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HIGHER FRAME RATES FOR MORE IMMERSIVE VIDEO AND TELEVISION

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BRITISH BROADCASTING CORPORATION

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Abstract

The frame and field rates that have been used for television since the 1930s cause problems for motion portrayal, which are increasingly evident on the large, high-resolution television displays that are now common. In this paper we report on a programme of experimental work that successfully demonstrated the advantages of higher frame rate capture and display as a means of improving the quality of television systems of all spatial resolutions. The greater realism of motion portrayal obtained at higher frame rates is required to present a truly immersive experience.

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Additional key words: High frame rate, shuttering, temporal resolution.

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1 INTRODUCTION

The frame rates used for film and television have been fixed for the best part of a century. A belief has arisen (e.g. Ferguson and Schultz [1]) that the frame rates chosen are close to an upper limit, and that little improvement can be expected from an increase. In this paper we will challenge this view, reporting on some experimental work that shows that the use of higher frame rates for capture, storage, transmission and display offers clear advantages at the resolutions associated with SD and HDTV. We will also explain why the frame rates currently in use will increasingly limit the quality of television pictures if the size of displays and/or the resolution of television systems continue to grow.

2 HISTORICAL OVERVIEW

In the days of silent cinema, frame rates were not standardised, and were largely in the range of around 16 to 24 fps (frames per second). Cameramen and projectionists sometimes varied the speed according to the subject matter portrayed. Thomas Edison however, for a time, recommended 46 fps, possibly to prevent flicker [2]. With the development of sound-on-film in the 1920s, film speeds and hence frame rates standardised at the now ubiquitous 24 fps.

To avoid visible flicker, a double or treble-bladed shutter was used to display each image two or three times in quick succession. A downside of this technique is that moving objects being tracked by the eye appear as two or three overlapping images or appear to jump backwards and forwards along their line of motion: an effect also known as "film judder" (Roberts [3]). One exception within the film industry is Douglas Trumbull's Showscan system [4] uses 65 or 70mm film running at 60 fps with a single-bladed shutter. This system is sometimes used for high-speed action films and ride simulations to provide more realistic motion.

The Marconi-EMI television system (now known as "405-line") was adopted by the BBC in 1937. These systems were described contemporaneously as "high-definition television". The Marconi-EMI system and all subsequent TV standards have used a field rate that is the same as the mains frequency (50Hz in Europe).

The reasons given at the time (BBC [5]) for synchronising the frame rate of television to the mains frequency were to avoid "beating" against the 100Hz brightness fluctuation in AC-driven studio lights and the 50Hz fluctuation induced by poor ripple-suppression in the HT generation circuitry of early CRT televisions (Engstrom [6]). The 60Hz mains frequency used in the USA similarly led to a 60Hz field rate in their television systems (Kell et al [7]). Subsequently, on the introduction of colour TV systems, a 1000/1001 adjustment was found necessary in the NTSC system, which means that TV systems described as "60Hz" are generally running at 59.94 fps. In addition, these rates are slightly above the 40Hz minimum that was found necessary to avoid visible flicker in the displayed image on contemporary television screens [6].

At that time, it was considered sufficient (Zworykin and Morton [8]) for the frame rate to be high enough merely to exceed the threshold for "apparent motion" – the boundary above which a sequence of recorded images appear to the eye as containing moving objects rather than being a succession of still photographs. Priority was not given to the elimination of motion artefacts such as smearing and jerkiness. Contemporary tube cameras suffered from image retention, which may have limited the benefits of a higher rate anyway.

A final benefit of choosing a field rate equal to the mains frequency is simple interoperability with cinematic film recording. In 50Hz countries, since the speed difference between 24fps and 25fps is generally imperceptible, a frame of film can be represented as two successive fields of video. In 60Hz countries alternate frames of film have to be represented as three successive fields (a frame and a half) of video, a process known as "3:2 pull-down" which introduces further judder artefacts.

In summary, it appears that the field rates originally determined for television (and kept ever since) were chosen to meet the following criteria:

- Greater than the perceptual threshold for apparent motion.
- High enough that flicker was imperceptible on contemporary televisions.
- Simple conversion to and from cinematic film.

3 EARLY WORK ON HDTV FRAME RATES

With research into HDTV commencing in the 1970s, the question of the appropriate frame rate for the new television standard was open for re-evaluation. The Japanese broadcaster NHK was the leader in this field, and the 1982 summary of their HDTV research to date by Fujio et al [9] identifies "frame frequency" as a parameter to be determined. There appears to be no published research from them on the subject, however, and the field rate of NHK's 1125-line interlaced HDTV standard remained essentially unchanged from the NTSC standard it replaced, at 60 fields per second.

The question of frame rate, amongst other parameters, was also investigated by the BBC's Research Department. Stone [10] performed a number of experiments with a tube camera and a CRT monitor, both modified to support non-standard field rates and other parameters set by the vertical deflection waveform. The issue of increased flicker perceptibility on increasingly large and bright television sets was well known by the 1980s, and taking a leaf out of cinema's book, the use of higher refresh rates was being considered to compensate (Lord et al [11]). Stone recognised that increasing the frame rate of television would not only reduce the visibility of flicker, but that it would also improve the portrayal of moving objects. He carried out subjective tests and found that for fast-moving subject material (corresponding to a camera pan at a speed of one picture-width per second), increasing the frame rate to 80Hz resulted in a subjective quality improvement of two points on the CCIR 5-point quality scale [10].

Despite this finding, the eventual standardised HDTV formats retained the 50/60Hz frame/field rate. In a 1988 article, Childs [12] attributes this simply to the increases in transmission bandwidth and storage capacity required for a higher rate.

As CRT televisions grew larger and brighter, manufacturers started using frame-doubling techniques to reduce flicker. However, the simple techniques initially employed made the portrayal of moving objects worse, by introducing a 50/60Hz "film-judder" effect (Philips [13]).

4 ISSUES WITH CONVENTIONAL FRAME RATES

Current television field and frame rates cause problems for motion portrayal. Objects stationary within the video frame are sharp, provided they are in focus, but objects that move with respect to the frame smear due to the integration time of the camera's sensor. Shuttering the camera to shorten the integration time reduces the smearing, but the motion breaks up into a succession of still images, causing jerkiness. The perceptual difference between moving and stationary subjects is increased with the increasingly sharper images due to new television systems with successively higher spatial resolutions, so long as the temporal resolution remains unchanged. We describe the ability of a television system to represent the spatial detail of moving objects as its "dynamic resolution". The problems of insufficient dynamic resolution – smearing, jerkiness or a combination of the two – are more noticeable with larger displays where the eye tends to follow the motion across the scene.

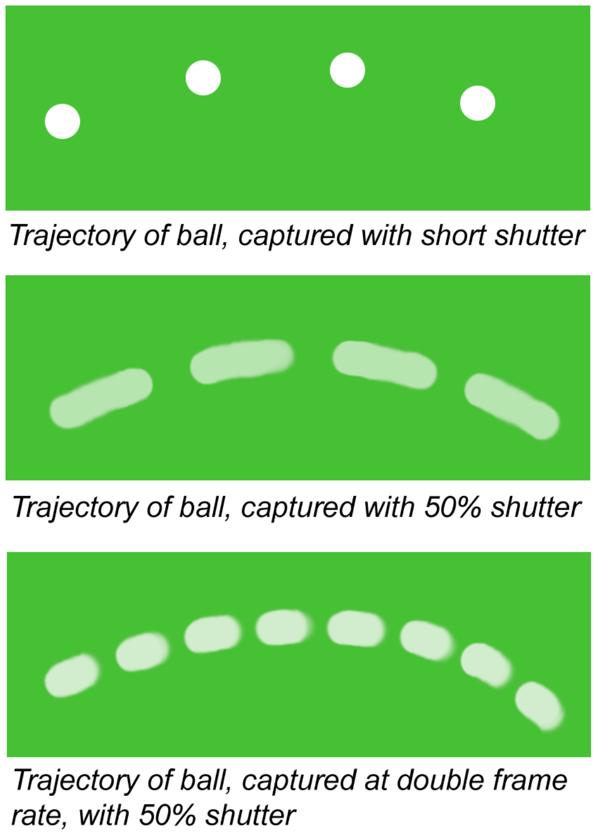

Figure 1 – Effects of frame rate and shuttering upon motion portrayal.

The problem is illustrated in Fig. 1, in terms of the movement of a ball across a plain background. In the top illustration, the trajectory of the ball is shown as if captured by a video camera with a very short shutter. Each frame would show the ball "frozen in time", and the motion would appear jerky when the video sequence was replayed. In the middle illustration, the effect of a (half-) open shutter is depicted. The camera integration smears the motion of the ball out over the background, removing any spatial detail and making it partially transparent. These effects would be clearly visible in the final video sequence. The bottom image shows the effect of doubling the frame rate: both the smearing and jerkiness are reduced. A substantial further increase in frame rate would still be required in this example to eliminate their effects, however.

In cinema, which evolved a high resolution-to-frame-rate ratio much earlier than television, production techniques have evolved in parallel to deal with the low dynamic resolution of the medium. Tracking shots and camera moves are commonplace, often used in conjunction with short depths of field, which help by softening backgrounds that if moving at different speeds to the tracked subject would otherwise appear to jerk and judder.

The decision to adopt interlaced video for Standard Definition television resulted in a lower spatial resolution and a higher image repetition rate than would have been the case in a progressively-scanned system of the same frame rate and bandwidth. Hence the dynamic resolution is better matched to the static spatial resolution and so the problems of motion portrayal were considerably ameliorated.

High-Definition television (by which we mean television with a vertical resolution of 720 or 1080 lines and a field or frame rate of 50/60Hz) has increased the spatial resolution without altering the frame rates used, however. Traditional television production techniques have been constrained by this change. For example, during camera pans to follow the action at sports events, HDTV trial viewers reported nausea as the static portion of the scene changed between sharp (when stationary) and smeared (when panning). The implied constraint of reducing the pan rate is not always practical in live coverage, but in practice compromises such as camera shuttering and deliberate softening of the images can help reduce the problem. Regardless of this, simple maths shows that motion of the camera or of objects within the scene at speeds higher than three pixels per field/frame eliminates all of the additional detail gained by the use of high definition, in the direction of motion. This effect is illustrated in Fig. 2. These problems will be compounded by any future increases in the spatial resolution of television.

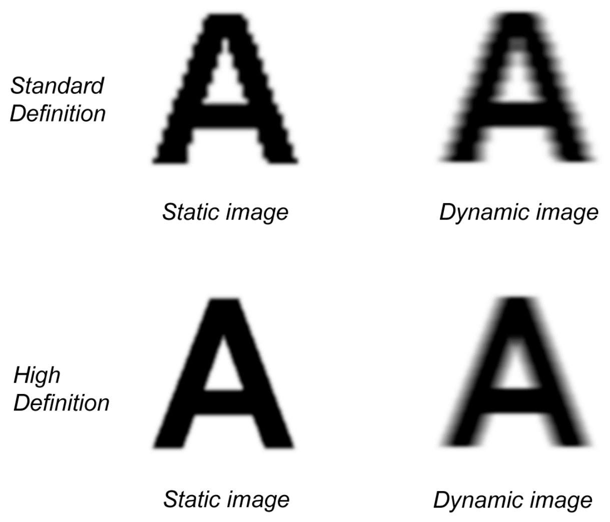

Figure 2 – Static & dynamic resolution at SD and HD.

Just as shuttering in the camera reduces the extent of smearing, a sample-and-hold characteristic in the final display increases it in a directly comparable fashion. This smearing arises with trackable motion in the displayed video where the eye is following the object across the screen, but where within each displayed image the object remains stationary for duration of the frame or field. This characteristic is to be found in the LCD televisions that are currently taking a dominant share of the market, and is the reason why these displays have a reputation for representing fast-moving material, such as sport, poorly. Manufacturers have added processing inside LCD televisions to perform a motion-compensated frame rate doubling, which ameliorates the problem to some extent at the cost of introducing other artefacts when the motion becomes too hard to predict, and during cuts and cross-fades.

In the light of these issues, we propose that higher frame rates be part of any future video format standard, tracking or exceeding any future increases in spatial resolution. This would help redress the imbalance between dynamic and spatial resolutions which exists in current television standards, and is a necessary precursor to further increases in spatial resolution if further undesirable constraints on production techniques are to be avoided.

5 PRACTICAL INVESTIGATIONS INTO THE EFFECTS OF HIGH FRAME RATES

5.1 Initial Experiment

To investigate the theoretical advantages of high frame-rate capture and display, in the summer of 2007 an intensive week of experiments was undertaken. Using a Vision Research Phantom V5.1 camera, a series of 25-second sequences were captured at a resolution of 1024x576 and a rate of 300 frames per second. This camera is capable of capturing video at up to 1,200 fps, and at resolutions of up to 1024x1024 pixels, but has only sufficient memory to capture four seconds of video at that resolution and rate. To obtain a TV-standard 16:9 aspect ratio we cropped the vertical image to 576 lines. The Bayer-pattern sensor implies a lower luminance resolution than this, similar in magnitude to the reduction in vertical resolution associated with the use of interlace in standard-definition television. A shooting frame rate of 300fps was chosen to allow for shots in excess of twenty seconds long, and to facilitate down-conversion to 25, 50 and 100 fps video. (300fps also has the advantage of simple down-conversion to 60fps.) Each 25-second sequence took around ten minutes to download from the camera.

A variety of subjects was chosen to explore the advantages of high frame-rate capture and display. These included a roulette wheel and a rotating bicycle wheel, for rotational motion; bouncing balls, table-tennis and juggling, as examples of fast-moving "sports" material, and a fast-panning camera shot with and without a tracked subject.

There are few displays that accept and display video at frame rates higher than around 60fps. CRT computer monitors can in some cases be driven at up to 200fps at reduced resolution, but with a display size much smaller than is normal for HD televisions. For the purposes of our experiments we chose a projector designed for frame-interleaved stereoscopy applications, which could be driven at 100fps at a sufficiently high resolution: the Christie Mirage S+4K. The material was sent to the display over DVI from a dedicated playout PC, reading uncompressed YUV video from a high-speed RAID array.

To create 100fps material, every three successive frames of the 300fps original were averaged to simulate an unshuttered 100fps camera. For comparison purposes, we also averaged every six successive frames to simulate an unshuttered 50fps camera, and then alternated between averaging six and dropping six successive frames to simulate a 25fps camera with film-style 50% shuttering.

Further material was computer-generated by taking a still image and simulating a sinusoidal pan across it, with camera integration to match the frame rates and shuttering choices described above. The still image chosen was the well-known "Kiel Harbour" photograph. The video sequence was rendered at a resolution of 1280x720.

Our observations were as follows. The most striking differences were seen in the panning shots – real and simulated – where the loss of spatial resolution in the detail of the background was particularly marked, particularly in the 720p Kiel Harbour simulated pan sequence. In the standard definition pan shot, lettering that was clearly legible in a static image was unreadable during the pan at frame rates below 100fps. The reduced motion blur on the tracked pan shot also gave a greater sense of realism and "three-dimensionality" as the improved dynamic sharpness of both the moving objects and the background improved the quality of the occlusion depth cue. The table-tennis sequence demonstrated that even 100fps was manifestly insufficient for coverage of this and similar sports when viewed perpendicular to the action. Motion blur was also still in evidence in the juggling sequence at 300fps, played back at 1/3 speed.

It is striking that significant improvements were discernable even at resolutions similar to standard definition television. This implies that high frame rate capture and display is a technique that can improve the quality of television in its own right, as well as a necessary consideration as the spatial resolutions of proposed television standards continue to increase.

5.2 Further experiments and BBC demonstration at IBC 2008

Following the success of the first experiments, a formal project was initiated, with material captured again at 300fps, this time using an Arri Hi-Motion camera [14], providing better video quality, at full HD resolution (1920x1080 pixels).

A wider variety of material was shot, and edited to produce a demonstration shown on the EBU stand at IBC 2008 (International Broadcasting Convention, Amsterdam). Again the main constraint was in the display, which was a projector again running at 100fps, and at sub-HD resolution. The results obtained were however quite dramatic, and the demonstration drew crowds of interested viewers, many of whom were most interested to see with their own eyes something they'd long suspected would yield a dramatic improvement in the realism of video presentation.

Figure 3. Still from BBC test shoot, above as it would have been captured with 50 Hz frame rate, and below, at 300 fps.

Fig.3 shows a pair of stills from the experiment, the top image being that representing the scene (a moving model railway locomotive) as it would have been captured in a conventional 50Hz TV system. The lower image shows the same image, as actually captured at 300 fps.

The experiment also bore out the results observed in the first experiment, but the resulting video material was of significantly higher quality, and covered a wider variety of content types, enabling convincing demonstrations to be given.

5.3 Experiments conducted by NHK in Japan

The Japanese state broadcaster, NHK, has subsequently conducted experiments intended to explore the frame rate requirements for Ultra High Definition TV (UHTV).

Sugawara [15] reported the results as indicating that future TV systems would require a display rate above about 80Hz to prevent large-area flicker (at the screen sizes and brightness expected), that a frame rate of greater than 100 Hz was required to prevent a stroboscopic (judder) effect with motion, and a capture time of below 1/320 of a second was required to prevent motion blur in the capture from detracting from the video quality.

Dr Sugawara's paper also posed the question as to whether 300 or even 600 fps was really feasible, however desirable it might be as a common multiple of current frame rates, and expressed the hope that we might none the less be able to agree a single worldwide standard for a higher frame rate. He also posed the question as to whether the 1000/1001 issue might be less of a problem in the future, and concluded by suggesting that the camera, transmission and display technologies to enable the use of a higher frame rate than 60Hz will be developed in the near future.

5.4 Work at Sony Corporation

Kuroki at Sony Corporation reports [16] the development of a 240fps 4k by 2k camera and display system intended for steresoscopic 3D reproduction. His psychophysical evaluations of sequences from 60 to 480fps found that a frame rate of around 250fps is close to the perception limit for both blur and jerkiness. He suggests that 240fps is "ideal" because it is a common multiple of both 24 and 60fps.

He noted that his first (2D) prototype gave a better impression of depth at a higher frame-rate, which he suggests might be due to more effective pictorial depth cues, such as occlusion, shading and texture gradient etc. He also notes that a flying ball in open space was harder to visualise. We wonder whether this might possibly be because of the loss of motion blur in the background behind a tracked object. It was this observation which stimulated his development of a single-lens stereoscopic 3D system.

5.5 Evolving frame rates for stereoscopic 3D in the cinema

Both Peter Jackson (*The Hobbit*) and James Cameron (*Avatar 2*) are challenging the convention of 24 fps in the cinema as a result of their experiences of stereoscopic 3D film production.

Earlier this year James Cameron shot a couple of test scenes at 24, 48 and 60 fps in stereoscopic 3D. He used these as the basis of a technical demonstration at CinemaCon, the official convention of the National Association of Theatre Owners in Las Vegas in March 2011. Cameron is reported [17] as saying that there is at least 18 months until he starts shooting Avatar 2, and that he fully intends to use higher frame rates and is looking seriously at 48 and 60 fps.

Peter Jackson confirmed on 11 April 2011 [18] that he had already been filming The Hobbit at 48 fps for several months, having tested both 48 and 60 fps. He is shooting at 48 fps with a 270 degree shutter angle. He reports that it looks more lifelike and easier to watch, especially in stereoscopic 3D and is hopeful that there will be enough theatres capable of projecting the film at 48 fps by the time of the film's release in December 2012.

6 FUTURE FRAME RATES FOR THE PRODUCTION AND DISTRIBUTION OF IMMERSIVE VIDEO CONTENT

The experiments and work described above have shown a very strong indication that a capture, transport and display frame rate higher than 100 fps will result in a much more realist, and hence immersive experience for the viewer. The work at NHK has shown that at higher resolutions (again required for a truly immersive experience) a shorter capture time is required to freeze the motion in the captured scene.

A frame rate for capture and production of 300 frames per second (or even 600 fps) has been suggested, as both suitable for easy down-conversion to conventional 50 and 60Hz transmission (very useful for international events), or even 24 fps for theatrical/film presentation, but also to enable advantage to be taken of greater artistic freedom for the producer of the content to adaptively select different temporal windows to reduce or eliminate temporal alias effects.

There is obviously a corresponding increase in raw data rate of material captured at such higher frame rates, but it is highly likely that the advantages of sharper images, a lower bit-depth requirement, and freedom from temporal aliases, would enable such material to be compressed with greater efficiency. Indeed, with compression systems using a long-GOP [19] (inter-frame) compression mode, where the limit on GOP-length is for example a duration of half a second, a faster frame rate implies more frames in each GOP, and hence more efficient coding. It is thus possible that the higher raw data rate could none the less result in little or no overhead once that video is compressed. This is an area which requires further study.

Another area for further study is the relation between measured noise levels on a video signal, and the visibility of that random noise to the observer, as the frame rate increases. Similarly a study is also required to consider the effect of reducing the bit-depth of a video signal, and the visibility or otherwise of the resulting quantising noise, with increasing frame rate.

7 CONCLUSION

The spatial resolution of broadcast television cameras and displays has reached the point where the temporal resolution afforded by current frame rates has become a significant limitation on the realism of video reproduction, particularly for fast moving genres such as sport. BBC Research & Development has successfully demonstrated that increasing the frame rate can significantly improve the portrayal of motion even at standard definition, leading to a more immersive experience. If the spatial resolution of television standards continues to increase, the importance of raising the frame rate to maintain the balance between static and dynamic resolution will only increase. Even at the spatial resolutions of SD and HDTV, the motion artefacts associated with 50/60Hz capture and distribution rates will become increasingly apparent as television display sizes continue to grow.

Even for television pictures transmitted and displayed at conventional frame rates, capturing at high frame rates can offer some improvement to picture quality through temporal oversampling, giving better control over temporal aliasing artefacts and offering a choice of "looks" to the director at the post-production stage. It also offers improved compatibility with the different conventional frame rates adopted internationally.

We assert that a higher capture and display frame rate leads to a step change in picture quality regardless of the spatial resolution. It is thus an important factor in making the presentation of video material more immersive.

Further work is required to decide whether 120, 240 or 300 fps is a suitable frame rate to standardise for future television delivery and programme interchange worldwide, particularly with regard to down-conversion for delivery in 50Hz (interlace field rate), 25Hz (progressive), and 59.94-based legacy formats. The question of whether acquisition and production might be undertaken at still higher frame rates than these (e.g. 600 fps) is not one which has to be settled at present, and can be left to develop later, as a way to further improve the delivered immersive content. Further work is also required to determine the noise-visibility characteristics of higher frame rate video material, and factors relating to its compression.

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Slide Presentation

Frame rate

- TV frame/field rates were chosen over 70 years ago.
- They were chosen to:
  - exceed the threshold for apparent motion
  - avoid visible flicker (on small screens)
  - avoid interaction with the mains frequency
  - provide a way of showing cinema film

Standard frame/field rates

- Current 50/60Hz TV was a match to
  - standard definition pictures
  - and smaller CRT displays
- Problems arise with
  - larger displays
  - increased picture resolution
  - sample-and-hold display technology

Loss of detail on moving objects

Motion Portrayal at 50/60Hz

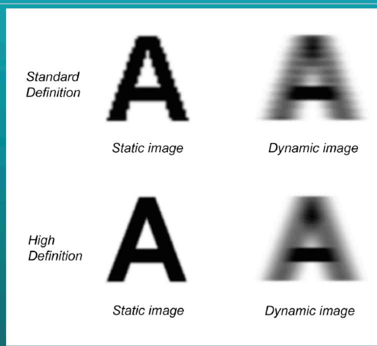
- The portrayal of motion is a trade off between
  - motion blur (long shutter)
  - temporal aliasing (short shutter), leading to jerky motion and spoked wheels running backwards
  - Short shutter also means less light, and hence increased noise

Dynamic Resolution at 50/60Hz

- When the camera pans the entire High Definition scene becomes blurred - for example when following the action during a football match
- As you increase the resolution so the rate of panning has to be reduced to keep the blurring under control

Dynamic Resolution at 50/60Hz

The dynamic resolution of HDTV is no better than SD



Impact on the Viewer

- Where there is a large difference between the resolution of a static and dynamic picture, this can lead to a feeling of nausea
- Therefore the higher the *static* resolution, the higher the *dynamic* resolution must be for comfortable & lifelike images

Up-converting Displays

- Create intermediate images using motion prediction
- But this is not High Frame Rate TV
  - Cannot reduce motion blur captured in camera
  - Cannot predict complex motion, cuts and cross-fades
- To make motion rendition more lifelike

  we need - higher frame rates in the camera
  - higher frame rates for distribution
  - and higher frame rates in the display

Higher Frame Rates

- We would suggest that:
  - **if** SD is acceptable at 50Hz
  - then full HDTV needs around 100-150Hz
  - as resolution increases, we may need 300Hz
- 300Hz is easy to convert to 50 or 60Hz and is compatible with mains frequencies

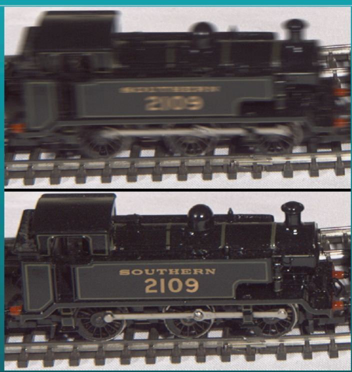
It may only be needed in the camera, not delivery?

Demonstration of High Frame Rate TV

- At IBC 2008, on the EBU Village
  - Video shot 1920 x 1080 at 300Hz
  down-converted to display at 1400 x 788 100Hz

Demonstration of High Frame Rate TV

50 Hz



300 Hz

Work at NHK (Japan's National Broadcaster)

- Experiments conducted to determine the frame rate for future Ultra-High Definition TV system
  - Require > 80 fps to prevent flicker
  - Require >100 fps to merge motion in eye
  - Require shutter opening < 1/320 second to prevent blur
- Proposal of 120 fps for UHDTV

Work at Sony

- Tested sequences between 60 & 480 fps
  - Require ~250 fps to prevent jerkiness
  - Require ~250 fps to prevent blur
- Proposal of 240 fps for compatibility with 24 and 60 fps
- Prototype 4k x 2k resolution, 240 fps stereoscopic camera and display

Frame rates in the cinema

- Showscan (60 fps) is 30 years old
  - Costly due to film consumption
  - Only really used for simulator rides
- 3D cinema films highlight motion judder
  - James Cameron considering 48 or 60 fps for *Avatar 2 & 3*
  - Peter Jackson is already shooting *The Hobbit* at 48 fps

Ways to achieve higher frame rate

We need to consider the whole TV system to understand how higher frame rates could be accommodated

Transmission data rate:
- Fewer I-frames (longer GOP length) whilst still retaining ½ s GOP
- Better noise masking at higher frame rates
- Sharper input frames = better motion prediction
- Less difference between static & moving images = better prediction

So will be more efficient to code

Conclusions

- Frame rate needs to increase alongside higher spatial resolution
- There is now a lot of evidence that higher frame rates improve the immersive experience