High speed sequential illumination with electronic rolling shutter cameras

Matis Hudon[1,2] Paul Kerbiriou[1] Arno Schubert[1] Kadi Bouatouch[2]

[1]Technicolor
975, Ave des Champs Blancs
35576, Cesson-Sévigné, France
paul.kerbiriou@technicolor.com
arno.schubert@technicolor.com

[2]IRISA
Campus de Beaulieu,
35042, Rennes, France
matis.hudon@irisa.fr
kadi.bouatouch@irisa.fr

Abstract

Nowadays flashes are commonly used in photography: they bring light and sharpness to images. It is very tempting to use flash lights in cinema, to take profit of controlled light as photographers may do. But using flashes with video recording is not as easy as in photography. Actually, flashes cause many temporal artifacts in video recordings, especially with high speed CMOS cameras equipped with electronic rolling shutters. This paper proposes a video recording method that uses periodic strobbed illumination sources together with any electronic rolling shutter camera, even without any synchronization device between the camera and the controlled lights. The objective is to avoid recording artifacts by controlling the timings and periods of the flash lights, and then reconstructing images using rows that correspond to the same flash instant. We will show that our method can be easily applied to photometric stereo.

Figure 1: Partial lighting example: typically happens while filming lightning. Lightning occurs while recording a video with an electronic rolling shutter. As the rows of the sensor integrate light sequentially, the illumination from lightning is only sensed by one part of the rows (here bottom rows). As a result, the bottom rows of the image appear brighter than the upper ones.

1. Introduction

Traditional cameras use a mechanical shutter to block entering illumination while sliding the chemical film to a new frame. Most digital cameras use an electronic rolling shutter as a substitute for the mechanical shutter. Unfortunately, electronic rolling shutters also cause new types of temporal artifacts, such as skew effect (spatio-temporal shear in images) or partial exposure lighting (an example of partial lighting during lightning is shown in figure 1). Some digital cameras are now equipped with a global electronic shutter. This technology completely resolves temporal artifacts issues caused by electronic rolling shutters. However, a large number of available cameras (consumer and professional) are still equipped with an electronic rolling shutter.

LED technology allows flashes to be more sustainable, cheaper and highly controllable. All those considerations make more tempting the idea of using flashes in cinema. Sharpening video images could be useful for post-production especially in special effects. Sequential recording with a stroboscopic flash is an interesting idea that is already used in many research projects such as light stage X [3]. For example the photometric stereo method can benefit from sequential recording (photometric stereo needs at least 3 separate images with different lightings) at high frame rate.

Our objective is to bring flashes into the video field, with the highest frame rate possible. However, cameras with highest frame rate capabilities are those equipped with an electronic rolling shutter. These cameras are highly sensitive to partial lighting artifacts. The electronic rolling shutter framework entails a significant time between the reading of the first and the last row of an image, resulting in artifacts such as partial exposure.

Figure 2 shows a model of an electronic rolling shutter

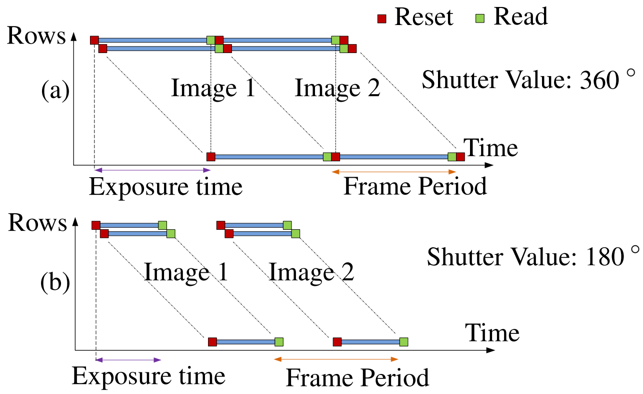


Figure 2: Electronic shutter functioning: a red square represents the reset of a pixel while a green squares represents reading times. (a) For a 360° shutter value and (b) for a 180° shutter value.

of a camera. This model was learned after experiments we conducted on raw cameras. It describes how an electronic shutter operates. Each parallelogram depicts the integration (accumulation of light energy reaching the sensor) of the rows of an image, a blue row represents the integration of light by one row of the sensor. A red square represents a row reset, while a green square corresponds to a row read. As there is no mechanical shutter, the sensor is always integrating light. At the beginning the first row is reset, which means that a new integration cycle starts for this row. Then, the second row is reset, etc. When the exposure time is up for the first row, the camera reads and saves the information. Then a reset is performed and a new cycle begins. This process is performed for all rows, therefore all rows have the same exposure time. The shutter value is the ratio of the exposure time to the frame period multiplied by 360° (expressed in degrees). If this ratio is less than 360°, then the camera waits for a time equal to $(frame_{period} - exposure_{time})$ between read and reset.

An explanation of partial lighting artifact, according to the electronic rolling shutter model, is described in figure 3. Parallelograms still represent different images taken by the camera (shutter value is set to 360°). Yellow rectangles were added to represent stroboscopic flashes. As the rows are not read and reset at the same time, a flash of a certain duration Δ lights several images. However, depending on the flash duration Δ only a subset of rows of an image are lit by one flash. For the example shown in figure 3 the flash triggered at T_1 lights the top rows of $image\ n$, while the bottom rows of $image\ n$ are lit by the flash triggered at T_2. As a result, some rows in $image\ n$ integrate the light of the flash triggered at T_1 and other rows integrate the light of the flash triggered at T_2. This type of artifact will henceforth be called inter-rows temporal artifact. Figure 3 shows another temporal artifact. Indeed, the rows of $image\ n$ between the two black dotted rows are composed of both lights integrated at T_1 and T_2. From now on, this type of artifact will be called intra-rows temporal artifact.

In this paper, we propose a video recordering method that allows the use of stroboscopic flashes with high speed electronic shutter cameras while maximizing the output frame rate. Our method can be used with a shutter value of 360° in a controlled indoor environment such as a movie studio. Our main contributions are: (1) an acquisition framework, relying on triggering stroboscopic flashes, which avoids only intra-rows temporal artifacts, this method allows the maximum possible frame rate using periodic flashes, it does not need any synchronization device between the camera and the flash; (2) a method and a framework, robust to albedo variations, to reconstruct a coherent sequence from a sequence containing only inter-rows temporal artifacts; (3) an adaptation the of above method to perform sequential recording with flashes of different durations; (4) a straightforward application of our method to photometric stereo.

In the following, we first describe the related work on camera and light synchronization, followed by a description of the theoretical aspects regarding our method. Then, we provide a framework and algorithms to use our method. Finally we present some results before concluding. A video explaining our method and presenting some results of our experiments can be found in supplementary materials.

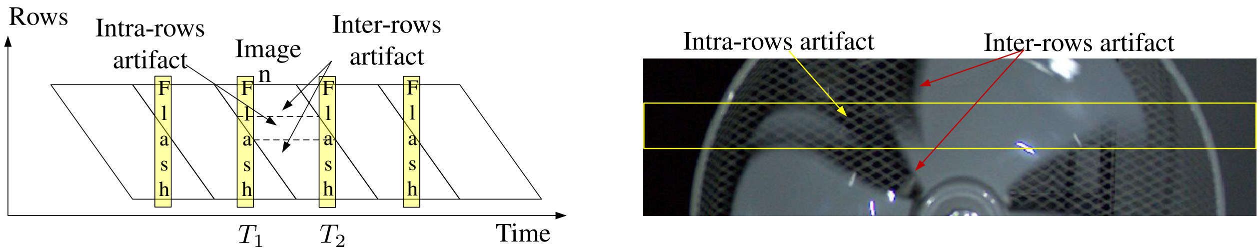
2. Related works

Computer vision and Electronic rolling shutter cameras.

Wilburn et al. [14] used an array of electronic rolling shutter cameras with precisely timed exposure windows to perform very high speed recordings. They warped images from calibrated cameras, by merging scanlines from the different views into a virtual one to reconstruct very high speed sequences with no distortion artifacts. Grundmann et al. [5] presented a calibration free rolling shutter removal technique based on a novel mixture model of homographies which faithfully models rolling shutter distortions. This technique adapts to the camera without any calibration and is robust to a wide range of scenarios while having an efficient rate of 5 - 10 frames per second. Magerand et al. [9] proposed a method to estimate a uniform motion, using constrained global optimization of a polynomial objective function, to automatically build robust 2D-3D correspondences. Magerand and Bartoli [10] proposed a rolling shutter model capable of handling both global and uniform rolling shutters.

Stroboscopic Illumination in computer vision.

Theobalt et al. [12] used consumer cameras and strobo-



(a) (b)

Figure 3: **(a):** Electronic shutter with periodic flashes, the two types of artifacts are shown in this schema. **(b):** Typical example of the two artifacts put forward when filming a rolling fan.

scopic illumination to capture high speed motions. In their experiments, they captured the motion of a hand and a ball in a baseball pitch. They used several still cameras with a long exposure time of 1 second and stroboscopic flashes at $75Hz$, which means that a high number of ball ghosts were visible on the output images. Linz et al. [8] used stroboscopic flashes to capture multi-exposure images that allowed to generate intermediate exposure views and synthetic motion blurs. Furlan et al. [4] patented a method to use flash lights with an electronic rolling shutter (with no temporal artifacts). It makes use of a rolling shutter timing mechanism based on an alterable translucent material in the optical path of light going to the sensor. Methods based on photometric stereo [15], such as those described in [7] and [6], use colored lights to obtain several images (with different lighting directions) in a single snapshot. Decker et al. [2] use both colored lights and time multiplexed images to perform photometric stereo (with more than 3 light directions) on video sequences. This method resolves low frame rate issues inherent in photometric stereo applied to video, but suffers from some issues. For example, the method fails when the spectra of one of the light sources and the object albedo do not overlap. Schechner et al. presented a general technique to multiplex lights. Several lights are turned on at each frame based on Hadamard patterns. The goal was to rise the intensity of flashed images, hence reducing the exposure time of the cameras. Wenger et al. [13] proposed a method to acquire live-action performance of an actor, allowing lighting and reflectance to be designed and modified in post-production. They obtain excellent results, but need a highly controlled environment and a synchronization device between lights and cameras.

Electronic shutters and stroboscopic illumination. Bradley et al. [1] used a controlled illumination to synchronize an array of rolling shutter cameras. The method consists in triggering flashes, with a high enough period to avoid any temporal artifact, and reconstructing images that are integrated in consecutive frames. As the duration of the flashes is short, the temporal shear of rolling shutter cameras is also avoided. With their approach the maximum frame rate is divided by two. It is mentioned that the frame rate can be rose with more computational effort to explicitly search for unexposed scanlines that separate the frames. Unfortunately the authors do not provide any theoretical nor experimental details.

Discussion

There is no denying that imaging objects under variable lighting is of foremost importance in computer vision and image-based rendering. Time-multiplexed illumination (TMI) is often considered for different applications, as mentioned above. However, TMI does not tackle the problem of getting the highest frame rate possible. Several TMI-based methods make use of stroboscopic illumination in computer vision, even with electronic rolling shutter cameras. However, no method focuses on increasing the frame rate. In this paper, we present a method that allows TMI (and sequential recording) with high speed electronic rolling shutter cameras, while maximizing the output frame rate.

3. The Rolling Flash

First of all, our method consists in removing intra-rows artifacts, which cannot be removed in a post-processing step because pixels of the same row integrate light multiple times which is non-reversible. We then reconstruct a coherent sequence combining rows corresponding to the same flash instant. From now on, the time, during which a flash is on, will be called flash instant. For our experiments we used a LED illumination system. Average LED response and falloff time is of the order of 10 nanoseconds. A Full HD electronic rolling shutter camera approximately reads one of its rows in 10 microseconds. As the average LED response time and falloff time are negligible with respect to the camera time constants, therefore the illumination can be considered as perfect square.

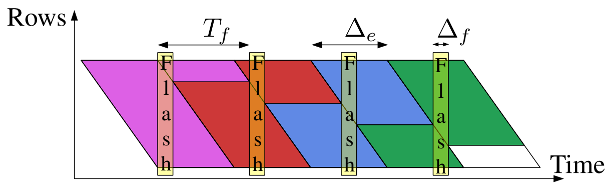


Figure 4: Illustration of the rolling flash method: our method allows to use flashes with electronic rolling shutter camera, fixing the stroboscopic period of flash to the sum of the exposure time Δ_e and the flash duration Δ_f.

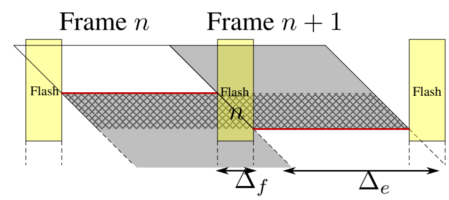


Figure 5: Detail of rolling flash method: the same flash instant illuminates two camera frames, the rows in grey contain all the information needed to reconstruct a coherent image.

3.1. Avoiding intra-rows artifacts

Our objective is to avoid intra-rows artifacts while maximizing the frame rate. Our strategy is to increase the period of stroboscopic flashes. To this end, we set the period T_f of the stroboscopic flashes as follows:

$$T_f = \Delta_f + \Delta_e, \tag{1}$$

where Δ_f is the flash duration and Δ_e the exposure time. With this formula we prevent a row from integrating light twice (at two different flash instants), which allows a maximum frame rate.

An illustration of this method can be seen in figure 4, each parallelogram represents an image, and each colored pattern represents rows that have integrated light from the same flash instant. A flash stops emitting light during the integration of the n^{th} row of frame k, next the flash starts $T_f = \Delta_f + \Delta_e$ seconds later, which exactly corresponds to the begining of the n^{th} row of frame $k+1$. Thus, each row only integrates light from a single flash, at a single flash instant (which duration is Δ_f). However not all the rows integrate light for the whole duration Δ_f. In a classical camera model the digital value N_d of a pixel is in direct relation with the exposure time Δ_e, the aperture f_s, the ISO sensitivity S, the calibration parameter K_c of the camera and the luminance L of the scene [11]:

$$N_d = \int_{\Delta_e} K_c \times \frac{S}{f_s^2} \times L \,\mathrm{d}t \tag{2}$$

L can be approximated to zero when there is no flash, thus the interval of integration is reduced to the duration of the flash Δ_f:

$$N_d = \int_{\Delta_f} K_c \times \frac{S}{f_s^2} \times L \,\mathrm{d}t \tag{3}$$

In our case of controlled illumination we can suppose L to be constant for a period Δ_f, and so:

$$N_d = \Delta_f \times K_c \times \frac{S}{f_s^2} \times L \tag{4}$$

Consequently, if a row integrates light for a duration Δ shorter than Δ_f, its digital value will be lower. Therefore those rows will appear darker on the resulting image. As the stroboscopic period of flashes is higher than the exposure time, the index of darker rows is never the same. On the resulting sequence darker rows roll over the image along consecutive frames. That is why we chose to call that method rolling flash.

T_f is the minimum stroboscopic period that makes possible to completely avoid intra-rows artifacts, which allows to maximize the output sequence's frame rate. Actually, the output frame rate is:

$$F = \frac{1}{\Delta_f + \Delta_e} = \frac{\frac{1}{\Delta_e}}{1 + \frac{\Delta_f}{\Delta_e}} \tag{5}$$

As explained before, our method works with a camera shutter value set to $360°$, which means that the inverse of camera exposure time $\frac{1}{\Delta_e}$ is equal to the camera frame rate F_c:

$$F = F_c \times \frac{1}{1 + \frac{\Delta_f}{\Delta_e}} \tag{6}$$

Typically the flash duration is much lower than the exposure time. As an example, if we use a $60H_z$ camera and a flash duration of $200\mu s$ we obtain an output frame rate of $59.29H_z$, which represents a loss of $0.71H_z$.

3.2. Reconstructing temporal-coherent rows

Now, we have an acquisition method that allows to avoid intra-rows temporal artifact. Unfortunately our sequence still contains inter-rows temporal artifacts. In this subsection we present a method to obtain a fully coherent sequence reconstructed from the rows (belonging to two subsequent captured images) integrating light from a same flash instant.

In figure 5, each row, colored in grey, has integrated light from the same flash instant. On frame n, the red row delimits rows that have integrated light from flash $n-1$ and rows that have integrated light from flash n. On frame $n+1$, the red row delimits rows that have integrated light from flash n and rows that have integrated light from flash $n+1$. Here we are interested in reconstructing a coherent image from flash n. On frame n and $n+1$ rows in grey integrated light from flash n. Rows that integrated light for the full flash duration Δ_f can be directly used to reconstruct our coherent image (bottom rows of frame n and top rows of frame $n+1$). The hatched rows did not integrate for the full duration Δ_f. Let us reconsider the integration equation presented in equation 4 for a pixel N of the n^{th} frame and the i^{th} row that did not integrate for the full flash duration:

$$N_n^i = (\alpha^i \times \Delta_f) \times K_c \times \frac{S}{f_s^2} \times L(n),\ 0 < \alpha < 1 \quad (7)$$

$L(n)$ is the luminance acquired of the scene illuminated by flash n. Let δ_n^i be the time between the beginning of flash n and the read of a row i that did not integrate during the full duration of flash n ($\delta_n^i < \Delta_f$), then α^i is given by:

$$\alpha^i = \frac{\delta_n^i}{\Delta_f} \quad (8)$$

If we consider that the time of one row read and reset is negligible compared to flash duration, then the digital value of the same pixel but in frame $n+1$ (which is illuminated by flash n) is expressed as:

$$N_{n+1}^i = ((1-\alpha^i) \times \Delta_f) \times K_c \times \frac{S}{f_s^2} \times L(n) \quad (9)$$

Consequently the sum of the two digital values is:

$$N_n^i + N_{n+1}^i = \Delta_f \times K_c \times \frac{S}{f_s^2} \times L(n), \quad (10)$$

which is the digital value corresponding to the flash instant n as if it had been fully integrated in one frame. Thus, to reconstruct those rows, we just need to sum the rows of same indices in frame n and frame $n+1$.

An example of reconstruction is shown in figure 6. The rows on the top of frame n integrated light during flash $n-1$, while the rows of the bottom of frame n integrated light during flash n. As the top rows of frame $n+1$ integrated light during flash n, a coherent image can be reconstructed from the top rows of frame $n+1$ and the bottom rows of frame n. The yellow hatched area on the reconstructed image represents the rows that have to be reconstructed as a combination of the same rows from frame n and $n+1$.

3.3. Flash illuminating 3 frames

As a flash has a non zero duration, and the shutter value of the camera is 360°, there is a strong probability for a flash to illuminate rows of 3 consecutive images. Then the reconstruction works exactly the same way as explained in the previous subsection. Indeed, the bottom rows have to

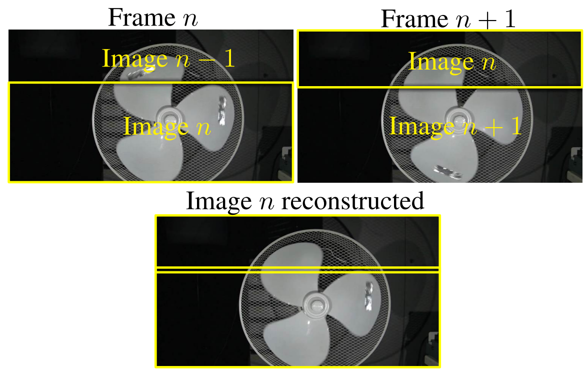


Figure 6: Example of reconstructed image: Image n is reconstructed from frame n and frame $n+1$.

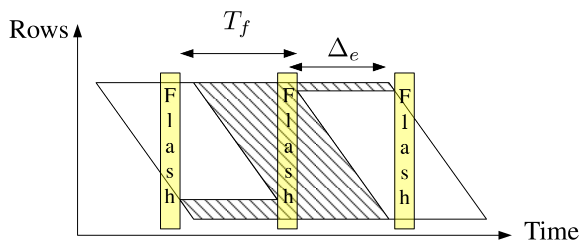


Figure 7: Flash illuminating three frames.

be reconstructed from frames $n-1$ and n, while the top rows have to be reconstructed from frames n and $n+1$. For simplicity reasons, this issue can be avoided by choosing a flash duration as follows:

$$\Delta_f = \frac{\Delta_e}{n}, n \in \mathbb{N}\backslash\{0,1\} \quad (11)$$

With a flash duration δ_f, being a divisor of the exposure time Δ_e, and a first flash triggered at the beginning of an exposure, the n^{th} flash ends exactly at the end of the exposure of frame n, which avoids the issue (of a flash illuminating rows of three frames) from happening. Unfortunately, in this case a synchronization device between the camera and the illumination device is needed to trigger the first flash at the right time.

4. Framework and algorithm

In this section we present the framework and the algorithm we used for our experiments.

4.1. Framework

We designed an electronic device that allows to drive our LEDs (flashes). A micro controller is used to send a pulse width modulation to the power stage driving the LEDs. LED response to current is fast enough to be neglected compared to the camera hardware. We have created a small interface to rapidly control the micro controller. In this device the following parameters can be tuned: (1) the stroboscopic frequency $f = \frac{1}{T_f}$, (2) the duty cycle of a burst allowing to control the power of the output light, (3) the frequency of a burst (linked to duty cycle), (4) the possibility to control several flashes with different parameters.

We control the parameters presented above through a C++ interface linked to the micro controller. The micro controller sends timed pulses width modulation to the power stage which generates current to the LEDs.

4.2. Reconstruction Algorithm

In this subsection, we propose an algorithm to reconstruct temporally coherent rows. The main idea of this algorithm is to search for the row with the lowest luminance energy. A color pixel consists of 3 components (red, blue and green). For each pixel i the luminance Y_i is calculated. Let N be the number of columns in the image, then the luminance energy of a row n is:

$$L_e^n = \sum_{i=0}^{N-1} Y_i \tag{12}$$

Unfortunately, finding the row with the minimum energy can be problematic when dealing with noisy images and/or scenes containing albedo variations. To improve robustness to albedo variations and noise, we have added a term that defines a zone in which the row of minimum luminance energy is excepted. Furthermore, this term drastically reduces the search window. The reconstruction algorithm is described in algorithm 1. This algorithm uses raw images. The first input image (captured image) is transformed to a linear gamma image (line 1). Then, the row of that linear image with the minimum luminance energy is determined (line 2). This row corresponds to the end of a flash instant and the beginning of the next one. We calculate the expected index offset between the rows of minimal energy of two consecutive images (line 3). Given that our shutter speed is set to $360°$, we can calculate the duration of a row read as the ratio of the exposure time Δ_e to the number of rows h of the sensor, therefore the index offset o is simply:

$$o = \frac{\Delta_f}{\Delta_e} \times h, \tag{13}$$

where Δ_f the flash duration. Then for each image in the sequence, we proceed as follows. In the current image $CurrentImage_l$, all the rows with an index lower than the one of the row with minimal luminance energy are set to zero (line 9). The index k_{est} of the minimal energy row for the next frame is estimated by adding (modulo the image height h) the offset o to the index of the minimum energy row calculated for the current image (line 10). After that, we compute the index k of the local minimum luminance energy row (in $NextImage$) around k_{est}

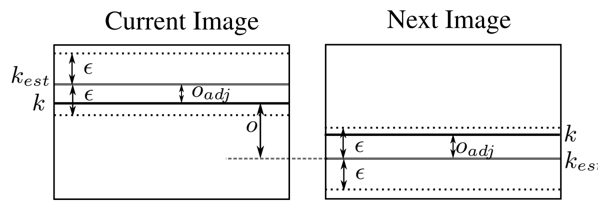


Figure 8: Computing the index k of the minimal luminance energy row for the current and subsequent images. k is determined within the range $[k_{est} - \epsilon, k_{est} + \epsilon]$. For our experiments we chose $\epsilon = \frac{h}{100}$, h being the height of a frame.

($k \in [k_{est} - \epsilon, k_{est} + \epsilon]$) and update an adjustment variable o_{adj} which avoids artifacts caused by minor drifts that could have occurred between the camera capture and the strobe illumination (line 13). An illustration of the latter process is given in figure 8. Rows of $NextImage_l$, with an index higher than the one of the row with minimal luminance energy, are set to zero (line 14). Then the two resulting images are summed (line 15). Finally we transform the summed image back into the original gamma space (line 16). All those steps are performed for all the images of the sequence.

Algorithm 1 ReconstructImage(InputVideoSequence M, OutputVideoSequence M_o) :

1: $FirstImage_l$ = LinearGamma($FirstImage$);
2: i = FindRowMinimalEnergy($FirstImage_l$);
3: o = CalculateOffset(Δ_e, Δ_f, h);
3:
4: $CurrentImage_l$ = $FirstImage_l$; // Current Image
5: k = i;
6: k_{est} = i;
7: o_{adj} = 0;
8: **for each** $Image \in M$ **do**
9: $CurrentImage_l$.SetToZeroRows(index $\leq k$);
9:
10: k_{est} = $k_{est} + o + o_{adj} \pmod h$);
11: $NextImage_l$ = LinearGamma($NextImage$);
12: k = RowMinEnergyAround($NextImage_l$, k_{est});
13: o_{adj} = $k - k_{est}$;
13:
14: $NextImage_l$.SetToZeroRows(index $\geq k$);
14:
15: $FinalImage_l = CurrentImage_l + NextImage_l$;
16: $FinalImage$ =OriginalGamma($FnialImage_l$);
17: Output($FinalImage$);
18: **end for**

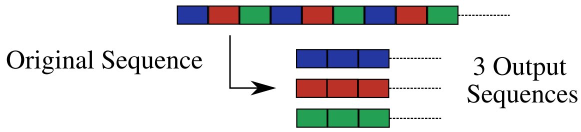


Figure 9: An illustration of sequential recording: the original sequence is shot with a periodically varying illumination. Each of the blue, red and green frames represent one illumination in the original sequence. After extraction we obtain 3 sequences of the same scene, each sequence with a proper illumination.

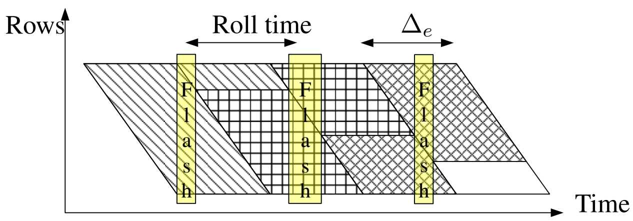


Figure 10: Rolling flash and sequential recording.

4.3. Sequential recording

The rolling flash method is an efficient way to use periodic flashes with an electronic rolling shutter camera. The use of high speed cameras originally aimed at performing sequential recordings. The goal of sequential recordings is to obtain several sequences of the same scene in a single shot. As an example, to perform stereo photometry [15] on a video the same scene is lit with at least 3 different illuminations. Another example is HDR (High Dynamic Range) recording which consists in capturing several sequences of the same scene with different exposure times. Usually a stereoscopic rig with two cameras (with aligned optical axes) is used to capture two sequences of the same scene with two different exposure times. In our method the real exposure time (when the sensor is currently integrating light) is completely controlled by the duration of flashes. Consequently, if consecutive flashes have different durations and if the frame rate is high enough to neglect motion in consecutive frames (or if there is a motion estimation process as in [13]), our method can be used for HDR recordings with a single camera. An issue, well addressed in HDR processing, is the difference of motion blur in the different sequence acquired (due to different exposure times). So, changing the power (but not the duration) of the flash between consecutive frames could provide HDR sequences with the same motion blur. An illustration of sequential recordings is shown in figure 9, the original sequence is shot with varying illuminations. In this example, three different illuminations are used. Each colored frame represents an illumination. Three different sequences are obtained by extracting frames with the same illumination. The output sequence frame rate is then divided by three, consequently it is very important to maximize the original sequence frame rate.

So, recordings with sequential illuminations are feasible by simply changing the duty cycle of the pulse width modulation at each illumination. But in order to obtain more different illuminations, we also need to be able to change the duration of the flash for each illumination. In figure 10 we show how to use the rolling flash method to perform sequential recordings with two different illuminations (by varying Δ_f). Note that the method works with any number of different illuminations. The following equations can easily be adapted to three or more illuminations. The idea is exactly the same, except that the period changes each time a flash is triggered. Actually, when the i^{th} flash is triggered with a duration Δ_f^i, the time T_f^{i+1} to wait before the next illumination, to avoid intra-rows temporal artifact, is:

$$T_f^{i+1} = \Delta_e + \Delta_f^i, \tag{14}$$

where Δ_e is the exposure time. Unfortunately the output frame rate is necessarily lower:

$$F \approx F_c \times \frac{1}{1 + \frac{\Delta_f^1 + \Delta_f^2}{2 \times \Delta_e}}, \tag{15}$$

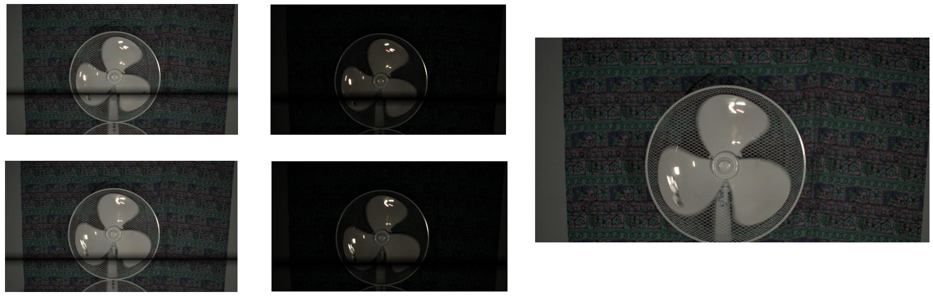
where Δ_f^1 and Δ_f^2 represent the duration of the two different flashes.

5. Experiment results

For our experiments we used a Sony F65 cinema camera at $60Hz$, using its electronic rolling shutter at $360°$. We shot a rolling fan because its frequency puts forward temporal artifacts due to periodic illumination. Some images can be found in figure 11, on the first column show the raw images from the F65 camera, on the second column we can see those images converted to a linear gamma images. The last image is a reconstructed image from the two previous images. There are no more temporal artifacts in the output image. Video results can be found in additional materials. We also provide a video resulting from a straightforward application of our method to photometric stereo. This video has been captured with an F65 camera at $120Hz$ and 3 multiplexed flashlights.

6. Conclusion

We described a model of electronic rolling shutter camera and explained why those types of camera may cause two types of temporal artifact when using stroboscopic flashes. We presented a method that allows to use periodic flashes with these high speed cameras and to remove the two types



(a) (b) (c)

Figure 11: **(a):** Two conscutive input frames from our experiments, **(b):** Linear version of the two input frames. **(c):** Our reconstruction result with gamma correction

of artifact presented while maximizing the output sequence frame rate. The method requires a shutter value of 360° and an active illumination setup in an indoor environment. On the other hand, the method needs a very light setup and does not require any synchronization device between the camera and the illumination setup. We described an acquisition framework for timing the stroboscopic illumination and provided a simple algorithm to reconstruct the output video frames. We also described an adapted method to perform sequential recordings with periodic flashes aiming at applications such as photometric stereo. Experiments have been conducted to demonstrate the efficiency of our method to avoid artifacts. Our method relies on flash duration to control the exposure time of the camera. As the flash duration is lower than the exposure time of the camera, motion blur can be avoided. Consequently, when the flash is turned off, the camera still integrates (shutter value of 360°), which can results in a higher noise in the output sequence.

References

[1] D. Bradley, B. Atcheson, I. Ihrke, and W. Heidrich. Synchronization and rolling shutter compensation for consumer video camera arrays. *Computer Vision and Pattern Recognition Workshops, CVPR Workshops,IEEE Computer Society Conference on*, 2009. 3

[2] B. de Decker, J. Kautz, T. Mertens, and P. Bekaert. Capturing multiple illumination conditions using time and color multiplexing. In *2009 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR 2009), 20-25 June 2009, Miami, Florida, USA*, pages 2536–2543, 2009. 3

[3] P. Debevec. The light stages and their applications to photoreal digital actors. In *SIGGRAPH Asia*, Singapore, Nov. 2012. 1

[4] J. Furlan and A. Braunstein. Digital photography device having a rolling shutter, Nov. 18 2008. US Patent 7,453,514. 3

[5] M. Grundmann, V. Kwatra, D. Castro, and I. Essa. Effective calibration free rolling shutter removal. *IEEE ICCP*, 2012. 2

[6] C. Hernández, G. Vogiatzis, G. J. Brostow, B. Stenger, and R. Cipolla. Non-rigid photometric stereo with colored lights. In *ICCV*, October 2007. 3

[7] H. Kim, B. Wilburn, and M. Ben-Ezra. Photometric stereo for dynamic surface orientations. In *Computer Vision - ECCV 2010, 11th European Conference on Computer Vision, Heraklion, Crete, Greece, September 5-11, 2010, Proceedings, Part I*, pages 59–72, 2010. 3

[8] C. Linz, T. Stich, and M. Magnor. High-speed motion analysis with multi-exposure images. In *Proc. Vision, Modeling and Visualization (VMV) 2008*, Oct. 2008. 3

[9] L. Magerand, A. Bartoli, O. Ait-Aider, and D. Pizarro. Global optimization of object pose and motion from a single rolling shutter image with automatic 2d-3d matching. In *Computer Vision - ECCV 2012 - 12th European Conference on Computer Vision, Florence, Italy, October 7-13, 2012, Proceedings, Part I*, pages 456–469, 2012. 2

[10] L. Magerand, A. Bartoli, O. Ait-Aider, and D. Pizarro. Global optimization of object pose and motion from a single rolling shutter image with automatic 2d-3d matching. In *Proceedings of the 12th European Conference on Computer Vision - Volume Part I*, ECCV'12, pages 456–469, Berlin, Heidelberg, 2012. Springer-Verlag. 2

[11] P. Peter D. Hiscocks. Measuring luminance with a digital camera. 2011. 4

[12] C. Theobalt, I. Albrecht, J. Haber, M. Magnor, and H.-P. Seidel. Pitching a Baseball – Tracking High-Speed Motion with Multi-Exposure Images. In *Proc. SIGGRAPH '04*, pages 540–547. ACM SIGGRAPH, 2004. 2

[13] A. Wenger, A. Gardner, C. Tchou, J. Unger, T. Hawkins, and P. Debevec. Performance relighting and reflectance transformation with time-multiplexed illumination. 24(3):756–764, July 2005. 3, 7

[14] B. Wilburn, N. Joshi, V. Vaish, E.-V. Talvala, E. Antunez, A. Barth, A. Adams, M. Horowitz, and M. Levoy. High performance imaging using large camera arrays. In *ACM SIGGRAPH 2005 Papers*, SIGGRAPH '05, pages 765–776, New York, NY, USA, 2005. ACM. 2

[15] R. J. Woodham. Photometric method for determining surface orientation from multiple images. *Optical Engineering*, 19(1):191139–191139–, 1980. 3, 7