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Using Optical Metrology to Reconstruct Sound Recordings

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Abstract: Prior to 1950 nearly all sound recordings were made on mechanical media such as wax, foil, shellac, lacquer, and plastic. Some of these older recordings contain material of great historical value or interest but are damaged, decaying, or now considered too delicate to play. Archives seek to preserve and also create broad access to their collections. An ongoing effort at Berkeley Lab has applied methods of optical metrology and image processing to reconstruct sound stored on these mechanical carriers. This approach was inspired by the use of precision optical metrology to align and fabricate silicon tracking arrays for high energy physics experiments and by track finding and fitting data analysis methods. The technology has matured to the point that an optical metrology system for sound restoration has been designed and built for the Library of Congress.

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Introduction

Sound was first recorded and reproduced by Thomas Edison in 1877. Until about 1950, when magnetic tape use became common, most recordings were made on mechanical media such as wax, foil, shellac, lacquer, and plastic. Some of these older recordings contain material of great historical value or interest but are damaged, decaying, or now considered too delicate to play.

The issues faced by archives and libraries as they strive to preserve, and create greater access to, their valuable collections are well described elsewhere [1-3]. This report focuses on a series of new techniques, inspired by methods used in particle physics, that have recently been applied to restoring damaged mechanical sound recordings.

Applying the approach and methods of particle physics to address a problem in a different field of study is a good example of outreach and can illustrate to a wide audience another value of basic research.

Sound Recording

In the mechanical sound recording process, pressure waves in the air are converted, either mechanically or electro-magnetically, into the movements of a cutting stylus. This stylus displaces or removes material from a soft recording media such as wax, lacquer, plastic, or metal forming a groove. Once recorded, the media may be played by a complimentary reading stylus. The primary media may be played directly or first reproduced using a mold forming and pressing procedure.

The recording media is either a disc or a cylinder. The cutting stylus is guided mechanically along a spiral (disc) or helical (cylinder) trajectory over the surface of the media. If the stylus is driven, by the audio signal, from side to side in a plane which contains the groove, the recording is referred to as lateral. If the stylus is driven into the surface by the signal the recording is referred to as vertical.

The sound playback process is inherently destructive due to the invasive nature of the mechanical contract of stylus to media. Furthermore older records suffer from handling damage, various chemical and physical breakdown processes, and are often considered increasingly delicate.

An Optical Playback Process

Historical sound archives and collections face two major tasks in dealing with mechanical sound recordings. Delicate records need to be preserved and stabilized to meet the needs of future users. Large and diverse collections need to be digitized to create broad public access.

An automated non-contact playback process could, in principle, address the needs of both preservation and access. Without physical contact, delicate media would suffer no further degradation. Using computer automation and robotic inspection and metrological procedures, large numbers of items could be measured efficiently.

Automated optical metrology is a process familiar to experimental particle physics and other fields. Beginning in the 1960's particle physics pioneered this process in-order-to scan bubble chamber films automatically. This in-fact predated the use of optical metrology in the inspection industry. In the modern era optical metrology is used extensively to align and inspect precision sensor arrays such as the ATLAS Semiconductor Tracker (SCT) for the CERN Large Hadron Collider.

The precision of modern optical metrology is on the sub-micron scale. This is well matched to the scale of groove undulations on mechanical sound carriers. The problem of optical playback can be reduced to a massive metrological survey of the sound carrier. Once the groove trajectory is measured and digitized the data set can be processed and the stylus trajectory computed thereby reconstructing the recorded sound. The processing of this data set is much like a track finding and fitting analysis in particle physics and offers similar opportunities for noise elimination, and global and local alignment.

At Lawrence Berkeley National Laboratory a program of research and development towards optical scanning of mechanical sound carriers grew out of the detector fabrication and analysis efforts of the ATLAS and CDF silicon trackers. The initial phase consisted of proof-of-principle tests [4,5]. When the method demonstrated potential it attracted the interest and support of major institutions with a stake in preservation of, and access to, recorded sound collections. At present the effort centers around a full scale prototype scanner for disc records built at LBNL and recently installed at the Library of Congress. Future directions include a cylinder scanner for the Library of Congress and targeted scans of items with particular historical value.

Proof-of-principle tests

In the first test, a 78 rpm shellac disc from 1950 was scanned and analyzed [4]. The groove orientation was lateral, therefore a digital micro-photographic image of the surface could resolve the undulations in the field of view (FOV). Such an image is referred to as two-dimensional (2D) since no precise depth information is recorded by photography (Figure 1). A “Smart Scope” inspection tool manufactured by Optical Gauging Products was used. This device was on-hand and in current use for the ATLAS SCT project. The tool supplements the digital microscope with precision motion stages. The motion and image analysis can be computer controlled via a proprietary menu-driven software system.

[Placeholder for Figure 1]

A program was written for the machine which followed the groove around the record while measuring its undulations on a set of discrete steps corresponding to 66 kHz sampling frequency. The following procedure for reconstructing the sound from the data is typical of the method:

- The data were acquired on the light-to-dark transitions between the coaxially illuminated groove bottom and the sloped walls in a given image. The data on both edges were recorded.
- The groove was covered with multiple overlapping FOV frames.
- The data from both sides were merged if the distance across the groove was consistent with the average for that region. The outliers were rejected, providing a significant noise reduction.
- The data from multiple frames were combined using the overlap regions to correct for the motion offsets between different regions.
- The sound waveform was extracted from the groove waveform.

The results from the sound reconstruction in the optical method are compared with the stylus playback of the same record and a digitally remastered magnetic recording of the same performance. There is a considerable similarity between different waveforms. The clip obtained with the stylus playback features lots of sharp spikes indicating to “clicks and pops” noise appearing in many old records. This noise source was greatly attenuated in the optical method.

The second test was performed on a wax cylinder record [5]. The cylinders features a vertical groove undulation, therefore one needs a 3D measuring method to be able to resolve the undulations well. For this purpose, a color-coded confocal probe was used. It acquires data point-by-point. It is possible to obtain a detailed topographic map of the surface when the scanned object is moved around (Figure 2).

[Placeholder for Figure 2]

The data in the test were acquired in scans along the cylinder axis. The cylinder was rotated between different scans. The rotational step corresponded to 96 kHz sampling frequency. A major difference as compared to the disc test was the availability of measurements across the full width of the groove. In the data analysis, the points in a groove "valley" were fit to a parabolic function approximating the curvature of the cutting tool. The 2nd degree coefficient was fixed to a constant value, and the fit was done iteratively to reject the outliers due to debris and surface imperfections. The height values from the groove's bottom obtained from the fit were combined in a single set of groove undulation measurements and converted into a sound waveform.

As in the previous test, considerable similarity between the waveforms obtained via the traditional stylus-based playback and the optical survey method are seen. Due to the large number of points measured across each "valley" significant noise reduction is achieved as well.

A Scanning Machine for Disc Records ("IRENE")

While the proof-of-principle tests showed the promise of optical scanning, they did not specifically address the practicality of the scan. The use of the available general-purpose equipment imposed a significant limitation on the speed of the scans. In both cases the speed was on the order of an hour of scanning time per second of audio. To assess the applicability of the method to the realistic need of an audio archive, a proposal to build a customized audio reconstruction machine specifically for disc records was submitted to the National Endowment for Humanities in 2004, and called IRENE ("Image Reconstruct Erase Noise Etc").

The proposal was funded, and the machine was built at LBL in 2005 and 2006. It was installed at the Library of Congress in August of 2006 for testing. The system was designed for 2D scans of disc records with lateral grooves, such as 78 rpm shellac and lacquer carriers. The setup is shown in Figure 3. It featured special provisions for fast scanning:

- A line scan CCD was used to achieve near dead-timeless imaging of the surface, which, in turn, allowed for a continuous movement of the disc by a motion stage.
- A vertical stage holding the imager was coupled with a feedback system based on a laser range-finder probe to keep the system in focus on warped disc surfaces.
- High intensity illumination allowed for short exposure times.
- An optimized control, acquisition, and data analysis package were developed to enable efficient operation and throughput.

[Placeholder for Figure 3]

IRENE is capable of scanning a 3 minute 78 rpm disc in about 15 minutes. A significant fraction of that time is due to data handling and file writing overhead. The actual scan portion occurs in nearly real-time. The machine has been tested on a variety of media including shellac, lacquer, and plastic discs in a range of conditions. Sound quality is consistent with expectations based upon the early proof-of-principle tests (Figure 4) but is acquired and analyzed by a robust and efficient process. A systematic study of a large sample of discs is underway.

[Placeholder for Figure 4]

A 3D Scanning Machine

A recent proposal is to develop and IRENE-like scanner for the full 3D reconstruction of cylinder and disc records. The proof-of-principle tests suggest that 3D scanning is a more powerful approach and can lead to increased noise-reduction. However 3D scanning speeds are limited by the available sensor technology and are unlikely to exceed many hours per second of recorded sound. None-the-less 3D scanning is seen as the ultimate preservation approach may even set a baseline for any conceivable playback. These issues will be explored further as the technology evolves.

Conclusions

Optical scanning of mechanical recorded sound carriers is moving from the realm of lab tests to production prototyping in the archive setting. This technology, as practiced at LBNL, originated in particle physics instrumentation and analysis efforts. It has been supported and encouraged enthusiastically by major public and private institutions with an interest in recorded sound preservation and access.

Acknowledgements

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References

[1] Hart, M., J. Audio Eng. Soc., vol. 49, pp. 667-670 (2001 July/August).

[2] Folk Heritage Collections in Crisis (Council on Library and Information Resources, Wachington, DC, 1996), ISBN 1-887334-82-3.

[3] Fox, B., New Scientist, pp. 40-43 (2003, Mar. 1).

[4] Fadeyev, V. and Haber, C., J. Audio Eng. Soc., vol. 51, pp. 1172-1185 (2003 Dec.).

[5] Fadeyev, V., Haber, C., Maul, C., McBride, J.W., and Golden, M., J. Audio Eng. Soc., vol. 53, pp. 485-508 (2005 June).

FIGURE CAPTIONS:

Figure 1. Two-dimensional image of grooves on a 78 rpm record. Illumination is coaxial.

Figure 2. Surface region of Edison Blue Amberol cylinder acquired with a confocal scanning probe.

Figure 3. A picture of IRENE setup.

Figure 4. A comparison of waveforms taken with a conventional stylus-based turntable (top) and with IRENE (bottom). Image data processing reduces some noise sources revealed as small-scale irregularities in the top graph.

Figure 1 (black and white for print publication).

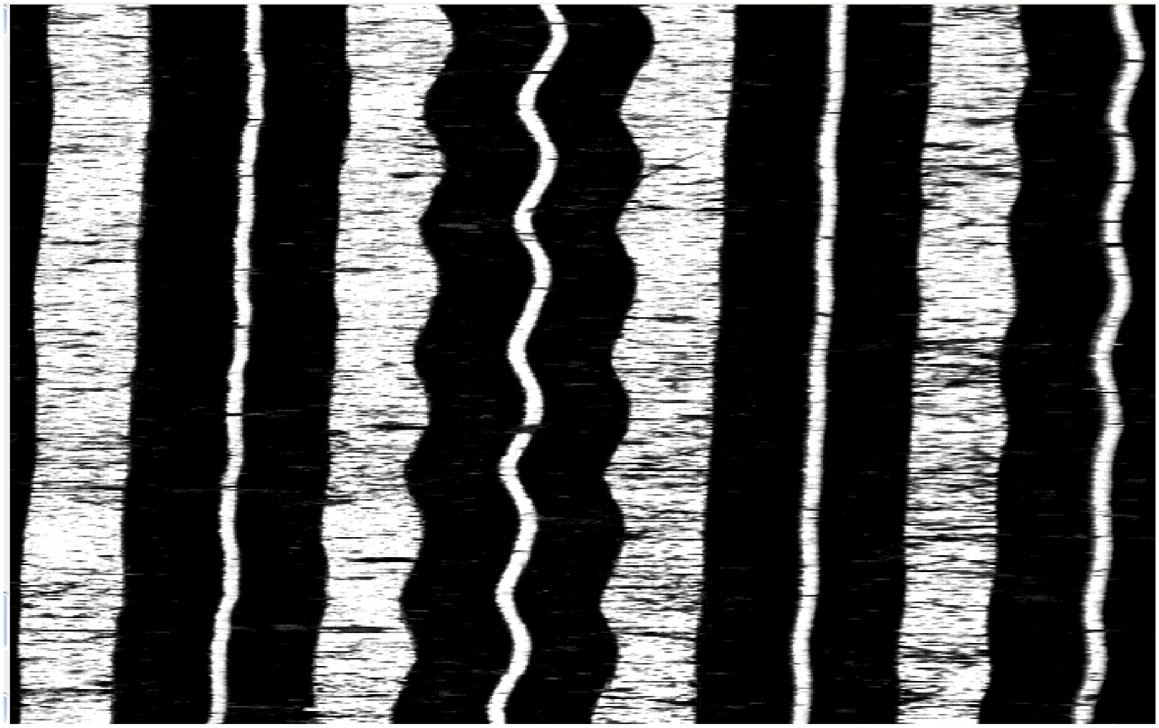

Figure 2 (black and white for print publication).

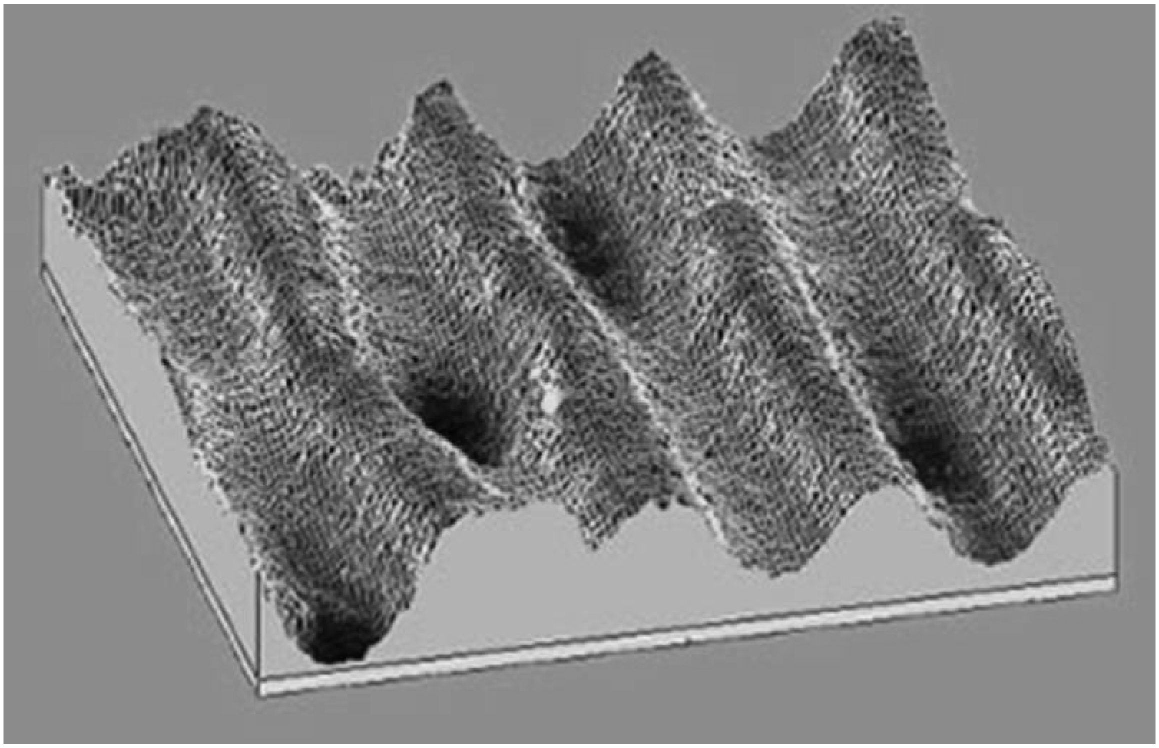

Figure 3 (black and white for print publication).

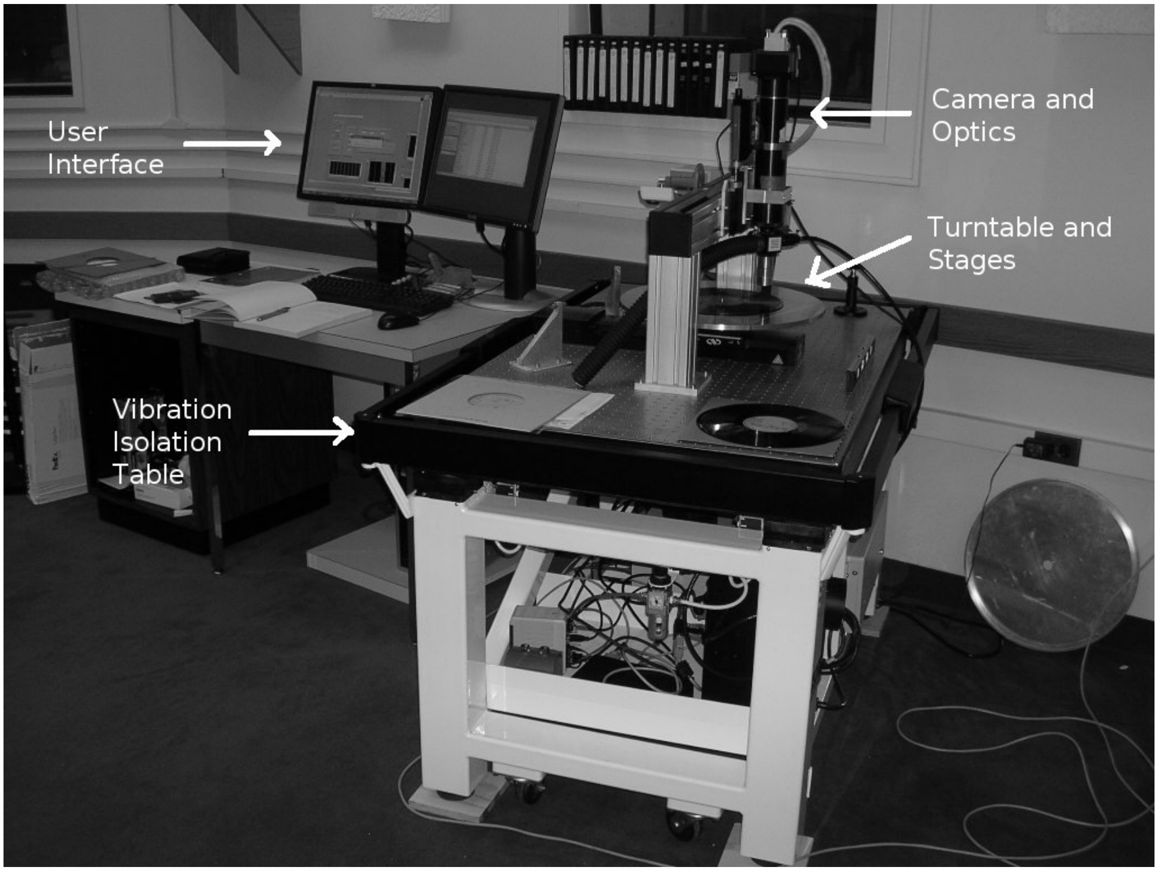

Figure 4 (black and white for print publication).