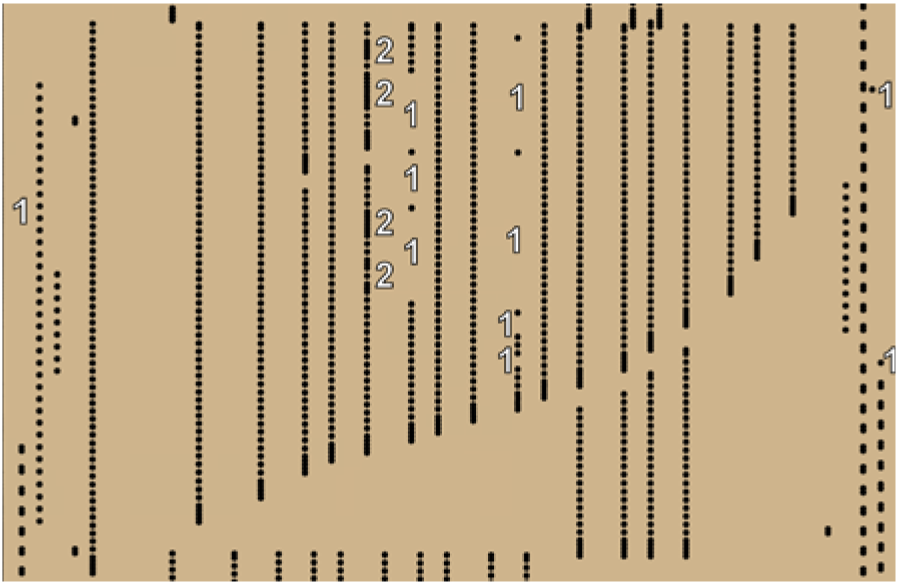

Fig. 10 Ampico roll 50715, *Reflets dans l'Eau* by Debussy, played by Leo Ornstein. First example with large numbers of missing punches.

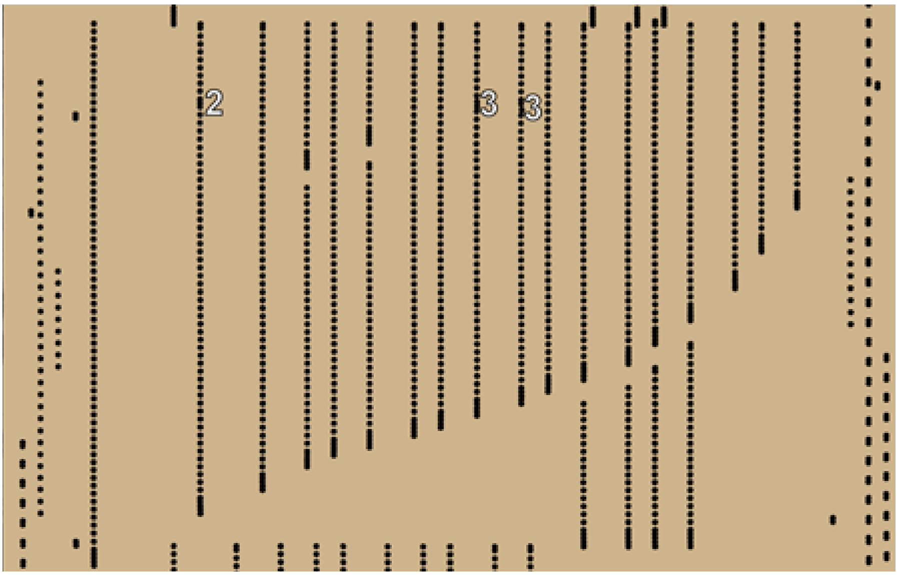

Fig. 11 Second copy of Ampico 50715 with fewer errors and in different places.

Emulating MIDI Files of Reproducing Piano Rolls for Playing on Contemporary MIDI Instruments

Peter Phillips

Abstract

The piano roll is an early form of a digital recording, in which perforations on a paper roll are control signals that are either on or off, or in digital terms, a 1 or a 0. It is, in effect, a MIDI file on paper. MIDI as a technology was introduced around 1983 and instruments that played music from a MIDI file soon followed. This chapter describes two ways of converting a paper roll to MIDI data, in which perforations in the roll are converted to MIDI notes. In the case of a reproducing piano roll, the expression perforations on this type of roll need to be processed to provide the information that determines how loudly notes should be played on a MIDI instrument. This process is called "emulation" and methods of achieving this are also described.

A reproducing piano roll is a form of recording on a paper roll that captures, in some way, all aspects of a performance of a live pianist. Ideally, a listener would be unable to tell the difference between hearing the roll played on a reproducing piano, or hearing the pianist who made the recording playing live. The accuracy of a reproducing piano roll recording is not considered in this discussion. Instead, we can say that these roll recordings have much to offer. A problem today is being able to play these rolls, as each brand of roll requires its brand of reproducing piano. The original instruments are now over 100 years old, and there are a declining number of these instruments that are in good playing condition. The rolls themselves are becoming more fragile as well. A solution to these problems is *emulation,* a process that converts a digitised version of a reproducing piano roll into a MIDI file that can be played on a contemporary MIDI mechanical piano such as a Disklavier, or a virtual piano.

Obtaining a MIDI File Suitable for Emulation

Today's self-playing pianos, either acoustic or virtual, generally operate from a MIDI signal. As pointed out elsewhere in this book, the relationship of hammer velocity and MIDI velocity is not standardised, although manufacturers such as Yamaha have established a widely used standard. In principle, this means a MIDI recording of a piano performance will have similar dynamics on instruments that conform to this accepted standard. The MIDI velocity values used in this chapter are applicable to Yamaha acoustic pianos and most virtual pianos.

Obtaining a MIDI file of a piano roll can be achieved with a pneumatic roll reader or with optical scanning. The most common method is optical scanning, in which an image of the entire roll is obtained by a camera or other optical means. Software then converts the image to a MIDI file, which I refer to as a *roll data* file. (Fig. 1)

Fig. 1 Roll scanner used by Stanford University. The scanner has a camera that takes a series of photos as the roll is fed past the camera. The result is an image file of the entire roll. A MIDI file is generated from the image by software.

A pneumatic roll reader (Fig. 2 and 3) is based on pneumatic player piano technology, in which the roll is played at its designated speed, passing over a tracker bar that suits that brand of roll. As it plays, pneumatic valves fitted with electronic sensors (Fig. 4) respond to the perforations, generating a signal that is fed into a MIDI encoder and recorded by a computer. In effect, the MIDI file is a replica of the pneumatic signals produced by the roll when played on its brand of reproducing piano. This type of MIDI file, which I refer to as an *e-roll* file, only needs the possible corrections described further on.

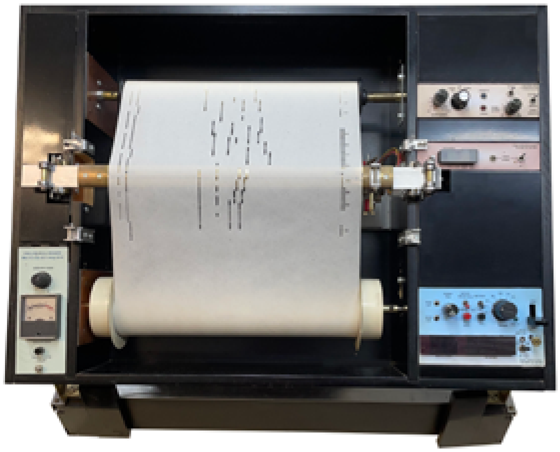

Fig. 2 and 3 Phillips' pneumatic roll reader, on the left without a roll, on the right set up to record Duo-Art rolls. The tracker bar is changed to suit the brand of roll. The reader has a precision roll drive motor, electronically controlled roll tracking system, braking and rewind motor. For Welte-Mignon rolls, the take-up spool is fitted to the top of the reader and the roll winds from the bottom. A small vacuum pump supplies suction to operate the electro-pneumatic sensors.

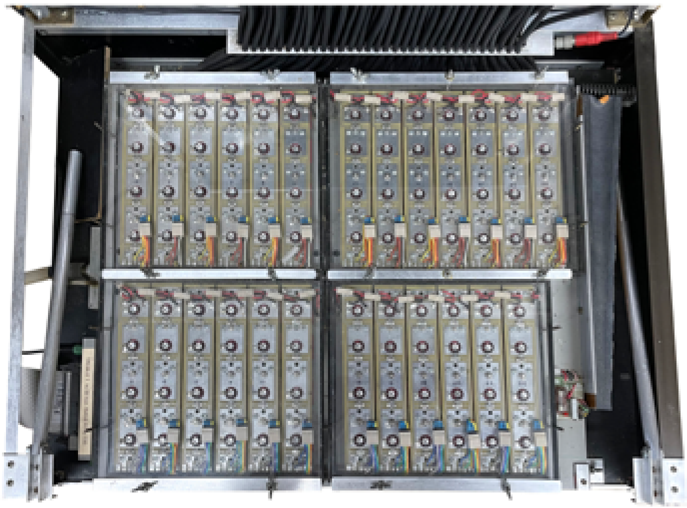

Fig. 4 The reader has 100 electro-pneumatic sensors that operate when a perforation in the roll uncovers a tracker bar hole, as in a pneumatic player piano. The sensors operate in the same way as pneumatic valves in a player piano, except a bipolar Hall effect device is triggered by a small magnet to produce an electric signal. The signals feed into a MIDI encoder and the MIDI output connects to a computer.

However, a roll data file from an optical scanner needs additional processing to account for paper acceleration and the effect of extending the playing time of all notes due to the perforations passing over holes in a tracker bar. This type of processing is further complicated by the design of some types of tracker bars. The simplest tracker bar is that found on Welte instruments, in which all holes in the bar are the same size and are positioned in a straight line. Other brands of reproducing piano have tracker bars with holes of different sizes, and in the case of the Duo-Art reproducing piano, holes that read expression perforations are offset to the holes that read playing notes.

In general, note lengths in a roll data file from an optical scanner must be extended to compensate for the travel time of a perforation across a tracker bar hole. Typically, notes are extended by between 20 and 30 milliseconds. It is also necessary to add acceleration to MIDI files derived from an optical scanner. The variables in the algorithm to calculate the required acceleration include the size of the take-up spool in the original recording apparatus. For Welte T-100 and Ampico files, the diameter of this spool is 67.5 mm. I also use this value with Duo-Art files, and 51 mm for Duca and Triphonola files. Other variables include the thickness of the roll paper, the paper length and the rotational speed of the take-up spool, which depends on the marked speed of the roll. I have determined by measurements that for most rolls the effective paper thickness is 0.086 mm. Paper length is often calculated by an optical roll scanner. The acceleration algorithm I use is given in the chapter by Wayne Stahnke titled “Seven Steps to Emulating a Reproducing Piano Roll Performance” in this book.

Preparing a MIDI File of a Roll for Emulation

The accuracy of the MIDI file of a piano roll, whether produced by a roll reader or an optical scanner, is affected by production errors in the roll and errors caused by the equipment producing the MIDI file of the roll. Together, these errors can cause incorrect note lengths and positions. A common problem is an insufficient gap between adjacent notes, preventing them from repeating correctly. As a guide, there should be a minimum gap between playing notes of 40 milliseconds. The minimum playing time of a note should also be around 40 milliseconds, depending on the instrument used to play the MIDI file.

Roll production errors include skew, in which the paper passing through a perforator is skewed to one side, resulting in notes on one side of the roll being out of alignment to notes on the other side. Roll reading or scanning can cause notes to no longer be aligned to their punch row, called scatter. If their combined effect results in an error of 10 milliseconds or less, the effect is inaudible. In general, timing errors of 20 milliseconds or less are inaudible to most people. In some cases, software routines can detect and fix timing errors due to skew and scatter. Short notes or short gaps between notes can be corrected with software, or manually using a MIDI editor program. A common error is the broken note, caused by a missing punch in a chain perforation due to a perforator problem. If not corrected, a broken MIDI note will repeat, rather than play once. Other changes to an e-roll MIDI file depend on the roll brand, as explained below.

The Principles of Emulation

The aim of an emulator is to create a MIDI file that sounds the same when played on a MIDI piano compared to the roll being played on a well-adjusted reproducing piano for that brand of roll. The most complex task is determining the playing volume of each note. This can be achieved in two ways: with analog electronic hardware modelling or software-based modelling of the pneumatic regulators[1] that control the playing volume in a reproducing piano. The author has used both methods, in which analog modelling provides a starting point for developing software models. The expression regulators are different in each brand of reproducing piano, so each brand of reproducing piano roll requires an emulator to suit.

The expression regulators in reproducing pianos all operate in accordance with two basic principles. The first is the *crescendo action*, in which the regulator causes the suction level to increase or decrease either quickly or slowly, as determined by expression perforations on the roll. The second method is the *step action*, in which the suction level changes from one level to another in discreet steps. The expression regulators in an Ampico operate with both crescendo and step action. The Duo-Art uses step action only (16 steps), the Welte, Hupfeld and Duca instruments use crescendo action only. A typical emulator develops a numerical value that represents the suction level at any one time as determined by the roll's expression perforations. Another function is to convert the pedal perforations to MIDI control codes. In all cases, pedals are either fully on, or fully off, as piano rolls do not record the position of a pedal.

An Example Emulator

Figure 5 shows the onscreen display of a software-based emulator called Rollmidi, developed by the author and software engineer David Gosden. It is used to emulate MIDI files of all types of Welte rolls (T-100, T-98 and Licensee) and Philipps Duca or Ducartist rolls. In principle, an e-roll MIDI file of a roll is loaded into the program and the emulated version is saved to disc. There are a range of adjustments achieved by on-screen sliders, shown in the centre of the image. Apart from the sliders under the Offset heading, the rest are adjustments found on a Welte reproducing piano.

The eight sliders on the right set the speeds of the slow and fast crescendo action, for bass and treble expression regulators. The settings for fast and slow crescendo as shown

1 Also called "expression regulators."

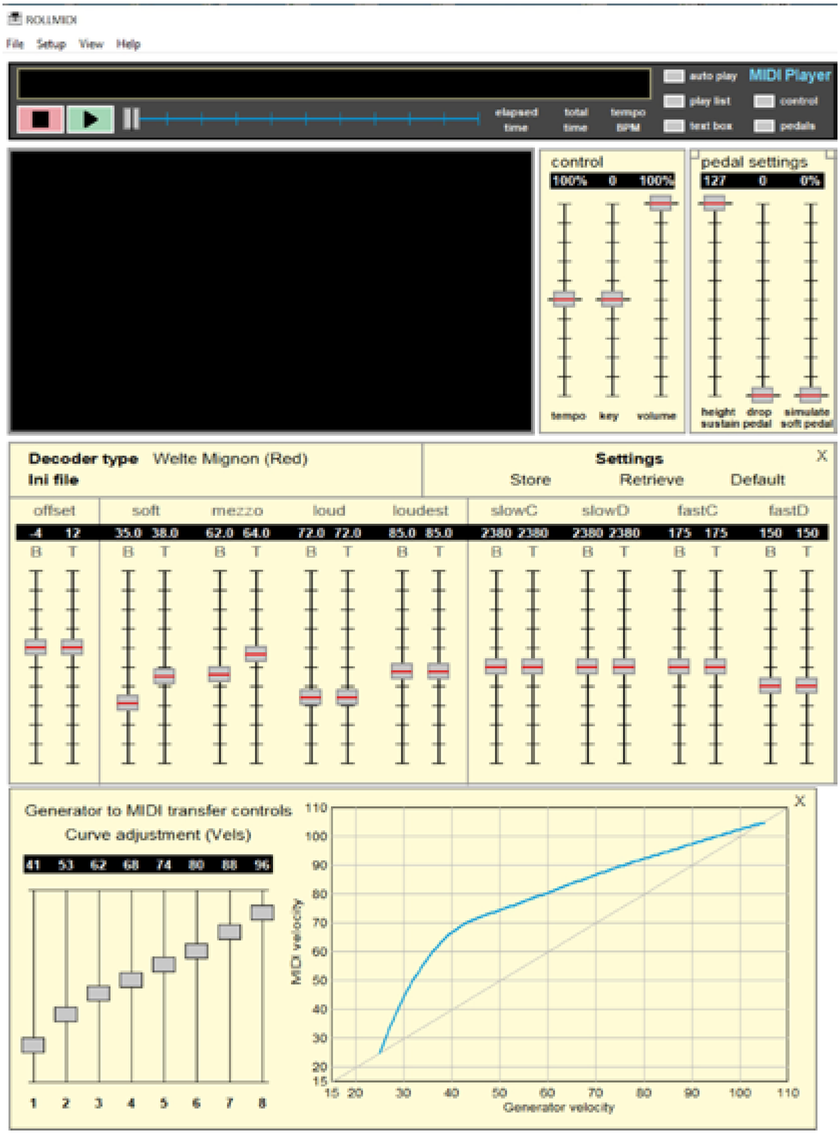

Fig. 5 Rollmidi, a program developed by Peter Phillips and David Gosden to emulate all types of Welte and Duca e-roll MIDI files.

in the image have been established using a MIDI file of a Welte test roll[2]. The soft, mezzo, loud and loudest dynamic levels are adjusted to suit the instrument the MIDI files will be played on. When set to emulate Duca rolls, a similar set of adjustments are displayed.

The six sliders at the top right of the image can be used with a standard MIDI file to adjust the tempo, key and volume. The pedal settings allow the travel distance of the damper pedal to be adjusted (for playing on a Disklavier), and the effect of a soft pedal can be simulated for files being played on mechanical pianos without a soft pedal actuator, such as the PianoDisc.

An emulator has the task of responding to the MIDI notes representing the expression perforations to produce a digital number between 1 and 127 that represents the suction level. This is achieved with a software algorithm referred to as a transfer curve. A typical range is MIDI 35 (softest playing) to MIDI 85 (loudest). The graph below the sliders shows the transfer curve used in the Rollmidi program. The relationship between MIDI and suction level is approximately logarithmic and in any reproducing piano, suction changes are linear as shown by the grey line below the *transfer curve*. The series of sliders to the left of the graph adjust the shape of the curve, and therefore the relationship between the calculated suction level and the resulting MIDI velocity value.

The two sliders on the left centre of the image are referred to as offset adjustments. In a pneumatic reproducing piano, piano keys are played by a pneumatic bellows. When air is withdrawn from the bellows, the hinged section driving a piano key collapses at a rate depending on how quickly the air is removed. The speed of closure is directly proportional to the applied suction, so a higher suction level applies a greater accelerating force to the piano hammer, therefore creating a louder sound. In general, the bellows in a pneumatic player piano are the same size, so for a given level of suction, the force applied to a piano hammer is the same across the keyboard. Because force = mass times acceleration, for the same applied suction, the lighter treble hammers are accelerated more than the heavier bass hammers. The effect is that all keys operated with same applied suction produce the same level of volume. As my thesis explains[3], if a pneumatic bellows is arranged to play a mechanical piano that can record a keyboard performance, such as a Disklavier, for the same level of applied suction, the MIDI levels recorded will be different across the keyboard. For example, on a typical Yamaha Disklavier, if the MIDI level recorded by middle C is MIDI 60, top C will register 72, and bottom C will register 56. The offset sliders are set to suit the piano the files are intended for, in which the MIDI velocity values calculated by the emulator are increased or decreased according to the position of the note on the keyboard, and therefore the weight of the hammer for that note.

2 The Welte test roll allows the fast and slow crescendo speeds to be accurately adjusted according to Welte specifications. Use of the test roll is explained in a handbook produced by Welte and Sons.

3 Phillips, Peter. *Piano Rolls and Contemporary Player Pianos: The Catalogues, Technologies, Archiving and Accessibility.* Diss., Sydney University 2016, 215.

MIDI and Pneumatic Player Actions

In a MIDI mechanical piano like a Disklavier, the key-playing solenoids are moved at a speed determined by the velocity value attached to the MIDI code for that note. Once the solenoid starts moving, the MIDI data has no further control over the closing speed of the solenoid. However, in a pneumatic player piano, the suction can change as a note-playing pneumatic closes, which means the speed of closure also changes. If the suction is increasing, the pneumatic will be closing at a faster speed when it strikes the hammer compared to its closing speed at the start of the travel.

In many cases, the fast crescendo expression perforations in Welte and Duca rolls overlap the notes to be accented. Their full effect is achieved in pneumatic pianos, but in a MIDI instrument, the effect will be limited to the level of calculated suction from the start of the fast crescendo note to the start of the accented note. Any overlap now has no effect. It is therefore necessary to edit the MIDI file of a Welte or Duca e-roll by moving the fast crescendo notes so they end just before the start of the note to be accented. This is done manually using a MIDI editor program such as Cubase, Cakewalk or Reaper, as the random placement of these expression notes does not allow the use of an algorithm to do it automatically.

In-line Emulator

When making corrections to an e-roll MIDI file in a MIDI editor, it is often necessary to listen to the effect of the changes being made. To achieve this, the author has developed a range of in-line emulators (Fig. 6), in which the e-roll MIDI file is fed to the input of the emulator and its output connects to a MIDI piano. The emulation process occurs in real time as the file is played into the emulator. A program like Rollmidi produces an emulated file by processing the entire e-roll MIDI file. An in-line emulator has a microprocessor that is programmed to do the necessary processing, and includes a MIDI in and MIDI out port. In some cases, the expression regulators are modelled with external analog electronics that produce a voltage analogous to suction. This voltage is fed into the microprocessor which is programmed to assign MIDI velocity values to the playing notes as they pass through the microprocessor. This type of emulator is simpler to design than a program such as Rollmidi.[4]

4 For a full description of emulators see ibid. Chapter 4.

Fig. 6 An in-line Welte emulator. The input is an e-roll MIDI file and the output MIDI signal is the emulated version of the e-roll file. This is used in conjunction with a MIDI editor when working on a Welte e-roll MIDI file. The output of the emulator connects to a MIDI piano, such as a Disklavier.

Conclusion

Reproducing piano rolls have become the subject of musicological research as they are often the only recordings made by historically significant pianists, such as German pianist Carl Reinecke (1824–1910). Performance practice during the 19th century differs from that of today, and reproducing piano roll recordings give valuable insight into how pianists interpreted a written score. Numerous composers, such as Claude Debussy recorded their compositions only on roll, sometimes not always exactly to their score. It is estimated that over 15,000 reproducing piano roll recordings of classical music were made by the five major companies (Welte, Philipps, Hupfeld, Duo-Art and Ampico) during the period 1905 to 1930. This library contains music that is often no longer heard today, plus most of the standard classical repertoire. Its value as an historical resource is well understood, and bringing this music to modern instruments, as outlined in this chapter, makes it accessible to all.

Seven Steps to Emulating a Reproducing Piano Roll Performance

Wayne Stahnke

Abstract

Emulating a reproducing piano roll performance from an optical scan of a roll involves seven discrete steps. The first step reduces the scan to a simpler form. Each succeeding step receives the data set created by the previous step and creates a new data set for use by the subsequent step. The final step produces a music file that can be played on an electronically-controlled acoustic piano or virtual piano.

Introduction

An optical scanner produces a visual image of a roll suitable for archival purposes and research if the scan is of high quality, but playing it requires first processing the scan using an *emulator*, a specialized program that models the behavior of the pneumatic instrument for which the roll was intended. In most cases, the emulator does not generate sound. Instead, it produces a performance file, often a MIDI file, that operates an electronically-controlled acoustic piano or virtual piano. The process of creating this file from the scan is called *emulation*.

The Steps

Emulating a reproducing piano roll performance involves seven successive steps, each of which produces a mapping, or transformation, of the data produced by the preceding step. For the first step, the source data is the scan itself. The procedure is as follows:

- Create a reduced scan.
- Remove skew and scatter.
- Incorporate tracker bar effects.
- Replace positions with times.
- Model the reproducing mechanism.
- Determine the hammer velocities and note times.
- Create a performance file.

Each step processes the entire performance from start to finish in preparation for the next step. The steps are performed in order, one at a time, in advance of auditioning the performance. This procedure is in contrast with playing a roll on a reproducing piano, which performs multiple operations simultaneously in real time as playing progresses.

We present an overview of the emulation procedure in the following sections. For steps 2, 4, and 6, we give references that provide further details.

Step 1: Create a Reduced Scan

Scanning creates a visual image of a roll. The image will have high contrast if the roll is backlit, ensuring sharp definition of the edges of the perforations. Some scanners use front lighting to capture labels, lyrics, expression lines, and other markings, often in conjunction with back lighting.

The first step is to reduce the scanned visual image to an ordered series of indications, called *events*, one each for the start and end of each perforation, specifying the type of event (actuate or release), the distance of the event from the start of the scan, and the tracker bar port associated with the event. The result is a *reduced scan*.

Determining the tracker bar ports requires knowing the lateral positions and the widths of the tracker bar ports, which differ from one manufacturer to the next. Some manufacturers revised their tracker bar designs over time, in which case it is necessary to date the roll to select the correct tracker bar type. The tracker bar geometry is used to create a virtual tracker bar image that is effectively superimposed on the roll image to create the reduced scan.

Reducing the scan is complicated by the fact that the roll weaves back and forth during scanning to a greater or lesser degree, depending on the condition of the roll and the paper-handling mechanism of the scanner. Rolls that have been stored improperly are often stretched or buckled in a way that increases this lateral meandering. The roll image therefore shifts back and forth along the length of the roll in the visual scan, so the virtual tracker bar image must be shifted back and forth to match, to ensure full coverage of each perforation by its associated tracker bar port image. This process, called *tracking*, is usually achieved using the roll edges as references, but since the edges can be damaged, it is better to determine the shift from the perforations themselves.

Step 2: Remove Skew and Scatter

After the reduced scan has been created, the locations of the actuate and release events are adjusted to reduce the magnitude of the errors introduced by *skew* (angular misalignment of the scan line with respect to the perforations) and *scatter* (the port-to-port offsets of the individual punches along the length of the roll due to tolerances and wear). The result of this step is an *improved reduced scan*.

For most scans, both the roll and the scanner suffer from skew. The skew in the scan is the sum of the skews in the roll and the scanner. Thus, the skews from the two skew sources will tend to cancel if they are of the opposite sense, but they will be compounded if they fall in the same direction. Skew in the roll results from angular misalignment of the punch-and-die set with respect to the direction of paper travel when the roll was perforated; skew in the scanner results from angular misalignment of the image sensor with respect to the paper-handling mechanism.

Scans also include scatter errors. Since the sensors in line-scan cameras have very little scatter, the scatter in scans made using them is due almost entirely to scatter in the roll, caused by manufacturing tolerances and wear in the punch-and-die set.

Scanners based on contact image sensor (CIS) arrays often introduce *bowing*, caused by an imperfectly straight sensor array, which appears as a bent scan line. Bowing is a form of scatter, albeit one in which there is a great deal of regularity, in contrast to the random offsets that result from imperfections in the punches. Thus, removing scatter also removes bowing if it is not excessive.

Removing skew and scatter markedly improves the accuracy of the positions of the events. This improvement is often great enough to make it possible to reconstruct the punch matrix, which removes not only errors due to skew and scatter, but also random errors from sources such as irregular paper advance in the perforator and misshapen holes, resulting in an error-free reduced scan that is the most accurate possible source material for emulation. For a discussion of the methods used for determining and removing skew and scatter and reconstructing the punch matrix, see *Skew, Scatter, and Pitch in Music Roll Scans* (this volume, p. 83).

Step 3: Incorporate Tracker Bar Effects

When a roll is played on a pneumatic reproducing piano, the perforations are sensed by advancing the paper over a tracker bar that alters their apparent lengths and positions. In particular, the perforation lengths are effectively increased by the nonzero height of the ports. In some reproducing pianos, several of the control ports are taller than the note ports, and some of these are also offset along the direction of travel of the roll.

Tracker bar effects are incorporated by convolving an image of the tracker bar with the perforations. In practice, this requires moving the actuate and release positions of each event by an amount determined by the dimensions and relative positions of the tracker bar ports and discarding any resulting out-of-order events. This step increases the apparent perforation length and removes the *webbing*, the short bridges between individual punches used to strengthen lengthy perforations.

Step 4: Replace Positions with Times

Step 4 marks a turning point. The operations in all of the previous steps are spatial, that is, related only to position. For many scanners, this is true even for the scanning process itself, because the scan lines are captured at discrete positions found by a rotating position sensor in contact with the roll, making scanning independent of time. Step 4 replaces the improved reduced scan event positions with the times at which they should take effect. All subsequent steps involve time, rather than position.

In principle, event times are found from the very simple relationship $t = s/v$, where t denotes time, s is the displacement of the event from the start of the roll, and v is the paper velocity, but there are two complications in finding accurate times. First, for some rolls such as Welte-Mignon T-100 rolls, the intended velocity is not known exactly and can be determined only from test rolls, which do not all agree. Second, pneumatic reproducing pianos advance the paper by pulling it with a rotating takeup spool, causing the paper to accelerate because of the increasing diameter of the takeup spool as the paper accumulates on it during playing. If we assume uniform acceleration, the event time is

$$t = \frac{2s}{v_0(1 + \sqrt{1 + 2As})},$$

where v_0 is the paper velocity at the start of the roll and the *acceleration constant* A is determined by the thickness of the paper and the diameter of the takeup spool in the recording equipment. For most reproducing pianos, the documentation that gives these dimensions has been lost. In addition, the speed of the pneumatic motor used to pull the roll droops as paper accumulates on the takeup spool during playing, increasing its diameter and the load on the motor. Consequently, there is a high degree of uncertainty regarding acceleration for most rolls. Late Ampico rolls are the sole exception, because a factory document survives that specifies the diameter of the recording machine's takeup spool and the nominal paper thickness, and makes it clear that the paper is accelerated uniformly. For further discussion and a derivation of the event time equation above, see *Acceleration in Music Rolls* (this volume, p. 129).

Step 5: Model the Reproducing Mechanism

After replacing positions with times in Step 4, the improved reduced file consists of a set of ordered "on" and "off" indications for each port, most of which specify the times that keyboard notes are to be actuated and released. The remaining indications control the reproducing mechanism, which determines the loudness and the pedaling. Step 5 models the behavior of the mechanism to reproduce the dynamics and pedaling.

The reproducing mechanism design differs from one manufacturer to the next, so a separate model is required for each mechanism. In addition, some manufacturers changed their designs over time, requiring a separate model for each time period. The appropriate model must be chosen for each roll depending on its issue date, which is known for rolls of the major reproducing pianos.

Creating an accurate reproducing mechanism model is the most difficult, and least understood, of all the problems of emulation. The mechanical simplicity of pneumatic mechanisms belies their complex behavior. This did not present a problem to the roll editors, who could adjust the positions of the control perforations in the roll by ear to produce the performances they sought, but it makes devising and implementing a model a demanding task.

The goal of modeling is to determine the bass and treble windchest pressures and pedal positions. Stepped dynamic control, such as Ampico intensities and Duo-Art steps, can be modeled by relatively quick ramps in windchest pressure. The simplest and most direct way to model steadily increasing or decreasing windchest pressures, such as those called for by Ampico crescendo pneumatics and Welte-Mignon expression pneumatics, is to use incremental numerical integration of first-order differential equations. The equations are nonlinear because the pressure drop across a timing orifice is proportional to the square of the flow rate through it. In contrast, damper movements are best modeled by simple up-down integrators, with the actuate speed less than the release speed.

One item of particular concern is the windchest pressure regulator, which is intended to maintain a more-or-less constant windchest pressure regardless of the number of notes being played at a given instant. Some regulators, such as those in Ampico and Welte-Mignon mechanisms, are relatively good at this task, but others such as the Duo-Art regulator are relatively ineffective, thus difficult to model.

Artrio-Angelus mechanisms do not have regulators, so this step and the next do not apply. Instead, the hammer velocities and note times must be found by modeling the flow through orifices selected by the roll. As of this writing, an accurate model for Artrio-Angelus mechanisms does not exist.

Step 6: Determine the Hammer Velocities and Note Times

Given the windchest pressure found in Step 5, Step 6 finds the hammer velocity for each keyboard actuate event. The relationship between windchest pressure and hammer velocity is given by

$$v_h = K_s\sqrt{w - W_s},$$

where v_h denotes hammer velocity, K_s is a constant that varies across the keyboard, w is windchest pressure, and W_s is the *pressure floor*, a constant that also varies across the keyboard. For a derivation of this relationship, see *Windchest Pressure and Hammer Velocity* (this volume, p. 149). The variation in W_s is small enough to be neglected, so a single value suffices for the entire keyboard compass, but K_s must vary across the keyboard to take into account the tapering of the hammers from bass to treble.

Some of the more sophisticated electronic reproducing pianos, among them the Bösendorfer SE, Live Performance LX, and Spirio pianos from Steinway and Sons, are designed to accurately reproduce hammer velocities. For other electronic reproducing pianos and virtual pianos, the hammer velocity must be adjusted for the note position in the keyboard compass, because hammer velocities are lower in the bass than in the treble for strikes of the same perceived loudness. A simple strategy that is often adequate is to assume that a given windchest pressure produces notes of uniform loudness across the keyboard, even though it is widely agreed that the bass register is relatively weak in pneumatic instruments. This yields an adjustment that is the inverse of that provided by the variation in K_s, so a single value suffices for the entire keyboard compass.

Step 6 also adjusts the event actuate and release times to form the note actuate and release times. As with hammer velocity, the instant at which a note speaks is determined by the windchest pressure. Note release times are independent of windchest pressure, so they can be found from event release times by simply adding the release delay.

Step 7: Create a Performance File

The last step in emulation is creating a performance file that can be used to control an electronic reproducing piano or virtual piano. Most commercially-available reproducing pianos use proprietary data formats, so the file format is determined by the choice of instrument used for playback.

Many instruments also accept MIDI files, the near-universal file format for virtual pianos. Unfortunately, more than 40 years after the MIDI specification was published, an industry standard for mapping hammer velocities to MIDI velocities has not yet been adopted or even proposed. However, manufacturers of reproducing pianos have generally settled on proprietary mappings based on the equation

$$V_{\text{MIDI}} = \text{round}\,(V_0 + K \log_b v_h),$$

where V_{MIDI} is MIDI key velocity confined to the range $0 < V_{\text{MIDI}} < 128$, V_0 and K are constants, v_h is hammer velocity in any units, and b is the base of the logarithm. Here round(x) denotes the integer closest to x, usually found using the floor function

$$\text{round}(x) = \lfloor x + \tfrac{1}{2} \rfloor.$$

Experience shows that a good choice is $V_0 = 52$, $K = 25$, $b = 2$ for middle C, yielding the mapping

$$V_{\text{MIDI}} = \text{round}\,(52 + 25 \log_2 v_h),$$

where v_h is in meters per second. This is the mapping used by Yamaha in their Disklavier pianos. The combination of $K = 25$ and $b = 2$ implies that MIDI velocity increases by 25 steps when the hammer velocity is doubled. These values have proved to be satisfactory for a wide variety of acoustic and virtual pianos that accept MIDI files. Here is a table of selected MIDI velocities and their corresponding hammer velocities using this mapping:

MIDI velocity (steps)	Hammer velocity (m/s)
1	0.243164
2	0.250000
27	0.500000
52	1.000000
64	1.394744
77	2.000000
102	4.000000
127	8.000000

Base two logarithms present a minor hurdle because most compilers do not support them, a shortcoming that can be readily overcome by applying the change-of-base relationship $\log_b x = \log_a x / \log_a b$, which gives the base two logarithm as $\log_2 x = \ln x / \ln 2$, where $\ln x$ denotes the natural logarithm of x, a function supported by all compilers.

Discussion

It should be clear from the foregoing that accurate emulation requires getting many details right. Emulating a roll successfully requires a deep understanding of the intricacies of the pneumatic reproducing mechanism for which it was intended. It is therefore not surprising that the accuracy of currently available emulators differs widely from one to the next, depending on the assumptions and approaches of the programmer.

Some emulators omit Step 2, leaving skew and scatter errors of unknown magnitude in the reduced scan and thus in the performance file. One well-known emulator dispenses with Step 6, resulting in grossly faulty dynamics. In view of these and other shortcomings, an emulator should be evaluated not only by listening, but also by learning about the assumptions and models that its author had in mind when creating it.

Skew, Scatter, and Pitch in Music Roll Scans

Wayne Stahnke

Abstract

We present methods for determining the skew, scatter, and pitch in the scanned image of a music roll by using the Method of Least Squares. The procedures are derived from a method given by Gauss for determining longitudes by chronometer. Skew and scatter are errors, so a roll scan is improved by finding and removing them, after which it is often possible to remove the remaining errors in the scan, regardless of their source, by reconstructing the punch matrix using a method we provide.

Introduction

Music rolls comprise an important part of the musical heritage of the first quarter of the twentieth century. These long rolls of perforated paper controlled the operation of the pneumatic automatic musical instruments of the period, some of which were highly sophisticated. Almost all of the great pianists of the Golden Age of the Piano made music roll recordings, which we can play on today's electronic reproducing pianos and virtual pianos by scanning the rolls and subsequently passing the scan data through a sequence of steps to create playable music files. The resulting performances will accurately recreate those of the original instruments—the performances the recording artists heard and approved—only if all of the steps are done accurately.

This note addresses one of the first processing steps, namely finding and removing errors in the scan arising from three error sources: imperfections in the roll-perforating machinery; errors in the rolls themselves caused by age, damage, and improper storage over the many decades since they were manufactured; and errors in the scanner itself. In the aggregate, these errors can be large enough to result in audible degradation of the performance unless they are removed. In this note, we present methods for isolating and removing the errors, thereby avoiding the quality issues that would otherwise ensue.

Errors in music roll scans are of two types: systematic and random. We can find the systematic errors by taking advantage of the fact that random errors are just that: random. If we take averages over many perforations, the random errors will tend to cancel, whereas the systematic errors will not. Averaging therefore reveals the systematic errors. The Method of Least Squares performs this averaging in an optimal way, so it is the method of choice. After the systematic errors have been determined and removed, it is often possible to remove the random errors by exploiting the fact that the perforations are confined to discrete positions, called *rows*, along the length of the roll. If the position of a perforation along the length is disturbed by a random error smaller than half the length of a row, its true position can be restored by moving it to the nearest row.

Two systematic errors affect music roll scans. These are *skew*, the tilt of a single row of perforations caused by angular misalignment of the scan line with respect to the array of punches in the perforator, and *scatter*, column-to-column deviations of the perforations from their nominal positions along the length of the roll due to manufacturing tolerances and wear in the punch-and-die set. The scatter of the leading edges, called *actuate scatter*, is distinct from *release scatter*, the scatter of the trailing edges. In an ideal scan, these errors would be zero. For our purposes, they are parameters to be determined so that they can be removed.

In addition to skew and scatter, three further parameters are required to characterize a music roll. One is *pitch*, the nominal row advance. Pitch varies slightly from roll to roll, even for rolls made on a single perforator in the same production run. Another is the *common offset*, the displacement of all of the perforations from the start of the scan. The final parameter is *punch length*, the apparent length of a perforation consisting of only a single hole.

The parameters are of different natures. Skew is an error that we wish to find so that we can remove it. Since skew can vary a great deal along the length of the roll, it requires separate treatment of its constituent components *static skew*, the mean skew over the length of the roll, and *dynamic skew*, the variations from the mean.

Scatter is another error that we wish to find and remove. It does not vary along the roll length, so it can be dealt with in a straightforward manner.

Pitch is a fundamental characteristic of the roll. It can vary along the length of the roll, but so slightly that we can consider it to be constant. An accurate pitch estimate is required to find the skew and scatter, and to reconstruct the punch matrix.

The common offset is an artifact of the scanning process. It is approximately the length of white space appearing after the start of the scan but before the first perforation. Since it results from an arbitrary choice of starting point by the scanner operator, it is not of interest.

Punch length, like scatter, does not vary along the length of the roll. Also like scatter, it differs slightly from column to column because of tolerances and wear in the punch-and-die set. It is best dealt with separately, after the other parameters have been found.

Two Mathematical Models

The first step in processing a music roll scan is creating a file called a *reduced scan*, which specifies the locations of the leading and trailing edges of each perforation by an ordered sequence of indications called *events*. Events are of two types: *actuate events* specify the locations of the leading edges, while *release events* specify the locations of the trailing edges.

There are usually many more events than there are parameters, so we cannot find the parameters directly from a reduced scan because the problem is overdetermined. Instead, we find estimates of the parameters by applying the Method of Least Squares, using the two mathematical models derived below.

Finding the parameters of a roll scan requires two models, rather than one, because the maximum skew that appears in a scan can be larger than the pitch. Skew displaces events from the positions they would have in its absence by a displacement proportional to the skew. This displacement can be large enough to move events to the vicinity of an adjacent row when the magnitude of the skew approaches or exceeds the pitch, an effect called *aliasing*, resulting in a false scatter estimate. To circumvent this problem, we create a model that finds an initial skew estimate by considering scatter to be random. This estimate is removed from the scan before applying the other model, which considers scatter to be constant, to find all of the parameters including skew. To derive the two models, we require several definitions. Let

$$\begin{aligned} i &= \text{event index,} \\ d &= \text{total number of columns in the music roll,} \\ n &= \text{total number of events,} \end{aligned}$$

where $0 \leq i < n$. There are four variables associated with each actuate or release event, which we denote by

$$\begin{aligned} q_i &= \text{position of event } i \text{ along roll length (rows),} \\ x_i &= \text{position of event } i \text{ across roll width (columns),} \\ y_i &= \text{measured displacement of event } i \text{ along roll length (meters),} \\ e_i &= \text{error in measured displacement } y_i \text{ (meters),} \end{aligned}$$

where $q_i = 0, 1, 2, \ldots$ and $x_i = 0, 1, 2, \ldots, d-1$. The variables q_i and x_i are integers and are therefore exact, satisfying the requirement of the Method of Least Squares for the independent variables to be free of uncertainty. The displacement y_i and error e_i are real numbers. We denote the parameters other than punch length by these symbols:

$$\begin{aligned} c &= \text{common offset (meters),} \\ m &= \text{slope (meters/column),} \\ p &= \text{pitch (meters/row),} \\ s_{x_i} &= \text{leading or trailing edge scatter of column } x_i \text{ (meters).} \end{aligned}$$

We use *slope*, the tilt appearing across a single column, instead of skew, the tilt that appears across the entire roll width, for a simpler presentation. Skew is given by $(d-1)m$. By choosing slope as a parameter, we eliminate the factor $d-1$ that would otherwise appear in many places.

With these definitions, the parameters and variables are related by the *displacement equations*

$$\begin{aligned} y_0 &= c + mx_0 + s_{x_0} + pq_0 + e_0, \\ y_1 &= c + mx_1 + s_{x_1} + pq_1 + e_1, \\ y_2 &= c + mx_2 + s_{x_2} + pq_2 + e_2, \\ &\vdots \\ y_{n-1} &= c + mx_{n-1} + s_{x_{n-1}} + pq_{n-1} + e_{n-1}. \end{aligned}$$

The goal of the procedures presented below is to create a modified version of the scan that is as free of errors as possible. A first improvement removes the slope estimate m and scatter estimate s_{x_i} from the reduced scan, creating an *improved reduced scan*. If the estimates are close to the true values, this yields the equations

$$\begin{aligned} y_0 &= c + pq_0 + e_0, \\ y_1 &= c + pq_1 + e_1, \\ y_2 &= c + pq_2 + e_2, \end{aligned}$$

and so forth. If the errors are small enough, we can find the row numbers q_0, q_1, q_2, $\ldots$ as follows. We subtract each equation from its successor, yielding the $n-1$ equations

$$(y_{i+1} - y_i) - (e_{i+1} - e_i) = p(q_{i+1} - q_i),$$

for $i = 0, 1, 2, \ldots, n-2$. In the absence of error, the row spacing $q_{i+1} - q_i$ would be the integer given by

$$q_{i+1} - q_i = (y_{i+1} - y_i)/p.$$

If the magnitude of the difference error $e_{i+1} - e_i$ is less than $1/2$ row, we can find the row spacing by rounding $q_{i+1} - q_i$ as found above to the nearest integer. The row numbers are then q_0, $q_1 = q_0 + \text{round}\big((y_1 - y_0)/p\big)$, $q_2 = q_1 + \text{round}\big((y_2 - y_1)/p\big)$, and so forth. This allows us to specify the locations of the actuate or release events by the coordinates x_i and q_i of each event i, where $0 \leq i < n$. Since actuate events and release events must alternate in each column, the two sets of n coordinates (for actuate and release events) can be combined to form a set of $2n$ coordinates ordered by row,

$$(x'_0, q'_0), (x'_1, q'_1), (x'_2, q'_2), \ \ldots, \ (x'_{2n-1}, q'_{2n-1}),$$

where $q'_0 \leq q'_1 \leq q'_2 \leq \cdots \leq q'_{2n-1}$. This combined coordinate set is equivalent to the *punch matrix*, the X-Y array of perforations in the sprocketed master roll that controlled the perforator during the manufacture of production rolls, one of which was used to create the scan. The process of finding the row numbers is called *punch matrix reconstruction*.

A punch matrix contains an actuate event and a release event for every punch, whereas the combined coordinate set contains an actuate event to delineate the start of a series of punches in successive rows for a given column and a release event to delineate the end of the series, so it is more compact. In what follows, we refer loosely to the combined coordinate set as the punch matrix. Both forms are free of the errors introduced by the perforating machinery, the roll, and the scanner.

Returning to the reduced scan, we take up determining the slope m and scatter s_{x_i} so that they can be removed.

Scatter is unique among the parameters in that we can consider it to be systematic or random, depending on our point of view. Gauss discusses errors of this sort at the outset of his landmark publication on the Method of Least Squares, *Theory of the Combination of Observations Least Subject to Errors*.[1] The two viewpoints give rise to the two mathematical models described in this section: the principal model regards scatter as constant; the alternate model regards it as random.

When we consider scatter to be constant, the displacement equation scatter terms s_0, s_1, s_2, …, s_{d-1} are parameters to be estimated, but when we attempt to determine them we are immediately faced with what seems to be an ambiguity: it appears that the common offset c and the slope m can take on any values by adjusting the scatter. The argument that supports this idea is as follows: let u and v be any real numbers, and let $c = c' + u$ and $m = m' + v$. Substituting gives

$$y_i = c' + m'x_i + s'_{x_i} + pq_i + e_i,$$

where $s'_{x_i} = s_{x_i} + u + vx_i$ is the adjusted scatter term. Since u and v can take on any values, so can c' and m'. However, the scatter cannot be adjusted in this way because it is constrained by the fact that when it is considered to be random it is subsumed into the error term, so it must exhibit the randomness properties of the original error term. In particular, it must have zero mean and must be uncorrelated with the parameters,

1 Gauss, 'Theoria Combinationis'.

resulting in two constraints. The first of these guarantees that the common offset cannot take on any value, and the second guarantees the same for the slope.

Strictly speaking, we cannot fulfill the requirement for the scatter to have zero mean because we do not know the true scatter, so instead we constrain the scatter estimates by setting their weighted mean to zero. This gives the first constraint $\sum W_k s_k = 0$, where s_k is the scatter estimate of column k, W_k is the weight of s_k, and the summation extends from $k = 0$ to $k = d - 1$. We accommodate roll columns that lack perforations by assigning $W_k = 0$ to each such column.

The requirement for scatter to be uncorrelated with slope requires the scatter and the column numbers to be uncorrelated, which implies that their covariance is zero, which in turn implies that the expectation of their product is the product of their expectations. We do not know the true scatter, so instead we ensure that the weighted scatter estimates are uncorrelated with the column numbers. Setting the expectation of their product to the product of their expectations yields the equation

$$\frac{1}{\sum W_k} \sum k W_k s_k = \left(\frac{1}{d} \sum k \right) \left(\frac{1}{\sum W_k} \sum W_k s_k \right),$$

where the summations extend from $k = 0$ to $d - 1$ as before. Simplifying gives

$$\sum k W_k s_k = \frac{d-1}{2} \sum W_k s_k.$$

Substituting the first constraint $\sum W_k s_k = 0$ gives the second constraint $\sum k W_k s_k = 0$.

These constraints ensure that scatter is free of both offset and skew, consistent with the intuitive notion of scatter as small deviations from the punch line caused by tolerances and wear in the punch-and-die set, and having nothing to do with the offset and skew in the scan.

Both constraints must be satisfied to resolve the two ambiguities mentioned above. They complicate the calculations, which are simplified if we postpone imposing them until after most of the calculations have been done. To that end, we abandon attempting to solve for slope and scatter at the same time. Instead, we subsume the slope into the scatter, eliminating the need for the second constraint, and we take the scatter of one of the columns to be known in lieu of the first constraint. The result is the *scatter model.* After applying it to find the pitch estimate and the scatter estimates, which will invariably include some amount of offset and slope, we impose the constraints to find the offset and slope in the scatter, which we then remove. The procedure for doing this is presented in Section . Thus, the scatter model can find all of slope, scatter, and pitch, but not in a single step.

If our goal is to produce an improved reduced scan for emulation or punch matrix reconstruction, we can omit the final step of finding and removing the offset and slope from the scatter, because removing scatter that includes them achieves the same end as removing offset, slope, and scatter separately. This avoids imposing the constraints altogether.

The scatter model is subject to false solutions if the scan contains a large amount of skew, so before applying it we must find and remove most of the skew. We therefore require the *skew model*, an alternate model that finds the skew separately. The two models are described in detail below.

The Scatter Model

To create the scatter model, we define the *composite scatter* $s'_{x_i} = mx_i + s_{x_i}$ in which the slope is subsumed into the scatter. Substituting into the displacement equations yields

$$\begin{aligned}
y_0 &= c + s'_{x_0} + pq_0 + e_0,\\
y_1 &= c + s'_{x_1} + pq_1 + e_1,\\
y_2 &= c + s'_{x_2} + pq_2 + e_2,\\
&\vdots\\
y_{n-1} &= c + s'_{x_{n-1}} + pq_{n-1} + e_{n-1}.
\end{aligned}$$

In the absence of error, these equations can be rewritten as

$$\begin{aligned}
y_0 - s'_{x_0} - pq_0 &= c,\\
y_1 - s'_{x_1} - pq_1 &= c,\\
y_2 - s'_{x_2} - pq_2 &= c,\\
&\vdots\\
y_{n-1} - s'_{x_{n-1}} - pq_{n-1} &= c,
\end{aligned}$$

which can be combined to form the multiple equation

$$y_0 - s'_{x_0} - pq_0 = y_1 - s'_{x_1} - pq_1 = y_2 - s'_{x_2} - pq_2 = \cdots$$

This is the first equation (except for having the order of the last two terms reversed and the opposite sign for s'_{x_i}) in a little-known paper by Gauss on geodesy[2] that applies least squares to determining longitudes by chronometer, the most accurate method in the early nineteenth century. The paper is of little interest today because longitudes are now determined using satellite navigation, which is more convenient and more accurate. However, the problem Gauss addresses is similar in form to the problem of determining the parameters of music roll scans, so we can apply his method directly. His paper even finds the contribution of irregular row advance to the weighting (Section).

Gauss gives a concise statement regarding the solution of the multiple equation[3] that we can paraphrase and adapt to the notation of the problem at hand as follows:

> In order for these equations to suffice for determining the parameters s'_{x_0}, s'_{x_1}, s'_{x_2}, ..., $s'_{x_{n-1}}$ and p we must consider one of the scatter terms to be given, and in addition there must be at least two different events in the same column, so that two or more of the quantities $s'_{x_0}, s'_{x_1}, s'_{x_2}, \ldots, s'_{x_{n-1}}$ are identical. If exactly two are identical, the problem is completely determined; otherwise it is overdetermined, and one must determine the unknown quantities such that the $n-1$ equations
>
> $$\begin{aligned}
(y_1 - y_0) - (s'_{x_1} - s'_{x_0}) - p(q_1 - q_0) &= 0,\\
(y_2 - y_1) - (s'_{x_2} - s'_{x_1}) - p(q_2 - q_1) &= 0,\\
(y_3 - y_2) - (s'_{x_3} - s'_{x_2}) - p(q_3 - q_2) &= 0,
\end{aligned}$$
>
> and so forth, are satisfied as closely as possible.

2 Gauss, 'Chronometrische Längenbestimmungen'.
3 Stahnke, 'Gauss's Method', 19.

This brief outline is the key to determining the parameters using the Method of Least Squares, which cannot be applied to the equations

$$y_i = c + s'_{x_i} + pq_i + e_i$$

without a loss of accuracy because the error terms e_i exhibit positive serial correlation for reasons given in Section , violating the requirement of independent errors. Gauss overcomes this difficulty by taking first differences, yielding the equations

$$y_j - y_i = (s'_{x_j} - s'_{x_i}) + p(q_j - q_i) + (e_j - e_i),$$

where $0 \le i < n-1$ and $j = i+1$. This is a set of $n-1$ difference equations in which the error terms $e_j - e_i$ are independent. Taking first differences also removes the common offset c. (Gauss resolves the ambiguity in the scatter by taking one of the scatters as given, rather than setting the weighted mean of their estimates to zero as called for by the first constraint.)

To see that taking first differences removes the serial correlation of e_j and e_i from the difference error $e_j - e_i$, let $e_i = e'_i + \epsilon$, where ϵ is the portion of e_i that is carried over to row j, and similarly let $e_j = e'_j + \epsilon$. The difference error is $e_j - e_i = (e'_j + \epsilon) - (e'_i + \epsilon) = e'_j - e'_i$, which is free of the mutual error ϵ. Since the original error terms suffer from positive serial correlation, the common error ϵ appears in e_j and e_i with the same sign.

Thus, we can find optimal estimates of the composite scatter and pitch by applying the Method of Least Squares to the residuals

$$r_{ji} = (y_j - y_i) - (s'_{x_j} - s'_{x_i}) - p(q_j - q_i),$$

where $0 \le i < n - 1$ and $j = i + 1$, and where the square of each residual is weighted using the weighting given in Section .

There is an implicit change of notation in this equation. The symbols s' and p no longer denote the true values of the composite scatter and pitch, which we do not and cannot know. Instead, they denote their least-squares estimates. Some researchers use a "hat" notation for the estimates (in our case $\hat{s}'$ and $\hat{p}$) to make the change explicit, but we avoid introducing yet more symbols in the interest of simplicity. In what follows, the meaning of the symbols should be clear from the context.

The Skew Model

When we regard scatter as random, each scatter term s_{x_i} is subsumed into the error term e_i, after which the event displacements are given by the n equations

$$\begin{aligned} y_0 &= c + mx_0 + pq_0 + e'_0, \\ y_1 &= c + mx_1 + pq_1 + e'_1, \\ y_2 &= c + mx_2 + pq_2 + e'_2, \\ &\vdots \\ y_{n-1} &= c + mx_{n-1} + pq_{n-1} + e'_{n-1}, \end{aligned}$$

where $e'_i = e_i + s_{x_i}$. The error terms are positively serially correlated, as in the scatter model, so we take first differences to remove the serial correlation. This yields the $n - 1$

difference equations

$$\begin{aligned} y_1 - y_0 &= m(x_1 - x_0) + p(q_1 - q_0) + (e_1' - e_0'), \\ y_2 - y_1 &= m(x_2 - x_1) + p(q_2 - q_1) + (e_2' - e_1'), \\ y_3 - y_2 &= m(x_3 - x_2) + p(q_3 - q_2) + (e_3' - e_2'), \end{aligned}$$

and so forth. As before, taking first differences removes the common offset c. If there are more than three event pairs (the usual case) there are more than two difference equations and the problem is overdetermined, so we solve for the values of m and p that minimize the sum of the squares of the residuals

$$r_{ji} = (y_j - y_i) - m(x_j - x_i) - p(q_j - q_i),$$

where $0 \leq i < n - 1$ and $j = i + 1$, and where the square of each residual is weighted using the weighting given in Section .

As with the scatter model, there is an implicit change of notation in this equation. Here, the symbols m and p denote the least-squares estimates of slope and pitch, not their true values. Also as before, the meaning of these symbols should be clear from the context.

Taking first differences removes positive serial correlation from both the scatter and skew models, but it introduces negative serial correlation into the skew model. To see this, we write the error term of the first difference equation as $e_1' - e_0' = (e_1 + s_{x_1}) - (e_0 - s_{x_0})$, which we can rewrite as $(e_1 - e_0) + (s_{x_1} - s_{x_0})$. For the second difference equation, the error term is $e_2' - e_1' = (e_2 - e_1) + (s_{x_2} - s_{x_1})$. Both error terms contain s_{x_1}, but with opposite signs, indicating negative serial correlation. This is true for all of the difference equations.

Serial correlation does not bias the estimates, but it reduces their accuracy because they are no longer the best linear unbiased estimates. The loss of accuracy is not a concern because the decrease in accuracy is small and because the skew model is used only to find an initial slope estimate. The final slope estimate is found using the scatter model, which does not suffer from either positive or negative serial correlation.

Iterative Refinement

The skew model estimates the slope m and pitch p by minimizing the sum of the weighted squares of the residuals

$$r_{ji} = (y_j - y_i) - m(x_j - x_i) - p(q_j - q_i).$$

When we attempt to form the sums, we encounter a fundamental difficulty: we do not know the row numbers q_j and q_i. In fact, these quantities are what we ultimately wish to determine by reconstructing the punch matrix. If we knew them, there would be no need to find skew and scatter estimates.

We do not need the row numbers, however, only the differences between them, as we see from the pitch term $p(q_j - q_i)$. The residuals are formed from the displacement equations by taking first differences, which replaces row numbers with row spacings. The spacings are usually small integers, because the displacement between successive events is rarely large. In the absence of error, the row spacings are given by

$$q_j - q_i = \frac{(y_j - y_i) - m(x_j - x_i)}{p},$$

which suggests a way to proceed. Starting with initial approximations to m and p, we calculate the row spacings $q_j - q_i$ as above to yield a quantity that is almost never an integer because of errors. We therefore round it to the nearest integer, giving the true row spacing if the approximations are close enough and the displacement errors are not too large. We use these spacings to find improved approximations to m and p and iterate until the desired accuracy has been achieved.

Rounding will result in faulty row spacing if the approximations to m and p are too far removed from their true values, even in the absence of displacement errors. We can find the circumstances in which this occurs as follows.

Define the slope error m_{err} and pitch error p_{err} by $m = m_0 + m_{\text{err}}$ and $p = p_0 + p_{\text{err}}$, where m_0 and p_0 are the true slope and pitch. If only the slope is in error, the rounded row spacing $q_j - q_i$ is correct if

$$|(m_0 + m_{\text{err}})(x_j - x_i)| < |m_0(x_j - x_i)| + p_0/2.$$

Solving for allowable slope error gives

$$-\frac{p_0}{2|x_j - x_i|} < m_{\text{err}} < \frac{p_0}{2|x_j - x_i|},$$

so small column spacings will accommodate large slope error. The weighting given in Section gives more importance to closely-spaced event pairs than to widely-spaced ones.

Similarly, if only the pitch is in error, the rounded row spacing $q_j - q_i$ is correct if

$$|(p_0 + p_{\text{err}})(q_j - q_i)| < |p_0(q_j - q_i)| \pm (p_0 + p_{\text{err}})/2,$$

where the positive sign applies for $p_{\text{err}} > 0$ and the negative sign for $p_{\text{err}} < 0$. Solving for allowable pitch error yields

$$-\frac{p_0}{2|q_j - q_i| + 1} < p_{\text{err}} < \frac{p_0}{2|q_j - q_i| - 1},$$

so small row spacings will accommodate large pitch error. As with slope, the weighting gives more importance to closely-spaced pairs than to widely-spaced ones.

If only the displacements are in error, the row spacing will be correct if $|e_j - e_i| < p_0/2$. This is always the case if the displacement errors are less than $p_0/4$ in magnitude.

Starting with initial approximations to slope and pitch found using the method of Section (for the first iteration) or the previous slope and pitch approximations, we find the incremental changes, called *adjustments*, that minimize the sum of the weighted squares of the residuals. We then update the parameter approximations and repeat until the adjustments are as small as desired. The mistaken row spacings due to aliasing usually become fewer and fewer as iteration proceeds, but for poorly-made rolls they may never be eliminated entirely, so the number of iterations must be limited.

Both models must use iterative refinement, so we introduce a change in notation to accommodate it. For the skew model, let M and P denote the current approximations to slope and pitch and let m and p denote the adjustments. With this notation, the adjusted approximations $M + m$ and $P + p$ minimize the sum, and the equation for the skew residual is

$$r_{ji} = (y_j - y_i) - M(x_j - x_i) - P(q_j - q_i) - m(x_j - x_i) - p(q_j - q_i).$$

We can simplify this equation and return it to its original form by introducing the concept of *corrected displacements*. Let y'_j be the event displacement y_j corrected for M and P,

$$y'_j = y_j - Mx_j - Pq_j,$$

and similarly for y_i. With this notation, the corrected displacement difference is

$$y'_j - y'_i = (y_j - y_i) - M(x_j - x_i) - P(q_j - q_i),$$

and the skew residual becomes

$$r_{ji} = (y'_j - y'_i) - m(x_j - x_i) - p(q_j - q_i).$$

The row spacing $q_j - q_i$ is approximated by

$$q_j - q_i = \text{round}\left(\frac{(y_j - y_i) - M(x_j - x_i)}{P}\right),$$

where $\text{round}(x) = \lfloor x + 1/2 \rfloor$ is the integer closest to x.

For the scatter model, let the current approximations to composite scatter and pitch be S'_0, S'_1, S'_2, …, S'_{d-1} and P, and let $s'_0, s'_1, s'_2, \ldots, s'_{d-1}$ and p be the adjustments required to minimize the sum of the weighted squares of the residuals, so that the sum is minimized by the adjusted approximations $S'_0 + s'_0$, $S'_1 + s'_1$, $S'_2 + s'_2$, …, $S'_{d-1} + s'_{d-1}$ and $P + p$. With this notation, the scatter residual is

$$r_{ji} = (y_j - y_i) - (S'_{x_j} - S'_{x_i}) - P(q_j - q_i) - (s'_{x_j} - s'_{x_i}) - p(q_j - q_i).$$

As with the skew model, we can return the residual equation to its original form by correcting the event displacements. Let y'_j be the event displacement y_j corrected for the effects of S'_{x_j} and P,

$$y'_j = y_j - S'_{x_j} - Pq_j,$$

and similarly for y_i. With this notation, the corrected displacement difference is

$$y'_j - y'_i = (y_j - y_i) - (S'_{x_j} - S'_{x_i}) - P(q_j - q_i),$$

and the scatter residuals become

$$r_{ji} = (y'_j - y'_i) - (s'_{x_j} - s'_{x_i}) - p(q_j - q_i).$$

In practice, we cannot apply the scatter model without first having an approximation to slope, because the model is susceptible to spurious solutions due to aliasing in the presence of a large amount of skew. To avoid a false solution, we must find a slope estimate M separately using the skew model and add a slope term to the corrected scatter displacement difference, which becomes

$$y'_j - y'_i = (y_j - y_i) - M(x_j - x_i) - (S'_{x_j} - S'_{x_i}) - P(q_j - q_i),$$

where the row spacing $q_j - q_i$ is approximated by

$$q_j - q_i = \text{round}\left(\frac{(y_j - y_i) - M(x_j - x_i) - (S'_{x_j} - S'_{x_i})}{P}\right).$$

Throughout the rest of this note, m, s', and p are the adjustments to the corresponding parameter approximations M, and S', and P.

Weighting for Least Squares Equations

As we saw in the previous sections, the Method of Least Squares refines approximations to the parameters of a music roll scan by minimizing the sum of the weighted squares of the residuals

$$r_{ji} = (y'_j - y'_i) - (s'_{x_j} - s'_{x_i}) - p(q_j - q_i)$$

for the scatter model, and

$$r_{ji} = (y'_j - y'_i) - m(x_j - x_i) - p(q_j - q_i)$$

for the skew model. The weights associated with the residuals are inversely proportional to the variances of the errors in the difference equations used to create the residuals, and are thus a measure of the relative accuracies of the difference equations. In this section, we show how to find the weights.

The uncertainties in each of the quantities y_j, y_i, m, and p contribute to the variance of the difference equation. Note that we do not consider scatter to be a separate source of uncertainty. In the skew model, the scatter s_{x_i} is subsumed into the displacement error e_i, and its uncertainty is subsumed with it. In contrast, in the scatter model we consider the uncertainty associated with the scatter, rather than the scatter itself, to be subsumed in this way. We consider the contribution of each of the quantities in turn.

The displacements y_j and y_i include random errors that arise from oddly-shaped holes caused by dull punches, manually-inserted punches, torn webbing, and similar sources. The error of each measurement is independent of the error of the other measurements, so in the absence of other sources of uncertainty, the variance of the displacement difference $y_j - y_i$ is twice the variance of y_j or y_i. We assign a weight of one to this inherent uncertainty of the displacements of an event pair, in keeping with Gauss's advice that "the weight of one of the classes of observations should be set to one."[4]

If the events in a pair are in different columns, nonzero slope alters the displacement difference $y_i - y_j$. The slope m adds a displacement $m(x_j - x_i)$ to $y_j - y_i$. The events can appear in any column, so the column spacing $x_j - x_i$ can be positive, negative, or zero. The variance associated with this slope displacement is $(x_j - x_i)^2 \operatorname{var}(m)$, where $\operatorname{var}(m)$ is the variance of m. Let X be the column separation at which the variance due to slope variation equals the variance of the displacements of an event pair. The weight due to slope is then $1/[(x_j - x_i)^2/X^2]$.

If the events in a pair are in different rows, the displacement difference $y_j - y_i$ is also disturbed by row-to-row pitch variations. This disturbance is analogous to that of the balance wheel of a chronometer, so once again Gauss's work on determining longitudes by chronometer applies directly to music rolls. In determining longitudes, the rotation of the Earth's surface, which is assumed to be uniform, is measured by a chronometer subject to irregular advance. Here the roles are reversed: the irregular row advance is measured by a highly uniform measuring roller. The underlying problem is identical.

The variance is proportional to the number of rows separating the events in a pair, which we can see as follows. (This derivation parallels the one given by Gauss for finding the variance of chronometer time.[5]) Let p be the mean pitch, let s_k be the displacement

4 Gauss, 'Theoria combinationis'.

5 Stahnke, 'Gauss's Method', 8.

of row k, and let ϵ_k be the error of row k due to irregular row advance from row $k-1$. We assume that the errors are independent and identically distributed with zero mean and variance σ^2. With these definitions, the displacement of row q_j is $s_{q_j} = s_{q_j-1}+(p+\epsilon_{q_j})$. Back substituting gives the displacement as $s_{q_j} = s_{q_j-2} + (p + \epsilon_{q_j-1}) + (p + \epsilon_{q_j})$, and continuing in this way to row q_i gives the displacement between rows q_j and q_i as

$$s_{q_j} - s_{q_i} = \sum_{k=q_i+1}^{q_j} (p + \epsilon_k).$$

The expectation of ϵ_k is zero, so the expectation of $s_{q_j} - s_{q_i}$ is $\sum_{q_i+1}^{q_j} p = (q_j - q_i)p$. Since p is a constant, the variance of $s_{q_j} - s_{q_i}$ is $\mathrm{var}\big(\sum_{k=q_i+1}^{q_j} \epsilon_k\big)$. The errors are independent and therefore uncorrelated, so the variance of their sum is the sum of their variances $\sum_{q_i+1}^{q_j} \sigma^2 = (q_j - q_i)\sigma^2$. These results are independent of the probability density.

Let Q be the row separation for which the variance due to irregular row advance equals the variance of the inherent uncertainty of the displacement of an event pair. The weight associated with irregular row advance is then $1/(|q_j - q_i|/Q)$ for any two different rows q_j and q_i.

The three sources of error are independent and therefore uncorrelated, so the variance of their sum is the sum of their variances. Let w_{ji} denote their combined weight, which is given by the inverse of the sum of the inverses of the individual weights, and is thus

$$w_{ji} = \frac{1}{1 + \dfrac{(x_j - x_i)^2}{X^2} + \dfrac{|q_j - q_i|}{Q}}.$$

The weight is unitless. The units of x_j, x_i, and X are columns, so the units of both the numerator and denominator of the term $(x_j - x_j)^2/X^2$ are square columns, which cancel. Similarly, the units of q_j, q_i, and Q are rows, so the units of the numerator and denominator of the term $|q_j - q_i|/Q$ cancel.

We do not need to include the slope contribution to the composite weight if the slope estimate is fairly accurate and we limit the event pairs to a short length of the roll, or after the dynamic skew has been removed (see Section). In both of these cases, the weight is given by

$$w_{ji} = \frac{1}{1 + \dfrac{|q_j - q_i|}{Q}}.$$

The values of X and Q are determined by the magnitude of the errors in a given roll, and should ideally be chosen on a roll-by-roll basis. However, since the weight does not need to be especially accurate, one set of values can be used for many different rolls. As a practical matter, considering a column separation of 25 mm and a row separation of 25 mm as having uncertainties equal to that of an event pair seems to be suitable for a wide variety of rolls. The column spacing of most rolls is around 3 mm, so $X = 8$ columns can be recommended as the column default. Similarly, the recommended row default is $Q = 25$ mm/pitch.

Refining Slope and Pitch Approximations with the Skew Model

The skew model, derived in Section , refines approximations to the slope and pitch of a music roll scan by minimizing the sum of the weighted squares of the residuals

$$r_{ji} = (y'_j - y'_i) - m(x_j - x_i) - p(q_j - q_i).$$

Let U be the sum and let w_{ji} be the weight as found in Section . The sum is

$$U = \sum w_{ji} r_{ji}^2 = \sum w_{ji} \left[(y'_j - y'_i) - m(x_j - x_i) - p(q_j - q_i)\right]^2.$$

We minimize U by equating its gradient to zero. It is well known that U is convex, so this approach finds a minimum, not a maximum or saddle point. Thus to minimize U, we take partial derivatives with respect to m and p and set both to zero:

$$\frac{\partial U}{\partial m} = -2\sum w_{ji}[(y'_j - y'_i) - m(x_j - x_i) - p(q_j - q_i)](x_j - x_i) = 0,$$
$$\frac{\partial U}{\partial p} = -2\sum w_{ji}[(y'_j - y'_i) - m(x_j - x_i) - p(q_j - q_i)](q_j - q_i) = 0.$$

These equations can be solved by substitution, since there are two equations in two unknowns, but we put them in matrix form instead for simplicity of presentation and for parallelism with the development of the scatter model in Section . To this end, we rewrite the equations as

$$m\sum w_{ji}(x_j - x_i)^2 + p\sum w_{ji}(q_j - q_i)(x_j - x_i) = \sum w_{ji}(x_j - x_i)(y'_j - y'_i),$$
$$m\sum w_{ji}(x_j - x_i)(q_j - q_i) + p\sum w_{ji}(q_j - q_i)^2 = \sum w_{ji}(q_j - q_i)(y'_j - y'_i),$$

which can be written in matrix form as

$$\begin{bmatrix} a_{00} & a_{01} \\ a_{10} & a_{11} \end{bmatrix} \begin{bmatrix} m \\ p \end{bmatrix} = \begin{bmatrix} b_0 \\ b_1 \end{bmatrix}.$$

For compactness, we write this as

$$\mathbf{A}[m\,p]^\mathsf{T} = \mathbf{b},$$

where $\mathbf{A}$ is the 2×2 coefficient matrix, $\mathbf{b}$ is the 2×1 product vector, and $[m\,p]^\mathsf{T}$ denotes the 2×1 vector $\left[\begin{smallmatrix} m \\ p \end{smallmatrix}\right]$ of solutions. The matrix elements are given by

$$a_{00} = \sum w_{ji}(x_j - x_i)^2,$$
$$a_{01} = \sum w_{ji}(q_j - q_i)(x_j - x_i),$$
$$a_{10} = \sum w_{ji}(x_j - x_i)(q_j - q_i),$$
$$a_{11} = \sum w_{ji}(q_j - q_i)^2.$$

As is well known, $\mathbf{A}$ is symmetric and positive definite, so $a_{10} = a_{01}$, which we can also see by examination. The components of the product vector $\mathbf{b}$ are

$$b_0 = \sum w_{ji}(x_j - x_i)(y'_j - y'_i),$$
$$b_1 = \sum w_{ji}(q_j - q_i)(y'_j - y'_i).$$

This derivation suggests the algorithm presented next for refining slope and pitch approximations using the skew model. It makes use of actuate events or release events, but not both, because the punch length is best determined at a later stage, after skew and scatter have been removed from the reduced scan.

For each event pair, we must compute the column spacing $x_j - x_i$ and the row spacing

$$q_j - q_i = \text{round}\left(\frac{(y_j - y_i) - M(x_j - x_i)}{P}\right).$$

We must also compute the corrected displacement difference

$$y'_j - y'_i = (y_j - y_i) - M(x_j - x_i) - P(q_j - q_i)$$

and the weight w_{ji}. After initializing the slope and pitch approximations M and P, we proceed as follows.

Algorithm 1. A first algorithm for refining slope and pitch estimates M and P.

```
procedure
▷ Initialize
    initialize 2 × 2 matrix A = 0
    initialize 2 × 1 vector b = 0
    initialize total number of events n
    initialize event i = null event
    select active event type (actuate or release)

▷ Fetch next event
    for j = 0 to n − 1 do
        fetch event j
        if event j is not of selected type then
            continue
        end if

▷ Fill matrix and vector
        if event i is null event then
            event i ← event j
        else
            compute column spacing x_j − x_i
            compute row spacing q_j − q_i
            compute corrected displacement difference y'_j − y'_i
            compute weight w_ji
            a_00 += w_ji(x_j − x_i)^2
            a_01 += w_ji(q_j − q_i)(x_j − x_i)
            a_11 += w_ji(q_j − q_i)^2
            b_0 += w_ji(x_j − x_i)(y'_j − y'_i)
            b_1 += w_ji(q_j − q_i)(y'_j − y'_i)
            event i ← event j
        end if
    end for
```

▷ Solve matrix equation and update parameter estimates
$a_{10} \leftarrow a_{01}$
solve $\mathbf{A}[m\ p]^\intercal = \mathbf{b}$
$M \mathrel{+}= m$
$P \mathrel{+}= p$
end procedure

The matrix **A** is symmetic and positive definite, so it can be solved using Gaussian elimination without pivoting. It can also be solved without filling a_{10} by using any method that exploits the symmetry of the matrix, again without pivoting.

This algorithm provides the adjustments for a single iteration. It must be placed within an iterate loop that exits when the adjustments become small enough, or when the number of iterations exceeds a predetermined limit.

Multiple First Differences

For most rolls, most difference displacement errors are less than the $1/2$ row limit required to find the row spacing correctly in the absence of other errors, so most of the row spacings will be correct, but an out-of-place perforation can disturb the row spacings in its vicinity. We can reduce the effects of a badly-placed perforation by pairing events more widely spaced than adjacent ones.

If we form first differences by subtracting each displacement equation from the one following its successor, rather than from the successor itself, we will effectively obtain two sets of equations: odd-numbered events will appear in one set, even-numbered events in the other. Each set traces a path through the roll, from (nearly) the first event to (nearly) the last. Similarly, the set of equations obtained by forming the usual first differences traces a full path, from the first event to the last. If we form first differences in both ways, we will trace three separate paths through the roll, yielding nearly double the number of equations, because almost every event will be paired with four nearby events rather than two. This decreases the deleterious effects of a single badly-placed perforation and reduces the effects of aliasing.

Pairing each event with events further removed from it will diminish the effects of poorly-placed perforations even more. Let the number of pairings be N. The number of paths through the roll is $1 + 2 + 3 + \cdots + N = N(N + 1)/2$. If t is the separation of the events in a pair, the number of pairs for a given t is $n - t$ if $n \geq t$, 0 otherwise. For $n \geq N$ (the usual case), the number of pairs, and thus the number of difference equations, is

$$(n - 1) + (n - 2) + (n - 3) + \cdots + (n - N) = nN - \frac{N(N + 1)}{2}.$$

If $n \gg N$ (also the usual case), the number of difference equations is only slightly less than nN, so the total number of equations is increased by nearly a factor of N.

Excluded Events

It sometimes happens that the events that appear in one or more columns in a scan are not aligned with rows, reducing the accuracy of the adjustments. The most common cause of unaligned events is torn roll edges, which can create spurious actuate and release events near the roll edges. Another cause is torn webbing, which can disturb many successive actuate or release events from their original positions. Yet another cause is manually-inserted perforations, which were often used at the factory to correct rolls in which the perforator failed to punch all of the holes. Such perforations were sometimes also inserted by roll owners to correct the same type of perforator errors if they were not previously corrected at the factory, or to modify the performance to the owner's sense of what it should have been, or to the owner's preference.

The accuracy of the estimates can be improved by excluding the events in the affected columns from the computations. The columns to be excluded must be selected by the operator in advance, based on visual examination of the roll or scan.

A Closer Look at Estimating Pitch

The skew model pitch estimate will be low if there are multiple events in a single row and the event stream has been sorted by displacement. There are usually two or more events in a single row when a chord is played, so chords satisfy the first condition. Most data formats used for reduced scans sort the event stream by displacement because they specify positions along the length of the roll using differential displacements for compactness, but negative displacements are not supported. Thus, the second condition too is satisfied. The resulting low pitch estimate comes about because the skew model residual

$$r_{ji} = (y'_j - y'_i) - m(x_j - x_i) - p(q_j - q_i)$$

attributes the corrected displacement difference $y'_j - y'_i$ to both slope and pitch for events in different rows, but for events in the same row the pitch term $p(q_j - q_i)$ vanishes, and consequently the displacement does not contribute to the pitch estimate. Sorting the events by displacement ensures $y_j \geq y_i$, so when contributions of $y'_j - y'_i$ to the pitch are omitted, the resulting pitch estimate is low.

The deficit in the pitch estimate depends on the value of N, the number of events paired with each actuate or release event. Larger values of N give rise to smaller deficits. For $N = 12$, the pitch estimate is low by typically one part in a few thousand.

The skew model is used to refine the slope and pitch approximations prior to applying the scatter model. If the pitch estimate it provides to the scatter model is too low, a perforation following a long white space may be seen as being a row late, and its scatter will be adjusted accordingly. The likelihood of this happening is proportional to the length of the white space. In most rolls, there is lengthy white space between the end of the performance and the rewind perforation, which has not appeared previously, risking faulty row assignments for the rewind perforation. We therefore improve the accuracy of the pitch adjustment by finding the matrix entries and vector components for the pitch using only events in different rows.

An Improved Algorithm for Refining Slope and Pitch Estimates

We can improve Algorithm 1 by using multiple first differences, excluding columns with unaligned events, and finding the pitch estimate using only events in different rows. The algorithm given here incorporates these improvements. It requires two ring buffers with a capacity of N events each, one each for slope and pitch, where N is the number of event pairings. Experience shows that $N = 12$ yields many event pairs without pairing events too far removed from each other along the roll length, so that value can be recommended for general use.

Algorithm 2. A second algorithm for refining slope and pitch estimates M and P.

```
procedure
▷ Initialize
    initialize slope ring buffer empty
    initialize pitch ring buffer empty
    initialize 2 × 2 matrix A = 0
    initialize 2 × 1 vector b = 0
    initialize total number of events n
    select event type (actuate or release)
    select columns to be excluded

▷ Fetch next event
    for j = 0 to n − 1 do
        fetch event j
        if event j is not of selected type then
            continue
        end if
        if event j column is excluded then
            continue
        end if

▷ Fill matrix and vector slope row
        if slope ring buffer is empty then
            install event j in slope ring buffer
        else
            for each event i in slope ring buffer do
                compute column spacing x_j − x_i
                compute row spacing q_j − q_i
                compute corrected displacement difference y'_j − y'_i
                compute weight w_ji
                a_00 += w_ji (x_j − x_i)^2
                a_01 += w_ji (q_j − q_i)(x_j − x_i)
                b_0 += w_ji (x_j − x_i)(y'_j − y'_i)
            end for
            if slope ring buffer is full then
                remove event at rear of slope ring buffer
            end if
            append event j to front of slope ring buffer
        end if
▷ Fill matrix and vector pitch row
        if pitch ring buffer is empty then
            install event j in pitch ring buffer
        else
            fetch event i at front of pitch ring buffer
            compute column spacing x_j − x_i
            compute row spacing q_j − q_i
```

```
        if (q_j − q_i) ≠ 0 then
            for each event i in pitch ring buffer do
                compute column spacing x_j − x_i
                compute row spacing q_j − q_i
                compute corrected displacement difference y'_j − y'_i
                compute weight w_ji
                a_10 += w_ji(x_j − x_i)(q_j − q_i)
                a_11 += w_ji(q_j − q_i)^2
                b_1 += w_ji(q_j − q_i)(y'_j − y'_i)
            end for
            if pitch ring buffer is full then
                remove event at rear of pitch ring buffer
            end if
            append event j to front of pitch ring buffer
        end if
    end if
end for

▷ Solve matrix equation and update parameter estimates
    solve A[m p]^T = b
    M += m
    P += p
end procedure
```

The matrix **A** is not symmetric and positive definite, unlike the matrix of Algorithm 1, so the full 2×2 matrix must be used to find the solution. However, **A** is diagonally dominant by both row and column, so pivoting is not required if the matrix equation is solved using Gaussian elimination or its variants. Diagonal dominance comes about because each contribution to a_{00} is the square of the column difference $x_j - x_i$ and each contribution to a_{11} is the square of the row difference $q_j - q_k$. These contributions are therefore always positive, whereas the contributions to the off-diagonal elements are the products of column and row differences, which are equally likely to be positive or negative, and thus tend to cancel. This heuristic argument can be sharpened by finding the expectations of the off-diagonal matrix elements.

Since **A** consists of only two rows, it is straightforward to solve the matrix equation by substitution. However, several of the other algorithms given in this note require a means of solving larger matrix equations, so it is convenient to use the same method here as is used elsewhere. In particular, the algorithm of Section can be used to solve the matrix equation.

As with Algorithm 1, the improved algorithm provides the adjustments for a single iteration, so it must be placed within an iterate loop as described previously. Also as before, the number of iterations should be limited.

This algorithm is robust. If it is provided with good initial approximations to slope and pitch it will unfailingly deliver accurate improved approximations, even from low-quality scans, scans of badly damaged rolls, and scans that contain large amounts of dynamic skew.

Finding the Initial Approximations

The procedures given above require initial approximations M and P to slope and pitch. Finding an approximation to P does not present any difficulties. The intended pitch is known for all of the common types of music rolls. For other rolls, it is usually possible to find a fairly accurate approximation by examining the roll itself, or a scan of the roll, if the pitch is not too fine. When this approach fails, the best alternative is to examine a histogram of the actuate event or release event spacings by eye, which gives excellent results in every case.

Finding an initial approximation to the slope is more difficult. If the skew is known to be small, we can take the initial slope to be zero. However, the magnitude of the skew is usually unknown, and since it can be large, the only way to find it reliably is by exhaustive search. After finding the pitch approximation, we find the sum U of the weighted squares of the skew residuals for a number of equally-spaced trial slopes encompassing the range of possible skew, and we select the trial slope that has the minimum sum as the initial approximation. As with estimating slope and pitch, this procedure benefits from pairing each event with a number of preceding events.

This approach finds the global minimum of U, thereby avoiding the possibility of a false solution caused by starting with a slope approximation near a local minimum. If the slope estimate found in this way is one of the extreme trial slopes, we cannot know if we have found the global minimum, which may lie beyond the range of the trial slopes.

If we form the matrix elements a_{00}, a_{01}, a_{10}, a_{11}, and the vector components b_0, b_1 for each trial slope as in Algorithm 2, in addition to forming the sum U, we can refine the selected trial slope and the pitch approximations immediately using the update procedure of Algorithm 2. A less ambitious approach dispenses with refining the pitch estimate. Instead, it finds only U, a_{00}, and b_0 for each trial slope. The slope adjustment is then $m = b_0/a_{00}$, and the refined selected trial slope is given by $M \mathrel{+}= m$.

To find the slope approximation, let the number of trial slopes be T, where $T \geq 2$, let t be the trial index, where $0 \leq t < T$, and let a_t and b_t be the values of a_{00} and b_0 for the index t. In addition, let M_{max} be the maximum trial slope and let $\Delta M = 2M_{\text{max}}/(T-1)$ be the slope increment. To ensure that a global minimum is found, the skew increment $(d-1)\Delta M$, where d is the total number of columns, must be less than the pitch. The following algorithm finds the slope approximation M and refines it.

Algorithm 3. Find approximation to slope M.

procedure
▷ Initialize
    initialize ring buffer empty
    initialize $T \times 1$ vector $\mathbf{a} = \mathbf{0}$
    initialize $T \times 1$ vector $\mathbf{b} = \mathbf{0}$
    initialize $T \times 1$ vector $\mathbf{U} = \mathbf{0}$
    initialize total number of events n
    select event type (actuate or release)
    select columns to be excluded

▷ Fetch next event
    for $j = 0$ to $n-1$ **do**

```
        fetch event j
        if event j is not of selected type then
            continue
        end if
        if event j column is excluded then
            continue
        end if

▷ Fill vectors
        if ring buffer is empty then
            install event j in ring buffer
        else
            for each event i in ring buffer do
                compute column spacing x_j − x_i
                if (x_j − x_i) = 0 then
                    continue
                end if
                initialize M = M_max
                for t = 0 to T − 1 do
                    compute row spacing q_j − q_i
                    compute corrected displacement difference y'_j − y'_i
                    compute weight w_ji
                    a_t += w_ji(x_j − x_i)^2
                    b_t += w_ji(x_j − x_i)(y'_j − y'_i)
                    U_t += w_ji(y'_j − y'_i)^2
                    M −= ΔM
                end for
            end for
            if ring buffer is full then
                remove event at rear of ring buffer
            end if
            append event j to front of ring buffer
        end if
    end for

▷ Find slope approximation
    initialize i = 0
    for t = 1 to T − 1 do
        if U_t < U_i then
            i ← t
        end if
    end for
    M = M_max − iΔM
    m = b_i/a_i
    M += m
end procedure
```

Refining Scatter and Pitch Approximations with the Scatter Model

The scatter model, derived in Section , refines approximations to the composite scatter and pitch of a music roll by minimizing the sum of the weighted squares of the residuals

$$r_{ji} = (y'_j - y'_i) - (s'_{x_j} - s'_{x_i}) - p(q_j - q_i).$$

Let U be the sum and let w_{ji} be the weight as found in Section . The sum is then

$$U = \sum w_{ji} r_{ji}^2 = \sum w_{ji} \left[(y'_j - y'_i) - (s'_{x_j} - s'_{x_i}) - p(q_j - q_i)\right]^2,$$

which we minimize by forming partial derivatives with respect to s'_{x_j}, s'_{x_i}, and p and equating them to zero, yielding a set of equations that we write in matrix form as

$$\mathbf{M}[s'_0\ s'_1\ s'_2 \cdots s'_{d-1}\ p\,]^\intercal = \mathbf{c},$$

where d is the number of columns in the music roll, each corresponding to a scatter term. The dimensions of the matrix $\mathbf{M}$ are $(d+1) \times (d+1)$, and both the solution vector $[s'_0\ s'_1\ s'_2 \cdots s'_{d-1}\ p\,]^\intercal$ and product vector $\mathbf{c}$ have dimensions $(d+1) \times 1$. The matrix is symmetric and positive definite.

To find the adjustments we fill the matrix and product vector, both initially zero, one event pair at a time. After all of the event pairs have been included, we solve the matrix equation to yield the adjustments. The equations resulting from setting the partial derivatives to zero are

$$\begin{aligned}
\frac{\partial U}{\partial s'_{x_j}} &= -2\sum w_{ji}[(y'_j - y'_i) - (s'_{x_j} - s'_{x_i}) - p(q_j - q_i)] = 0,\\
\frac{\partial U}{\partial s'_{x_i}} &= -2\sum w_{ji}[(y'_j - y'_i) - (s'_{x_j} - s'_{x_i}) - p(q_j - q_i)](-1) = 0,\\
\frac{\partial U}{\partial p} &= -2\sum w_{ji}[(y'_j - y'_i) - (s'_{x_j} - s'_{x_i}) - p(q_j - q_i)](q_j - q_i) = 0.
\end{aligned}$$

These equations correspond to rows x_j, x_i, and d of the matrix.

The first two partial derivative equations are additive inverses. If the events in a pair are in the same column, the updates that these equations imply are not necessary because they cancel, reflecting the fact that there is nothing to be learned about scatter from two events in the same column. We rewrite the equations as

$$\begin{aligned}
s'_{x_j}\sum w_{ji} - s'_{x_i}\sum w_{ji} + p\sum w_{ji}(q_j - q_i) &= \sum w_{ji}(y'_j - y'_i),\\
-s'_{x_j}\sum w_{ji} + s'_{x_i}\sum w_{ji} - p\sum w_{ji}(q_j - q_i) &= -\sum w_{ji}(y'_j - y'_i).
\end{aligned}$$

We include the contribution of an event pair to the sums in the first of these equations by updating row x_j of the matrix and product vector as follows:

$$\begin{aligned}
m_{x_j,x_j} &\mathrel{+}= w_{ji},\\
m_{x_j,x_i} &\mathrel{-}= w_{ji},\\
m_{x_j,d} &\mathrel{+}= w_{ji}(q_j - q_i),\\
c_{x_j} &\mathrel{+}= w_{ji}(y'_j - y'_i).
\end{aligned}$$

Similarly, we include the contribution of an event pair to the sums in the second of the equations by updating row x_i of the matrix and product vector in this way:

$$\begin{aligned} m_{x_i,x_j} &\mathrel{-}= w_{ji}, \\ m_{x_i,x_i} &\mathrel{+}= w_{ji}, \\ m_{x_i,d} &\mathrel{-}= w_{ji}(q_j - q_i), \\ c_{x_i} &\mathrel{-}= w_{ji}(y'_j - y'_i). \end{aligned}$$

Finally, we rewrite the third partial derivative equation as

$$s'_{x_j} \sum w_{ji}(q_j - q_i) - s'_{x_i} \sum w_{ji}(q_j - q_i) + p \sum w_{ji}(q_j - q_i)^2 = \sum w_{ji}(q_j - q_i)(y'_j - y'_i).$$

We include the contribution of an event pair to the sums in this equation by updating row d (the pitch row) of the matrix and product vector in the following way:

$$\begin{aligned} m_{d,x_j} &\mathrel{+}= w_{ji}(q_j - q_i), \\ m_{d,x_i} &\mathrel{-}= w_{ji}(q_j - q_i), \\ m_{d,d} &\mathrel{+}= w_{ji}(q_j - q_i)^2, \\ c_k &\mathrel{+}= w_{ji}(q_j - q_i)(y'_j - y'_i). \end{aligned}$$

If the events in a pair are in the same column, the first two updates cancel because $x_j = x_i$. No updates take place if $q_j = q_i$, so contributions from events in the same row are neglected, resulting in a low pitch estimate if the events are sorted by displacement (see Section).

After all of the event pairs have been included, the matrix **M** and product vector **c** are complete. Before we can solve the matrix equation, however, we must impose a constraint on the matrix, because the system is indeterminate. To see this, let $\sigma'_k = s'_k + u$ for $0 \leq k < d$, where u is any real number. If $s'_{x_j} - s'_{x_i}$ is the scatter difference of an event pair, so is $\sigma'_{x_j} - \sigma'_{x_i}$ because

$$\sigma'_{x_j} - \sigma'_{x_i} = (s'_{x_j} + u) - (s'_{x_i} + u) = s'_{x_j} - s'_{x_i}.$$

The ambiguity was introduced by taking first differences. Following Gauss, we resolve it by taking the scatter of one of the columns to be known. It is simplest to consider the scatter to be zero. There is no loss of generality in this choice, which offsets the mean composite scatter by an amount equal to the composite scatter of the selected column, because if the scatter is taken to be some value other than zero, that value can be added to all of the scatter terms.

There are several ways to set the scatter of a selected roll column t to zero. The simplest removes row t and column t from the matrix, which can be achieved by overwriting row and column t with zero after the matrix is filled, or by refraining from filling them. Both approaches leave a vacant row and column that must be accommodated by the procedure that solves the matrix equation. However, this is not a new requirement because most rolls have many unused columns, leaving other vacant rows and columns.

With the results above, we are prepared to present an algorithm for refining composite scatter and pitch approximations. Much of this algorithm parallels the Algorithms in Section for refining slope and pitch.

The scatter model is subject to false solutions caused by aliasing if the scan contains a significant amount of skew, so the skew model must be applied first as described in Section to provide initial approximations to the slope M and pitch P. Since scatter is small, we can set the initial values of the composite scatter estimates $S'_0, S'_1, S'_2, \ldots, S'_{d-1}$ to zero. There is no danger of a spurious solution due to aliasing, as there is with skew.

The algorithm makes use of a ring buffer with a capacity of N events, where N is the number of previous events to be paired with each current event, a matrix **M** with dimensions $(d+1) \times (d+1)$, and a column vector **c** with dimensions $(d+1) \times 1$. For each event pair, we must compute the column spacing $x_j - x_i$ and the row spacing

$$q_j - q_i = \text{round}\left(\frac{(y_j - y_i) - M(x_j - x_i) - (S'_{x_j} - S'_{x_i})}{P}\right).$$

We must also compute the corrected displacement difference

$$y'_j - y'_i = (y_j - y_i) - M(x_j - x_i) - (S'_{x_j} - S'_{x_i}) - P(q_j - q_i),$$

and weight w_{ji}. In addition, we must select a roll column with at least one perforation as the column t for which the scatter is considered to be zero. The algorithm follows.

Algorithm 4. A first algorithm for refining composite scatter and pitch estimates S' and P.

procedure
▷ Initialize
    initialize ring buffer empty
    initialize $(d+1) \times (d+1)$ matrix $\mathbf{M} = \mathbf{0}$
    initialize $(d+1) \times 1$ vector $\mathbf{c} = \mathbf{0}$
    initialize total number of events n
    select active event type (actuate or release)
    select columns to be excluded
▷ Fetch next event
    for $j = 0$ to $n - 1$ **do**
        fetch event j
        if event j is not of selected type **then**
            continue
        end if
        if event j column is excluded **then**
            continue
        end if

▷ Fill matrix and vector
        if ring buffer is empty **then**
            install event j in ring buffer
        else
            for each event i in ring buffer **do**
                compute column spacing $x_j - x_i$
                compute row spacing $q_j - q_i$
                compute corrected displacement difference $y'_j - y'_i$

compute weight w_{ji}
if $(q_j - q_i) \neq 0$ **then**
$m_{d,d} \mathrel{+}= w_{ji}(q_j - q_i)^2$
$c_d \mathrel{+}= w_{ji}(q_j - q_i)(y'_j - y'_i)$
end if
if $(x_i - x_j) = 0$ **then**
continue
end if
if $x_j \neq t$ **then**
$m_{x_j,x_j} \mathrel{+}= w_{ji}$
$m_{x_j,x_i} \mathrel{-}= w_{ji}$
$m_{x_j,d} \mathrel{+}= w_{ji}(q_j - q_i)$
$m_{d,x_j} \mathrel{+}= w_{ji}(q_j - q_i)$
$c_{x_j} \mathrel{+}= w_{ji}(y'_j = y'_i)$
end if
if $x_i \neq t$ **then**
$m_{x_i,x_j} \mathrel{-}= w_{ji}$
$m_{x_i,x_i} \mathrel{+}= w_{ji}$
$m_{x_i,d} \mathrel{-}= w_{ji}(q_j - q_i)$
$m_{d,x_i} \mathrel{-}= w_{ji}(q_j - q_i)$
$c_{x_i} \mathrel{-}= w_{ji}(y'_j - y'_i)$
end if
end for
if ring buffer is full **then**
remove event at rear of ring buffer
end if
append event j to front of ring buffer
end if
end for

▷ Solve matrix equation and update parameter estimates
solve $\mathbf{M}[s'_0\ s'_1\ s'_2\ \cdots\ s'_{d-1}\ p]^\mathsf{T} = \mathbf{c}$
for $k = 0$ to $d - 1$ **do**
$S'_k \mathrel{+}= s'_k$
end for
$P \mathrel{+}= p$
end procedure

The index i is not required to perform the updates to the matrix elements and vector components, only the values of y_i and x_i, so there is no need to store i in the ring buffer.

Since the matrix **M** is symmetric and positive definite, it can be readily solved using symmetric Gaussian elimination without pivoting. The usual procedure must be modified to accommodate empty rows and columns.

As with the previous algorithms that find slope and pitch adjustments, this algorithm provides the adjustments for a single iteration, so it must be included within an iterate loop. Also as before, the number of iterations must be limited.

Minimizing Matrix and Vector Storage

For the procedure of the preceding section, much of the matrix storage—usually well more than half—is unneeded for two reasons: roll columns that lack perforations leave vacant rows and columns in the matrix that do not contribute to the solution, and the matrix is symmetric. In this section, we improve the procedure by removing unused rows and columns and the redundant matrix elements and vector components to minimize the storage requirements.

Most rolls have many columns that do not have perforations anywhere along the length of the roll. In particular, columns corresponding to notes near the extremes of the keyboard are often unused. To remove the resulting unused matrix elements and vector components, we define a mapping function $f(k)$ that maps each roll column k to a positive integer that is used as a matrix and vector index. The mapping is arbitrary; it is only necessary for each active column x_i (a column with at least one perforation along the roll length) to be mapped to a unique integer $X_i = f(x_i)$ in the range $0 \leq X_i < h$, where h is the number of active columns.

As before, any active roll column can be selected as the one for which scatter is taken to be known. Let t be the selected column. The implementation is simplified slightly by assigning $f(t) = h - 1$, a choice that we adopt in what follows. There is no loss of generality in this choice, because any active roll column can be mapped to $h - 1$. Since matrix row and column $h - 1$ are not used by column t, they must be assigned to the pitch to avoid introducing a vacant row and column.

The column numbers of inactive roll columns (those with no perforations) should be mapped to a single value beyond the range of the mapped active columns, to allow determining whether a given column is active or not by examining its mapped value. Mapping inactive roll columns to a positive value beyond the active range (such as h or d), rather than to a negative value, ensures that the mapped index of a roll column is less than $h - 1$ only for active roll columns other than t, simplifying the implementation slightly.

The mapping removes unused rows and columns from the matrix, thereby relieving the procedure that solves the matrix equation of the need to accommodate vacant rows and columns. To implement it, we define the composite scatter of a mapped column X_i as $\sigma'_{X_i} = s'_{x_i}$.

Mapping typically reduces the storage requirements by about 20%. Whether or not mapping is used, storage requirements can be reduced by almost half by solving the matrix equation using a procedure that exploits the symmetry of the matrix, such as symmetric Gaussian elimination, LDL^T decomposition (or its upper triangle counterpart, U^TDU decomposition), or Cholesky decomposition, allowing us to store only the lower or upper triangle. The only modification required to do this is to refrain from updating matrix elements outside the selected triangle.

Here is the relevant portion of the Algorithm 4 above, revised to use column mapping and the upper triangle of the matrix. These changes reduce the storage requirements to a minimum.

Algorithm 5. A second algorithm for refining composite scatter and pitch estimates S' and P.

procedure

```
▷ Initialize
    ...
    initialize upper triangle of h × h matrix M = 0
    initialize h × 1 vector c = 0
    ...
▷ Fetch next event
    for j = 0 to n − 1 do
        ...
▷ Fill matrix elements and vector components
        if ring buffer is empty then
            install event j in ring buffer
        else
            for each event i in ring buffer do
                compute column spacing x_j − x_i
                compute row spacing q_j − q_i
                compute corrected displacement difference y'_j − y'_i
                compute weight w_ji
                if (q_j − q_i) ≠ 0 then
                    m_{h−1,h−1} += w_ji (q_j − q_i)^2
                    c_{h−1} += w_ji (q_j − q_i)(y'_j − y'_i)
                end if
                if (x_j − x_i) = 0 then
                    continue
                end if
                X_j ← f(x_j)
                X_i ← f(x_i)
                if X_j < h − 1 then
                    if X_i < X_j then
                        m_{X_i,X_j} −= w_ji [sic]
                    end if
                    m_{X_j,X_j} += w_ji
                    m_{X_j,h−1} += w_ji (q_j − q_i)
                    c_{X_j} += w_ji (y'_j − y'_i)
                end if
                if X_i < h − 1 then
                    if X_j < X_i then
                        m_{X_j,X_i} −= w_ji [sic]
                    end if
                    m_{X_i,X_i} += w_ji
                    m_{X_i,h−1} −= w_ji (q_j − q_i)
                    c_{X_i} −= w_ji (y'_j − y'_i)
                end if
            end for
            ...
        end if
    end for
```

▷ Solve matrix equation and update parameter estimates
    solve $\mathbf{M}[\sigma'_0\ \sigma'_1\ \sigma'_2\ \cdots\ \sigma'_{h-2}\ p]^\intercal = \mathbf{c}$
    for $k = 0$ to $d - 1$ **do**
        $X_k \leftarrow f(k)$
        if $X_k < h - 1$ **then**
            S'_k += σ'_{X_k}
        end if
    end for
    P += p
    ...
end procedure

The matrix **M** is symmetric and positive definite, so it can be solved in a number of ways, including Gaussian elimination without pivoting. It does not contain empty rows and columns, so the usual procedures do not need to be modified to accommodate them. As with the previous algorithms for determining adjustments to slope and pitch or scatter and pitch, it should be included within an iterate loop. Also as before, the loop must limit the number of iterations.

An Improved Algorithm for Refining Scatter and Pitch Approximations

A further improvement to the algorithm for refining scatter and pitch approximations increases the accuracy of the pitch adjustment by finding the pitch row separately from the scatter rows in the same way as is done in Section for the skew model. The two preceding algorithms can be modified to do this by using two ring buffers, one each for scatter and pitch.

Here is the algorithm of the previous section, which minimizes storage and uses only the upper triangle and last row of the matrix, modified to find the pitch matrix entries and vector component separately. The last row and column are no longer transposes of each other, so the last row must be of full width. Some widely-used computer languages, including C, provide an elegant way to provide storage for the upper triangle and lowest row efficiently by allocating matrix storage from the heap and organizing it as a pointer to an array of pointers to rows, allowing the individual rows to be of different lengths and to be only partially filled. The following algorithm makes use of the upper triangle to accommodate this pointer-based organization.

Algorithm 6. A third algorithm for refining composite scatter and pitch estimates S' and P.

procedure
▷ Initialize
    initialize scatter ring buffer empty
    initialize pitch ring buffer empty
    initialize upper triangle and last row of $h \times h$ matrix $\mathbf{M} = \mathbf{0}$
    initialize $h \times 1$ vector $\mathbf{c} = \mathbf{0}$
    initialize total number of events n
    select active event type (actuate or release)
    select columns to be excluded

```
▷ Fetch next event
  for j = 0 to n − 1 do
      fetch event j
      if event j is not of selected type then
          continue
      end if
      if event j column is excluded then
          continue
      end if

▷ Fill matrix and vector scatter rows
      if scatter ring buffer is empty then
          install event j in scatter ring buffer
      else
          for each event i in scatter ring buffer do
              compute column spacing x_j − x_i
              if (x_j − x_i) = 0 then
                  continue
              end if
              compute row spacing q_j − q_i
              compute corrected displacement difference y'_j − y'_i
              compute weight w_ji
              X_j ← f(x_j)
              X_i ← f(x_i)
              if X_j < h − 1 then
                  if X_i < X_j then
                      m_{X_i,X_j} −= w_ji [sic]
                  end if
                  m_{X_j,X_j} += w_ji
                  m_{X_j,h−1} += w_ji(q_j − q_i)
                  c_{X_j} += w_ji(y'_j − y'_i)
              end if
              if X_i < h − 1 then
                  if X_j < X_i then
                      m_{X_j,X_i} −= w_ji [sic]
                  end if
                  m_{X_i,X_i} += w_ji
                  m_{X_i,h−1} −= w_ji(q_j − q_i)
                  c_{X_i} −= w_ji(y'_j − y'_i)
              end if
          end for
          if scatter ring buffer is full then
              remove event at rear of scatter ring buffer
          end if
          append event j to front of scatter ring buffer
      end if
```

```
▷ Fill matrix and vector pitch row
        if pitch ring buffer is empty then
            install event j in pitch ring buffer
        else
            fetch event i at front of pitch ring buffer
            compute column spacing x_j − x_i
            compute row spacing q_j − q_i
            if (q_j − q_i) ≠ 0 then
                for each event i in pitch ring buffer do
                    compute column spacing x_j − x_i
                    compute row spacing q_j − q_i
                    compute corrected displacement difference y'_j − y'_i
                    compute weight w_ji
                    X_j ← f(x_j)
                    X_i ← f(x_i)
                    if X_j < h − 1 then
                        m_{h−1,X_j} += w_ji(q_j − q_i)
                    end if
                    if X_i < h − 1 then
                        m_{h−1,X_i} −= w_ji(q_j − q_i)
                    end if
                    m_{h−1,h−1} += w_ji(q_j − q_i)^2
                    c_{h−1} += w_ji(q_j − q_i)(y'_j − y'_i)
                end for
                if pitch ring buffer is full then
                    remove event at rear of pitch ring buffer
                end if
                append event j to front of pitch ring buffer
            end if
        end if
    end for

▷ Solve matrix equation and update parameter estimates
    solve M[σ'_0 σ'_1 σ'_2 ··· σ'_{h−2} p]^T = c
    for k = 0 to d − 1 do
        X_k ← f(k)
        if X_k < h − 1 then
            S'_k += σ'_{X_k}
        end if
    end for
    P += p
end procedure
```

Solving the Matrix Equations

The standard approaches cannot be used to solve the matrix equation of Algorithm 6, for which the matrix is a special case of a *mixed matrix* (a square matrix that contains a square symmetric positive definite submatrix in its upper-left corner). The algorithm given here can solve the matrix equation of Algorithm 6 or any of the matrix equations in this note that do not contain empty rows and columns.

Let **A** be an $n \times n$ mixed matrix that contains an $m \times m$ submatrix. The following algorithm uses Gaussian elimination to solve $\mathbf{Ax} = \mathbf{b}$, where **b** is the $n \times 1$ product vector and **x** is the $n \times 1$ solution vector, placed in the storage area for **b**. (A more elaborate approach uses Doolittle's method, either by itself or in combination with Cholesky or $U^T DU$ decomposition for the submatrix, eliminating the ratio r below.) It solves the matrix equation for a full square matrix if $m = 0$, a mixed matrix equation if $0 < m < n$, and a symmetric positive definite matrix equation if $m = n$.

Algorithm 7. Solve mixed matrix equation using Gaussian elimination.

```
procedure
▷ Forward elimination
    for j = 0 to n − 1 (or n − 2) do
        i ← j + 1

▷ Submatrix rows
        while i < m do
            r ← a_ji / a_jj
            for k = i to n − 1 do
                a_ik −= r a_jk
            end for
            b_i −= r b_j
            i += 1
        end while

▷ Rows beyond submatrix
        while i < n do
            r ← a_ij / a_jj
            for k = j + 1 to n − 1 do
                a_ik −= r a_jk
            end for
            b_i −= r b_j
            i += 1
        end while
    end for

▷ Back substitution
    for i = n − 1 to 0 do
        for j = i + 1 to n − 1 do
            b_i −= a_ij b_j
        end for
        b_i ← b_i / a_ii
    end for
end procedure
```

This algorithm does not include pivoting, which is not needed to solve any of the preferred matrix equations in this note. In particular, it is not required to solve the mixed matrix equation of Algorithm 6. Since the submatrix is symmetric and positive definite, pivoting is not required for the submatrix rows. The only row beyond the submatrix is the pitch row, which is strictly row diagonally dominant because scatter has only a weak effect on pitch, which we can see as follows.

Strict row diagonal dominance requires the magnitude of the diagonal element to be greater than the sum of the magnitudes of the other elements in the row. That is the case for the pitch row of the matrix of Algorithm 6, because the contribution of an event pair in different rows of the roll to the pitch row diagonal element is $w_{ji}(q_j - q_i)^2$, whereas the contributions to the off-diagonal elements are $w_{ji}(q_j - q_i)$ for row j and $-w_{ji}(q_j - q_i)$ for row i (see Section). An event pair in the same row of the roll does not contribute to the pitch row. If $|q_j - q_i| > 2$, the pitch row diagonal element grows faster than the sum of the magnitudes of the off-diagonal elements of the row. That is the case for most pitch row contributions, because for each row q_j we make contributions using many unique rows q_i, so $|q_j - q_i| \leq 2$ for at most two of them. In addition, since the contributions to the off-diagonal elements are both positive and negative, they tend to cancel.

Finding and Removing Residual Slope

The method of Algorithm 6 finds composite scatter and pitch, which is all that is required for creating an improved reduced scan for emulation or punch matrix reconstruction. The composite scatter may contain a small amount of slope, and its weighted mean will likely not be zero, but when it is removed from the reduced scan, the slope will be removed with it and the nonzero mean will alter the common offset, which is not of interest.

However, we may also wish to find *simple scatter*, that is, scatter free of slope and with a weighted mean of zero, along with an improved slope estimate that includes the slope from the composite scatter, if only to present the operator with an accurate skew estimate or an accurate display of the scatter. In this section, we find the *residual slope* (slope in the reduced scan not accounted for in the slope estimate), add it to the slope estimate, and remove it from the composite scatter, yielding simple scatter.

We find the residual slope by considering simple scatter to be a random error, the approach of the skew model. Finding the residual slope in this way avoids the negative serial correlation of the skew model (see Section), increasing the accuracy of the slope estimate. Composite scatter S'_k and simple scatter S_k are related by

$$S'_k = S_k + m'k + b',$$

where k is the column number, m' is the residual slope, and b' is the offset introduced by taking the composite scatter of one of the roll columns to be zero. We determine m' and b' by finding the line of best fit through the composite scatter, which we consider to be points on the Cartesian plane with coordinates (k, S'_k), using weighted least squares.

If there were perforations in all of the roll columns, the coordinates of the points would be $(0, S'_0)$, $(1, S'_1)$, $(2, S'_2)$, $\ldots$, $(d-1, S'_{d-1})$, where d is the total number columns in the roll. If there are no perforations in roll column k, the corresponding point (k, S'_k) does not exist, so the total number of points is h, the number of active columns in the roll, rather than d. The line of best fit is $m'k + b'$, so the residuals are

$$r_k = S_k = S'_k - m'k - b'.$$

A straightforward application of weighted least squares produces the matrix equation

$$\begin{bmatrix} \sum W_k & \sum kW_k \\ \sum kW_k & \sum k^2 W_k \end{bmatrix} \begin{bmatrix} b' \\ m' \end{bmatrix} = \begin{bmatrix} \sum W_k S'_k \\ \sum kW_k S'_k \end{bmatrix},$$

where W_k is the weight of S'_k (zero for inactive columns) and the summations extend over $0 \leq k < d$. We write this equation as $\mathbf{A}[b'\ m']^\intercal = \mathbf{c}$ by defining $\mathbf{A}$ and $\mathbf{c}$ in the obvious way. The matrix $\mathbf{A}$ is symmetric and positive definite.

We can show that solving this equation imposes the constraints of Section as follows. The first constraint is $\sum W_k S_k = \sum W_k(S'_k - m'k - b') = 0$, which we rewrite as

$$b' \sum W_k + m' \sum kW_k = \sum W_k S'_k,$$

the equation of the upper row of the matrix and product vector. Similarly, the second constraint is $\sum kW_k S_k = \sum kW_k(S'_k - m'k - b') = 0$, which can be rewritten as the equation of the lower row.

After solving for m' and b', the slope estimate is updated by $M \mathrel{+}= m'$. The simple scatter estimates are the residuals $S_k = S'_k - m'k - b'$.

The following algorithm finds simple scatter by determining the slope and offset of the composite scatter, removing them, and updating the slope estimate. The algorithm is divided into two parts. The first part finds the weights, which we approximate by the diagonal elements of the matrix $\mathbf{M}$ of Section . It accesses events in the same way as in previous algorithms, so finding the weights can be included in any of them, saving a pass through the reduced scan. The second part finds the residual slope and scatter offset, includes the residual slope in the slope estimate, and removes the slope and offset from the composite scatter, yielding simple scatter.

Algorithm 8. Refine slope estimate M and find simple scatter estimate S.

procedure
▷ Initialize
  initialize ring buffer empty
  initialize $d \times 1$ vector $\mathbf{W} = \mathbf{0}$
  initialize total number of events n
  select active event type (actuate or release)
  select columns to be excluded

▷ Fetch next event
  for $j = 0$ to $n - 1$ **do**
    fetch event j
    if event j is not of selected type **then**
      continue
    end if
    if event j column is excluded **then**
      continue
    end if

▷ Fill weights
    if ring buffer is empty **then**

```
            install event $j$ in ring buffer
        else
            for each event $i$ in ring buffer do
                compute column spacing $x_j - x_i$
                if $(x_j - x_i) \neq 0$ then
                    compute row spacing $q_j - q_i$
                    compute weight $w_{ji}$
                    $W_j \mathrel{+}= w_{ji}$
                    $W_i \mathrel{+}= w_{ji}$
                end if
            end for
            if ring buffer is full then
                remove event at rear of ring buffer
            end if
            append event $j$ to front of ring buffer
        end if
    end for

▷ Initialize and fill matrix and vector
    initialize upper triangle of $2 \times 2$ matrix $\mathbf{A} = \mathbf{0}$
    initialize $2 \times 1$ vector $\mathbf{c} = \mathbf{0}$
    initialize total number of roll columns $d$
    for $k = 0$ to $d - 1$ do
        if $W_k = 0$ then
            continue
        end if
        $a_{00} \mathrel{+}= W_k$
        $a_{01} \mathrel{+}= kW_k$
        $a_{11} \mathrel{+}= k^2 W_k$
        $c_0 \mathrel{+}= W_k S'_k$
        $c_1 \mathrel{+}= kW_k S'_k$
    end for

▷ Solve matrix equation and update estimates
    solve $\mathbf{A}[b'\ m']^\intercal = \mathbf{c}$
    $M \mathrel{+}= m'$
    for $k = 0$ to $d - 1$ do
        if $W_k > 0$ then
            $S_k \leftarrow S'_k - m'k - b'$
        end if
    end for
end procedure
```

The matrix **A** is symmetric and positive definite, so it is readily solved using Algorithm 6 or any variant of symmetric Gaussian elimination including Cholesky decomposition, or by substitution.

The Scatter Plot

Finding and removing skew and scatter from a scan of a music roll proceeds by a sequence of steps, each of which improves the accuracy of the parameter approximations obtained by the previous step. It is useful to provide the operator with visual displays of the approximate parameters as processing proceeds, to give a feel for the quality of the scan and to pinpoint issues that require further investigation and possibly remedial action, such as editing the visual scan or repairing the roll and scanning it anew.

As an example of this visual representation, Figure 1 gives the actuate scatter plot of Licensee Roll No. 7000, *Tango in D* by Albéniz-Godowsky, played by Leff Pouishnoff, issued March, 1925, and scanned by the author on July 20, 1997. The roll conforms to the American standard, with 100 columns spaced 9/inch across the paper width of $11\frac{1}{4}$ inches. The two outermost columns (0 and 99) are not used by Licensee rolls.

The plot shows the actuate scatter after finding initial skew and pitch approximations (Algorithm 3, Section), refining them (Algorithm 2, Section), determining the composite scatter and refining the pitch (Algorithm 6, Section), and removing the residual slope from the composite scatter (Algorithm 8, Section). These steps yield the slope, simple scatter, and refined pitch.

There are many unused columns in this roll, most of them near the extremes of the keyboard. Counting the dots in the scatter plot shows that only 78 columns are used. The roll is well made and exhibits a minimal amount of scatter, which is nevertheless large enough to interfere with reconstructing the punch matrix if it is not removed.

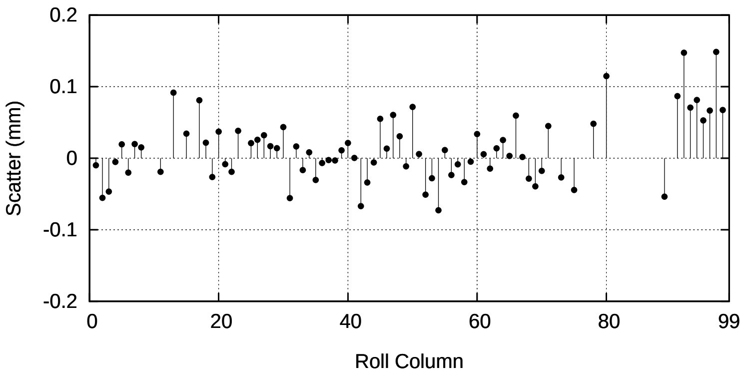

Fig. 1 Licensee 7000 Actuate Scatter

Finding and Removing Dynamic Skew

The skew in a music roll scan varies along the length of the roll. The peak-to-peak variation in skew can be as large as several rows, whereas the magnitude of the mean skew is rarely more than a single row unless the scanner camera is badly misaligned. Skew of this magnitude will cause audible timing and dynamic errors, and will thwart all attempts at punch matrix reconstruction.

The approaches in the preceding sections determine mean skew, scatter, and pitch with a high degree of accuracy. The next step is finding the dynamic skew (the variation in skew from the mean along the roll length) so that it can be removed.

Some variation in skew is caused by warpage of the roll itself, largely due to improper storage, but in many cases most of the variation is caused by faulty paper handling by the scanner roll transport. Whether the scanner advances the paper by pulling it with a takeup spool or a capstan, the paper must be manually centered at the start of the scan. If the paper is pulled with a takeup spool and the connecting tab at the start of the roll was not properly centered at the factory, the roll will be off center at the outset and tend to oscillate from side to side, causing a proportionate variation in skew.

Dynamic skew changes slowly over the length of the roll, so it is relatively uniform throughout a short length of paper, which suggests a way to determine it. We assume that the mean skew over a length of the roll about equal to its width, called a *page*, is the skew of the events near the center of the page. Beginning at the start of the roll, we find the mean skew of the first page and record it to create a lookup table, after which we advance the page boundaries along the roll length by a small amount, say 1/10 of the page length, and repeat the process. The resulting table can be used to remove dynamic skew from the scan. To determine the skew in a page, we find the slope in each page by minimizing the sum of the weighted squares of the residual

$$r_{ji} = (y'_j - y'_i) - m(x_j - x_i),$$

where the corrected displacement difference is given by

$$y'_j - y'_i = (y_j - y_i) - M(x_j - x_i) - (S_{x_j} - S_{x_i}) - P(q_j - q_i)$$

for simple scatter, or

$$y'_j - y'_i = (y_j - y_i) - M(x_j - x_i) - (S'_{x_j} - S'_{x_i}) - P(q_j - q_i)$$

for composite scatter, using the refined approximations to M, S or S', and P found in the previous sections. The weight w_{ji} should not include the skew term, because the slope estimate is fairly accurate and a page is only a short section of the roll; see Section for the simplified expression for the weight. The approximate slope of the first page must be found by exhaustive search as in Section , but each succeeding page can refine the slope of its predecessor. There may not be enough events in the first page to find the approximate slope reliably, in which case the length of the first page must be increased.

Removing the dynamic skew can reintroduce a small amount of static skew and scatter, so after dynamic skew is removed, the slope and scatter should be refined anew.

The Skew Graph

In addition to a scatter plot, a graph of the dynamic skew as a function of displacement is also valuable. Figure 2 shows the actuate dynamic skew of Licensee Roll No. 7000 after the steps listed in Section . The static skew is -0.534 mm.

The variation in skew along the length of the roll derives from warpage in the roll and from the paper-handling mechanism in the scanner. For badly warped rolls, or for scanners with defective paper handling, dynamic skew can exceed the pitch. The skew shown in Figure 2 is minimal, and is representative of what can be expected from scanning a well-made roll in good condition with a scanner that minimizes the meandering of the paper from side to side during scanning. Nevertheless, even the modest amount of dynamic skew that appears in Figure 2 will disturb punch matrix reconstruction if it is not removed.

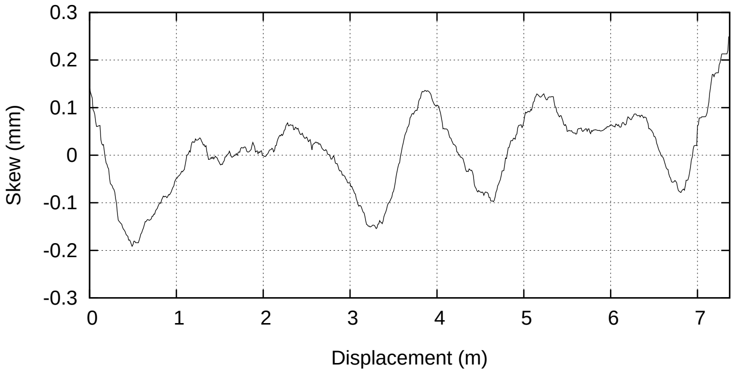

Fig. 2 Licensee 7000 Actuate Skew

Refining Release Scatter and Punch Length Approximations

The one parameter not addressed in the previous sections is punch length, the apparent displacement between the actuate event and the release event for a perforation consisting of a single hole. To place the release events in their intended positions, they must be moved by an amount equal to the difference between the punch length intended by the manufacturer and the sum of the mean punch length and release scatter.

Release scatter would be identical to actuate scatter if the punch length were uniform across the width of the roll. Thus, we can think of release scatter as consisting of the sum of actuate scatter and column-to-column differences in punch length, which are small and unvarying for a given roll. (The choice of actuate scatter as the reference is arbitrary; it is equally valid to refer actuate scatter to release scatter.) In this view, there is nothing to be gained from determining actuate scatter and release scatter separately, so we can focus our attention on finding the mean punch length and punch length differences instead. We adopt this approach in what follows, with actuate scatter as the reference scatter.

We start by finding refined approximations to the slope M, the scatter S, and the pitch P of the actuate events and removing the dynamic skew, all as presented in the previous sections. With these approximations at hand, let L be the mean punch length estimate, let $T_0, T_1, T_2, \ldots, T_{d-1}$ be the estimates of release scatter with a weighted mean of zero, and let t_k be the adjustment to T_k. We initialize L to the nominal punch length and set $T_k = S_k$ for $0 \leq k < d$, after which we refine the estimates by minimizing the sum of the weighted squares of the residuals $r_{ji} = (y'_j - y'_i) - t_j$. For each residual, we must compute the corrected displacement difference

$$y'_j - y'_i = (y_j - y_i) - M(x_j - x_i) - P(q_j - q_i) - (T_{x_j} - S_{x_i}) - L),$$

with the understanding that event j is a release event and event i is an actuate event. In addition to finding the corrected displacement difference, we must compute the row spacing for each event pair,

$$q_j - q_i = \text{round}\left(\frac{(y_j - y_i) - M(x_j - x_i) - (T_{x_j} - S_{x_i}) - L}{P}\right).$$

To update the release scatter estimates, we add the individual adjustments and subtract the weighted mean of the adjustments, which we also add to the mean punch length, yielding refined release scatter approximations and a refined approximation to mean punch length.

Algorithm 9. Refine estimates of punch length L and release scatter T.

```
procedure
▷ Initialize
    initialize ring buffer empty
    initialize (d + 1) × 1 vector t = 0
    initialize (d + 1) × 1 vector W = 0
    initialize total number of events n
    select columns to be excluded

▷ Fetch next event
    for j = 0 to n − 1 do
        fetch event j
        if event j column is excluded then
            continue
        end if

▷ Fill vectors
        if event j is actuate event then
            if ring buffer is full then
                remove event at rear of ring buffer
            end if
            append event j to front of ring buffer
        else if event j is release event then
            for each event i in ring buffer do
                compute column spacing x_j − x_i
                compute row spacing q_j − q_i
                compute corrected displacement difference y'_j − y'_i
                compute weight w_ji
                t_{x_j} += w_ji(y'_j − y'_i)
                t_d += w_ji(y'_j − y'_i)
                W_{x_j} += w_ji
                W_d += w_ji
            end for
        end if
    end for

▷ Update estimates
    L += t_d/W_d
    for k = 0 to d − 1 do
```

if $W_k > 0$ **then**
$T_k \mathrel{+}= t_k/W_k - t_d/W_d$
end if
end for
end procedure

As with several of the algorithms given in this note, Algorithm 9 provides adjustments for a single iteration, so it must be placed within an iterate loop as described for the previous algorithms, with a limit on the number of iterations.

We can avoid finding the simple scatter S by replacing it with the composite scatter S' if we also replace the release scatter with the *composite release scatter* $T'_0, T'_1, T'_2, \ldots, T'_{d-1}$. To make this change, substitute S' for S and T' for T in Algorithm 9 above.

Finding the mean punch length and release scatter is the last step prior to removing the errors from the reduced scan to create an improved reduced scan, free of skew and scatter. The improved file can be created in several different ways. The author has found this procedure to be effective:

- Find initial approximations to M and P (Algorithm 3, Section).
- Refine the initial approximations to M and P (Algorithm 2, Section).
- Initialize the composite scatter S' and refine it and the pitch approximation P using the scatter model (Algorithm 6, Section).
- Find the residual slope, add it to the slope approximation M, and remove it from the composite scatter approximation S' to create simple scatter S (Algorithm 8, Section). Display the simple scatter for the operator to review.
- Find the dynamic skew (Section), display it, and remove it.
- Refine the approximations to composite scatter S' and pitch P for the second time.
- Find the residual slope, add it to the slope approximation M, create the simple scatter S and display it, all for the second time.
- Find the dynamic skew, display it, and remove it for the second time.
- Find the mean punch length L and the release scatter T (Algorithm 9, Section).
- Create an improved reduced scan by removing M, S, and T from the reduced scan and moving the release events using L. Adjust the pitch and punch length in the improved reduced scan to the values intended by the manufacturer.
- If possible, reconstruct the punch matrix (Section , following).

Algorithm 7 (Section), which implements a form of Gaussian elimination without pivoting, can be used to solve all of the matrix equations that appear in these steps.

Reconstructing the Punch Matrix

The estimates of skew, actuate scatter, and release scatter found by the methods presented above can be removed from the reduced scan, yielding an improved reduced scan largely free of systematic errors. However, some vestiges of mean skew and scatter will remain, because even though the estimates are close to the true values, they are likely to differ slightly. Moreover, finding the dynamic skew is compromised by the fact that we must approximate the skew at a given point in the roll by the mean skew over a page, so some amount of dynamic skew will not be removed.

In addition to vestigial skew and scatter, there are the random disturbances caused by imperfect row advance in the perforator, irregular shapes of individual perforations, and random errors in the scanner. For many rolls, these errors can also be removed, yielding the punch pattern that controlled the perforator during production. This pattern is called the punch matrix, after the X-Y array of perforations in the sprocketed master roll used to control the perforator. A punch matrix is free of the systematic and random errors introduced by the perforator, roll, and scanner, so it is the preferred starting point for all further processing, including emulation.

It is usually possible to reconstruct the punch matrix from the scan of a well-made roll if the pitch is not too fine. Rolls with a pitch of about 0.75 mm or more, which includes all American-made rolls, are candidates for punch matrix reconstruction unless the roll is poorly made or suffers from severe paper slips.

Reconstructing the punch matrix removes errors from all sources by moving each actuate event and release event in the improved reduced scan to the nearest row. If the distance the event is moved is less than 1/2 row, the event will likely be restored to its intended position. We can gauge the reliability of this operation from the distance the event is moved. Small moves are more reliable than large ones. The row assignment for an event moved by a distance approaching 1/2 row is suspect, so for such moves the operator should be alerted to confirm the row assignment or alter it manually, based on visual inspection of the roll or the scan.

Before we can move an event to coincide with the nearest row, we must determine the displacement of that row. The only information we have available for doing this is the improved reduced scan, so we must find row displacements from event displacements. Fortunately, there is an analogous problem in the field of digital communications, namely recovering a local clock from an incoming data stream, that has been the subject of study for many decades, so there is a well-known solution that we can apply to determining row displacements.

The long-established solution uses a phase-locked loop, usually abbreviated PLL, to generate the local clock. A PLL is a closed-loop control system in which the forward path of the loop consists of a phase comparator, a loop filter, and an oscillator whose frequency is controlled by the loop. We can consider the feedback path as having unity gain. The loop ensures that the phase of the oscillator coincides with the phase of the incoming data stream, which implies that the frequency too matches that of the data stream.

To apply this solution to our problem, we must replace all phase-locked loop variables related to time with variables related to displacement. This is identical to the change of variables required to apply Fourier transforms, which are usually presented as a method for representing a function of time in terms of frequency, to represent a function of displacement in terms of spatial frequency. The relevant quantities and their units are:

Temporal quantity	Spatial quantity
cycles (unitless)	rows (unitless)
period (seconds/cycle)	pitch (meters/row)
frequency (cycles/second)	spatial frequency (rows/meter)
phase (cycles)	phase (rows)
time (seconds)	displacement (meters)

The spatial units are found from the temporal units by replacing cycles with rows and seconds with meters.

With this change in variables, we can reconstruct the punch matrix using a phase-locked loop. The first question that arises is what type of PLL to use. In order of increasing capability and decreasing stability, the three most-used PLL configurations are called Type 1, Type 2, and Type 3; they differ only in the complexity of their loop filters.

Loop stability is maximized by using the simplest PLL that will accommodate the expected disturbances in the incoming data stream. Here are the steady-state phase errors in the locally-generated clock in response to three different disturbances for each of the three PLL types:

Disturbance	Type 1	Type 2	Type 3
Phase step	zero	zero	zero
Frequency step	constant	zero	zero
Frequency ramp	increasing	constant	zero

Zero phase error ensures that the phase of the local clock generated by the PLL is identical to that of the incoming signal. A constant phase error signifies a fixed phase difference between the local clock and the input signal with a magnitude proportional to that of the frequency step. Increasing phase error signifies that the local clock phase increases with time. When this occurs, the PLL is not locked to the incoming signal.

For most music rolls the pitch, and thus the spatial frequency, is remarkably uniform from start to finish. (The case in which pitch increases uniformly is addressed in Section .) Thus we will not see frequency steps or frequency ramps, but step changes in phase caused by paper slips during perforating are common and must be accommodated.

Even though the pitch is nearly uniform, it is still subject to small increases caused by creep (see Section). The steady-state response to a pitch error is a constant phase error proportional to the magnitude of the spatial frequency errror, thus inversely proportional to the pitch error. However, since the mean pitch estimate produced by the method of Section is highly accurate, this phase error will be small, and will not disturb the operation of the loop.

These considerations imply that the best choice for punch matrix reconstrution is the simplest of the three, Type 1. However, since the pitch is extremely uniform and its value is known with a high degree of accuracy, the Type 1 PLL can be simplified further by replacing the variable-frequency oscillator with one that generates a fixed frequency, along with an element that provides variable delay. The PLL variant incorporating this replacement is known as a delay-locked loop, or DLL.

In essence, a DLL is identical to a PLL except that phase is the only state variable, so a first-order control loop in which the loop filter consists of an integrator yields a steady-state phase error of zero in response to a step change in phase; the steady-state pitch error response is constant phase error. These responses are identical to those of a Type 1 phase-locked loop. For these reasons, a DLL is the PLL type of choice.

Before reconstructing the punch matrix, there are two adjustments that must be made to the improved reduced scan.

First, we must increase the length of unusually short perforations caused by poorly-shaped holes due to dull punches, torn webbing resulting in partially-filled holes, and undersize manually-inserted holes. The length of short perforations should be increased to the mean punch length by moving the actuate and release events in equal amounts, but in opposite directions.

Second, we must adjust the displacement of each release event by moving it toward the start of the roll by a distance equal to the difference between the punch length and the pitch. (This distance is negative if the pitch is larger than the punch length, in which case the release event is moved toward the end of the roll.) This operation aligns release events with rows, a necessary condition for row assignment.

These adjustments can be performed one at a time or in a single pass that lengthens short perforations before moving the release events. Both approaches can reorder the event displacements. The punch matrix reconstruction method given here accommodates out-of-order events, but it is usually simpler to sort them by displacement in advance. If this is not done, there is a danger of assigning row 0 to the first event, only to discover that a succeeding event precedes it, requiring reassigning the previous events.

To reconstruct the punch matrix using a delay-locked loop, we define these variables:

$$
\begin{aligned}
i &= \text{event index } (0, 1, 2, \dots), \\
q_i &= \text{row assignment for event } i \text{ (unitless)}, \\
\Delta q_i &= \text{row advance from event } i-1 \text{ to event } i \text{ (unitless)}, \\
s_{q_i} &= \text{displacement of row } q_i \text{ (meters)}, \\
\sigma_{q_i} &= \text{adjusted displacement of row } q_i \text{ (meters)}, \\
y_i &= \text{displacement of event } i \text{ (meters)}.
\end{aligned}
$$

We also define the following constants:

$$
\begin{aligned}
p &= \text{pitch (meters)}, \\
w &= \text{weight (unitless)}.
\end{aligned}
$$

Here i, q_i, and Δq_i are integers. The other variables and the constants are real numbers.

The procedure for assigning row numbers to events is as follows. By definition, the row advance Δq_i is the integer that satisfies $|(y_i - (\sigma_{q_{i-1}} + p\Delta q_i)| \leq p/2$. (If y_i falls exactly halfway between two rows there are two such integers; either one can be used.) Solving for Δq_i yields $\Delta q_i = \text{round}\big((y_i - \sigma_{q_{i-1}})/p\big)$. We determine $q_i = q_{i-1} + \Delta q_i$ and its displacement $s_{q_i} = \sigma_{q_{i-1}} + p\Delta q_i$ and assign row q_i to event i. If the magnitude of the distance $y_i - s_{q_i}$ between y_i and the nearest row q_i approaches or equals $p/2$, the operator should be alerted to a questionable row assignment. We close the loop by finding the adjusted displacement $\sigma_{q_i} = (1-w)s_{q_i} + wy_i$, where w must fall within the range $0 < w < 1$ to ensure that σ_{q_i} will fall between s_{q_i} and y_i.

The weight w (not to be confused with the weight w_{ji} of residual terms of least-squares sums) determines the loop gain, and must be chosen with care. If it is too small, the loop will not properly track changes in phase, possibly resulting in faulty row assignments. If it is too large, a single out-of-place event will disturb subsequent row displacements, again risking wrong row assignments. Experience suggests that the weight can be as large as $1/2$ for well-made rolls, but that it should be smaller for rolls that are poorly made. Experience shows that a value of $1/4$ is a good choice for general use.

This procedure requires an initial value for σ_{q_0}. The simplest choice is $\sigma_{q_0} = y_0$, which assumes that y_0 lies close to its intended position. An improved approach finds the sums of the weighted squared residuals for the events in the first page of the scan for a set of trial displacements offset from y_0 by a number of symmetrical equally-spaced offsets encompassing the range $-p/2$ to $p/2$. The offset that yields the minimum sum is added to y_0 to yield the initial value of σ_{q_0}.

In practice, only a single variable is required for each of q_i, Δq_i, s_{q_i}, and σ_{q_i}. Let the variables be q, Δq, s, and σ. We set $q = 0$ and initialize $\sigma = \sigma_{q_0}$ as found above, after which we process all of the events, including event 0, by updating the variables as follows:

$$\begin{aligned} \Delta q &\leftarrow \text{round}\big((y_i - \sigma)/p\big), \\ q &\leftarrow q + \Delta q, \\ s &\leftarrow \sigma + p\Delta q, \\ \sigma &\leftarrow (1 - w)s + wy_i. \end{aligned}$$

After processing all of the events, the punch matrix is complete.

Paper slips during perforating cause affected rows to be shorter or longer than usual, which can result in incorrect row assignments. In most cases, these can be avoided by an expanded procedure that includes a parameter t to specify the maximum expected row slip, where $-1/2 < t < 1/2$. A positive value of t corrects short rows, whereas a negative value corrects long rows. (In practice, short rows are much more common than long ones.) Let Δq_{slip} denote the slip row advance. The expanded procedure is:

$$\begin{aligned} \Delta q &\leftarrow \text{round}\big((y_i - \sigma)/p\big), \\ \Delta q_{\text{slip}} &\leftarrow \text{round}\big((y_i - \sigma)/p + t)\big), \\ q &\leftarrow q + \Delta q_{\text{slip}}, \\ s &\leftarrow \sigma + p\Delta q_{\text{slip}}, \\ \sigma &\leftarrow (1 - w)s + wy_i. \end{aligned}$$

The operator should be informed of a paper slip correction if $\Delta q \neq \Delta q_{\text{slip}}$.

The slip update procedure can be used in the absence of slips by setting $t = 0$, so it is not necessary to create two procedures and select one or the other depending on whether we wish to correct paper slips.

As a practical matter, it is useful to provide means to selectively exclude updating the adjusted displacement for one or more columns if they can give rise to spurious events. Columns near the edges of the roll are especially prone to generating such events if the edges are torn. Events for excluded columns are treated in the same way as other events, except that the last step (update σ) is omitted.

Punch matrix reconstruction is possible for most rolls that do not have too fine a pitch, too much row-to-row pitch variation, or severe paper slips. It is an important tool for creating accurate emulations and for making high-quality copies of rolls.

Stretched Rolls

Most music rolls are perforated by advancing the paper a fixed distance from one row to the next, resulting in uniform pitch from start to finish, but if rolls have been stored for years or decades while tighly wound, their overall length can increase slightly due to creep. Since the tension in a tightly-wound roll is higher near the end of the roll than near the start, creep will be more pronounced toward the end, and as a consequence the pitch will increase along the length of the roll. The increase is small; century-old rolls perforated with uniform pitch rarely exhibit a ratio of ending pitch to starting pitch exceeding 1.0005, small enough to be neglected when determining skew, scatter, and mean pitch and when reconstructing the punch matrix.

In contrast, some rolls were made with continously-increasing pitch to compensate for the uniform acceleration of the instruments that played them. Such rolls, which we call *stretched rolls*, exhibit a high pitch ratio. The only such rolls known to the author were made by the Rudolph Wurlitzer Company under U.S. Patent 1085986. A simple approach to accommodating scans of stretched rolls, whether or not the pitch increase is uniform, divides the roll into sections short enough to allow neglecting the increase in pitch in each section. The individual sections are processed separately, and the resulting reconstructed punch matrices are joined to form a whole. This method is suprisingly successful, given its clear shortcomings.

An obvious improvement removes stretch from the reduced scan before processing it. The usual concept of acceleration considers it as taking place in time, but it is equally valid to think of it as existing in space, which allows us to remove acceleration without regard to velocity or time. The displacement s of a roll is related to the displacement u at the surface of the takeup spool by the equation[6]

$$s = u + \tfrac{1}{2}Au^2,$$

where A is an acceleration constant determined by the paper thickness and takeup spool diameter. Solving this equation for u gives[6]

$$u = \frac{2s}{1+\sqrt{1+2As}}.$$

The spool diameter and paper thickness, and thus the acceleration constant, are known with a fair degree of accuracy for Wurlitzer rolls.

An optimal approach would extend the methods presented earlier in this note to refine the acceleration constant by considering acceleration to be one of the parameters to be determined using the Method of Least Squares. With a change of notation, let A denote an initial approximation to the acceleration constant, found from the paper thickness and takeup spool diameter, in units of meters/meter/meter (inverse meters). After removing the acceleration due to A, the displacement equations of Section ,

$$\begin{aligned} y_0 &= c + mx_0 + s_{x_0} + pq_0 + e_0, \\ y_1 &= c + mx_1 + s_{x_1} + pq_1 + e_1, \\ y_2 &= c + mx_2 + s_{x_2} + pq_2 + e_2, \end{aligned}$$

and so forth, would be expanded to include the acceleration adjustment a, yielding

$$\begin{aligned} y_0 &= c + mx_0 + s_{x_0} + pq_0 + \tfrac{1}{2}aq_0^2 + e_0, \\ y_1 &= c + mx_1 + s_{x_1} + pq_1 + \tfrac{1}{2}aq_1^2 + e_1, \\ y_2 &= c + mx_2 + s_{x_2} + pq_2 + \tfrac{1}{2}aq_2^2 + e_2, \end{aligned}$$

and so forth, where a is in meters/row/row. Taking first differences as before gives rise to the equation

$$y_j - y_i = m(x_j - x_i) + (s_{x_j} - s_{x_i}) + p(q_j - q_i) + \tfrac{1}{2}a(q_j^2 - q_i^2) + (e_j - e_i),$$

where $j = i + 1$. This equation poses what appears to be an insurmountable problem: there is no way to find the row positions q_j and q_i other than punch matrix reconstruction,

6 Stahnke, 'Acceleration'.

so we cannot form $q_j^2 - q_i^2$. In Section , we found the row spacing $q_j - q_i$ by rounding, which was possible because the spacing is small. There is no similar approach that can be used to find $q_j^2 - q_i^2$.

To circumvent this difficulty, we expand on the ad hoc approach outlined above to form an iterative procedure for determining acceleration. We start by determining the approximate acceleration A from the takeup spool diameter and paper thickness, after which we de-accelerate the improved reduced scan. We partition the result into two or more pages, each of an intermediate length (usually about 3-4 meters), long enough to contain sufficient events to form an accurate mean pitch estimate, but short enough to justify neglecting the pitch increase within a page. The pages can be of unequal lengths. We take the mean pitch for each page to be the pitch at the center of the page, and we use the pitch estimates to approximate the acceleration adjustment a corresponding to the acceleration remaining in the reduced scan. Finally, we update $A \leftarrow A + a$ and iterate until the required accuracy is achieved or until we have reached the point at which no further improvement is possible, which usually occurs after only a few iterations.

We determine a as follows. We start by considering the pitch p to be an incremental displacement Δs along the length of the paper. Similarly, we regard the pitch p_0 at the start of the roll, where the paper is in contact with the takeup spool, as an incremental displacement Δu at the surface of the takeup spool. With this notation, the pitch is

$$p = \Delta s = \frac{ds}{du}\Delta u \approx p_0(1 + au).$$

We therefore define the pitch p at any point along the length of a stretched roll with uniform pitch increase by $p = p_0(1 + au)$. With this definition, the rate of change of pitch with respect to takeup spool displacement is

$$\frac{dp}{du} = p_0 a.$$

We note that dp/du is also given by

$$\frac{dp}{du} = \frac{dp}{ds}\frac{ds}{du},$$

where dp/ds is the rate of change of pitch with respect to the roll displacement. Making the appropriate substitutions and solving for dp/ds yields

$$\frac{dp}{ds} = p_0 \frac{a}{1 + au},$$

which reflects the fact that dp/ds decreases along the length of the roll. The decrease is small because $au \ll 1$ throughout the roll if the acceleration adjustment a is small. We therefore neglect it, yielding the equation for a at the start where $s = u = 0$,

$$a = \frac{1}{p_0}\frac{dp}{ds},$$

which we use to approximate a throughout the roll length. To determine dp/ds, we find the line of best fit to the mean pitch estimates using least squares. The slope of this line is an approximation to dp/ds, and the offset is a refinement of the starting pitch p_0. We iterate until the magnitude of the slope is small. This method allows us to refine the acceleration constant, making it possible to determine and remove stretch from the reduced scan in addition to skew and scatter.

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Acceleration in Music Rolls

Wayne Stahnke

Abstract

When a music roll is played on an instrument of the period, the paper is pulled over a tracker bar onto a rotating takeup spool driven by a pneumatic or electric motor. The steadily accumulating layers of paper on the takeup spool increase its diameter, resulting in continuously increasing paper velocity. Many rolls compensate for this change in paper speed by a graduated increase in the lengths and spacings of the perforations along the direction of travel. An optical scan of such a roll includes this compensation, which must be removed when the scan is emulated for playing on an electronically-controlled acoustic piano or virtual piano to avoid the timing errors that would otherwise occur. We present a method for determining the compensation so that it can be removed.

Introduction

Most automatic musical instruments built during the first half of the twentieth century use lenghty rolls of perforated paper as their recorded medium. When a roll is played on one of these instruments, the paper is moved across a tracker bar that senses the presence or absence of the perforations. Most instruments advance the paper by pulling it with a rotating takeup spool, causing the paper to accelerate because the diameter of the takeup spool increases with the continuously-increasing paper load. The resulting speed increase is small if the roll is short and many rolls, especially rolls of popular music, make no attempt to adjust for it, but some manufacturers compensated for the acceleration by increasing the lengths and spacings of the perforations along the direction of travel. An emulator must determine this compensation and remove it to avoid the timing errors that would otherwise occur.

Not all instruments of the period accelerate their rolls. The Mills Violano-Virtuoso, which plays one or two violins and a piano with a 44-note compass, is one of the few that does not. In a Violano-Virtuoso, the paper passes over a contact roller that drives a flyball tachometer, which in turn controls the speed of the electric takeup spool motor with a make-and-break governor, yielding more-or-less constant paper speed. (Late models replace the flyball tachometer with a ring tachometer.) Other instruments of the era move the roll with a constant-speed capstan to achieve the same result.

In this note, we investigate the acceleration that occurs in instruments that pull the music roll with a takeup spool, a category that includes all player pianos and reproducing pianos. We start by considering the uniform acceleration that results from driving the takeup spool at a constant speed, which is the case for instruments that use an electric motor or a spring-wound motor with a centrifugal governor for the purpose, after which we investigate the acceleration compensation for certain types of rolls, Ampico and Welte-Mignon T-100 rolls in particular. Finally, we examine the consequences of driving the takeup spool with a pneumatic motor, which exhibits a significant droop in speed as the paper load increases during playing.

Uniform Acceleration

The first step in emulating a music roll is to reduce the visual scan created by the scanner to an ordered sequence of indications, called *events*, that specify the positions of the start and end of each perforation along the length of the roll, along with the positions across its width. A later step finds the times at which the events occur from their positions along the length. In this section, we develop a simple relationship that finds these times if the roll is pulled by a takeup spool rotating at a constant angular velocity, resulting in uniform acceleration. There are several ways to find this relationship. The derivation given here uses only simple mathematical tools and avoids calculus. To model the acceleration, we define the following variables:

$$\begin{aligned} r &= \text{radius of outer layer of paper on takeup spool (meters)},\\ s &= \text{paper displacement (meters)},\\ t &= \text{time (seconds)},\\ u &= \text{takeup spool surface displacement (meters)},\\ U &= \text{reciprocal of takeup spool displacement (inverse meters)}. \end{aligned}$$

We also define the following constants:

$$\begin{aligned} a &= \text{acceleration (meters/second/second)},\\ A &= \text{acceleration constant (inverse meters)},\\ h &= \text{paper thickness (meters)},\\ L &= \text{acceleration length (meters)},\\ r_0 &= \text{takeup spool radius (meters)},\\ v_0 &= \text{takeup spool surface velocity (meters/second)},\\ \pi &= \text{ratio of circumference of circle to diameter (unitless)}. \end{aligned}$$

With these definitions, we can find the radius r of the outer layer of paper on a takeup spool of radius r_0 in terms of the takeup spool surface displacement u by noting that r increases by the paper thickness h once per rotation of the takeup spool. For simplicity, we consider the cross-sectional paper profile to be a spiral, rather than stepped. The number of rotations is given by the takeup spool surface displacement u divided by the circumference of the empty spool, so $r = r_0 + h(u/2\pi r_0)$. For conciseness, we define the *acceleration constant* $A = h/2\pi r_0^2$, which gives the radius of the outer layer of paper as a function $r(u)$ of the spool displacement as

$$r(u) = r_0\,(1 + Au).$$

The acceleration constant serves as a measure of acceleration. An alternate measure is the *acceleration length* $L = \pi r_0^2/h = 1/(2A)$, the length of paper required to form a solid cylinder of radius r_0, that is, a conceptual cylinder of the same diameter as the empty takeup spool. Of the two measures, L is the more intuitive because it corresponds to a physical model that is easy to visualize.

We can find the radius r of the outer layer of paper on the takeup spool as a function of the paper displacement s as follows. The cross-sectional area πr^2 of the takeup spool and the paper accumulated on it is the sum of the cross-sectional area πr_0^2 of the takeup spool and the cross-sectional area hs of the paper load, that is, $\pi r^2 = \pi r_0^2 + hs$. Rearranging yields $(r/r_0)^2 = 1 + (h/\pi r_0^2)s = 1 + 2As$. This gives the radius of the outer layer of paper as a function $r(s)$ of the paper displacement as

$$r(s) = r_0\sqrt{1+2As}.$$

Equating $r(u)$ and $r(s)$ and solving for s yields

$$s = u + \tfrac{1}{2}Au^2,$$

which we call the *displacement equation*. Applying the quadratic formula gives u as

$$u = \frac{-1+\sqrt{1+2As}}{A},$$

where we disregard the negative root because only solutions for which $u \geq 0$ are of interest. This solution suffers from a loss of accuracy when the terms of the numerator are nearly equal in magnitude, which occurs when s is small (near the start of the roll) and when A is small (when there is little acceleration). It fails completely for $A = 0$. We overcome these shortcomings by solving for the reciprocal displacement $U = 1/u$ with $u \neq 0$ and inverting the result. Multiplying the displacement equation by U^2 gives

$$sU^2 - U - \tfrac{1}{2}A = 0,$$

and applying the quadratic formula to find the nonnegative root yields

$$U = \frac{1+\sqrt{1+2As}}{2s}.$$

Inverting gives the preferred solution for $u = 1/U$,

$$u = \frac{2s}{1+\sqrt{1+2As}},$$

which is not subject to the loss of accuracy of the first solution. Note that this equation gives the correct solution $u = 0$ for $s = 0$, even though the derivation assumes $u \neq 0$. It also gives the correct solution $u = s$ for $A = 0$. If $A \neq 0$, it can be written in terms of the acceleration length as

$$u = \frac{2s}{1+\sqrt{1+s/L}}.$$

The results thus far were derived from the geometry of the takeup spool and paper, and are independent of time. Next we assume that the takeup spool rotates at a constant angular velocity, which we show produces uniform acceleration of the paper. A constant angular velocity produces a constant velocity at the surface of the takeup spool, which is also the starting velocity v_0 of the roll, so the surface displacement is given by $u = v_0 t$. Substituting into the displacement equation gives

$$s = v_0 t + \tfrac{1}{2}Av_0^2 t^2,$$

which is just the standard equation for uniformly accelerated motion

$$s = s_0 + v_0 t + \tfrac{1}{2}at^2,$$

where the initial displacement is $s_0 = 0$, the initial velocity is v_0, and the acceleration is $a = Av_0^2$. This shows that the paper is accelerated uniformly in time and justifies the name "acceleration constant" for A.

We find the time at which an event at displacement s occurs by substituting the preferred solution for u into $u = v_0 t$ and solving for t. The result is

$$t = \frac{2s}{v_0\left(1+\sqrt{1+2As}\right)}.$$

As before, if $A \neq 0$ we can write this equation in terms of the acceleration length as

$$t = \frac{2s}{v_0\left(1+\sqrt{1+s/L}\right)}.$$

Acceleration Constants

The model derived in the previous section requires knowledge of the acceleration constant A or the acceleration length L to find the acceleration. In this section, we consider data from surviving documents and artifacts of various pneumatic reproducing pianos to determine or estimate the values of L for a few types of music rolls.

Ampico Rolls

The acceleration length is known exactly for rolls recorded on the late Ampico recorder, which replaced an earlier recorder that may have used capstan drive (see U.S. Patent 1,370,614). In the new recording machine, the takeup spool diameter was 2.75 inches and the paper thickness was considered to be 0.00265 inches, as described in Ampico Research Laboratory Experiment No. 191 (February 24, 1929). The document is now part of the Howe Collection of Musical Instrument Literature, ARS.0167, Stanford Archive of Recorded Sound, Stanford University. It is located in Box 260, Folder 11. These values yield an acceleration length of

$$L = \frac{\pi \times (2.75/2)^2}{0.00265} = 2241.35 \text{ in} = 56.930 \text{ m}.$$

The acceleration constant is $A = 1/(2L) = 0.008784 \text{ m}^{-1}$. This is also the acceleration constant of late Ampico playback instruments, determined as follows.

To find the takeup spool diameter in the New Ampico (now commonly referred to as the "Ampico B"), introduced in 1929, we refer to *The Ampico Service Manual 1929*, which states that at Tempo 87.5 the takeup spool should rotate at 12 rpm (p. 43), so its angular velocity is $\omega = (12 \text{ revolutions/minute} \times 2\pi \text{ radians/revolution}) = 24\pi$ radians/minute. Since $\omega = v_0/r_0$, the takeup spool diameter is $D = 2r_0 = 2v_0/\omega$. Thus,

$$D = \frac{2 \times 8.75 \text{ feet/minute} \times 12 \text{ inches/foot}}{24\pi \text{ radians/minute}} = 2.785 \text{ inches}.$$

This is within about 1% of the diameter in the new recording machine. It seems likely that the diameter is intended to be 2.75 inches, and that the rotational speed of 12 rpm is an approximation used for convenience.

I own the takeup spool from the first New Ampico. Dr. Clarence Hickman of the American Piano Company acquired the piano soon after it was built. He still owned it when I interviewed him at his home in New York on May 19, 1979, and on that occasion he gave it to me. Its diameter is 2.738 inches, very close to the 2.75 inch diameter in the late recording machine. It seems reasonable to assume that the diameter was intended to be 2.75 inches.

Since New Ampico instruments use the same takeup spool diameter as the late Ampico note recorder, and since the takeup spool is driven by an electric motor with a centrifugal governor to maintain constant angular velocity, we conclude that New Ampico pianos exhibit the same acceleration as the late Ampico recorder. Thus the compensation in the roll cancels the acceleration on playback, resulting in correct timing throughout the performance.

We know that the late recording machine was in service on March 19, 1926, when the Ukrainian-born English pianist Benno Moiseiwitsch recorded Chopin's *My Joys*, Op. 74, No. 5, because the original roll that passed through the note recorder during the recording session survives. I acquired it in the late 1970s. The roll does not have any perforations, because work on it was abandoned prior to perforating. It may have been set aside in favor of a recording of the same composition by Moriz Rosenthal less than a month later, on April 12, 1926. Mr. Rosenthal's performance was issued as Ampico 66603 in October, 1926.

Most Ampico rolls made before the late recording machine was placed in service appear to have no compensation, consistent with a recorder using capstan drive. For example, the nine recordings Rachmaninoff made for Ampico on March 17, 1919, are not compensated, as I discovered in the mid-1990s when I emulated all of Rachmaninoff's rolls for the Telarc 2-CD set *A Window in Time*. I compared six of the nine Ampico recordings with records Rachmaninoff made of the same titles, three of which he recorded for Edison on March 23, 1919, less than a week after he recorded for Ampico. I found that matching the rolls to the records required playing them without acceleration. The remaining three rolls also benefitted from being played without acceleration to avoid the *decelerando poco a poco* throughout that resulted from considering the rolls to have any amount of compensation. The last of Rachmaninoff's uncompensated rolls is 65771, recorded on December 22, 1925, and for Victor on December 29, 1925, one week later.

Anthony Robinson, who has scanned and emulated many Ampico rolls, reports that some early Ampico recordings appear to be compensated to varying degrees. Since no documentation of the earlier recorder survives apart from the patent mentioned above, we can judge only by listening—a highly inexact way of approaching the problem.

Mr. Moiseiwitsch made a notable comment about acceleration in early Ampico rolls when he was interviewed on October 26, 1962 by Denys Gueroult for a radio broadcast aired by the BBC on December 23, 1962. The interview is available on BBC Archives LP 28654. When asked about the authenticity of his Ampico rolls, Mr. Moiseiwitsch replied, "But what, I will [say] staggered me, [were] some changes in the tempi that sounded to me as foreign to me was in the *Hark, Hark, the Lark* and the *Capriccio* of Brahms." These are Ampico 59731 and 59084, both early recordings. Mr. Moiseiwitsch went on to make it clear that by "changes in the tempi" he meant "acceleration." His remark is explained if the rolls in question do not contain acceleration compensation, and thus accelerate when played on Ampico instruments of any vintage.

Mr. Gueroult said in response: "That's very interesting, because the tempo on the piano roll is fixed, and once it's set on the piano, it remains the same throughout the playing of the roll," which reveals a complete lack of awareness of the issues addressed in this note. He continued by asking Mr. Moiseiwitsch if it were possible that he had changed his interpretation over the years, to which Mr. Moiseiwitsch tactfully replied that he was "dubious."

When I spoke with Dr. Hickman in 1979, I mentioned that there was some evidence, including a patent, that the earlier recording machine used capstan drive, and I asked him if that was so. His response was disappointing: he said that it was a very long time ago, and that he could not remember. Thus, we are left to guess what acceleration to use, if any, for early Ampico recordings.

Welte-Mignon T-100 Rolls

An original Welte-Mignon recording machine used in the United States for recording organ rolls, and possibly T-100 rolls, has found its way to the *Museum für Musikautomaten* in Seewen, near Basel. I examined the machine on September 20, 2019, thanks to the generosity of Dr. Christoph Hänggi, director of the museum, who gave me unlimited access to it. I found that the takeup spool is driven on one end by a large electric motor through a lengthy drive path. The opposite end drives a flyball tachometer that indicates the takeup spool speed on an uncalibrated dial. I measured the diameter of the takeup spool at 67.51 mm (2.658 inches).

The thickness of the paper used in the recording machine is unknown, but the paper was most likely of the same type as that used for the T-100 secondary master rolls, of which a number survive. These are easily identified by the fact that they are on lined white paper. I own one of these rolls (Welte-Mignon 4123, *Two Preludes* by Rachmaninoff, played by Vladimir Horowitz, perforated on March 18, 1927 by Kaiser). I measured the thickness of 10 layers of this roll using a dial caliper and found it to be 0.028 inches, so the thickness of one layer is 0.0028 inches (0.0711 mm).

This value is slightly too small because the caliper compresses the paper. To get a more accurate value, I measured the diameter of the roll at the start of the first perforation, with the paper tightly wound, and again at the end of the rewind perforation. These diameters are 1.975 and 1.095 inches, respectively. (There is a long trailer after the rewind perforation; the core diameter is 0.932 inches.) The cross-sectional area of the roll is $(\pi/4)(1.975^2 - 1.095^2) = 2.122\ \text{in}^2$. I measured the distance between the start and end points, which was 17.309 meters (681.46 inches), from which we find the paper thickness to be $2.122/681.46 = 0.00311$ inches (0.0790 mm).

If we accept that the Seewen recording machine, or a similar machine, was used to record T-100 rolls, and if we accept the paper thickness given above, we can find the acceleration length for T-100 rolls. It is

$$L = \frac{\pi \times (0.06751/2)^2}{0.0790 \times 10^{-3}} = 45.311\ \text{m}.$$

I also own a wooden T-100 takeup spool removed from a Welte-Mignon vorsetzer made in Germany after World War I. It has a diameter of 2.748 inches. This value is larger than the 67.51 mm (2.658 inch) diameter of the Seewen recording machine takeup spool, but only slightly so.

The similarity in the takeup spool diameters suggests that the designers regarded the diameters as identical, making the compensation in the rolls match the acceleration of the playback instruments if the droop in wind motor speed is neglected. Since T-100 instruments do not have feed spool brakes, the droop is small.

T-100 Phonograph Accompaniment Rolls

The T-100 rolls numbered 8001-8017 and 8501-8525, issued by the Welte-Mignon factory in Poughkeepsie around 1916-1917, are an alternate source of acceleration information. Very little is known about these limited-edition rolls, which accompanied Victor and Edison phonograph records. Synchronization was achieved by using timing perforations in an otherwise unused port in the tracker bar, adjacent to the rewind port. The lengths and separations of these perforations, for which the duty cycle is about 50%, increase along the length of the roll due to acceleration.

There seems to have been considerable interest in synchronizing player pianos and phonographs around the time these rolls were issued. A description of one interesting effort appears in an article entitled *Combined Piano Player and Talking Machine*, Scientific American, vol. 109, no. 16, October 18, 1913. The article names Charles F. Stoddard (designer of the Ampico mechanism) as the inventor, and explains that "On an 88-note player [piano], the duct [port] for the highest note, which is seldom used in the score [rarely played], is utilized to control the pneumatic coupling [synchronization]." Thus Mr. Stoddard's approach used only a single tracker bar port for synchronization, as we see in the T-100 accompaniment rolls.

The Welte-Mignon firm did not use Mr. Stoddard's invention, however. Instead, they built an apparatus called the *Synchronizing Device* or the *Synchronizer* (always capitalized at the time), invented by Heinrich Bockisch, brother of Karl Bockisch, the co-inventor (with Edwin Welte) of the Welte-Mignon. It sold for $200.00 in late 1916, by which time most of the accompaniment rolls had been issued. The Synchronizer was protected by U.S. Patents 1,279,639, 1,279,640, and 1,324,779, all of them bearing the title *Mechanism for Synchronizing the Operations of Moving Parts*. We know these details thanks to collector and historian David Krall, whose research included reviewing the extensive correspondence between the Poughkeepsie factory and John J. Raskob, a customer who purchased two Synchronizers, one each for his T-100 vorsetzer and his Welte Philharmonic organ.

It is clear from the patents that each synchronizing perforation in the roll corresponds to one rotation of the phonograph turntable. The phonograph was free running and the piano was synchronized to it to avoid the unacceptable variation in pitch that would occur if the roles were reversed. Since the turntable rotates at a uniform angular velocity, the synchronizing perforations occur at uniform time intervals. Today we would characterize the Synchronizer as a Type 1 phase-locked loop.

Many years ago, I set out to learn what I could about T-100 acceleration from the accompaniment rolls. Toward that goal, I read three such rolls, 8502, 8503, and 8504, corresponding to Edison Diamond Disk records 82067 (for 8502) and 82072 (for the other two rolls) on September 24, 1994. I say *read*, rather than *scanned*, because I used the electropneumatic roll reader that I built in the early 1970s for the transfer. (Optical roll scanning did not exist at the time; it was not until nearly two years later, in June of 1996, that advances in technology made it possible to replace my roll reader with the first optical roll scanner.) I determined the acceleration of these accompaniment rolls in the following way.

Let the number of synchronizing perforations be N. (I disregard the first perforation because it is longer than the others, with a larger gap between it and its successor, perhaps to allow the phonograph motor to come up to speed at the start.) Assign an index i in the range $0 \leq i < N$ to each perforation in the order in which they appear. Let s_i

and t_i denote the displacement and time of the leading edge of perforation i. Uniform acceleration produces the displacement

$$s_i = s_0 + v_0 t_i + \tfrac{1}{2} A v_0^2 t_i^2,$$

where s_0 is the leader length, v_0 is the velocity at the surface of the takeup spool, and A is the acceleration constant (see above). The time of the leading edge of perforation i is $t_i = Ti$, where $T = 60/rpm$ is the period of rotation and rpm is the rotational speed of the phonograph record in revolutions per minute. Thus, the surface of the takeup spool advances by a displacement $U = v_0 T$ with each rotation of the turntable, where U is a constant because it is the product of two constants. Thus $Ui = v_0 Ti = v_0 t_i$, and substituting yields

$$s_i = s_0 + Ui + \tfrac{1}{2} A U^2 i^2.$$

This equation relates paper displacement s_i and the displacement $u_i = Ui$ at the surface of the takeup spool, so it regards acceleration as taking place in displacement rather than time. It allows us to determine the acceleration using only the scan itself, without taking into account the tempo of the roll or the rotational speed of the phonograph, neither of which is accurately known. To simplify the derivations that follow, we rewrite it as

$$s_i = x_0 + i x_1 + i^2 x_2$$

by defining x_0, x_1, and x_2 in the obvious way. In terms of these quantities, the parameters are given by $s_0 = x_0$, $U = x_1$, $A = 2x_2/x_1^2$, $L = x_1^2/4x_2$.

We can find optimal estimates $\hat{x}_0$, $\hat{x}_1$, $\hat{x}_2$ for x_0, x_1, and x_2 by applying the Method of Least Squares as follows. The *residual* r_i of perforation i is the difference between the measured displacement and the displacement predicted by the uniform acceleration model, so it is given by

$$r_i = s_i - (\hat{x}_0 + i\hat{x}_1 + i^2\hat{x}_2).$$

The Method of Least Squares finds estimates of $\hat{x}_2$, $\hat{x}_1$, and $\hat{x}_0$ by minimizing the sum S of the squares of the residuals

$$S = \sum r_i^2 = \sum (s_i - \hat{x}_0 - i\hat{x}_1 - i^2\hat{x}_2)^2,$$

where the summations extend over $0 \le i < N$. When S is a minimum its gradient is zero, which implies that its partial derivatives with respect to all of $\hat{x}_0$, $\hat{x}_1$, and $\hat{x}_2$ are equal to zero:

$$\frac{\partial S}{\partial \hat{x}_0} = -2 \sum (s_i - \hat{x}_0 - i\hat{x}_1 - i^2\hat{x}_2) = 0,$$
$$\frac{\partial S}{\partial \hat{x}_1} = -2 \sum (s_i - \hat{x}_0 - i\hat{x}_1 - i^2\hat{x}_2) i = 0,$$
$$\frac{\partial S}{\partial \hat{x}_2} = -2 \sum (s_i - \hat{x}_0 - i\hat{x}_1 - i^2\hat{x}_2) i^2 = 0.$$

This yields three simultaneous linear equations in the three unknowns $\hat{x}_0$, $\hat{x}_1$, and $\hat{x}_2$,

$$\left(\sum 1\right) \hat{x}_0 + \left(\sum i\right) \hat{x}_1 + \left(\sum i^2\right)\hat{x}_2 = \sum s_i,$$
$$\left(\sum i\right) \hat{x}_0 + \left(\sum i^2\right)\hat{x}_1 + \left(\sum i^3\right)\hat{x}_2 = \sum i s_i,$$
$$\left(\sum i^2\right)\hat{x}_0 + \left(\sum i^3\right)\hat{x}_1 + \left(\sum i^4\right)\hat{x}_2 = \sum i^2 s_i,$$

which we can write in matrix form as

$$\begin{bmatrix} \sum 1 & \sum i & \sum i^2 \\ \sum i & \sum i^2 & \sum i^3 \\ \sum i^2 & \sum i^3 & \sum i^4 \end{bmatrix} \begin{bmatrix} \hat{x}_0 \\ \hat{x}_1 \\ \hat{x}_2 \end{bmatrix} = \begin{bmatrix} \sum s_i \\ \sum i s_i \\ \sum i^2 s_i \end{bmatrix},$$

or more compactly as $\mathbf{M}\hat{\mathbf{x}} = \mathbf{b}$, where the elements of $\mathbf{M}$ and the components of $\hat{\mathbf{x}}$ and $\mathbf{b}$ are as shown in the matrix equation above. The element in the upper-left corner of $\mathbf{M}$ is $m_{00} = \sum 1 = N$. We can minimize the calculations by finding the remaining elements using Faulhaber's formula for the sum of powers of a positive integer. Let $n = N - 1$. Faulhaber's formula gives the matrix elements as

$$\begin{aligned} m_{00} &= \textstyle\sum 1 &&= n + 1, \\ m_{01} = m_{10} &= \textstyle\sum i &&= \tfrac{1}{2}n^2 + \tfrac{1}{2}n, \\ m_{02} = m_{11} = m_{20} &= \textstyle\sum i^2 &&= \tfrac{1}{3}n^3 + \tfrac{1}{2}n^2 + \tfrac{1}{6}n, \\ m_{12} = m_{21} &= \textstyle\sum i^3 &&= \tfrac{1}{4}n^4 + \tfrac{1}{2}n^3 + \tfrac{1}{4}n^2, \\ m_{22} &= \textstyle\sum i^4 &&= \tfrac{1}{5}n^5 + \tfrac{1}{2}n^4 + \tfrac{1}{3}n^3 - \tfrac{1}{30}n. \end{aligned}$$

We can simplify the calculations further by noting (as Faulhaber did) that $\sum i^3 = (\sum i)^2$.

The matrix $\mathbf{M}$ is symmetric and positive definite, so the equation $\mathbf{M}\hat{\mathbf{x}} = \mathbf{b}$ is readily solved using symmetric Gaussian elimination or any of its variants. After solving the matrix equation, we can find $U = \hat{x}_1$ and $L = \hat{x}_1^2/4\hat{x}_2$.

I applied the Method of Least Squares in this way to Welte-Mignon 8502. Doing this revealed a problem: a plot of the residuals shows that individual perforations are as much as 5 mm ahead or behind the positions they would occupy if the takeup spool angular velocity and the turntable angular velocity were truly constant, as we see from Figure 3. The phonographs of the period were driven by spring-powered motors equipped with centrifugal governors, which provide excellent speed regulation, so we conclude that the angular velocity of the takeup spool in the recording machine varied over the recording time of several minutes.

The long runs of positive and negative residuals are characteristic of a random walk, which is a nonstationary process. Thus, the parameter estimates found from this model are unreliable because the requirement of stationary behavior is not met.

We overcome this difficulty in the usual way, by taking first differences. Doing this removes x_0, which is not of interest, from the equations. With the change of variables $x_1 \leftarrow x_0$ and $x_2 \leftarrow x_1$, this yields the difference equation

$$s_i - s_{i-1} = [i - (i-1)]x_0 + [i^2 - (i-1)^2]x_1 = x_0 + (2i-1)x_1.$$

We wish to find optimal estimates $\hat{x}_0$ and $\hat{x}_1$ for x_0 and x_1. The residual r_i is the difference between the measured and fitted displacements,

$$r_i = (s_i - s_{i-1}) - [\hat{x}_0 + (2i-1)\hat{x}_1].$$

The sum S of the squares of the residuals is

$$S = \sum r_i^2 = \sum [(s_i - s_{i-1}) - \hat{x}_0 - (2i-1)\hat{x}_1]^2,$$

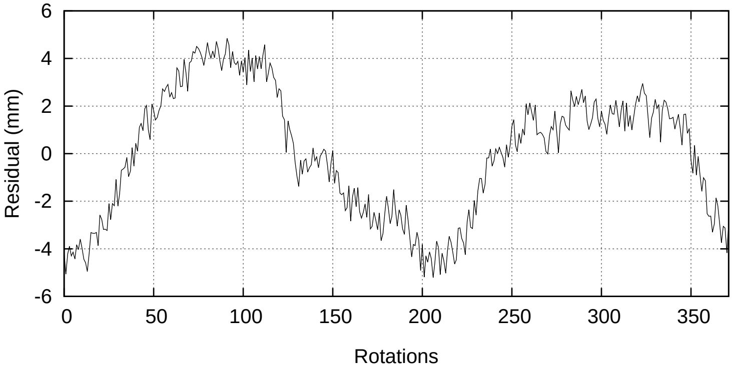

Fig. 3 Residuals for Welte-Mignon 8502

where the summations extend over $1 \le i < N$. The Method of Least Squares minimizes S by equating its partial derivatives with respect to $\hat{x}_0$ and $\hat{x}_1$ to zero:

$$\frac{\partial S}{\partial \hat{x}_0} = -2\sum\left[(s_i - s_{i-1}) - \hat{x}_0 - (2i-1)\hat{x}_1\right] = 0,$$
$$\frac{\partial S}{\partial \hat{x}_1} = -2\sum\left[(s_i - s_{i-1}) - \hat{x}_0 - (2i-1)\hat{x}_1\right](2i-1) = 0.$$

This is a system of two linear equations in the two unknowns $\hat{x}_0$ and $\hat{x}_1$ that we write in matrix form as

$$\begin{bmatrix} \sum 1 & \sum(2i-1) \\ \sum(2i-1) & \sum(2i-1)^2 \end{bmatrix} \begin{bmatrix} \hat{x}_0 \\ \hat{x}_1 \end{bmatrix} = \begin{bmatrix} \sum(s_i - s_{i-1}) \\ \sum(2i-1)(s_i - s_{i-1}) \end{bmatrix},$$

or more concisely as the matrix equation $\mathbf{M}\hat{\mathbf{x}} = \mathbf{b}$. We can find the matrix elements directly by using the well-known identities for the sums of odd integers and their squares. As before, let $n = N - 1$. In terms of n, the matrix elements are

$$m_{00} = \sum 1 = n,$$
$$m_{01} = m_{10} = \sum(2i-1) = n^2,$$
$$m_{11} = \sum(2i-1)^2 = \tfrac{1}{3}n(4n^2-1).$$

We can simplify further by noting that $\sum(s_i - s_{i-1}) = s_n - s_0$. Substituting gives the matrix equation as

$$\begin{bmatrix} n & n^2 \\ n^2 & \frac{1}{3}n(4n^2-1) \end{bmatrix} \begin{bmatrix} \hat{x}_0 \\ \hat{x}_1 \end{bmatrix} = \begin{bmatrix} s_n - s_0 \\ \sum(2i-1)(s_i - s_{i-1}) \end{bmatrix}.$$

The matrix $\mathbf{M}$ is symmetric and positive definite, so the matrix equation can be solved as before, but since the matrix dimensions are only 2×2 it can also readily be solved by substitution. After finding $\hat{x}_0$ and $\hat{x}_1$ we can determine $U = \hat{x}_0$ and $L = \hat{x}_0^2/4\hat{x}_1$.

The residuals for the first difference model for 8502 are well behaved, with no evidence of nonstationary behavior, as we see from Figure 4. In addition, the residual plot does not exhibit any discernable bowing, indicating uniform acceleration throughout the length of the roll, as expected. The first-difference residual plots for 8503 and 8504 are similar.

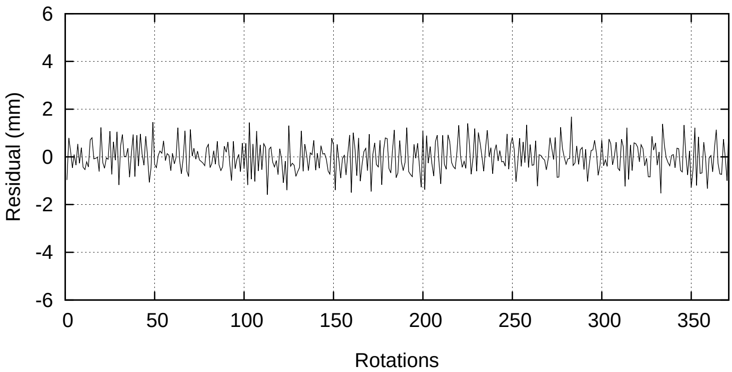

Fig. 4 First Difference Residuals for Welte-Mignon 8502

I performed calculations using first differences for the three T-100 accompaniment rolls that I read in 1994. Here are the results, along with the length of the perforated region of each roll.

Roll	Length (m)	N	U (mm)	L (m)
8502	14.008	372	34.41	40.43
8503	13.725	369	34.26	52.08
8504	10.707	290	33.69	38.89

The different acceleration lengths for the different rolls come as a surprise. Since there is a complete lack of documentation of the recording machine and its use, we must make some assumptions before attempting to explain them.

I assume that recordings for the two sides of a phonograph record were made on the same equipment at about the same time, most likely during the same recording session. This rules out using two different recording machines, changing the takeup spool, or using two different thicknesses of paper. With these assumptions, the only explanation for the different acceleration lengths is that two of the recordings were made one following the other, but without removing the first recording from the takeup spool before starting the second.

This explanation is consistent with recording 8503 on the heels of 8504 (these two recordings accompany Edison 82072). The acceleration length of 8504 is about 39 meters, and its length is almost 11 meters. If the operator allowed 2 meters of paper to accumulate on the takeup spool between recordings to provide a trailer on the first recording and a leader on the second of 1 meter each (about what we see in the secondary master roll of Welte-Mignon 4123), or if about 2 meters of paper passed while readjusting the takeup spool speed for a second recording, the acceleration length would be $39 + 11 + 2 = 52$ meters, a good fit. The recording machine may have been stopped between takes.

Note that 8503 could not have been recorded immediately following 8502, because 8502 is about 14 meters long. Adding this to its acceleration length of about 40 meters gives a total of 54 meters, larger than the acceleration length of 8503, without allowing for a trailer and a leader between recordings. If recordings were made in pairs, each pair corresponding to the two sides of a record, 8502 must have been recorded immediately prior to 8501.

In summary, we can draw these conclusions about the T-100 accompaniment rolls made in Poughkeepsie:

- The rolls exhibit uniform acceleration, consistent with pulling the paper with a takeup spool rotating at a constant angular velocity.
- The acceleration lengths differ from one roll to another and depend on whether the takeup spool was empty when recording started.
- The acceleration length for rolls recorded starting with an empty takeup spool is approximately 40 meters.

The acceleration lengths found from the accompaniment rolls are definitive. The synchronizing perforations occur at equal time intervals determined by a precision timing source, the phonograph motor governor. The Method of Least Squares combines the displacements of the perforations in an optimal way to form its result, yielding an accurate estimate of the acceleration length, which is independent of the rotational speed of the phonograph motor and the roll speed.

The acceleration length found from the recording machine takeup spool diameter and presumed paper thickness is about 10% greater than that found using the accompaniment rolls. The recording machine at Seewen was used to record organ rolls, some of which were accompaniment rolls, so we can be certain that the takeup spool diameter is correct. Thus, the paper used for recording must have been thicker than that of the secondary master rolls by about 10%, possibly due to a coating for recording.

Welte-Mignon T-98 Rolls

It is widely believed that T-98 rolls were perforated from the master rolls used for T-100 rolls. If this assumption is correct, a T-98 roll is just a T-100 roll shrunk in length and with the T-100 lock-and-cancel perforations replaced by extended perforations, implying an acceleration length L_{98} of T-98 rolls

$$L_{98} = \frac{v_{98}}{v_{100}} L_{100},$$

where v_{98} and v_{100} are the starting velocities of T-98 and T-100 rolls, respectively, and L_{100} is the acceleration length of T-100 rolls.

Welte-Mignon DeLuxe Rolls

Very little is known about the outstanding proprietary recording machine, known as the "seismographic" recorder, that was designed and built by the Licensee firm in the early 1920s for recordings sold under the DeLuxe label. It was used for DeLuxe rolls numbered 6321 (approximately) through 7925 (the last issue). Earlier recordings were transfers of T-100 rolls. To the best of my knowledge, no acceleration experiments have been done using these rolls.

The roll transports of Licensee instruments are similar to those of Ampico instruments built prior to 1929. Collector Joshua Rapier reports that the takeup spool diameters of his pre-1929 Ampico and Licensee pianos are 1.885 and 1.873 inches, respectively. These diameters match within better than 1%, and they are both very close to 1-7/8 = 1.875 inches, which suggests that that was the intended diameter for both. The paper thickness of Licensee rolls is very close to that of Ampico rolls, so the acceleration of Licensee instruments is likely to that of early Ampico pianos.

However, our goal is to match the acceleration of the seismographic recorder, rather than the acceleration of the playback instruments. It is reasonable to assume that the rolls include uniform acceleration, as is known to be the case for late Ampico rolls and T-100 phonograph accompaniment rolls, and that this acceleration attempted to match that of the playback instruments.

I assume uniform acceleration for DeLuxe rolls in my work. I take the paper thickness to be 0.00265 inches (Dr. Hickman's value for Ampico rolls), with a takeup spool diameter of 2-3/8 = 2.375 inches, yielding an acceleration length of about 42 meters. I settled on this value after extensive listening tests of Licensee rolls made from 1923 to 1930, the period that the seismographic recorder is known to have been in use.

Playback using Pneumatic Motors

A roll played on an instrument that advances the paper using a pneumatic motor does not undergo uniform acceleration, because the tension in the paper grows during playing due to the increasing takeup spool diameter and (in instruments with a feed spool brake) the decreasing feed spool diameter, causing a steadily-increasing droop in pneumatic motor speed as playing progresses. In this section, we develop a model for the increased roll tension and find its effect on paper speed. We demonstrate the validity of the model by using it to explain the measured paper speed of Ampico 63243, a very long roll.

Pneumatic Motor Speed

The speed of a pneumatic motor is controlled by an adjustable orifice interposed between the motor and a pressure regulator that provides a fixed reference pressure p_{ref}, ensuring that wind motor speed is unaffected by changes in pump pressure. The pressure p_{wm} inside the wind motor is proportional to the torque T, so $p_{\text{wm}} = k_1 T$, where k_1 is a constant of proportionality that depends on the construction of the motor.

The pressure drop $p_{\text{ref}} - p_{\text{wm}}$ across the orifice is proportional to the square of the flow i, the rate of change of the volume of air exhausted from the motor, so the flow is proportional to the square root of the pressure difference, that is, $i = k_2\sqrt{p_{\text{ref}} - k_1 T}$ for a constant of proportionality k_2 that depends on the geometry of the orifice.

The angular displacement of the wind motor is proportional to the volume of air exhausted from the motor. (This statement is true for one complete revolution of the wind motor if we neglect the compressibility of air, which is small at the pressures under consideration, and it is true instantaneously if in addition we neglect the ripple created by the use of individual pneumatics to rotate the crankshaft.) The angular velocity ω of the crankshaft is proportional to the flow i, so $\omega = k_3 i = k_2 k_3\sqrt{p_{\text{ref}} - k_1 T}$ for a constant of proportionality k_3 that depends on the construction of the motor.

The maximum angular velocity ω_0 occurs with the wind motor unloaded ($T = 0$), so $\omega_0 = k_3 k_2 \sqrt{p_{\text{ref}}}$. The maximum torque T_{max} that the motor can produce appears when it is stalled ($\omega = 0$), so $p_{\text{ref}} = k_1 T_{\text{max}}$. Substituting yields

$$\frac{\omega}{\omega_0} = \frac{k_2 k_3 \sqrt{k_1 T_{\text{max}} - k_1 T}}{k_2 k_3 \sqrt{k_1 T_{\text{max}}}} = \sqrt{1 - (T/T_{\text{max}})}.$$

Thus, the normalized speed-torque behavior of a pneumatic motor is independent of the parameters k_1, k_2, and k_3 determined by the construction of the wind motor, orifice, and governor. Figure 5 is a graph of the speed-torque characteristic of the wind motor. It applies to all wind motors, regardless of construction.

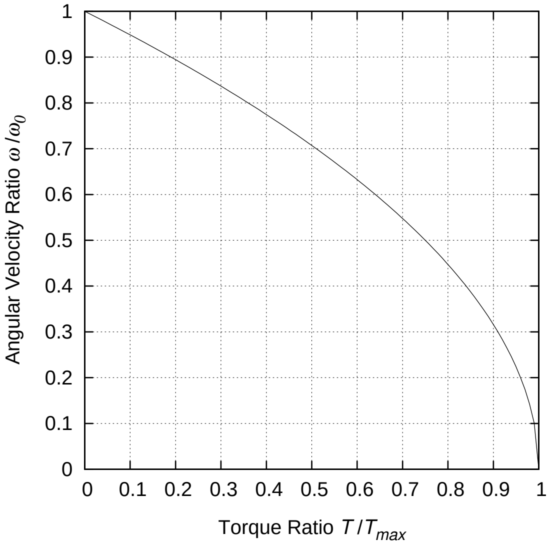

Fig. 5 Wind Motor Speed-Torque Characteristic

The designers of pneumatic instruments sized the wind motor such that the maximum available torque is significantly greater than the torque required near the end of the roll, where the load is at a maximum, so the operating region falls within the upper-left corner of this graph. In that region, the droop in wind motor speed is nearly proportional to torque.

Pneumatic Motor Speed Droop

We see from Figure 5 that the pneumatic motor speed depends on the torque required to move the paper, which results from the tension in the paper. The tension in turn results from tracker bar drag and the braking torque applied to the feed spool. We consider these sources in order.

Tracker bar drag is the force needed to overcome the friction between the tracker bar and the paper, which is pressed against the tracker bar by the difference between the atmospheric pressure on its outer surface and the lower windchest pressure on its inner surface. This is sliding friction, which we model in the usual way as $F_{\text{drag}} = \mu N$, where F_{drag} is the tension in the paper, μ is the coefficient of friction, and N is the normal force of the paper against the tracker bar. The force N is the product of the pressure p and the area A on which it acts, so $N = pA$, and by substitution $F_{\text{drag}} = \mu pA$. Since μ and A are constants, the tension F_{drag} is proportional to the pressure p.

Without special precautions, the increase in tension with tracker bar pressure would decrease the paper speed during loud passages, but some reproducing pianos (among them pre-1929 Ampico pianos and Welte-Mignon instruments) attempt to compensate for this undesired effect by altering the wind motor reference pressure p_{ref} in response to changes in the pressure p.

It is difficult to model the effect of tracker bar drag because the parameters μ and A that determine it are unknown, the pressure p is greater in loud passages than in soft ones, and the effectiveness of the compensation varies from one instrument to another, but we can approximate the drag torque by considering the pressure to be constant. Since μ and A are fixed for a given instrument, the force F_{drag} is also constant.

The torque presented to the takeup spool by F_{drag} is the product of F_{drag} and the radius r of the outer layer of paper on the takeup spool, which was found above to be $r = r_0\sqrt{1 + s/L}$, where L is the acceleration length. Thus, the torque acting on the takeup spool due to tracker bar drag is

$$T_{\text{drag}} = F_{\text{drag}} r_0 \sqrt{1 + s/L}.$$

For Ampico A instruments (Ampico pianos built before 1929) the takeup spool diameter is 1-7/8 inches, so the radius r_0 is $(1.875/2) = 0.9375$ inches. Assuming a paper thickness h of 0.00265 inches, the acceleration length L is

$$L = \frac{\pi r_0^2}{h} = \frac{\pi(1.875/2)^2}{0.00265} = 1041.95 \text{ in} = 86.83 \text{ ft}.$$

The feed spool brake maintains a small amount of tension in the paper to aid in tracking (ensuring that the perforations in the roll align laterally with the ports in the tracker bar). The brake usually consists of a spring-loaded felt pad that applies pressure to a smooth cylinder rotated by the feed spool. Thus the torque provided to the feed spool by the brake is constant, but the tension in the paper increases as playing progresses.

For the takeup spool, the torque T_{brake} is the product of the radius r of the outer layer of paper and the paper tension F, so $F = T_{\text{brake}}/r$. The same is true for the feed spool, so $F = T_{\text{feed}}/r'$, where T_{feed} and r' refer to the feed spool. Equating these expressions gives the *torque ratio*

$$T_{\text{brake}}/T_{\text{feed}} = r/r'.$$

The radius of the outer layer of paper on the takeup spool is $r = r_0\sqrt{1 + s/L}$ as before. For the feed spool it is given by $r' = r'_0\sqrt{1 + (S - s)/L'}$, where r'_0 is the radius of the feed spool core, $L' = \pi {r'_0}^2/h$ is the feed spool acceleration length, S is the length of the roll, and $0 \leq s \leq S$. Substituting yields

$$T_{\text{brake}} = T_{\text{feed}} \frac{r_0}{r'_0} \sqrt{\frac{1 + s/L}{1 + (S - s)/L'}}.$$

The feed spool core is 7/8 inches in diameter, so the feed spool acceleration length is

$$L' = \frac{\pi {r'_0}^2}{h} = \frac{\pi(0.875/2)^2}{0.00265} = 226.91 \text{ in} = 18.91 \text{ ft}.$$

Figure 6 gives a graph of the feed spool brake torque ratio for Ampico A instruments. It shows that the takeup spool torque increases more rapidly near the end of the roll than at the start, and that the starting torque (and thus the starting speed, which is a function of starting torque because of droop) depends on the length of the roll, so a longer roll will begin at a higher speed than a shorter one for the same tempo setting.

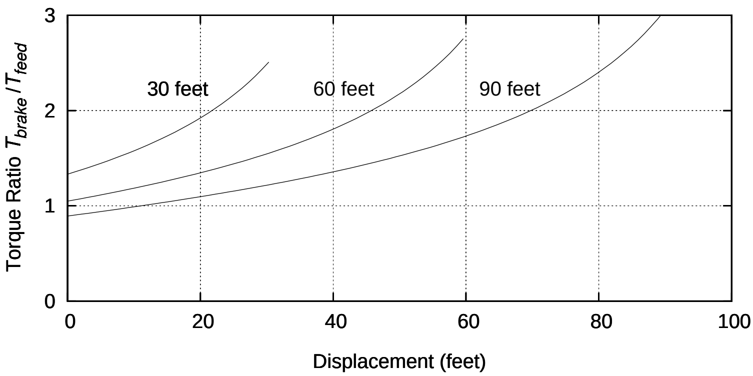

Fig. 6 Feed Spool Brake Torque Ratio

We are now in a position to find the paper speed v as a function of the displacement s. The retarding torque T at the takeup spool due to both tracker bar drag and the feed spool brake is the sum of the individual torques, so $T = T_{\text{drag}} + T_{\text{brake}}$. Substituting into the speed-torque equation $\omega = \omega_0\sqrt{1-(T/T_{\max})}$, which applies to the takeup spool as well as the wind motor crankshaft, gives the takeup spool angular velocity as $\omega = \omega_0\sqrt{1-(T_{\text{drag}}+T_{\text{brake}})/T_{\max}}$. Finally, multiplying by the radius $r = r_0\sqrt{1+s/L}$ of the outer layer of paper on the takeup spool yields the paper speed

$$v = \omega_0 r_0 \sqrt{\left(1+\frac{s}{L}\right)\left(1-\frac{T_{\text{drag}}+T_{\text{brake}}}{T_{\max}}\right)},$$

where T_{drag} and T_{brake} are functions of s as given above.

Acceleration in Practice

The results of the previous section explain the droop in roll speed, but they cannot predict it for a given instrument because the parameters are not known with sufficient accuracy. However, the reverse is true. If we measure the roll speed, we can find the parameters (up to a scale factor) by fitting the model derived above.

It appears that few measurements have been made of roll speed in practice. The only such measurement known to me was made by Anthony Robinson from an audio recording of Ampico 63243, *Hungarian Gypsy Dances* by Tausig, played by Josef Lhévinne. This recording, made for the BBC Sound Archives, was later issued on a monophonic LP record (Argo DA41) in 1966. The piano was a 1925 Grotrian-Steinweg instrument with a factory-installed Ampico mechanism, owned by John Farmer.

To make his measurement, Mr. Robinson first located, borrowed, and scanned an original copy of Ampico 63243. He then inserted timing marks into it to match the timing of the audio recording. In doing this, he found that the starting speed was Tempo 86.89 and the final speed was Tempo 104.98; the difference is due to acceleration. The length of the reconstructed punch matrix of 63243 is 24898 rows, excluding the rewind perforation and the roll number beyond it. Ampico rolls of the period were perforated at 356 rows per foot, giving a playing length of $24898/356 = 69.94$ feet.

The velocity indication on the roll is Tempo 85. The audio recording of John Farmer's piano starts out faster, which can be attributed (at least in part) to the contemporaneous test roll (Ampico 61391, *Inspector's Ampico Test Roll*) for calibrating the tempo. It is a medium-length roll, whereas 63243 is very long.

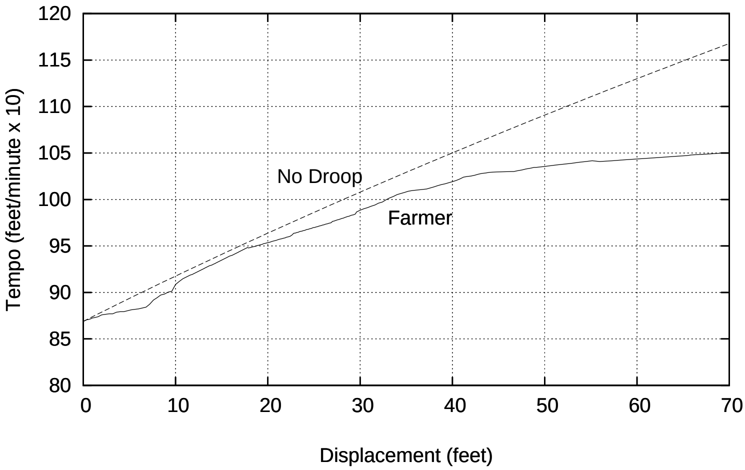

Fig. 7 Tempo of Ampico 63243 on John Farmer's Piano

The droop is the difference between the measured paper velocity and the velocity that it would have if the takeup spool speed were constant. The acceleration length for Ampico A pianos is 86.83 feet, as found above, so in the absence of droop the final tempo would be $v = v_0\sqrt{1 + s/L} = 86.89 \times \sqrt{1 + 69.94/86.83} = 116.75$, which implies that the wind motor speed falls by $104.98/116.75 = 0.8992$, for a droop of about 10%.

Figure 7 shows the tempo for Ampico 63243 as found by Anthony Robinson from the BBC recording of John Farmer's instrument, along with a graph of what the tempo would be in the absence of droop. These graphs show that the droop increases rapidly toward the end of the roll, as expected.

We can use Mr. Robinson's data set to demonstrate the validity of the droop model. We choose an arbitrary value for T_{max}, and we adjust scale factors for T_{drag} and T_{brake} for

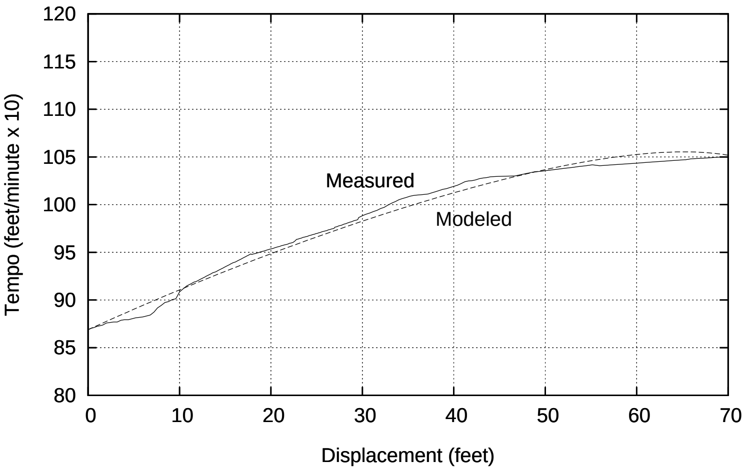

Fig. 8 Measured and Modeled Tempo for John Farmer's Piano

best fit. Figure 8 shows the resulting modeled paper speed along with the measured speed. The two speeds match closely, confirming the validity of the model.

An emulator should correct for acceleration compensation in the roll, but it would be a mistake to attempt to mimic the complex behavior of pneumatic instruments. There is no reason to believe that rolls of the period contain the compensation required to match the droop in wind motor speed caused by the variation in paper tension during playing. It is more likely that compensation was achieved by pulling the paper in the recording machine with a constant-speed takeup spool, yielding uniform acceleration, which is known to be the case for the late Ampico recorder and the recording machine used for T-100 phonograph accompaniment rolls.

Windchest Pressure and Hammer Velocity

Wayne Stahnke

Abstract

We find two relationships between windchest pressure and hammer velocity. The first of these, originally derived many years ago, was believed to be correct until recently. By comparing it with experiment, we show that it does not apply in all circumstances. We derive the second relationship from fundamental principles and confirm its validity by fitting it to several experimental data sets.

Introduction

One of the steps in emulating a reproducing piano roll performance is determining the hammer velocity that results from a given windchest pressure. In this note, we derive the relationship between windchest pressure and hammer velocity by forming a mathematical model of the playing mechanism and piano action and solving the differential equation that results, and we demonstrate that the solution is valid by using it to model several sets of experimental data.

However, we first derive an alternate relationship of historical interest, based on the principle of conservation of energy, that was believed for many years to be correct. We show that it is inconsistent with experimental data, so we now know it is false.

Solution Using Conservation of Energy

In the early 1980s, a relationship between windchest pressure and hammer velocity was derived independently by several researchers by applying the principle of conservation of energy. That relationship adequately explains well-known experimental data for a given note and a given pneumatic, as shown in Section , which supported the mistaken belief that the model describes the underlying physics. We derive that model in this section so that we can compare and contrast it with the correct model, derived in the next section.

Let w denote the windchest pressure and let V be the volume of air extracted from the pneumatic as the hammer moves from its rest position to the point of letoff. We assume that w does not change over the stroke, and that its magnitude is low enough for the compressibility of air to be neglected. Under these assumptions, the energy abstracted from the windchest is wV. Some portion of this energy is expended in elevating the dead weight of the hammer and other moving parts as the hammer approaches the string, and a further fraction is expended in overcoming dynamic friction, which we take to be independent of velocity. Let the energy expended for these purposes be W_cV, where W_c is a constant called the *pressure floor*.

Piano technicians go to great lengths to ensure that the action weight (the static force required to depress the keys) is uniform across the keyboard. The frictional forces too are uniform, because the bushings in the action are of identical construction across the keyboard, and the technician will "ease" (expand) them if they display any sign of binding, so a single value of W_c applies across the keyboard.

Energy is also expended in accelerating the inertial load consisting of the movable wall of the pneumatic, the linkage between it and the key, and the piano action, including the hammer. We assume that velocities are low enough to neglect flexing of the various levers in the piano action. We assume further that the moments of inertia of the action elements and the mass of the linkage can be modeled by an effective moment of inertia I at the pneumatic. (This assumption is justified in Section .) By the work-energy theorem, the energy expended in delivering the movable wall of the pneumatic with angular velocity ω to the point at which the hammer is at letoff is the resulting kinetic energy $(1/2)I\omega^2$.

Conservation of energy requires the energy abstracted from the windchest to equal the sum of the energy expended in supporting the action weight, overcoming friction, and accelerating the load, so $wV = W_cV + (1/2)I\omega^2$. Rearranging gives

$$\frac{1}{2}I\omega^2 = V(w - W_c).$$

Solving for ω and multiplying by the lever advantage between the movable wall of the pneumatic and the tip of the hammer at letoff gives the letoff hammer velocity v_h as

$$v_h = K_c(w - W_c)^{1/2},$$

where K_c is a constant of proportionality.

For reference, we list the assumptions used in the derivation above.

- Windchest pressure does not vary over the stroke.
- Pressures are low enough to neglect the compressibility of air.
- Friction is independent of velocity.
- Velocities are low enough to neglect flexing.
- The various masses can be modeled by an effective moment of inertia.

Solution Using the Stack Equation

An alternate approach to determining the relationship between windchest pressure and hammer velocity proceeds by forming a mathematical model of the playing mechanism and piano action and solving the differential equation that results. The form of the solution is identical with that of the previous section, but the predicted hammer velocities are lower. There are other differences, discussed in Section .

Formulating the Stack Equation

In this section we formulate the *stack equation*, a differential equation relating windchest pressure and the angular velocity of the movable wall of the pneumatic, by combining a mathematical model of the playing mechanism and a mathematical model of the piano action. The equation is

$$I\,\frac{d\omega}{dt} = wA - F - RA^3\omega^2.$$

We model the behavior of the playing mechanism by applying the pneumatic analog of Kirchhoff's Law of Potentials, which states that in an electrical circuit the sum of the increases or decreases in electric potential (voltage) around a closed path is zero. The pneumatic equivalent states that the sum of the increases or decreases in pressure around a closed path is zero. In what follows, we sum pressure increases along a path starting and ending with the atmosphere. We take atmospheric pressure to be the reference pressure for convenience, and we assign it a value of zero. (Summing the decreases, or choosing any other starting and ending point or reference pressure, would yield the same result.) We assume that the pressures at every point along the path are low enough to neglect the compressibility of air.

The first element in the path is the pump, which reduces the pressure to its lowest level in the path. The expression regulator, interposed between the pump and the windchest, raises the pump pressure to a somewhat higher level, still below atmospheric pressure, determined by special perforations in the music roll. Let the *decrease* in pressure from the atmosphere to the windchest be w. The pressure *increase* is the negative of this quantity, or $-w$. We assume that the regulator is capable of maintaining this pressure difference with the atmosphere as air is withdrawn from the pneumatic.

Next, the path passes through the valve and the connecting channel to the pneumatic. The limited throat area and throw of the valve, and the limited cross-sectional area of the channel, constrict the flow and thereby cause an increase in pressure. The pressures and flow rates in a reproducing piano give rise to turbulent flow that produces a pressure increase proportional to the square of the flow rate. Thus, the pressure increase due to the constrictions is Ri^2, where R is the *pneumatic resistance* of the valve and channel and i is the flow rate.

The last element in the path is the note pneumatic. We consider pneumatics to be transducers that convert pneumatic energy to mechanical energy. Energy conversion works equally well in the opposite direction; the pumps in most reproducing pianos consist of a set of large motor-driven pneumatics.

When the interior of the note pneumatic is below atmospheric pressure, the pressure difference between its exterior and interior walls creates a distributed force on the movable wall that produces a torque. Let the pressure difference be p and let the resulting torque be T. For pneumatics of the usual hinged design, sometimes called "clamshell" pneumatics, these quantities are related by a nonlinear function of the angular displacement θ of the movable wall because the airtight rubberized cloth used to enclose the pneumatic, which also contributes to the torque, folds inward as the pneumatic collapses. We model this behavior by $T = Ap$, where A is the *effective area* of the movable wall. Solving for the pressure increase yields $p = T/A$.

The work done by the movable wall as it rotates through the differential angle $d\theta$ is given by $Td\theta$. By the law of conservation of energy, this work is equal to the pneumatic energy pdV expended in bringing about the rotation, so $Td\theta = pdV$. Dividing both sides by dt yields $T(d\theta/dt) = p(dV/dt)$. Let $\omega = d\theta/dt$ be the angular velocity of the movable wall. The flow rate is $i = dV/dt$. Substituting these quantities and $p = T/A$ yields $T\omega = (T/A)i$, or $i = A\omega$.

By Kirchhoff's Law, the sum of pressure increases in the loop described above is zero, that is, $-w + Ri^2 + T/A = 0$. Substituting $i = A\omega$ and rearranging terms yields

$$T = wA - RA^3\omega^2,$$

where A is a function of θ, R is a constant, and the sense of the torque is such that upward motion of the movable wall corresponds to a positive magnitude for T. This is our mathematical model of the playing mechanism. It does not take into account the moment of inertia of the movable wall and the friction in the hinge, both of which are included in the piano action model that we find next.

A piano action consists of three linked levers, each of which rotates about an axis. The topmost lever consists of the shank and the hammer affixed to it, followed (proceeding downward) by the wippen and the key. The torque applied to the key by the pneumatic causes a note to speak by providing the mechanical energy required to raise the dead weight of the levers, counteract the friction in their felted bushings and linkages, and accelerate them to the desired speed. We assume that the levers are rigid, so no energy is expended in flexing them.

The dead weight of each lever exerts a torque on the lever determined by the mass of the lever, the location of its center of mass, the acceleration due to gravity, and the lever angle. Since the torque is affected by the angle, it changes as the lever rotates. At any angle, the torque can be reflected to the lever beneath by multiplying by the lever ratio between the levers, which changes as the levers rotate. If the reflected torque is added to the dead-weight torque of the lower lever, the sum models the dead weight of both. One further step models the dead weight of all three levers at the key by a composite torque, called the *effective dead-weight torque*, that varies with the angles of the levers.

Similarly, the frictional torque in the bushing of a lever can be reflected to the lever beneath, along with the torque due to the sliding friction of the linkages between the levers, yielding a torque at the key that models the friction in all three levers and their linkages. We make the usual assumption that dynamic friction is independent of velocity. However, the composite torque at the key, called the *effective frictional torque*, varies with the lever angles because of the changes in the lever ratios.

As with torque, the moment of inertia can be reflected from lever to lever, resulting in an *effective moment of inertia* at the key that varies with the angles of the levers. The moment of inertia of a lever must be multiplied by the square of the lever ratio, rather than by the lever ratio itself, when it is reflected to the lever beneath, because both the torque and the angular velocity of a lever are proportional to the lever ratio.

If the playing mechanism uses finger drive, the finger is yet another lever and the effective dead-weight torque, effective frictional torque, and effective moment of inertia at the key must be reflected to the finger. This step is omitted for poppet drive. In either event, the connection to the pneumatic is by means of a vertical connecting rod and a felted bushing attached to the movable wall of the pneumatic. The effective torques and effective moment of inertia at the key or finger can be reflected to the movable wall. Adding the torque and moment of inertia of the linkage and the movable wall itself yields the effective dead-weight torque, effective frictional torque, and effective moment of inertia that appear at the pneumatic.

Let F be the *retarding torque*, defined as the sum of the effective dead-weight torque and the effective frictional torque presented to the movable wall of the pneumatic. It has a positive magnitude, and its sense is such that it tends to cause downward motion of the movable wall. By Newton's Third Law of Motion, an opposing torque of the same magnitude and opposite sense is required to raise the dead weight and overcome friction. The difference between a driving torque T and this opposing torque, which has magnitude F, will accelerate an inertial load with an effective moment of inertia I according to $dL/dt = T - F$, where $L = I\omega$ is the angular momentum, by Newton's Second Law of Motion. Solving for T gives

$$T = \frac{dL}{dt} + F.$$

This is our model of the piano action, its linkage to the pneumatic, and the movable wall of the pneumatic. The drive torque is that produced by the pneumatic,

$$T = wA - RA^3\omega^2,$$

as found above. Equating these torques and rearranging terms yields

$$\frac{dL}{dt} = wA - F - RA^3\omega^2.$$

Solving this equation as it stands requires finding a differentiable analytic expression for the effective moment of inertia I, a complicated function of the geometry of the piano action and its linkage to the pneumatic, because $dL/dt = I(d\omega/dt) + \omega(dI/dt)$. We sidestep this difficulty by considering I to be a constant. We can take this step because engineer and piano technician John Rhodes has demonstrated analytically that the lever ratios between the various elements of the piano action are nearly constant. His colleague, engineer and piano builder Darrell Fandrich, confirmed the result experimentally. In response to my inquiry, John wrote (private communication, January 9, 2024):

> The ratio for the first few degrees of hammer rotation (coming off the rest position) is slightly higher than for the remaining rotation, which is very nearly constant. The higher initial ratio explains the observation that it takes a few extra grams of weight on the front of the key to initiate movement of the hammer from rest, which once initiated then proceeds to letoff without assistance. The slight non-linearity is created by the jack-knuckle interaction. The key-to-wippen ratio is constant for a properly-configured action.

We expect the lever advantage between the pneumatic and key to be nearly constant as well, because it is proportional to the product of the cosines of the angles of travel of the key and the movable wall of the pneumatic, both of which are small. Thus, we can consider the lever advantages as unchanged throughout the stroke, which implies that the product I of the moments of inertia of the individual elements, weighted by the squares of the lever advantages between them, is constant as well. With this approximation, we can omit the term $\omega(dI/dt)$ from the equation above, yielding the stack equation given at the beginning of this section.

The assumptions used to derive the stack equation are the same as those of Section , along with the additional assumption that the pressure that appears across the pneumatic resistance is proportional to the square of the flow rate. We summarize the definitions of the symbols used in the equation here for reference.

A = effective area of movable wall of pneumatic,
F = effective retarding torque of piano action and pneumatic,
I = effective moment of inertia of piano action and pneumatic,
R = pneumatic resistance due to constriction,
t = time,
w = magnitude of windchest pressure,
ω = angular velocity of movable wall of pneumatic.

Solving the Stack Equation

In this section, we solve the stack equation found in the previous section and show that its solution gives the hammer velocity v_h at letoff for a given note and given pneumatic as

$$v_h = K_s(w - W_s)^{1/2}.$$

This equation is identical in form to the one found in Section using the conservation-of-energy model. We start with the stack equation

$$I\,\frac{d\omega}{dt} = wA - F - RA^3\omega^2,$$

in which A and F are functions of the angular displacement θ of the movable wall of the pneumatic and each term denotes a torque; the last term gives the torque lost to pneumatic resistance in the valve and the passageway connecting it to the pneumatic. The equation relates angular velocity ω and time t, but to determine the angular velocity at the point of letoff we require an equation that relates ω and θ instead. To find it, we note that $d\omega/dt = (d\theta/dt)(d\omega/d\theta) = \omega(d\omega/d\theta)$. Substituting gives

$$I\omega\,\frac{d\omega}{d\theta} = wA - F - RA^3\omega^2.$$

Before considering the general solution of this equation, we solve it for the special case when R is negligible, which removes the last term. The resulting equation is separable. Multiplying by $d\theta$ and integrating yields

$$\frac{1}{2}I\omega^2 = w\int A(\theta)\,d\theta - \int F(\theta)\,d\theta + C.$$

The constant of integration C is determined by the initial condition $\omega = 0$ at $\theta = 0$, corresponding to the angular velocity and angular displacement of the pneumatic at the onset of motion. Instead of finding C directly, we make use of the Fundamental Theorem of Calculus, which states that the solution to the general initial value problem

$$y_0 = y(x_0), \quad f(x) = \frac{dy}{dx}$$

is given by

$$y = y_0 + \int_{x_0}^{x} f(t)\,dt,$$

where t is a dummy variable of integration. Using this approach, we find the solution as

$$\frac{1}{2}I\omega^2 = w\int_0^\theta A(x)\,dx - \int_0^\theta F(x)\,dx,$$

where x is a dummy variable of integration. This is the conservation-of-energy equation of Section ,

$$\frac{1}{2}I\omega^2 = V(w - W_c),$$

which we see by examining the integrals. Let the angular displacement of the movable wall of the pneumatic when the hammer arrives at the point of letoff be Θ, so that $\theta = \Theta$ at letoff. The first integral $\int_0^\Theta A(x)\,dx$ evaluates to the volume V of air extracted from the pneumatic, a constant. Similarly, the second integral $\int_0^\Theta F(x)\,dx$ evaluates to a constant that we write as W_sV. Substituting these quantities gives the equation at the start of this section, which is identical in form to the conservation-of-energy equation of Section . The solutions are identical, so $K_s = K_c$ and $W_s = W_c$.

Returning to the general case with $R \geq 0$, we find that the equation

$$I\omega\,\frac{d\omega}{d\theta} = wA - F - RA^3\omega^2$$

cannot be solved as it stands because it is nonlinear, so we linearize it by a change in the dependent variable from ω to the kinetic energy $u = (1/2)I\omega^2$ of the inertial load. On taking differentials, we have $du = I\omega\,d\omega$. Substituting yields

$$\frac{du}{d\theta} = wA - F - \frac{2R}{I}A^3u,$$

in which each term denotes a torque, as before. The coefficient of the last term, which represents the torque lost to pneumatic resistance, is inversely proportional to the effective moment of inertia I. Thus, the energy for a bass note will be greater then the energy for a treble note, because bass hammers are heavier than treble hammers due to the tapering of the hammer heads from bass to treble, so I is greater in the bass than in the treble.

To solve the linearized equation, we put it in the standard form

$$\frac{du}{d\theta} + Pu = Q$$

by defining $P(\theta) = (2R/I)A^3(\theta)$ and $Q(\theta) = wA(\theta) - F(\theta)$. In this form, it can be solved by multiplying each term by the integrating factor $e^{T(\theta)}$, where $T'(\theta) = P(\theta)$. We define $T(\theta) = \int P(\theta)d\theta = (2R/I)\int A^3(\theta)d\theta$, where we omit the usual constant of integration because the requirement $T'(\theta) = P(\theta)$ is fulfilled without it, simplifying the integrating factor.

The product of $e^{T(\theta)}$ and $du/d\theta + Pu$ is an integrable combination, and by the product rule it is the derivative of $e^{T(\theta)}u$. Thus, multiplying by $e^{T(\theta)}$ and integrating yields the equation

$$e^{T(\theta)}u = w\int e^{T(\theta)}A(\theta)\,d\theta - \int e^{T(\theta)}F(\theta)\,d\theta + C,$$

where the constant of integration C is determined by the initial conditions $\omega = 0$ (which requires $u = 0$) at $\theta = 0$. Applying the Fundamental Theorem of Calculus as before, we see that the solution incorporating the initial condition $\omega = 0$ at $\theta = 0$ is

$$e^{T(\theta)}u = w\int_0^\theta e^{T(x)}A(x)\,dx - \int_0^\theta e^{T(x)}F(x)\,dx,$$

where x is a dummy variable of integration. We rewrite this equation as

$$e^{T(\theta)}u = w[M(\theta) - M(0)] - [N(\theta) - N(0)],$$

where $M(\theta) = \int_0^\theta e^{T(x)}A(x)\,dx$ and $N(\theta) = \int_0^\theta e^{T(x)}F(x)\,dx$. Substituting $u = (1/2)I\omega^2$ and rearranging terms gives

$$\omega^2 = \frac{2e^{-T(\theta)}}{I}\big\{w[M(\theta) - M(0)] - [N(\theta) - N(0)]\big\}.$$

Let Θ and Ω be the values of θ and ω when the hammer has arrived at letoff. Substituting yields

$$\Omega^2 = \frac{2e^{-T(\Theta)}}{I}[M(\Theta) - M(0)](w - W_s),$$

where the pressure floor $W_s = [N(\Theta) - N(0)]\,/\,[M(\Theta) - M(0)]$ is a constant. Solving for Ω and multiplying the result by the lever advantage between the movable wall of the pneumatic and the hammer at letoff gives the letoff hammer velocity v_h as

$$v_h = K_s(w - W_s)^{1/2},$$

where K_s is a constant of proportionality. The values of both K_s and W_s are determined only by the geometry, mass, and friction of the elements of the pneumatic stack and piano action.

The energy abstracted from the windchest and the energy expended in overcoming the dead weight and friction of the moving parts are identical to those of the conservation-of-energy model. Energy is dissipated in the pneumatic resistance if $R > 0$, whereas no such energy loss takes place in the conservation-of-energy model. Thus for $R > 0$, the hammer velocity is lower for the stack model than for the conservation-of-energy model for a given windchest pressure.

Experimental Verification

The derivations in Sections and both give the relationship between letoff hammer velocity v_h and windchest pressure w as

$$v_h = K(w - W)^{1/2}.$$

In this section, we show that the equation above is a close fit for two historical data sets of hammer velocity as a function of windchest pressure, confirming the validity of the form of the solution of both derivations. There remains the problem of determining which of them represents the underlying physics. The difference between the two is that the stack equation model of Section takes the pneumatic resistance R into account, whereas the conservation-of-energy model of Section neglects it. Thus, deciding which model applies hinges on determining whether the pneumatic resistance is negligible.

The simplest way to determine which model is correct is by finding the hammer velocities for pneumatics of different sizes. From Section , the relationship for the conservation-of-energy model is

$$\frac{1}{2}I\omega^2 = V(w - W_c),$$

from which it follows that $\omega^2 = (2V/I)(w - W_c)$. This relationship shows that ω, and thus the hammer velocity, increases without limit as the volume V of the pneumatic increases. The stack equation predicts a different outcome. From Section , the stack equation is

$$I\frac{d\omega}{dt} = wA - F - RA^3\omega^2.$$

The terms that do not include the factor A can be neglected when A is very large, yielding $\omega^2 = w/RA^2$. This relationship shows that ω, and thus the hammer velocity, approaches zero as the area A of the movable wall of the pneumatic, and thus the volume, increases without limit. When the volume is large, almost all of the pneumatic energy abstracted from the windchest is dissipated in the pneumatic resistance.

Verification for a Pneumatic of a Given Size

To verify the correctness of the form of the solution that both models yield, I fitted it to the graphs of windchest pressure and hammer velocity that appear in *A Spark Chronograph Developed for Measuring Intensity of Percussion Instrument Tones*, by Clarence N. Hickman, in the inaugural issue of the Journal of the Acoustical Society of America, October, 1929 (pp. 138-146). Dr. Hickman worked at the Ampico Research Laboratory in the 1920s, and he was a founder of the Acoustical Society. His Curve 1 is reproduced below as Figure 9.

I set about fitting the relationship to the data points on this graph many years ago. To find the values to be fitted, I measured the points on the graph in a preprint of the paper that Dr. Hickman gave me when I interviewed him at his home in New York on May 19, 1979. I used a dial caliper to find the values as closely as possible, and I documented them in a Memorandum for Record, *Expression Tables for Ampico B Mechanism*, May 1, 1989 (unpublished).

I fitted the model to the data set using least squares. In doing this, I omitted the data points for the three lowest windchest pressures, labeled 000, 00, and 0 on the graph, because the points are close together and difficult to read accurately. In addition, the data points 000 and 00 are fictitious; in the Ampico mechanism, the lowest two intensities are achieved by moving the hammers closer to the strings, rather than by reducing the windchest pressure below that of the 0 level. The fitted parameters are

Hammer	K	W
Bass	0.4800	4.131
Treble	0.5642	4.136

where W is in units of inches of water and K contains a hidden units conversion factor because v_h is in meters/second, inconsistent with the units of W.

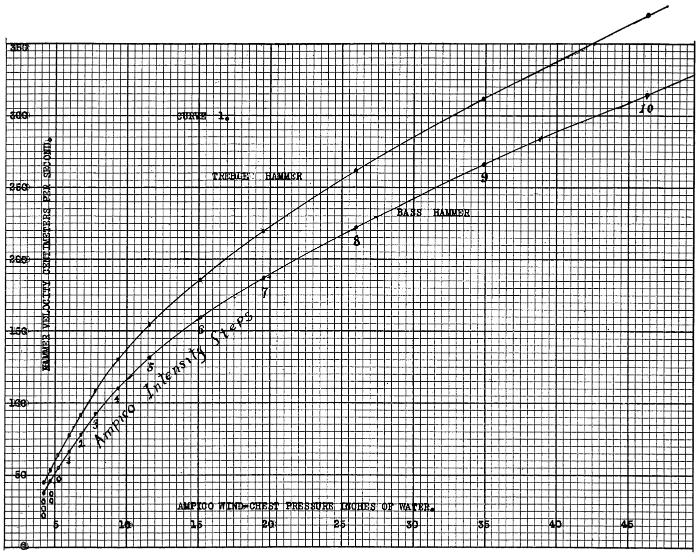

Fig. 9 Hickman's Curve 1 (Journal of the Acoustical Society)

The curves that result from these values are plotted in Figure 10, which shows close agreement between the measured data points and the fitted curves. However, the close agreement between the published curves and the Ampico steps of intensity seemed to me to be too good to be true, which led me to suspect that the published curves were calculated, rather than measured. I also noted that the values for *W* are nearly identical. The conservation-of-energy model predicts the same values if the frictional forces are identical, whereas the stack equation model predicts different values for the different hammer masses, suggesting that the conservation-of-energy model was used to calculate the curves.

To investigate the validity of the solution further, I turned to a data set created by Dr. Hickman several years earlier in an unsuccessful attempt to identify the source of a deficit in hammer velocity that he speculated could result from the difference between using a "puppet" or a "finger" to drive the key. The word "puppet" is a variant of "poppet" that has fallen into disuse; by "finger," Dr. Hickman meant a short lever. (Early Ampico pianos used poppet drive, whereas later ones used finger drive.) The data set appears in the memorandum for record *Comparison of hammer velocities using puppet drive and finger drive*, Experiment No. 113, September 30, 1925. The original document is now part of the Howe Collection of Musical Instrument Literature, ARS.0167, Stanford Archive of Recorded Sound, Stanford University. It is filed in Box 260, Folder 8.

Dr. Hickman seems to have taken unusual care with this experiment, judging from the close agreement among the four trials at each windchest pressure. This agreement also demonstrates that his spark chronograph hammer-velocity measuring system was highly repeatable.

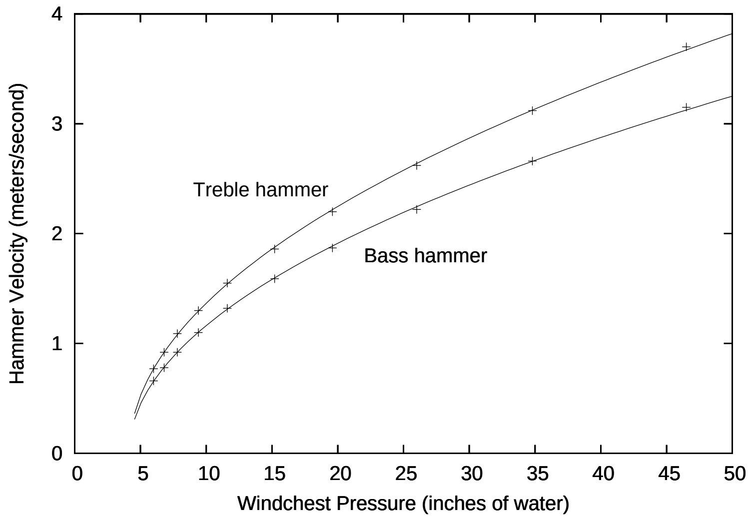

Fig. 10 Acoustical Society Measured and Fitted Hammer Velocity

Here is the data set as it appears in the memorandum. In this table, windchest pressure is in inches of water and the numbered columns give hammer velocity in centimeters per second for four different drive configurations using a finger or a poppet; the details do not concern us. The hammer velocities match closely for the four different drives, so Dr. Hickman concluded that the type of drive has little effect.

Pressure	[Trial]			
in Inches	1.	2.	3.	4.
4	82	80	80	78
5	103	106	103	102
6	123	123	123	120
8	153	149	150	151
10	179	179	175	179
15	230	222	224	227
20	267	267	267	267
25	308	303	300	308
30	333	330	328	328
35	357	357	357	350
40	400	385	374	400

The different drives were the only variable. Dr. Hickman notes that the tests used "the same primary valve; the same secondary valve; the same wind chest; the same pneumatic;

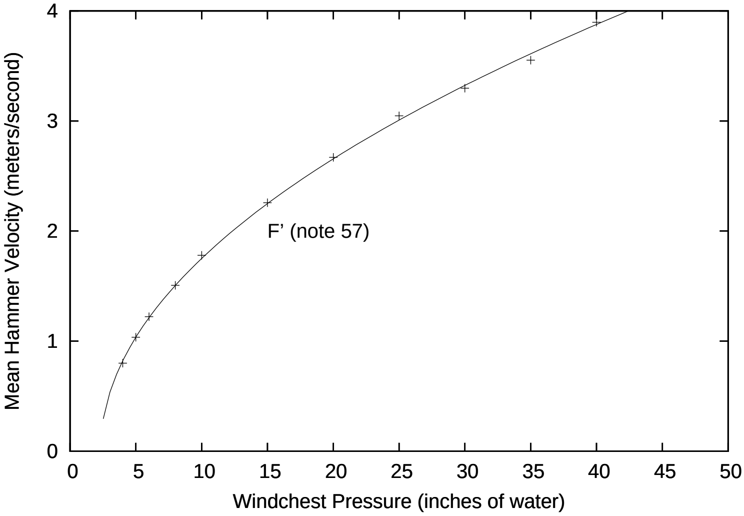

Fig. 11 Experiment No. 113 Measured and Fitted Hammer Velocity

the same hammer; the same key; in fact all the conditions were exactly duplicated." This suggests that we can consider the tests to be four trials under the same conditions, so I fitted the average of the four hammer velocities at each windchest pressure, again using least squares. The results are shown in Figure 11.

The fit is remarkably close, especially at lower windchest pressures and lower hammer velocities. The discrepancies between the measured and modeled hammer velocities are larger at higher velocities. This is to be expected, because the spark chronograph did not measure hammer velocity directly; instead, it found the elapsed time between two trip points along the hammer's travel, the second placed close to the point at which the tip of the hammer was in contact with the string, so hammer velocity and measurement error are both inversely proportional to the time interval, thus proportional to hammer velocity.

We conclude that the form of the solution of Sections and is correct to within the error of measurement using a spark chronograph, confirming the validity of the form.

Verification for Pneumatics of Different Sizes

In the previous section, we found that the relationship of windchest pressure to hammer velocity derived in both Sections and is valid. In this section, we establish that the derivation of Section does not predict the behavior of the pneumatics and valves used in Ampico pianos, which are representative of those used in other instruments. We conclude that the conservation-of-energy model of Section does not describe the behavior of pneumatic player pianos and reproducing pianos.

The data set that we use for further investigation was created by Dr. Hickman in Experiment No. 37, *Efficiency of Power Pneumatics as a function of their length*, June 24-26, 1924, also in the Howe Collection at Stanford University, in Box 260, Folder 11. The word "efficiency" in the title is misleading, because it suggests that the goal of the experiment was to determine the ratio of the kinetic energy of the hammer at letoff to the pneumatic energy abstracted from the windchest. Instead, it finds the hammer velocities produced by pneumatics of various lengths, but fixed in their other dimensions.

The pneumatic lengths were 2, 3, 4, 5, and 6 inches. All of the other parameters were unchanged. The experiment was conducted using a Chickering action model, presumably the same one used for Experiment No. 113, using the hammer for F′ (note 57). There were two trials at each pressure. Figure 4 gives graphs of the mean hammer velocity as a function of windchest pressure for the data set of Experiment 37. The values for the 4 and 5 inch pneumatics are so close that Dr. Hickman omitted the 4 inch pneumatic from his graph, and we do the same.

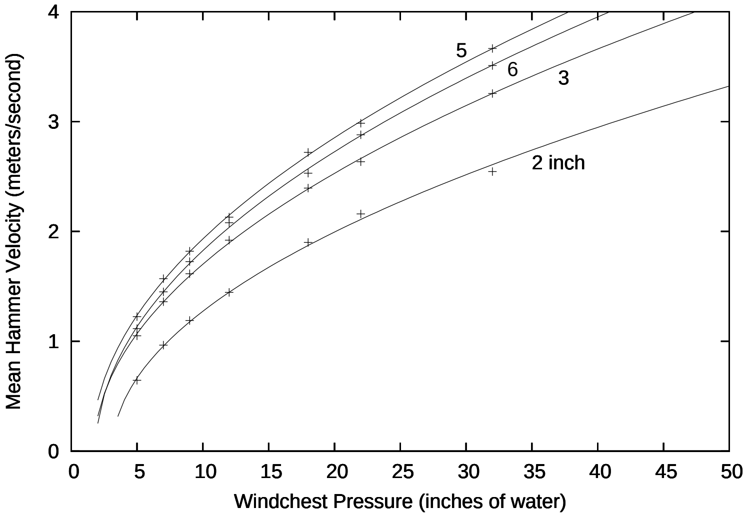

Fig. 12 Experiment No. 37 Measured and Fitted Hammer Velocity

We see from Figure 12 that hammer velocity increases as volume increases for small pneumatics, but that after reaching a peak with pneumatics of lengths 4 and 5 inches it drops off slightly as the length is increased further to 6 inches, exactly as expected. Dr. Hickman concluded "…it is easy to see that the maximum efficiency of the pneumatic is reached somewhere between the pneumatics of four and five inch length."

This behavior is explained by the stack model derivation of Section , but not by the conservation-of-energy derivation of Section , which predicts that hammer velocity will increase without limit as the volume of the pneumatic increases; it fails because it does not take into account the energy dissipated in the constrictions of the valve and connecting channel to the pneumatic. In contrast, the success of the stack model justifies its underlying assumptions and confirms the correctness of the formulation and solution of the stack equation.

Discussion

The conservation-of-energy model and the relationship between windchest pressure and hammer velocity that it implies were first derived by various researchers, including me, in the late 1980s, and I relied on it in the design of my emulators for many years thereafter. However, there were hints all along that the model did not fully explain the behavior that we see in pneumatic instruments, such as a statement in *The Ampico Service Manual 1929* that suggests that the Ampico firm went to unusual lengths to ensure that the valves that control the note pneumatics had a uniform resistance to the flow of air. A brief passage on p. 35 of the Ampico Service Manual states, "The amount of valve travel between its [the valve's] seats is very accurately adjusted so that all valves pass the same amount of air [at a given pressure]. To attain this accuracy, the top seat is pressed into the correct position by a specially designed automatic machine, the operation of which is controlled by the amount of air flowing through the valve."

A stronger hint appears in the discussion at the close of Experiment No. 37, in which Dr. Hickman stated "…it is believed that constriction either in the secondary valve or in the channels limits the velocity of the hammer and that the power or area of the pneumatic is not the all important question." As it turns out, Dr. Hickman's intuition was correct. This statement tells us too that in mid-1924, when the experiment was conducted, Dr. Hickman had not worked out the stack equation model of Section for himself. Whether he ever did so is open to question. He makes no mention of it in the reports of the Ampico Research Laboratory. However, in his paper for the Acoustical Society, he states that the energies of a bass hammer and a treble hammer are "approximately the same" for a given windchest pressure, which is true for the stack equation model (a bass hammer has slightly more energy) but not for the conservation-of-energy model, which predicts the same energy for the two hammers. That short statement may indicate that Dr. Hickman was in possession of the solution to the stack equation. There is no doubt that he had the background and skills required to derive it for himself.

In addition to the relationship of windchest pressure and hammer velocity, there are two further relationships that the emulator designer requires: one that gives the variation in hammer velocity across the keyboard, and another for the transport time from the rest position to the point of letoff, which also varies across the keyboard. Both topics are beyond the scope of this note.

Appendix

List of Figures

Glossary

This glossary contains a few terms from the context of self-playing pianos and, above all, from the context of piano roll digitisation. It is far from complete, as this could only be achieved within the framework of a systematic ABC of self-playing pianos and the associated topics, which does not yet exist. The desirability of such a lexical handbook has been demonstrated in the course of the research project on which this book was based, as many terms were by no means used consistently, especially in the non-English-speaking circles of the research community.

For this reason, some terms that are of particular importance for the topics covered in this book are taken up here and their use and meaning are explained very briefly in the context of this publication. For ease of understanding, these terms are not listed in strict alphabetical order, but are sorted into three subject areas: a) types, brands and components of self-playing pianos, b) types and components of piano rolls, and c) digitisation of piano rolls.

Types, brands and components of self-playing pianos

Disklavier brand of reproducing piano manufactured by Yamaha Corporation, Japan; first model introduced in 1987

Pianola originally the brand name of Aeolian's push-up piano player launched in 1897; it is now more widely regarded as the generic term for any player piano operated by a pianolist

player piano historical, pneumatically operated self-playing piano, which in many cases only plays the pitch and duration of the individual notes automatically with the help of the rolls provided for this purpose, while the player (pianolist) influences dynamics and tempo with the help of levers and foot pedals, and thus interprets the musical material

reproducing piano historical, pneumatically operated self-playing piano, which automatically reproduces the musical interpretation (tempo, dynamics, pedal) in addition to the pitch and duration of each note using the rolls provided for this purpose

self-playing piano unless otherwise specified, generic term used in this book for player pianos and reproduction pianos

take-up spool motor-driven spool onto which the roll is wound after it has passed over the tracker bar or through the scanning area

tracker bar part of the spool box of a self-playing piano with holes spaced to align with the perforation tracks on the paper roll. The tracker bar senses the perforations and controls their musical realisation

Types and components of piano rolls

acceleration continuously increasing velocity of paper when a roll is pulled through a piano by the take-up spool

chaining, webbing paper bridges inserted at intervals across long slots to strengthen the roll, thin enough to be invisible to the tracker bar which perceives the chains as continuous slots

hand-played roll created by capturing the hand-played performance of one or more pianists upon a piano connected to a recording machine in real time

master roll, stencil music roll made of thicker cardboard or paper and with a longer length and clearly separated rows, from which the production rolls offered for sale were copied

metronomic roll created either by a metronomic transcription of the score or "regularised" from a hand-played performance, with bars equally spaced throughout the roll

Metrostyle red graphic line introduced in 1903 by the Aeolian Co. on their player piano rolls to guide performance phrasing

music roll generic term for paper rolls, consisting of perforations for pitch and duration of each note, used to drive various instruments such as pianos, various types of organs, orchestrions and others

music storage media object such as a piano roll or a pinned barrel that does not contain the sound (such as a record or a CD) but controls the production of sound on a musical instrument

standard (88 note) roll, player piano roll roll for player piano, consisting of the perforations for pitch and duration of each note; in addition to very simple rolls, there are also more elaborate ones that can automatically reproduce expressive details through extra perforations (Themodist) or contain graphic lines that serve as a guide for interpretation by the pianolist (Metrostyle)

perforator punch-and-die set a set of punches which are driven through the paper into a corresponding set of close-fitting holes in a die plate that form the cutting edges; the punched paper chads fall through the die plate and are collected for disposal

production roll copy of the roll sold to the public

reproducing roll roll for reproducing piano, consisting of the perforations for pitch and duration of each note as well as extra perforations in the margins which automatically control the dynamics and pedals

Themodist expression system invented in 1900 by the Aeolian Co., consisting of small perforations that emphasise individual notes, later taken up by the other makers of player pianos

Digitisation of piano rolls

CIS (contact images sensors) image sensors used in flatbed scanners and for a while in the optical scanning of piano rolls

digitising converting all information stored on a piano roll into a digital (i.e. computer-readable) format by scanning and processing the roll, not to be confused with digital indexing (= cataloguing)

emulation creating a performance file from a scan by a program that models the behaviour of the pneumatic instrument for which the roll was intended, and which can then operate an electronically-controlled acoustic piano or a virtual piano

File formats in chronological order of processing:

1. **scan image file, raw file** file based on the pixels in the scan image, which documents the start and end coordinates of every note, including those for every individual punch in the chaining; usable with restrictions for recutting, not suitable for playback

2. **punch file, web file** file that contains an exact representation of the punches in the roll including the chaining/webbing by specifying the row and column coordinates of each punch; usable for recutting or further processing to produce playable files

3. **e-roll file, bar file** file in which the events of the scan image are lengthened and shifted to compensate for the apertures and any offsets in the tracker bar, such that these files operate player pianos equipped with MIDI valves in exactly the same way as the roll would

4. performance file broad term for any file (not necessarily MIDI) containing note dynamics, including emulations of reproducing rolls; suitable for playback on an electronically-controlled acoustic piano or virtual piano

line scan camera camera for producing two-dimensional images using a one-dimensional sensor element; now used as standard for optical scanning of piano rolls

MIDI acronym that stands for Musical Instrument Digital Interface; industry standard introduced in 1983 for exchanging musical information between electronic instruments

MIDI velocity touch dynamics of electric musical instruments, which has 127 different values and in this context emulates the touch dynamics of a self-playing piano

scanning production of a visual image of a roll

scatter channel-to-channel offsets of the individual punches on a roll from their nominal in-line positions

skew angular misalignment of the perforations on a roll with respect to the scan line

phase noise short-term fluctuations in the magnitude of perforator steps, most likely due to paper slippage or backlash in the perforator's gearing

processing conversion of the image data obtained during scanning into other file formats

punch matrix reconstruction recreation of a master roll in electronic form from a production roll by assigning each punch to its correct row and column

roll reader device based on the technology of the pneumatic piano, in which the roll is pneumatically sensed while passing over a tracker bar and the signals thus received are converted into computer data

List of Authors

Judith Kemp first worked as an editor for the *Österreichische Musikzeitschrift* after completing her doctorate in musicology on Munich's first cabaret, *Die Elf Scharfrichter.* She subsequently held a position as a research associate in the Collection of Musical Instruments and later was a fellow at the Research Institute of the Deutsches Museum. In addition to her responsibilities in press and public relations at the Symphonieorchester des Bayerischen Rundfunks, she works freelance on the conception and realisation of exhibitions, most recently for the Museum of Music and Integration in Bubenreuth.

Peter Phillips' interest in piano rolls began in 1976. In 1978 his technically-advanced Duo-Art vorsetzer was used to make an award-winning recording of the Grieg Piano Concerto played by Percy Grainger from his piano rolls, accompanied by the Sydney Symphony Orchestra. Phillips began digitising Ampico piano rolls in 1979 using his custom-built roll reader. The recordings were first stored on magnetic tape, and in 1982, prior to the MIDI standard, Phillips wrote software to store the files on floppy disk for playing from an Apple II computer. In 2011, he commissioned his new roll reader designed to read all brands of rolls as MIDI files. He has since digitised over 8000 rolls. In 2017, he was awarded a PhD by Sydney University for his thesis titled: *Piano Rolls and Contemporary Player Pianos: The Catalogues, Technologies, Archiving and Accessibility.* He has worked with various symphony orchestras performing with piano rolls, including Gershwin playing his *Rhapsody in Blue* and Josef Hofmann playing Chopin's E minor piano concerto. He has given many local and international presentations that include performances of his roll MIDI files playing on a Disklavier or Steinway Spirio.

Anthony Robinson started work in 1970 as a television engineer at the BBC's news studio in Southampton. In 1985, he left the BBC to become a self-employed designer of data monitoring equipment for British Telecom. It was the acquisition of a Yamaha Disklavier in 1990 that first led to his interest in scanning piano rolls. Now retired, he continues to write software programs for the roll scanning community. In 2015, he presented his design of a line-scan camera roll scanner to the Reactions to the Record symposium at Stanford University, which led to them adopting the design as the basis for their own roll scanner.

Wayne Stahnke is an American engineer and computer scientist who has devoted his professional life to advancing electronic reproducing piano technology and to the accurate scanning and emulation of music rolls. Stahnke pioneered techniques for digitizing rolls in 1973 and developed the first optical music roll scanner in 1996. His software suite for processing scan data – employing the sophisticated mathematical techniques presented in this book – makes it possible to recover original punch matrices from production music rolls, a crucial advance in accurate preservation. His extensive research into the physics of music rolls and pneumatic expression systems led to his developing accurate emulation software. In the mid-1990s, Stahnke utilized these innovations to produce a two-album set of recordings of Rachmaninoff's complete piano roll performances entitled *A Window in Time,* realized using his best-known invention, the Bösendorfer SE reproducing piano, and released by TELARC. He also developed several retrofittable reproducing piano mechanisms, culminating in the Live Performance Model LX. Over a 30-year period, Stahnke has served as technical consultant to Bösendorfer, QRS Music, Yamaha Corporation, and Steinway & Sons.

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