
MOTION PICTURE RESTORATION
Video Supplement

by

Anil Christopher Kokaram

Churchill College

To accompany a dissertation submitted to the
University of Cambridge for the degree
of Doctor of Philosophy



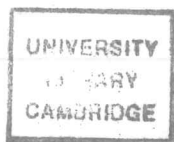
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MOTION PICTURE RESTORATION : VIDEO SUPPLEMENT

This video tape is included as a complement to the main body of work reported in the thesis entitled *Motion Picture Restoration*. The tape is approximately 30 minutes long and contains examples of the sequences discussed in the thesis as well as additional demonstrations of the complete system. The results discussed in Chapters 6,7,8 of the thesis can be viewed on the tape and there exist three sections of video (2-9, 10-15, and 16-28 respectively) corresponding to those chapters.

Excepting the very last demonstration sequence, the frames used are all of size 256×256 , and they should occupy most of the normal viewing screen. In some instances, the frames are shown in a smaller area so that the entire frame can be compared at the same time. Unless otherwise stated the frame rate used is 25 frames/sec, ie PAL video rate, and the sequences are played backward and forward for about 20 seconds.

The actual algorithms used to generate the various sequences are described in the thesis. Item groups 2,10 and 16 are all taken directly from the thesis material and the various parameter values can be found there. No values are given for the real sequences since they are not standard and the values were simply chosen to give a good visual result. For all these cases a multilevel Block Matching algorithm (with 2 to 4 levels) was used for motion estimation.

To allow the reader to easily follow the video sections, the text below lists and describes the various sequences and title screens. The time from the start of the tape to the beginning of each sequence is also listed in { *sequence number* : *minute* : *second* } format¹. Each text screen is enumerated below so that the item number and the sequence number are not the same, sequence numbers for introductory text screens are set to 00. The effects on the tape are best seen at a distance of about 1 to 2 metres from a 20 inch television monitor. The length of the video may be discouraging, but the last 10 mins (items 29-45) are demonstrations of performance on real degraded signals. The viewer is directed to these last minutes as a good example of the results that are possible.

¹Vertical Interlace Time Code (VITC) has been put on the tape.

1. 00:05:02 Titles
2. 00:05:30

MOTION COMPENSATED SPATIO-TEMPORAL MEDIAN FILTERING

3. 01:05:44 The degraded Cheers sequence.

Two frames are shown side by side of resolution 256×256 . A sequence of 32 frames is shown. The right hand sequence is degraded with square Blotches of randomly distributed size ranging from 2×2 to 6×6 . They occur with probability 0.002 and are either black or bright white (probability 0.5). Some Blotches of the same amplitude occur at the same position in two frames.

4. 02:06:35 A restoration using a multilevel median filter.

Two frames (of the 32 frame sequence) are shown side by side of resolution 256×256 . The left hand sequence is the degraded portion of sequence 1. The right hand sequence shows a restoration using the SDI detector to control an ML3Dex filter. The restoration shows that some portion of some of the Blotches has not been removed. This is because of multiple occurrences of Blotches along a motion trajectory (in this case the same position in 2 frames). When this occurs the detector cannot detect any discontinuity in temporal information. Even if this were possible, the median filter could not remove the distortion for the same reason.

5. 03:07:40 A restoration using a multilevel median filter.

A portion of two frames are shown side by side of resolution 256×128 . This is the proper viewing size. The sequence of 62 frames is played forward and backward for approximately 20 secs. The left hand sequence is the clean portion of sequence 1. The right hand sequence shows the same restoration as in item 4. This sequence allows a direct comparison between the clean original and restored sequences.

The motion of the hand of the central figure is very severe in this sequence; there is a great deal of motion blur in the original. Because of this, the Multilevel Block Matching algorithm used for motion estimation cannot estimate useful motion vectors in that region and some portion of the hand is detected as a scratch by the Blotch detector. The median filter then introduces some distortion. The observed artefact takes the form of a breaking up of the fast moving hand at the bottom and top of its arc.

6. 04:08:50 Controlled Vs Global operations.

A portion of two frames is shown side by side of resolution $256 \times 128 \times 62$ frames at the proper viewing size. The left hand sequence shows the restoration using the SDI detector to control an ML3Dex filter, as shown in the previous clip. The right hand sequence shows the result of a global application of the same filter.

This sequence highlights very well the artefacts that arise with a global operation. The right hand sequence is seen to have lost much detail. The overall impression is one of a faded picture. In particular the hair of the central figure and the face of the woman just to the left, have much less detail in the right hand sequence than in the left hand sequence. This fading is the expected result after global filtering with a median operation since such operations tend to remove rapid fluctuations in signal level and therefore prefer planar regions.

7. 05:10:02 Controlled Vs Global operations: The Bi-directional filter.

A portion of two frames is shown side by side of resolution $256 \times 128 \times 62$ frames. This is the proper viewing size. The sequence of 62 frames is played forward and backward for approximately 20 secs. The left hand sequence shows the restoration using the SDI detector to control an ML3Dex filter, as shown in the previous clip. The right hand sequence shows the result of a global application of the Bi-directional filter introduced by Arce.

As expected the Bi-directional filter cannot remove the an entire Blotch of this size. It can only remove the edges, however, it does not affect the image detail in any observably detrimental way. The ML3Dex filter can be seen to introduce some fading, but this is offset in this case by the rejection of almost all Blotches.

8. 5A:10:59 Controlled Vs Global operations: The Bi-directional filter.

A portion of two frames are shown side by side of resolution $256 \times 128 \times 62$ frames. This is the proper viewing size. The left hand sequence shows the degraded sequence from sequence 1. The right hand sequence shows the restoration using the SDI detector to control an ML3Dex filter, as shown in the previous clip.

This gives the viewer a better feel for the improvement that the ML3Dex filter yields when faced with such a high probability of large Blotches. It is to be noted that this heavy degradation is not likely in practice.

9. 06:11:48 A real application: *The Odd Couple*.

Two frames are shown side by side of resolution $256 \times 256 \times 32$ frames. This is not the proper viewing size but gives a good view of the entire frame that was processed. The left hand sequence shows the degraded original sequence. The right hand sequence shows the restoration using the SDI detector to control an ML3Dex filter. The restoration can be seen to remove all the Blotches that occur. Note the central area and the region to the right of the head of the figure wearing the towel.

10. 00:12:40

THREE DIMENSIONAL AR MODELLING FOR SUPPRESSING IMPULSIVE NOISE IN IMAGE SEQUENCES.

11. 07:12:58 Restoration using the 3D AR model.

A portion of two frames is shown side by side of resolution $256 \times 128 \times 62$ frames. This is the proper viewing size. The left hand sequence is again the degraded Cheers sequence shown previously. The right hand sequence shows the result after using the SDIa detector to control a 3D AR 9:0 interpolator.

The detail in the restoration is well preserved. Again there is some distortion in the fast moving hand, but this is due to the choice of a model with a support which is not in the current frame. Therefore errors in motion estimation lead to more interpolation artefacts than would be the case with a 9:8 model, for instance. Again, some Blotches cannot be detected.

12. 08:13:50 Restoration using the 3D AR model: Comparing with the clean signal.

The presentation is the same as in the previous item. The left hand sequence is the clean original Cheers sequence shown previously as sequence 3. The right hand sequence shows the result after using the SDIa detector to control a 3D AR 9:0 interpolator. This comparison shows to what extent the detail in the sequence is preserved. The restoration is encouraging in this respect.

13. 09:14:50 Restoration using the 3D AR model: Comparing with the median filtered signal.

The presentation is the same as in the previous item. The left hand sequence shows the restored sequence using the SDIa detector to control a 3D AR 9:0 interpolator, as previously shown in sequences 11,12. The right hand sequence shows the result after using the same detector (with the same parameters) and the ML3Dex filter.

The model based restoration is superior to the median filtered result. The fast moving hand is better preserved by the 3DAR interpolator, and the face of the woman to the left of centre does not flicker as it moves up the frame. The fidelity of this interpolator is therefore much better than the median operation.

14. 10:15:55 A real application: *Clochemerle*

The presentation is the same as in the previous item except that 25 frames are shown. The left hand sequence shows the degraded original. The right hand sequence shows the restored result using the SDIa detector to control a 3D AR 9:0 interpolator.

This clip from *Clochemerle* shows a central figure with a rapidly moving arm. There is only one large Blotch toward the end of the sequence that is situated at the V of the cloak. The detector has no difficulty in detecting the distortion and the interpolator acts effectively.

There were false alarms at the tips of the fingers as they touch the hat, but these were also dealt with satisfactorily.

15. 11:16:49 *Clochemerle* : Comparison with median filtering.

The presentation is the same as for the previous item. The sequence of 25 frames is played forward and backward for approximately 20 secs. The left hand sequence shows the restored result using the SDIa detector to control a 3D AR 9:0 interpolator, and the right hand result shows the operation of the ML3Dex filter in the same situation.

The median filtered sequence seems identical to the model based interpolated result. However, the false alarms that occur at the tips of the fingers (as they touch the hat of the central figure) are not well treated by the median filter. This can be observed on a large enough screen (20 inch). This comparison reinforces the statements made in the thesis; the model based interpolator is more robust to motion estimation errors that would give rise to false alarms from the detector.

16. 00:17:45

NOISE REDUCTION FOR IMAGE SEQUENCES

17. 12:17:58 The degraded Cheers sequence

Two frames (of a 20 frame sequence) are shown side by side of resolution 256×256 . This is not the proper viewing size. The left hand sequence shows the clean original sequence and the right hand, the sequence degraded with Gaussian noise of variance 100, giving a 20dB SNR. This is the same sequence used for the results shown in Chapter 8 of the thesis.

18. 13:18:55 The 3D Frequency Domain Wiener filter

A portion of two frames (of a 20 frame sequence) is shown side by side of resolution 256×128 . This is the proper viewing size. The left hand sequence shows the degraded signal as above, and the right hand shows the restoration using a 3D Frequency Domain Wiener filter with $\beta = 1.1$, $\sigma_{nn}^2 = 100$.

The Wiener filter performs well although there is some residual noise, due to the noise margin chosen to avoid signal degradation. Note that moving regions are not degraded by any observable artefacts.

19. 14:19:27 The 3D Frequency Domain Wiener filter.

The presentation is the same as the previous item. The left hand sequence shows the original clean signal as in sequence 1, and the right hand shows the restoration using a 3D Frequency Domain Wiener filter with $\beta = 1.1$, $\sigma_{nn}^2 = 100$. This affords a good visual assessment of the quality of the restored version. Note the residual noise.

20. 15:20:10 A Comparison with the 3D FIR Filter.

The presentation is the same as the previous item. The left hand side shows the restoration using a 3D Frequency Domain Wiener filter as above. The right hand side shows the 3D FIR result using the same parameters and a cubic filter shape occupying a $3 \times 3 \times 3$ pixel volume.

The FIR result does show more residual noise than the Frequency Domain result. But this is of a very low level and so can be better seen if the brightness of the viewing equipment is increased.

21. 16:21:02 A Comparison with the temporal Wiener filter.

The presentation is the same as the previous item. The left hand side shows the restoration using a 3D Frequency Domain Wiener filter as above. The right hand side shows the result using single tap Wiener filter which makes observations using three pixels in the temporal direction. The same parameters were used.

As expected the temporal filter leaves more noise in the image. There is also a slight *Dirty Window* effect, so called because the residual noise field does not give the impression of high activity and so it seems that the image is being viewed through a dirty window.

22. 17:21:41 A Comparison with the temporal averaging filter.

The presentation is the same as the previous item. The left hand side shows the restoration using a 3D Frequency Domain Wiener filter as above. The right hand side shows the result using the 3 tap temporal averaging filter.

As stated earlier for the median filtering examples the motion estimation is not accurate in the region of the fast moving hand. Therefore the averaging operation yields much blurring in moving areas. This is well illustrated at the top of the trajectory of the hand when it waves rapidly over a small distance. The Wiener filter is able to compensate for erroneous motion estimation because of the high temporal activity that such an error would cause. When this occurs, the Wiener filter reduces its attenuation and so leaves more noise in the sequence at that location. Since the object at that location is fast moving anyway, there is no visible degradation even though there is more residual noise. This is preferable to the blurring that would result as is well illustrated here. Note however that this reduction in attenuation by the Wiener filter in this situation is not governed by any human visual criteria and so is not guaranteed to be always effective.

23. 18:22:27 A Comparison with the temporally recursive filter.

The presentation is the same as the previous item. The left hand side shows the restoration using a 3D Frequency Domain Wiener filter as above. The right hand side shows the result using the temporally recursive filter due to Dubois et al.

The recursive filter can be seen to perform similarly to the temporal Wiener filter. This filter can be adjusted to increase the attenuation of noise, but at the detriment of the signal. Note that it requires more parameters than the Wiener filters for it to respond correctly to erroneous motion estimation (See Chapter 8 of the thesis).

24. 19:23:09 A real application: *The Lonely Dog*

A portion of two frames are shown side by side of resolution 256×128 . This is the proper viewing size. The cartoon sequence of 62 frames is played forward and backward for approximately 20 secs. The right hand side shows the restoration using a 3D Frequency Domain Wiener filter with the left hand side showing the degraded original.

The restoration is effective in removing much of the noise without affecting the signal. Its performance is not visibly harmed by large motion.

25. 20:24:08 *The Lonely Dog* : Comparison with the temporal Wiener filter.

The same presentation format is used as above. The left hand side shows the restoration using a 3D Frequency Domain Wiener filter with the right hand side showing the result of Temporal Wiener filtering with the same parameters. As expected the temporal filter cannot reject as much noise as the Wiener filter. The signal is not visibly degraded in either version.

26. 21:25:05 *The Lonely Dog* : Comparison with the temporal averaging operation.

Again, the presentation is the same as above. The left hand side shows the restoration using a 3D Frequency Domain Wiener filter with the right hand side showing the result of temporal averaging. As expected the temporal averaging filter is sensitive to erroneous motion estimation. This sequence is a particularly severe example of this problem. The cartoon shapes alter drastically from frame to frame and it is understandable that the motion estimation is affected. The blurring caused by the averaging operation is therefore severe.

27. 22:25:56 *The Lonely Dog* : Comparison with the temporal recursive filter.

The left hand side shows the restoration using a 3D Frequency Domain Wiener filter with the right hand side showing the result of temporal filtering after Dubois et al. The result is visually similar to the case of temporal Wiener filtering shown earlier.

28. 23:26:51 *The Lonely Dog* : The distortion introduced by the Frequency Domain filter

A portion of two frames is shown side by side of resolution 256×128 . This is the proper viewing size. The cartoon sequence of 3 frames is played forward and backward for approximately 20 secs at a frame rate of 0.5 frames per second. The left hand side shows the original sequence, and the right shows the restoration using a 3D Frequency Domain Wiener filter.

At this much reduced speed it is easier to see the artefacts that are caused by the Wiener filter in areas where motion is not estimated properly. The forelegs of the lion undergo a severe change in shape through the frames, and around these regions there is a larger amount of noise and also some sort of ringing artefacts. When motion is tracked, however, for example the interior of the lion and the background, the residual noise is much less and the operation is more successful.

29. 00:27:40

THE COMPLETE SYSTEM

These last seven items show the operation of both the scratch suppression algorithm and the 3D Frequency Domain Wiener filter in cascade. All the sequences were digitized from television and are therefore useful for assessing the performance of the complete system in a real situation. The restored versions are shown previous to the original in some cases in order to leave the observer unbiased as to the quality of the restoration. The restored sequences must stand as sequences in their own right, the viewer would not normally have access to, or knowledge of, the degraded original. These sequences are not numbered on tape since they have individual names.

Excepting the cartoon sequences, the SDIa was used to detect Blotches and the ML3Dex filter used to interpolate the missing information. Where applied, this was followed by a 3D Frequency Domain Wiener filter as described in the thesis using some noise margin and a 16×16 block size. The cartoon sequences were treated only with the noise reduction filter since they show noise as the chief degradation.

30. 24:27:56 *Clochemerle*: Restored

The entire frame of resolution 256×256 is shown here. The 60 frames in the sequence are played backward and forward for approximately 20 secs. The restoration was achieved using the SDIa detector and ML3Dex filter for scratch suppression and a 3D Frequency Domain Wiener filter for noise reduction. The sequence shows small motion and so does not pose a problem as far as motion estimation is concerned.

31. 25:28:31 *Clochemerle*: Original

The entire frame of resolution 256×256 is shown here. The 60 frames in the sequence are played backward and forward for approximately 20 secs. Note the large quantity of Dirt and Sparkle as well as the high level of noise.

32. 26:29:07 *Clochemerle*: Original/Restored

Two frames are shown side by side of resolution 256×128 . The 60 frames in the sequence are played backward and forward for approximately 20 secs. The left hand side shows the original and the right hand side the restored. All Dirt and Sparkle is removed in the restoration but there is some blurring caused by the Wiener filter. The noise reduction process is very subjective. A real time implementation of the algorithm would enable a user to better achieve that difficult compromise between noise reduction and signal degradation. It has been observed that viewers prefer a small amount of noise in the sequence even if the restoration is not blurred.

33. 27:29:40 *The Lonely Dog (1)* : Original/Restored

The entire 60 frames of resolution 256×256 are shown. Only a 3D Frequency Domain Wiener filter was applied for noise reduction since the sequence is corrupted in the main by noise. This is the same sequence as in item 24. The vertical line in the image separates the original left half from the restored right half. This is merely a method of viewing the entire frame while at the same time comparing the restored and original versions. The cartoon figures therefore continually cross between the noisy half image and the clean portion. There is never a case where one could see the same frame portion in the restored and original versions. Nevertheless, the noise is not a local effect and therefore the overall impression is useful.

34. 28:30:35 *The Odd Couple*: Restored

The entire 60 frames of resolution 256×256 is shown here. The restoration was achieved using the SDIa detector and ML3Dex filter for scratch suppression and a 3D Frequency Domain Wiener filter for noise reduction. The sequence is the same as that used for item 9.

35. 29:31:15 *The Odd Couple*: Original

The corresponding degraded original sequence is shown here. Note the large scratches in the central region and to the right of the towel clothed figure. The level of noise is not large in these frames.

36. 30:31:55 *The Odd Couple*: Original/Restored

Two frames are shown side by side of resolution 256×128 in a similar manner to the *Clochemerle* sequence. There is an artificially imposed right to left pan which allows more of the frames to be seen. The left hand side shows the original and the right hand side the restored. All Dirt and Sparkle is removed in the restoration and the noise is removed effectively without causing blurring.

37. 31:32:40 *Star Trek* : Horizontal split screen

60 frames are shown in a split screen format. The top 128×256 portion shows the original sequence and the bottom, the restored. This sequence is also corrupted by vertical banding due to interference from other devices during digitizing. No attempt was made to remove this artefact. The degraded sequence shows a number of vertical scratches which are not completely removed in the restoration. This is because of the low contrast of the scratches with the surrounding area in the previous and next frames. The scratches are therefore not completely detected.

38. 32:33:27 *The Lonely Dog* (2) : Restored/Original

The entire 60 frames of resolution 256×256 are shown. Only a 3D Frequency Domain Wiener filter was applied for noise reduction since the sequence is corrupted in the main by noise. The vertical line in the image sweeps from left to right and reveals the restored

portion as it does so. This is another method of viewing the entire frame while at the same time comparing the restored and original versions. Because of memory constraints in the frame grabber used, the line sweeps from left to right once, across the 60 frames. Therefore there is never a case where one could see the same frame portion in the restored and original versions. Again, the noise is not a local effect and therefore the overall impression is useful.

39. 33:34:10 *The Lonely Dog* (2) : Horizontal split screen

In a similar manner to past screens, this split screen shows a portion of the original sequence in the top half screen and the corresponding restored sequence in the bottom half screen. Note that despite the fast motion in this sequence, the noise is reduced without introducing visible degradation.

40. 34:34:52 *I Can't Take It Anymore* : Restored

Again, this restored sequence of $256 \times 256 \times 60$ frames is shown in its entirety. Note that there are still some visible line scratches in the restored version, and these cannot be addressed at all by the current processes introduced. The sequence gets its name from the speech of the woman in this short clip; the words are well shaped and the viewer can easily lip read in this case.

41. 35:35:28 *I Can't Take It Anymore* : Original

The degraded original sequence of $256 \times 256 \times 60$ frames is shown in its entirety. There is heavy degradation in the sequence consisting of Dirt, Sparkle, noise and line scratches.

42. 36:36:05 *I Can't Take It Anymore* : Horizontal split screen

The top half of the screen here shows the original sequence and the bottom half the restored sequence. The restoration is quite good, although there is arguably some blurring. This was caused primarily by false alarms from the SDIa detector that was used. Note that the line scratches are reduced in intensity even if they are still present. This is due to a combination of the SDIa detector flagging some portions of the lines as Blotches and the Wiener filter acting as a smoothing operation.

43. 37:36:49 *Journey Together* : Restored

These last three clips show a restoration of a 5 second clip of video as supplied by Channel 4 Television in London, England. The frames were digitized at full PAL resolution although only a 512×512 portion was used. The recordings are not of excellent quality as they are second generation copies of the original restored version which is on Professional Sony Betacam video tape. Nevertheless they are sufficiently stable to be useful.

This first clip shows the restored sequence. In this instance a 3D FIR Wiener filter was used for noise reduction since at the time that the Channel 4 equipment was made available, the frequency domain software was not yet written. Note the slight dirty window effect that was left by the filter. The viewer would notice that there is still noise in the frames.

44. 38:37:24 *Journey Together* : Original

The original sequence is heavily degraded with large quantities of Dirt and Sparkle. Just before the scene change, there are a set of fingerprints that cover several frames. These are removed in the restoration. It must be stated that a scene change detector was not used here, but the two parts of the sequence across the cut were processed separately. The implementation of a scene cut detector can be done using a MAE criterion to assess the difference between frames.

45. 39:37:58 *Journey Together* : Horizontal split screen

In a similar manner to past split screens this view gives the observer a chance to compare the restored and original versions. Note that the noise reduction is very effective although there is some blurring of the background.

46. 00:38:40 End Credits