Optical Reading and Playing of Sound Signals from Vinyl Records

Arnold Hensman

Department of Informatics, School of Informatics and Engineering
Institute of Technology Blanchardstown, Dublin 15, Ireland
Email: Arnold.Hensman@itb.ie

Kevin Casey

Faculty of Computing, Griffith College Dublin
South Circular Road Dublin 8, Ireland
Email: Kevin.Casey@gcd.ie

Abstract

While advanced digital music systems such as compact disk players and MP3 have become the standard in sound reproduction technology, critics claim that conversion to digital often results in a loss of sound quality and richness. For this reason, vinyl records remain the medium of choice for many audiophiles involved in specialist areas. The waveform cut into a vinyl record is an exact replica of the analogue version from the original source. However, while some perceive this media as reproducing a more authentic quality then its digital counterpart, there is an absence a safe playback system. Contact with the stylus provided by a standard turntable causes significant wear on the record (or phonograph) over time, eventually rendering it useless. Couple this with the historic value and an abundance of such vinyl media, and the need for a non-contact playback system becomes evident. This paper describes a non-contact method of playback for vinyl records which uses reconstruction of microscopic images of the grooves rather than physical contact with the stylus.

Keywords: Waveform Reproduction, Image Stitching, Vinyl Record, Groove Tracking, 78rpm

1   Introduction

Since a vinyl record is an analogue recording, many claim that the application of a sample rate when making digital recordings for CDs and DVDs results in too great a loss in sound quality. Natural sound waves are analogue by definition. A digital recording takes snapshots of the analogue signal at a certain sample rate and measures each snapshot with a certain accuracy. For CDs the sample rate is 44.1 kHz (44,100 times per second at 16-bit). The sample rate for DVD audio is 96 kHz or 192 kHz for High-Definition DVD (HD –DVD). A digital recording, however, cannot capture the complete sound wave; at best it is a close approximation and many claim that, although high quality, it still cannot fully reproduce the fidelity of sound that vinyl records can. Figure 1 illustrates the application of a sample rate upon a simple sound wave. Sounds that have fast transitions, such as drum beats or a trumpet's tone, will be distorted because they change too quickly for the sample rate. Historical recordings archived for posterity are often fragile with owners not wanting to risk the use of conventional stylus playback. The development of a non-contact player that carefully reconstructs a restored image of the original analogue groove would not only remove this risk, but it would make safe playback possible for records that are severely damaged. Normally the downside of playing an analogue signal is the fact that all noise and other imperfections are also heard. So, if there is a period of silence on a record you hear background noise. With the proposed system any background noise that was present could be removed since the optical player would detect this noise in advance and simply ignore it.
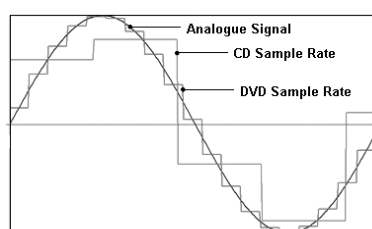

Figure 1:   Comparison of CD and DVD sample rates upon an analogue waveform

1.1   Conventional playback methods for vinyl records

The first method of recording sound was the phonograph created by Thomas Edison in 1877. He used a mechanism consisting of a needle and collection horn to store an analogue wave mechanically by cutting a waveform directly onto a cylindrical sheet of tin. The use of flat records with a spiral groove was an improvement on Edison's machine by Emil Berliner in 1887. The stereo evolution of this method - High Fidelity (Hi Fi) - didn't lose popularity until compact disks revolutionised the consumer market in the early 1980's. Only the most advanced digital systems can rival its fidelity. At microscopic level this groove resembles an undulating track with varying width. A turntable stylus follows these undulations along the groove towards the centre thus following the waveform along the way. Records skip when the bass information is too loud and the stylus is thrown into a neighbouring section of the groove. Vocal sibilance and sudden loud symbol crashes can also cause a rapid increase in frequency so the stylus faces a pronounced 'S' effect in the groove that could potentially cause it to skip. The traditional method of a diamond shaped stylus running along a V-shaped groove also applies constant weight and pressure to the groove and results in a increase in temperature causing further damage. A system that views the waveform up close without any contact would completely remove this problem. Skipping of grooves would be eliminated along with unwanted background noise, scratches and distortion from tiny particles.

1.2   Assumptions

The terms LP record (LP, 33, or 33-1/3 rpm record), EP, 16-2/3 rpm record (16), 45 rpm record (45), and 78 rpm record (78) all refer to different phonographs for playback on a turntable system. The rpm designator refers to the rotational speed in revolutions per minute. They are often made of polyvinyl chloride (PVC), hence the term vinyl record. For the purposes of this study, monaural signals only are processed, i.e. vinyl 78rpm records. The groove may be viewed clearly in two dimensions so image acquisition may be performed more easily. Since most historic recording are stored on 78s that are now considered antiques, it makes sense to restrict this study to that media.

1.3   Evaluation of Existing Non-Contact Systems

The main technology currently using a method for non-contact playing of vinyl records is the Japanese ELP corporation's laser turntable ™ [ELP, 2003]. This impressive system can play grooved, analogue 33.3, 45 or 78 RPM discs by illuminating the walls of each groove with five laser beams [Smart, 2003]. In essence, to play the sound, a laser views the image by reflecting back the amplitudes of the waveform. At a basic price over US$10,000 it will hardly ease into the mass production market. In fact to play 78s it requires the advanced model with extra sensors to monitor speed. The laser of the basic model cannot accurately track the groove at such speed without the risk of intermittent pauses throughout playback. The cost of the advanced model is almost twice the basic price plus additional costs for the patching of scratches and noise. Any noise, damage or dirt will be picked up as the laser cannot overcome serious flaws on the disk. If the disk is slightly bent or warped in any way, the laser turntable will reject it. It works best with black records rather than coloured or vinyl with added graphics. The system was invented by Robert E. Stoddard, a graduate student at Stanford University in 1986 [USPO, 1986]. The dual beam model was patented in 1989 [USPO, 1989].

The same result could be achieved by a microscopic imaging system at a fraction of the cost. Since the objective is to play the sound data without contact with a stylus, a microscopic imaging camera could be used to replace the stylus. The added advantage of this method is that an image could easily be enhanced to smooth out noise at source and overcome damage. Ofer Springer proposed the idea of the virtual gramophone [Springer, 2002]. Springer's system scans the record as an image and applies a virtual needle following the groove spiral form. P. Olsson's Swedish team developed this to use digital signal processing methods such as FIRWiener filtering and spectral subtraction to reduce noise levels [Olsson et al., 2003]. These two systems however only used a basic scanner, limiting the resolution to a maximum of 2400dpi or 10 per pixel. At this resolution, quantisation noise is high because the maximum lateral travel of the groove is limited. Fadeyev and Haber's 2D method reconstructs mechanically recorded sound by image processing [Fadeyev and Haber, 2003]. The resolution was much higher due to the use micro-photography. Baozhang Tian proposed a 3D scene reconstruction method using optical flow methods to generate a virtual 3D image of the entire groove valley [Tian, Bannon, 2006]. But as we shall see, quality results can be achieved by processing 2D images of the 2D sound signals from 78rpm records.

2   Specification of Proposed Methods

The objective of this system is a process for optical playing of vinyl records (for the purposes of this system, 78rpm phonographs will be used) by reconstructing a restored image of the original analogue. The surface reconstruction will be two dimensional as that is all that is necessary in the case of 78s. Image analysis techniques will be used to stitch together a longitudinal image of the overall groove There are four stages of implementation in order to achieve this. This section will briefly describe each of those stages in sequence and the problems encountered at each and how they are overcome. The four main sections in this playback process are:

    (i)   Image collection
    (ii)   Stitching of overlapped Images
    (iii)   Groove tracking
    (iv)   Waveform creation from the tracked groove and sound file creation.
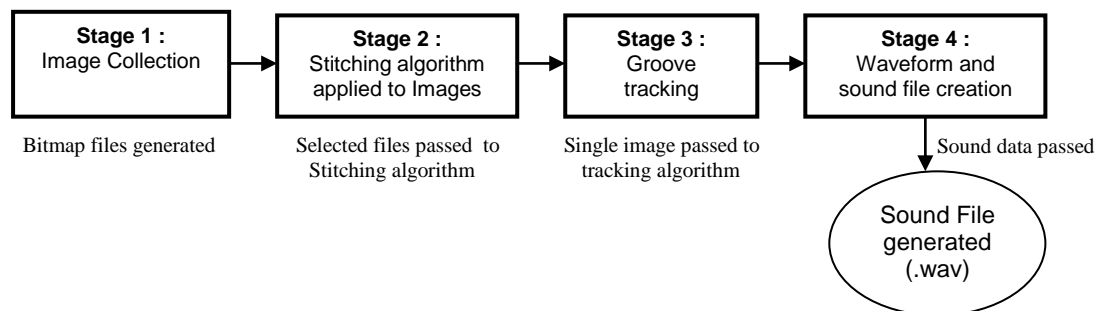
The following chart indicates the flow of each phase.

Stage 1 : Image Collection	→	**Stage 2 :** Stitching algorithm applied to Images	→	**Stage 3 :** Groove tracking	→	**Stage 4 :** Waveform and sound file creation
Bitmap files generated		Selected files passed to Stitching algorithm		Single image passed to tracking algorithm		Sound data passed

Sound File generated (.wav)

Figure 2: Stages in development of optical playback process

2.1   Image Collection Phase – Stage 1

Perhaps the most important and significant stage in the process is the image collection phase. If proper images of high quality are not collected initially it will be inevitable that further problems will occur in the stitching and groove tracking phases. Potential hazards to the collection of data will now be explored so that they may be foreseen and overcome in advance. Figure 3 illustrates how the images are retrieved using a computer microscope and a stepper motor to turn the record. The stepper motor takes the place of a turntable and is connected to the record in such a manner that any partial rotations cause it to move in discrete steps.

For each step the motor takes (the exact distance of which is controlled by software), the microscope will in turn take an image of a small section of the groove. On subsequent movements, the stepper motor will position the next section of the groove for imaging and the microscope will take further pictures. Each image is saved in bitmap format and converted to greyscale to optimise the stitching algorithm at a later stage by keeping the images as simple as possible.
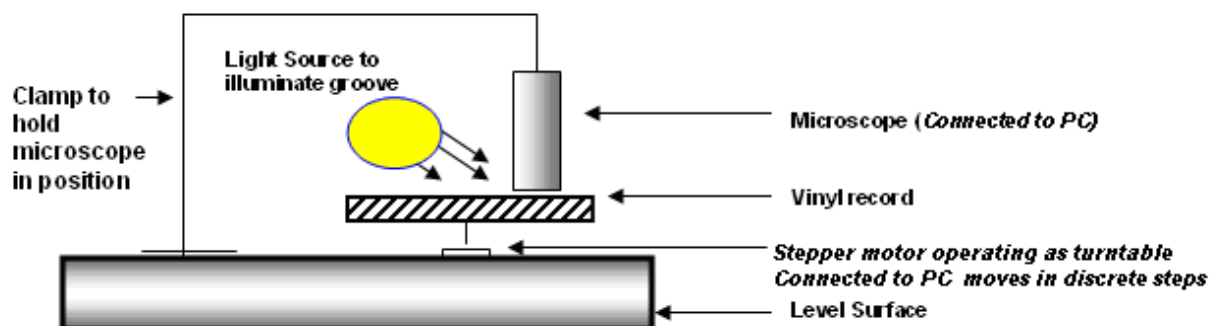

Figure 3: Image Collection Stage

One of the most important factors in maintaining consistency of image quality is to ensure that the microscope remains in focus. Any tiny variation in the record from its level position will move the lens slightly out of focus. That is, the focal length (distance between the record and microscope lens) will increase or decrease. For this reason, a focus detection algorithm is incorporated so as to warn the user when re-focusing is required. A second motor may be added to automatically readjust the focus, which would slightly add to the system's cost. Warped or slightly bent disks will also gain from this feature as they are prone to going out of focus.

Figure 4 shows a set of a sample images maintaining a consistency of three groove sections per frame all to be stitched together into a panoramic view. There is a deliberate overlap - most evident in pictures (c) and (d). This overlap can easily be controlled by the stepper motor which acts as the turntable. It is incorporated to aid the stitching process and to ensure that the correct panoramic image has been obtained.
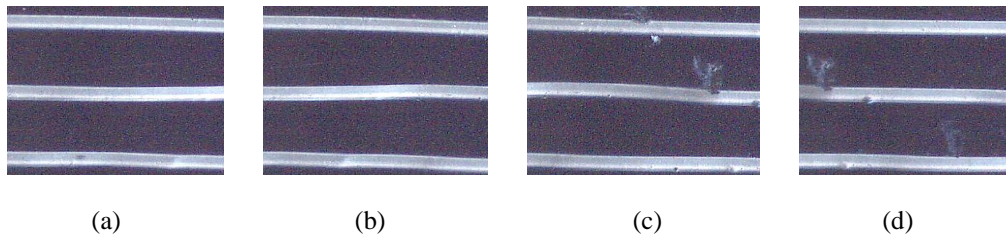

| (a) | (b) | (c) | (d) |

Figure 4:   Sample set of microscopic groove images (x200 Magnification)

Approximately 60 to 100 slightly overlapping images will be required to capture one revolution of a 78rpm groove. A simple algorithm to detect de-focus is added to automatically pause the image collection phase and re-adjust microscope focal length using a second stepper motor before resuming image taking. The MilShaf ltd stepper control motor that was used used has a minimum shift capability of 0.25° [MilShaf SMC]. This means it takes exactly 60 images (6° x 60 = 360°) to capture one complete revolution of a groove image i.e. it will take 24 steps of the stepper motor before the microscope should take the next image.

| 1 step = 0.25° => | 1 Image shift | = 24 steps | = 0.25° * 24 | = 6° |
| Frame width = 320 pixels => | Pixel shift per step | = 320 / 24 | = 13 pixels | |

This high level of accuracy meant that the potential overlap can be set to within 13 pixels. Although the 6° movement will be the same throughout the collection process, the above calculations only consider the outer circumference of the record. A revolution of the groove will become smaller as it gets closer to the centre of the record. The angular speed of vinyl is constant, so the speed of the needle at the center is lower than at the outside. Therefore the information density is lower on the outside. So it is beneficial if there is a lot of overlap towards the center. The overlap can always be changed as the central grooves are captured to better contribute towards capturing the higher density data there more accurately. In the case of a 6° set of steps at the outer circumference, the image will perform a 13 pixel shift. Take this outer circumference as being radius **r,** the radius of the record, as the centre approaches the radius will become **r'**. To obtain the number of pixels for a 6° set of steps at radius r' the following equations are formed.

(a) Circumference * %movement = 13   at radius **r**
(b) Circumference * %movement is unknown   at radius **r'**
(a) $(2\Pi r)$ * (a/360) = 13
(b) $(2\Pi r')$ * (a/360) = pixel movement at r '   where a is the movement in degrees

Dividing (a) by (b) gives r/r' = 13/ pixel movement at r '   => pixel movement at r ' = (13r')/r

Image collection was performed using oVWF.ocx, a Video for Windows ActiveX control that required no external interaction or use of a DLL. It could easily be incorporated into our software providing the required versatility in taking images. It was created by Ofer LaOr, director of Design by Vision [LaOr 1997]. This control has all the convenience of any ActiveX control and can easily be used in the Microsoft suite of programming languages. It can prompt dialogs to allow you to change the settings of

the bitmap being imaged (i.e. 16 colour, 256 colour etc). Hence our need to obtain greyscale images was met.

2.1.1 Overcoming Potential Hazards in Image Collection

(a) *Image drift:* In a sample containing three grooves as in Figure 5, one of the grooves would often move to the top of the video window after several shots were taken and eventually go out of sight as illustrated in Figure 6(b). This was due to the way in which the record was first centred upon the turntable. Any tiny variation off-centre at this level of magnification would be noticed. However, even if the geometric centre of the record is chosen with perfect accuracy, the spiral centre cut onto the groove may be slightly different

(b) *De-Focus:* Figure 5(b) is clearly not as sharp as Figure 5(a). This is only after 25 frames have been taken in a particular set. The focal length (the distance between the record and microscope lens) would increase or decrease due to a slightly unlevelled record causing the image to go out of focus. A simple algorithm to give a deterministic value for focus is used based on the contrast of images.

(a)   (b)

Figure 5: Contrast within frames is used to gauge the focus level

Since the image is converted to greyscale, every pixel has a value between 0 and 255. The deterministic value obtained is the *average contrast per adjacent pixel* of any image. Converting these values to a percentage value between 0 and 1, will allow us to apply the algorithm. For example consider the following 3 by 4 bitmap matrix A:

$$
A \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \end{bmatrix}
$$

The absolute row-contrast differences may be determined by:

$$
\begin{bmatrix} |a_{11}-a_{12}| & |a_{12}-a_{13}| & |a_{13}-a_{14}| \\ |a_{21}-a_{22}| & |a_{22}-a_{23}| & |a_{23}-a_{24}| \\ |a_{31}-a_{32}| & |a_{32}-a_{33}| & |a_{33}-a_{34}| \end{bmatrix}
$$

It is possible to approximate the row contrast R, by calculating the sum of these absolute differences. The absolute column-contrast differences may be determined by:

$$
\begin{bmatrix} |a_{11}-a_{21}| & |a_{12}-a_{22}| & |a_{13}-a_{23}| & |a_{14}-a_{24}| \\ |a_{21}-a_{31}| & |a_{22}-a_{32}| & |a_{23}-a_{33}| & |a_{24}-a_{34}| \end{bmatrix}
$$

It is possible to approximate the column contrast C, by calculating the sum of these absolute differences.

$$\text{Total Contrast} = R + C$$

If this is applied to the initial frame to get a focus standard, and further applied to all adjacent elements of a bitmap matrix, the average contrast per pixel can be used as the deterministic coefficient for determining whether or not an image is in focus.

2.2 Image Stitching – Stage 2

Stitching of the images collected from Stage 1 is based on determining the exact positions where frames overlap. Image mosaics are collections of overlapping images that are transformed in order to

result in a complete image of a wide angle scene. Two frames at a time were stitched together to build up the mosaic image. The simplest algorithm in stitching simple images together is the least squares algorithm which determines a set of overlap errors for various overlapping positions. The position with the lowest error will be taken as the point where the two images overlap. These positions will then be saved in a text file in order to reproduce the stitched image at any time. For every subsequent pair of images, the overlap positions will thus be recorded. Baozhang Tian suggests a similar method of image acquisition involving complex use of surface orientation analysis to record the image [Tian, Bannon, 2007]. Stitching algorithms however provide a more simple approach, since a delay will be present anyway in both methods. The images are converted to grayscale in the capture process so we will get a bitmap matrix of values between 0 and 255. The images will be taken under similar lighting conditions and will not vary greatly in content. When dealing with panoramic images, there is usually the source position issue to contend with. Our images will be taken from a new point of reference above the vinyl record at each instance to suit the microscope as the record moves on the turntable, so this is angular distortion is not an issue as illustrated in Figure 6.
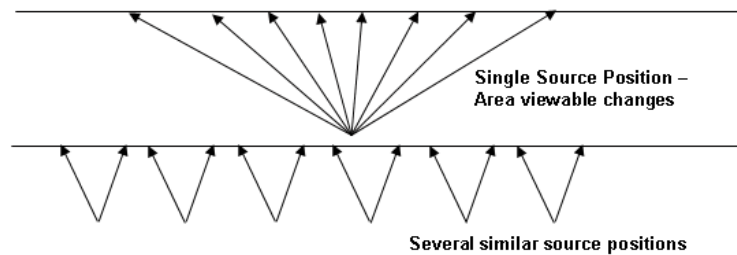

Figure 6: Angular positioning problem will not be present

The stitching algorithm may be defined as follows:

```
sum = 0
For all overlapping pixels
       pixel1 = Numeric pixel value in the first image
       pixel2 = Corresponding numeric pixel value in the second image
       sum = sum + (pixel1 - pixel2)²
  End For
error = sum / X ,   where X is the total number of overlapping pixels
```

The minimum overlap can be chosen by the user in form that executes the stitching, but essentially every test of the least squares algorithm operates in a similar way. A column by column test is performed for every overlap beginning with the overlap of the upper midway position of height and width of the first frame of a pair. Frame 2 is then tested at the same column position, but on the next row down, and so on, until it overlaps midway with the lower half of frame1. At this point the column shift should take place towards the left and the procedure begins again. It will stop when the column position of frame2 reaches the minimum overlap point. The basic process used is outlined below. The height and width will be the same for both frames.

```
For column = Width/2 To MinOverlap
    For row =  (Height + Height/2) To  (Height - Height/2)
             Perform Least Squares algorithm upon the overlap
        Next row
    Next column
```

Two 2D arrays; pic1[ ][ ] and pic2[ ][ ] are passed to the function *image( )* contained within a file. They will contain integer values between 0 and 255 since the images are converted to greyscale. Each array is essentially a bitmap matrix of the two frames being stitched together.
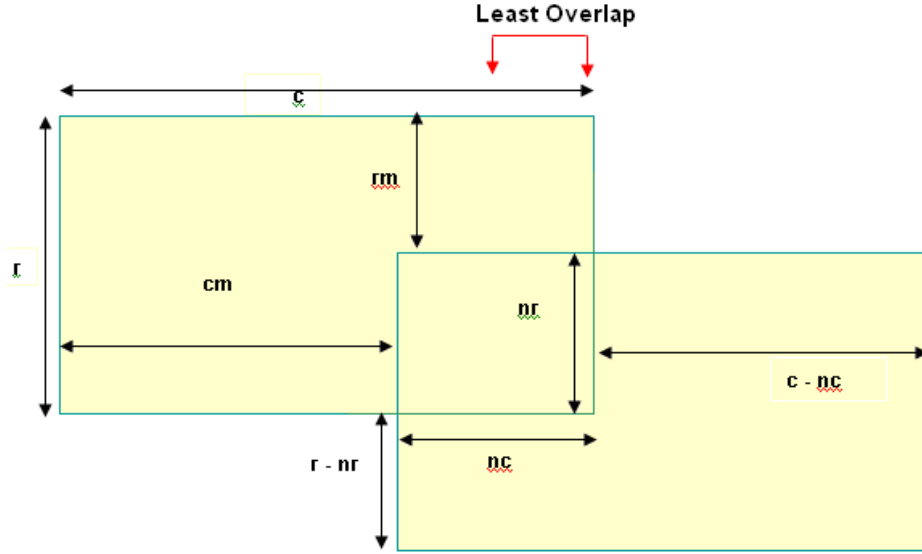
Figure 7: Dimensions of two overlapping images

The values indicated in Figure 7 represent the dimensions processed within the algorithm. The values for *rm* and *cm* will change continually as the least squares error is determined for each position. The values for the number of rows - *r,* columns - *c* and the *least_overlap* field (representing the minimum overlap input by the user) are also passed as parameters. The least squares algorithm is conducted based on the for every changing values *nr* to test if the correct stitching position has been found.

2.2.1 Testing the stitching process

The Minimum overlap was included for two reasons:
1. To speed up the stitching process as less positions are tested
2. In cases where the overlap is small, the summations made by the algorithm are also small. The possibility therefore exists that a smaller error in one of these positions will be returned instead of the true overlap position.

Along with the text file containing the top and left positions for overlapping images, a second file is created. This is called *errorfile.txt* and it contains a list of all the errors calculated for every X and Y value tested for the pair of overlapping images. It is used to confirm that the correct overlap position has in fact been obtained. Graphically viewing this error data (when capturing three grooves per frame), reveals that there are usually three possible overlaps to consider, Figure 8.
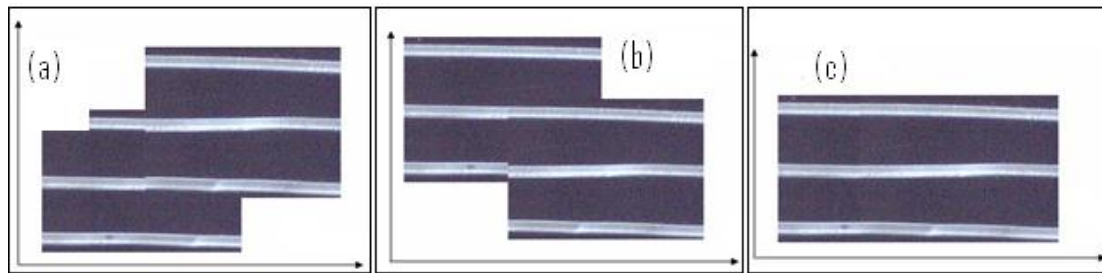

Figure 8: Potential overlap positions (a) Case 1 (b) Case 2 (c) Case 3

On observation, case three appears to be the correct version, but a more structured testing approach is adopted. A surface plot is generated from the error file containing all error values for the overlaps, at each X and Y position. The three potential overlaps can be seen in Figure 8. The x and y co-ordinates indicated above correspond to those shown in the images of Figure 9. The lowest error value (z -axis) can be seen in the centre surface plot. Note the protruding lower value of the central set of errors. According to the graph, this lowest error, in the range of 0 to 200 is to the order of 4 times lower then the closest match in either of the other two errors sets which begin at 800. By including a minimum

overlap in the algorithm the number of positions tested can be calculated as follows: ***Positions tested = 240 * (320-minimum overlap)***
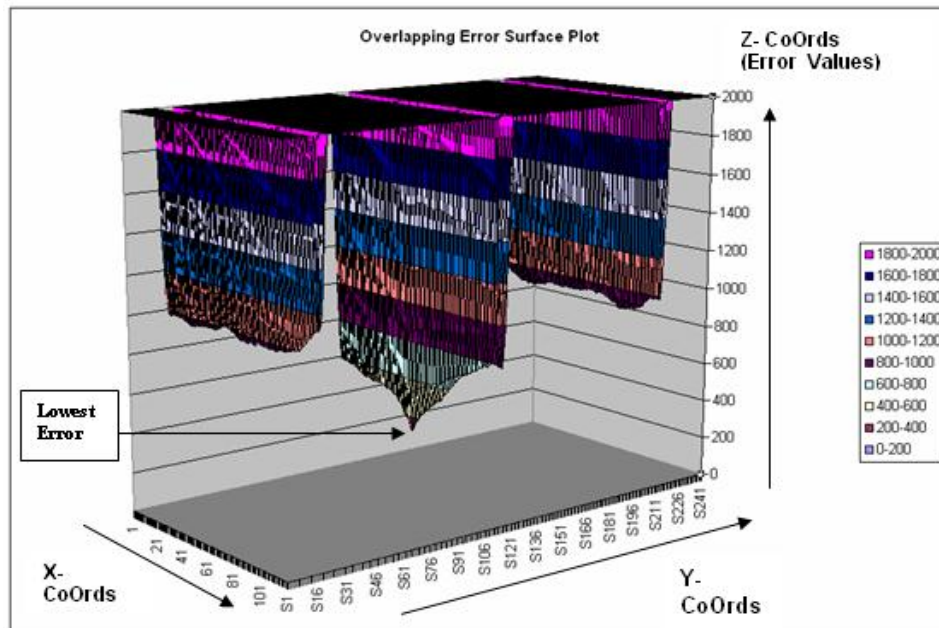

Figure 9: The lowest error value as seen on surface plot.

2.3   Groove Tracking

The next stage of the system deals with the tracking of a groove across the stitched images in order to create a waveform of sound data. As stated, the record groove is in fact the representation of the sound waveform. Our system allows the user to select the first image from which to begin the tracking process. The image focus algorithm will determine whether or not this is an appropriate frame to begin with.
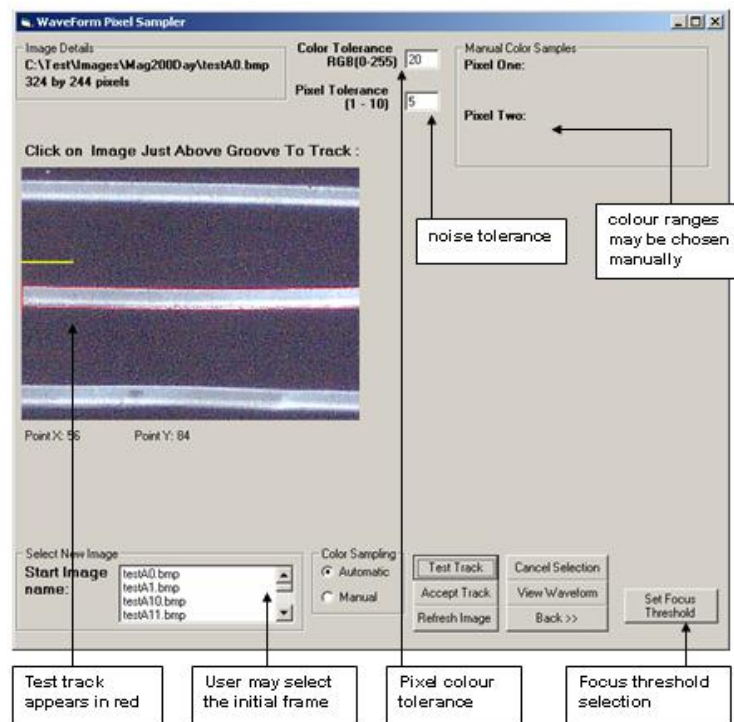

Figure 10: Groove tracking process

Once the initial frame is loaded the user simply clicks on a pixel slightly above the groove they wish to track. The test track button performs the tracking algorithm and displays a sample of exactly which range of pixels will be considered. Figure 10 illustrates how this is achieved by displaying the groove outline in red. If the user is satisfied with this groove, and the default settings appear to trace it accurately, the accept groove button is chosen and a set of text files are generated containing the groove information. The upper and lower tracks of the groove. Two ranges of pixel values are considered when tracking the groove:

1. Those considered to be in the range of the groove colour (**White**)
2. Those considered to be in the range of the non- groove colour (**Black**)

The default settings for groove/non-groove ranges are based on the first frame that is loaded. Every pixel is then compared to this range so the algorithm can make an accurate estimation of which pixels belong to the groove.

The ranges for groove/non–groove values may also be chosen manually for better accuracy in the case where the defaults are unsatisfactory. This is done by sampling a pixel in a typical position on the groove (white) and another which is not part of the groove (black). The focus threshold value may also be set by the user by accepting the average contrast per pixel of the selected image as the optimum focus value. All other frames will be tested relative to this focus range.

3   Sound file creation – Stage 4

The data saved in the *waveform.txt* file is prepared for transfer to a .wav file. This file contains a series of undulating vertical values (y-axis) along a horizontal plane (x-axis). The graphic of this file may be displayed in our system's software. The minimum vertical value is calculated so that the relative offsets from this minimum can be manipulated such that the lowest value becomes 0 and the upper limit of the waveform becomes 255. This is merely a manipulation to enable the file to be placed into a wav file. There are several methods of .wav file creation once the waveform has been stored in a text file. There are also a number of off-the-shelf packages that will create the image of any sound signal you record through a microphone, and allow you to modify the image for playback. Such programs could too be incorporated by this system to playback the image of the record groove. The simplest way to ensure the correct sound signal has been recorded is to test it by creating a .wav file from the data. There is a sampling rate applied but this would merely be for testing purposes only. Many off the shelf products will play such waveform once created.

4   Conclusions

This paper described a method for non-contact playing of vinyl records by stitching together smaller microscopic images of the waveform into one larger panoramic view. This enables playback of the waveform from the image rather than through contact with a stylus. Previous attempts did not consider the added simplicity involved in restricting the image to a two-dimensional greyscale format. The grooves of 78rpm phonographs can be seen clearly in a two-dimensional format with relatively inexpensive equipment.

Stitching algorithms, although simpler in approach to computer vision techniques such as optical flow and surface orientation, will perform competitively with higher processing speeds. Serious scratches and even broken records may be played and enhanced by image manipulation. The laser turntable cannot do this and has problems with even slightly warped disks. The disadvantage of this method is in the timescale required to fully execute the image stitching process. This renders instant playback impossible since the image must first be collected. However, once the image is in fact collected, and a mosaic stitched together, virtual real-time playback is possible with added features of noise reduction, no skipping and broken segments causing no obstructions. Since all other proposed methods, apart from the expensive laser turntable have similar delays in image acquisition, it can be argued that the image collection process that is the most paramount to the systems success.

The image stitching method proposed in this paper used 2D greyscale microscopic pictures rather than a full 3D groove construction which will obtain a large amount of redundant data. Since older 78s contain mono signals only, the grooves can be viewed in two dimensions. If a delay is inevitable, then the time required for image acquisition in such systems becomes secondary to the quality of images taken.

Further enhancements would include ways to more accurately obtain this overall record image while minimizing the hazards outlined in sections 2.1.1 above, namely image drift and de-focus. Image drift could be instantly eliminated by using a method of keeping the record stationary and moving the microscope instead over it in grid like movements through two by two sections rather than following the groove specifically. The fact that no specific groove is followed would mean the image drift problem disappears. The same stitching methods could be used to stitch grid sections. This sectioning of the image would also give more control and flexibility than one long groove image. The fact that the record is stationary would mean that de-focus is less of a problem as zero movement of the disc will not create an unlevelled surface (unless of course the disc is warped) and thus focal length should remain more or less consistent. To make real time playback possible while the imaging is taking place a system of buffered images might be incorporated where there would only be one initial short delay. With the current system, image analysis methods to dismiss the majority of unsuccessful overlaps would have to be developed to speed up the process. Essentially however, it does indeed appear possible for this system to be used as an inexpensive way to safely transfer the information from rare, antique or damaged records so they can be played in analogue form.

References

[ELP, 2003] ELP Laser Turntable ™, No needle No wear. Web reference www.elpj.com

[Fadeyev and Haber, 2003] Fadeyev, V. and Haber, C, 2003. Reconstruction of Mechanically Recorded Sound by Image Processing. Journal of Audio Engineering. Society. Pgs: 1172–1185.

[LaOr 1999] Ofer LaOr, 1999. A Video for Windows ActiveX control. Dr Dobbs Programmers Journal. June 1999.

[MilShaf SMC] StepperControl.com, a division of MilShaf technologies inc.
Web reference: www.steppercontrol.com/motors.html

[Olsson et al., 2003] Olsson, P, Ohlin. R. Olofsson, D., Vaerlien, R., and Ayrault, C, 2003. The digital needle project - group light blue. Technical report, KTH Royal Institute of Technology, Stockholm, Sweden. Web reference: www.s3.kth.se/signal/edu/projekt/students/03/lightblue/

[Smart, 2003] The amazing laser turntable. Smart Devices Journal, Aug 2003.
Web reference www.smartdev.com/LT/laserturntable.html

[USPO 86] Stoddard, Robert E, Finial Technology Inc, 1986. United States Patent Office. Number 4,870,631. Optical turntable system with reflected spot position detection,

[USPO 89] Stoddard, Robert E et al, Finial Technology Inc. 1989. United States Patent Office, Number 4,972,344. Dual beam optical turntable,

[Springer, 2002] Springer, O, 2002. Digital needle - a virtual gramophone.
Web reference: www.cs.huji.ac.il/~springer/

[Tian, Bannon, 2006] Baozhang Tian and John L.Barron, 2006. Reproduction of Sound Signals from Gramophone Records using 3D Scene Reconstruction. Irish Machine Vision and Image Processing Conference.

[Tian, Bannon, 2007] Baozhang Tian and John L.Barron, 2007. Sound from Gramophone Record Groove Surface Orientation. 14th IEEE-Intl Conferece on Image Processing.