

Rolling Shutter Camera Synchronization with Sub-millisecond Accuracy

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Abstract: A simple method for synchronization of video streams with a precision better than one millisecond is proposed. The method is applicable to any number of rolling shutter cameras and when a few photographic flashes or other abrupt lighting changes are present in the video. The approach exploits the rolling shutter sensor property that every sensor row starts its exposure with a small delay after the onset of the previous row. The cameras may have different frame rates and resolutions, and need not have overlapping fields of view. The method was validated on five minutes of four streams from an ice hockey match. The found transformation maps events visible in all cameras to a reference time with a standard deviation of the temporal error in the range of 0.3 to 0.5 milliseconds. The quality of the synchronization is demonstrated on temporally and spatially overlapping images of a fast moving puck observed in two cameras.

1 INTRODUCTION

Multi-camera systems are widely used in motion capture, stereo vision, 3D reconstruction, surveillance and sports tracking. With smartphones ubiquitous now, events are frequently captured by multiple devices. Many multi-view algorithms assume temporal synchronization. The problem of multiple video synchronization is often solved by triggering the cameras by a shared signal. This solution has disadvantages: it is costly and might put a restriction on the distance of the cameras. Cheaper cameras and smartphones do not have a hardware trigger input at all.

Content-based synchronization can be performed offline and places no requirements on the data acquisition. It has received stable attention in the last 20 years (Stein, 1999; Caspi et al., 2002; Tresadern and Reid, 2003; Cheng Lei and Yee-Hong Yang, 2006; Padua et al., 2010). Some of the methods require calibrated cameras, trackable objects, laboratory setting or are limited to two cameras. The vast majority of the methods requires overlapped views. For analysis of high-speed phenomena, a very precise synchronization is critical. The problem of precise sub-frame synchronization was addressed in (Caspi et al., 2006;



Figure 1: Four cameras with rolling shutter sensors capturing a scene when a photographic flash was fired. Part of image rows integrated light from the flash. The leading and trailing edges are easily detectable and on the ice rink also clearly visible. The edges serve as very precise synchronization points.

Tresadern and Reid, 2009; Dai et al., 2006).

We propose a very simple yet sub-millisecond accurate method for video data with abrupt lighting changes captured by rolling shutter cameras. Such lighting changes could be induced for example by photographic flashes, creative lighting on cultural events or simply by turning on a light source. In controlled conditions, it is easy to produce necessary lighting changes with a stock camera flash.

It is very likely that an existing multi-view imaging system uses rolling shutter sensors or that a set

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of multi-view videos from the public was captured by rolling shutter cameras. The expected image sensor shipment share for CMOS in 2015 was 97% (IHS Inc., 2012). Most of the CMOS sensors are equipped with the rolling shutter image capture.

The proposed method assumptions are limited to:

- a few abrupt lighting changes affecting most of the observed scene, and
- cameras with rolling shutter sensors.

The method does not require an overlapping field of view and the cameras can be heterogeneous with different frame rates and resolutions. The proposed method works with frame timestamps instead of frame numbers. This means that the method is robust to dropped frames.

When a lighting abruptly changes during a rolling shutter frame exposure, the transition edge can be reliably detected in multiple cameras and used as a sub-frame synchronization point. An example of captured frames with an abrupt lighting change caused by a single photographic flash is shown in Figure 1.

Let us illustrate the importance of precise sub-frame synchronization on an example of tracking ice hockey players and a puck. Players can quickly reach a speed of 7m/s (Farlinger et al., 2007) and the puck 36m/s (Worobets et al., 2006). When we consider 25 fps frame rate, a player can travel 28cm, and a puck can move 1.44m in the 40ms duration of one frame. When a synchronization is accurate up to whole frames, the mentioned uncertainties can lead to poor multi-view tracking performance.

2 RELATED WORK

The computer vision community keeps stable attention to the video synchronization problem. The issue was approached in multiple directions. Synchronization at the acquisition time is done either by a special hardware or using a computer network to synchronize time or directly trigger cameras. A more general approach is video content-based synchronization. The advantage is that it does not have special acquisition requirements. We already mentioned a number of content-based methods. We will review works that make use of a rolling shutter sensor or photographic flashes which are the most relevant to our method.

(Wilburn et al., 2004) construct rolling shutter camera array that was able to acquire images at 1560 fps. The cameras were hardware synchronized, and the rolling shutter effect was mitigated by outputting slices of a spatio-temporal image volume.

(Bradley et al., 2009) approach the rolling shutter image capture in two ways. First, they acquire images with stroboscopic light in a laboratory setting, and extract and merge only rows affected by a light pulse that possibly span over two consecutive frames. By changing the frequency and duration of the flashes they effectively create a virtual exposure time and a virtual frame rate. Second investigated approach merges two consecutive frames by a weighted warping along optical flow vectors. This is similar to the spatio-temporal method.

Cinematography focused methods for the rolling shutter sensor acquisition were studied by (Hudon et al., 2015). They analyse stroboscopic light artefacts for the purpose of image reconstruction.

(Atcheson et al., 2008) applied the rolling shutter flash based synchronization and spatio-temporal volume slice approach to capture gas flows for a 3D reconstruction.

The use of photographic flashes for synchronization appeared to our knowledge first in (Shrestha et al., 2006). They find a translation between two video sequences by matching sequences of detected flashes. The final synchronization is accurate to the whole frames.

None of the rolling shutter or flash based approaches known to us pays attention to dropped frames and a camera clock drift.

3 METHOD

The inputs for the synchronization algorithm are frame timestamps extracted from video files or network streams and detected transition edges of abrupt lighting changes. We will refer to the transition edges as *synchronization events* or simply *events*. We find synchronization transformations $s^c(f, r) \rightarrow t^{\text{ref}}$ for all cameras c (except a reference camera c_{ref}) that map each camera temporal position (f, r) to the reference camera time t^{ref} . The temporal position is defined by a frame, row pair (f, r) . The situation is presented in Figure 3.

To correctly model the sub-frame accurate synchronization transformation we have to take into account missing frames, different frame rates, a drift of image sensors clock and hidden *dark rows* in image sensors.

3.1 On Time Codes

An ideal timing of video frames assumes a stable frame rate fps and no skipped frames. Time of the first row exposure of a frame i is then $t(i) = i \cdot \frac{1}{\text{fps}} + t_0, i \in$

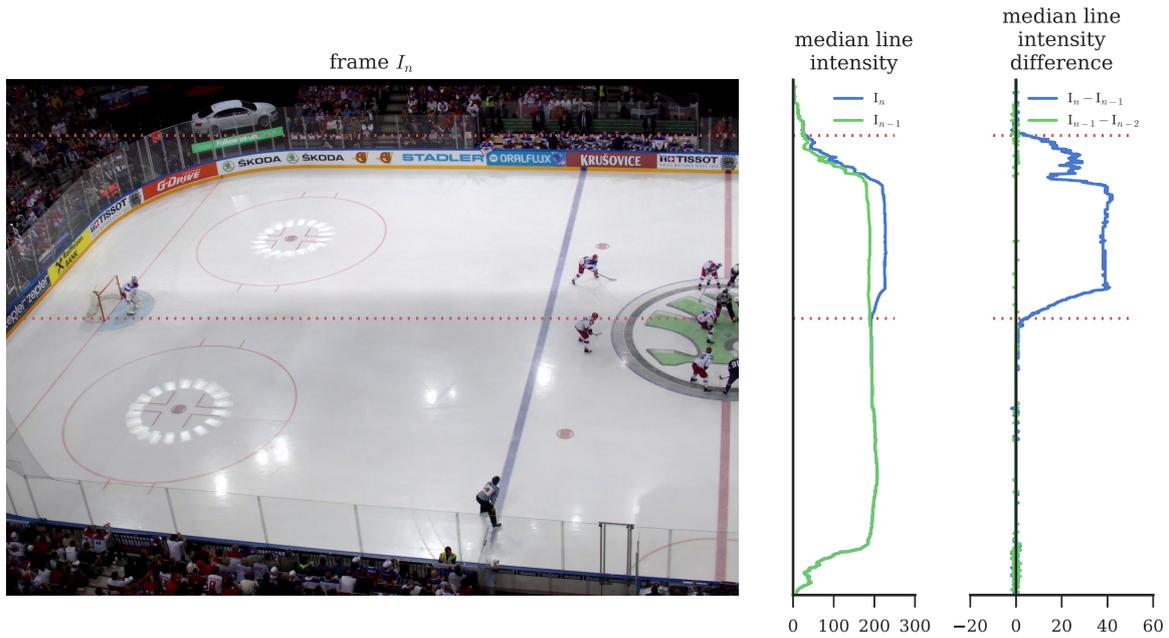


Figure 2: Detection of an abrupt lighting change. A photographic flash fired during the acquisition of the frame I_n . The flash duration is shorter than the frame duration. Only the lines that were integrating light when the flash was illuminating the scene were affected. The red dotted lines mark the leading and trailing edges of the bright region. The profiles on the right show pixel intensity changes in the frame before the abrupt change and in the frame with the change.

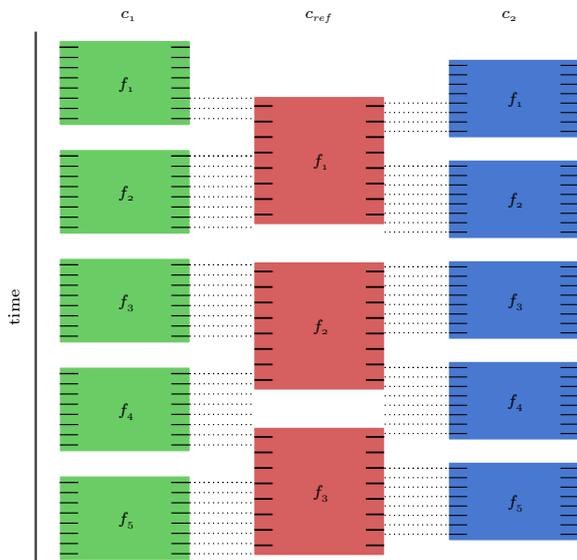


Figure 3: Sub-frame synchronization of the cameras c_1 and c_2 with respect to the reference camera c_{ref} . Frame rates, resolution and temporal shifts between cameras differ. The short black lines on the sides of frame rectangles represent image rows. We find an affine transformation $s^c(f, r) \rightarrow t^{ref}$ for every camera c that maps a time point specified by a frame number f and a row number r to the reference camera time t^{ref} . The dotted lines show a mapping of time instants when rows in c_1 and c_2 are captured to the reference camera time.

$\{0, 1, \dots\}$. Unfortunately, this is not true for most of the real-world video sequences. The most common deviation from the ideal timing is a dropped frame caused by high CPU load on the encoding system. When a frame is not encoded before the next one is ready, it has to be discarded. Almost all video sources provide frame timestamps or frame durations. This information is necessary to maintain very precise synchronization over tenths of minutes. We'll briefly present frame timing extraction from container format MP4 and streaming protocol RTP.

Video container files encapsulate image data compressed by a video codec. The timing data is stored in the container metadata. The MP4¹ file format is based on Apple QuickTime. Frame time-stamps are encoded in *Duration* and *Time Scale Unit* entries. The *Time Scale Unit* is defined as “the number of time units that pass per second in its time coordinate system”.

A frequent streaming protocol is Real Time Transfer Protocol (RTP). The codec compressed video data is split into chunks and sent typically over UDP to a receiver. Every packet has an RTP header where the *Timestamp* entry defines the time of the first frame in the packet in units specific to a carried payload: video, audio or other. For video payloads, the *Timestamp*

¹officially named MPEG-4 Part 14

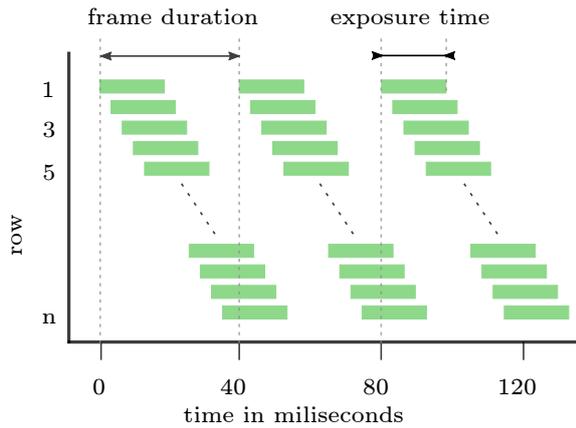


Figure 4: The figure illustrates rows exposure in time. The green rectangles represent the time spans when a row is integrating light. In rolling shutter sensors the rows do not start to integrate light at the same time. Instead the integration begins sequentially with small delays.

frequency is set to 90kHz.

3.2 Rolling Shutter

Historically, cameras were equipped with various shutter systems. To name the mechanical shutters, prevalent were the focal plane shutters - where two curtains move in one direction or the diaphragm shutters where a number of thin blades uncover circular aperture. The electronic shutters implemented in image sensors are either global or rolling. CCD type image sensors are equipped with a global shutter, but are already being phased out of the market. Most of the CMOS sensors have a rolling shutter. Recently, a global shutter for the CMOS sensors was introduced, but consumer products are still rare.

All shutter types except the global shutter exhibit some sort of image distortion. Mostly different regions of the sensor (or film) integrate light in a different time or the exposure time differs.

The rolling shutter equipped image sensor integrates light into the pixel rows sequentially. In the CMOS sensor with the rolling shutter, an electrical charge integrated in all pixels can not be read at once. The readout has to be done row by row. For illustration see Figure 4. To preserve constant exposure time for all pixels on the sensor, the exposure starts has to be sequential exactly as the readouts are. This means that every row captures the imaged scene in a slightly different moment. Typically a majority of the row exposure time is shared by spatially close rows (ON Semiconductor, 2015; Sony, 2014).

To properly compute the start time of a row exposure we have to take into account hidden pixels around the active pixel area. The most image sensors use

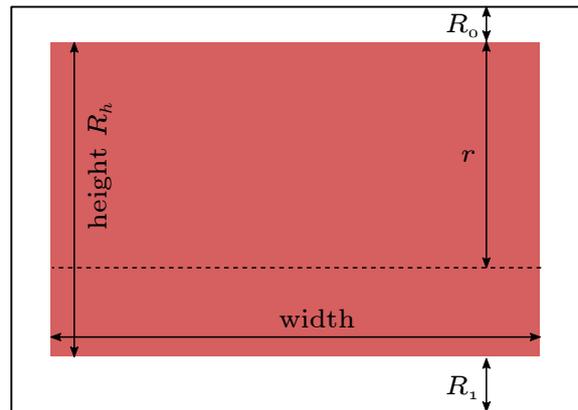


Figure 5: The active pixel matrix on image sensor is surrounded by a strip of hidden pixels, sometimes also called “dark” pixels. They serve for black colour calibration or to avoid edge effects when processing colour information stored in the Bayer pattern (ON Semiconductor, 2015). The rolling shutter model (Equation 1) assigns a sub-frame time to a row r .

the hidden pixels to reduce noise and fix colour interpretation at the sensor edges (Figure 5). This means that there is a delay, proportional to $R_0 + R_1$, between reading out the last row of a frame and the first row of the next one. Camera or image sensor specifications often include *total* and *effective* pixel count. The difference between the two values is the number of hidden pixels.

Now it is straightforward to compute sub-frame time for a frame f and a row r as

$$t(f, r) = t_f + \frac{R_0 + r}{R_0 + R_h + R_1} \cdot T_{\text{frame}}, \quad (1)$$

where R_0, R_h, R_1 are row counts specified in Figure 5, t_f is the frame timestamp and T_{frame} is the nominal frame duration. The constants R_0 and R_1 can be found in the image sensor datasheet or the summary value $R_0 + R_h + R_1$ of total sensor lines can be estimated, as demonstrated in Subsection 3.4.

3.3 Abrupt Lighting Changes

Abrupt lighting changes are trivially detectable and are suitable for sub-frame synchronization with rolling shutter sensors.

The only requirement is that the majority of the observed scene receives light from the source. Many multi-view recordings already fulfil the requirement. Professional sports photographers commonly use flashes mounted on sports arena catwalks to capture photos during indoor matches², mobile phones or DSLRs flashes are used at many social occasions

²<http://www.2.ljworld.com/news/2010/mar/>

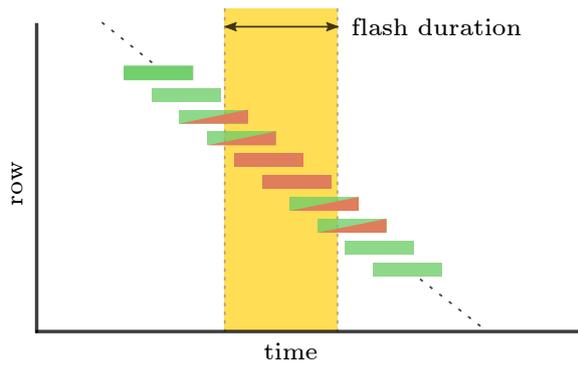


Figure 6: Short abrupt lighting event, e.g., photographic flash, affects only part of the frame rows, in red colour, due to the rolling shutter capture. Rows, depicted half filled in green and red, are being captured at the time of the lighting change. Such rows integrate light of the lighting event only partially. The longer the exposure time the more rows capture an onset of an event.

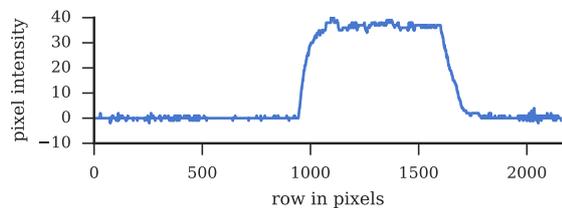


Figure 7: Median line intensity difference between consecutive frames in a moment of a flash. Rows in range 950-1700 were captured when the photographic flash has illuminated the scene. An exponential character of the leading and trailing edges is related to the physical process of the capacitor discharge in a flashtube.

that are recorded. Creative rapidly changing lighting is frequent at cultural events such as concerts.

For photographic flashes (Figures 1, 6), it is possible to detect both leading and trailing edges. A flash duration is typically one order of magnitude shorter than a frame duration. Flashes produce light for $1/1000$ to $1/200$ of a second in contrast to 40 ms frame duration of a 25 fps recording.

An example profile of the captured light intensity by a rolling profile sensor is in Figure 7. The shape of the profile is formed by two processes. The exponential form of the transition edges corresponds to the physical properties of the lighting source. The partially affected rows at the start and end of an event contribute with a linear ramp to the profile shape.

The detection of the abrupt lighting changes is robust and straightforward. As we require that the lighting affects most of the scene, the maximum of difference of median line intensity for a frame shows distinct peaks, see Figure 8. We simply threshold the

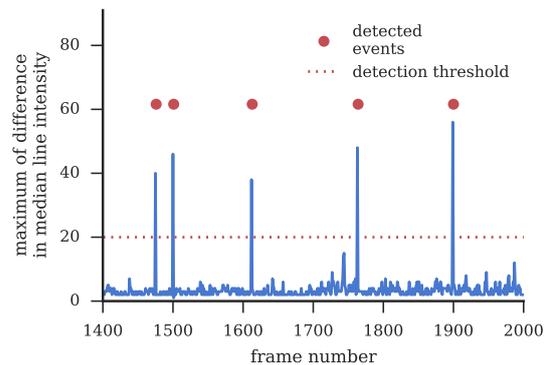


Figure 8: Detection of the abrupt lighting changes. A median line intensity profile is computed for every frame. Then the profiles in consecutive frames are subtracted. The difference maxima for range of frames is plotted above. The clearly visible peaks correspond to the lighting changes. We threshold the values and detect the events marked on the plot by the red dots.

Algorithm 1 Detection of synchronization events

Input: image sequences

Output: synchronization events

foreach camera do

foreach frame do

$m_f :=$ line median intensity (frame)

$m_f \in \mathbb{N}^n$, where n is frame height

end

foreach frame do compute difference profiles

$d_f := m_f - m_{f-1}$

$d_f \in \mathbb{Z}^n$, where n is frame height

end

for f in $\{f \mid \max(d_f) > \text{threshold}\}$ do

$r :=$ find raising edge row in d_f

 event $:= (f, r)$

end

end

return events

values to get the frames with the *events*. We use the leading edge as the *synchronization event*. The *event* row is found in the differences of median line intensity profiles, see Figure 2. The method is summarized in Algorithm 1.

3.4 Synchronization

We model the time transformation $s^c(f, r) \rightarrow t^{\text{ref}}$ from a camera c to a reference camera c_{ref} as an affine mapping similar to (Padua et al., 2010). Substantial difference is that we operate on timestamps instead of frame numbers. The transformation maps the *events* detected in camera c to the same *events* in the

time of a reference camera c_{ref} . The dominant part of the transformation $s^c(f, r)$ is a temporal shift between cameras c and c_{ref} . The synchronization model consisting of a constant temporal shift is usable only for shorter sequences. We found out in experiments that camera clocks maintain stable frame duration, but the reported time units are not precisely equal. This deficiency is known as the clock drift. We compensate the drift by a linear component of the transformation.

The proposed transformation is

$$s(f, r; \alpha, \beta) = \alpha t_f + \beta + r \cdot \frac{T_{\text{frame}}}{R}, \quad (2)$$

where α is the camera clock drift compensation, β is the temporal shift, f is the frame number, r is the row number, t_f is the frame acquisition timestamp and $R = R_0 + R_h + R_1$ is the total number of sensor rows.

The goal of the synchronization is to find $s^c(f, r; \alpha^c, \beta^c)$ for all cameras in $C = \{c_1, c_2, \dots, c_n\}$ except for a reference camera c_{ref} .

For an event observed in camera c and c_{ref} at (f^c, r^c) and $(f^{c_{\text{ref}}}, r^{c_{\text{ref}}})$ the synchronized camera time and the reference camera time should be equal:

$$s^c(f^c, r^c; \alpha^c, \beta^c) = t^{c_{\text{ref}}}(f^{c_{\text{ref}}}, r^{c_{\text{ref}}}). \quad (3)$$

We have demonstrated how to detect abrupt lighting changes in Subsection 3.3. In the next step, we manually align time in cameras c and c_{ref} up to whole frames, e.g., for the first matching event, and automatically match the rest of the events to get:

$$E^{c, c_{\text{ref}}} = \left\{ \left\{ (f_1^c, r_1^c), (f_1^{c_{\text{ref}}}, r_1^{c_{\text{ref}}}) \right\}, \dots, \left\{ (f_k^c, r_k^c), (f_k^{c_{\text{ref}}}, r_k^{c_{\text{ref}}}) \right\} \right\}. \quad (4)$$

Now we can construct overdetermined system of Equations 3 for k pairs of matching events $E^{c, c_{\text{ref}}}$. The least squares solution gives the unknowns α^c, β^c . Optionally also the sensors properties $T_{\text{row}}^c := T_{\text{frame}}^c / R^c$ and $T_{\text{row}}^{c_{\text{ref}}} := T_{\text{frame}}^{c_{\text{ref}}} / R^{c_{\text{ref}}}$ can be estimated, when these are not available in the image sensors datasheets.

When synchronizing more than two cameras, one system of equations for all cameras has to be constructed to estimate the reference camera *time per image row* $T_{\text{row}}^{c_{\text{ref}}}$ jointly.

We summarize the synchronization process in Algorithm 2. The single global time for a frame f and row r is computed using Equation 1 for a reference camera and using Equation 2 for other cameras.

4 DATA

The ice hockey data consists of one complete USA versus Russia match captured by 4 cameras. The

Algorithm 2 Multi-camera Synchronization

Input: frame timestamps, detected synchronization events, reference camera c_{ref}

Output: synchronization parameters

```

foreach  $\{c \in C \mid c \neq c_{\text{ref}}\}$  do
   $E^{c, c_{\text{ref}}} := \text{match events in } c \text{ and } c_{\text{ref}}$ 
  foreach event in  $E^{c, c_{\text{ref}}}$  do
     $\{(f^c, r^c), (f^{c_{\text{ref}}}, r^{c_{\text{ref}}})\} := \text{event}$ 
     $t^c := \text{time stamp for frame } f^c$ 
     $t^{c_{\text{ref}}} := \text{time stamp for frame } f^{c_{\text{ref}}}$ 
    add equation:
     $\alpha^c t^c + \beta^c + r^c \cdot T_{\text{row}}^c = t^{c_{\text{ref}}} + r^{c_{\text{ref}}} \cdot T_{\text{row}}^{c_{\text{ref}}}$ 
    to the system of equations
  end

```

end

solve the system in a least squares sense

return $\{\alpha^c, \beta^c, T_{\text{row}}^c \mid c \in C \text{ and } c \neq c_{\text{ref}}\}, T_{\text{row}}^{c_{\text{ref}}}$

company Amden s.r.o. provided us the data recorded on the International Ice Hockey Federation World Championship 2015. Example images from the cameras are on Figure 1. The cameras 1 and 2 are observing the ice rink from sides, the cameras 3 and 4 are focusing on the defending and attacking zones, that is from the blue lines to the ends of the rink. The camera pairs 1 and 2, and 3 and 4 are identical models with the same lenses. The cameras 1 and 2 use camera model Axis P1428E with resolution 3840×2160 px, the cameras 3 and 4 are equipped with camera model Axis P1354 with resolution 1280×720 px.

The data was delivered in the Matroska file format and later converted to mp4. The frame timestamps were extracted using `ffprobe` command line utility included in the `ffmpeg` package.

5 EXPERIMENTS

The subsection 3.3 and Algorithm 1 describe the method to detect *synchronization events*. We processed the first 5 minutes of the ice hockey match in the four video streams and detected 18, 22, 13 and 15 flashes in the cameras 1, 2, 3 and 4 respectively. For the sake of simplicity, we omitted the flashes that crossed the frame boundary. The *event* distribution is depicted in Figure 9.

We performed two experiments, first we synchronized four cameras jointly by solving a single system of equations, secondly we synchronized camera pairs independently. The results are presented in Table 1 and Table 2. The deviation of the synchronized time from the reference time for the detected *events*, which in ideal case should be 0, can be inter-

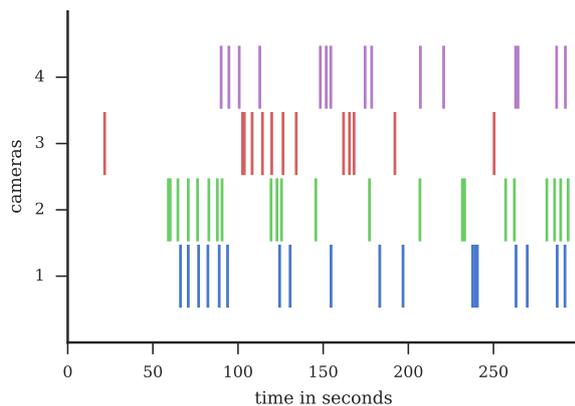


Figure 9: Flashes detected in cameras 1-4. The temporal position of the *events* is always in the camera specific time. The inter camera shift is clearly visible unlike the clock drift. The drift error accumulates slowly and is not noticeable in this visualization.

preted as a measure of method accuracy. The standard deviation of the synchronization errors is 0.5 ms for the joint synchronization and in range from 0.3 ms to 0.5 ms for the camera pairs. We can claim that our method is sub-millisecond precise.

We validated the found sub-frame synchronization with an observation of a high-speed object in overlapping views. A puck is present in two consecutive frames in the camera 1 and in the time between in the camera 3. We interpolated the puck position in the camera 1 to the time of the puck in camera 3. The puck position in the camera 3 and the interpolated position should be the same. Figure 10 shows that the interpolated puck position is close to the real one from camera 3.

We implemented the system in Python with help of the NumPy, Matplotlib and Jupyter packages (Hunter, 2007; Perez and Granger, 2007; van der Walt et al., 2011).

6 CONCLUSIONS

We have presented and validated a sub-frame time model and a synchronization method for the rolling shutter sensor. We use photographic flashes as sub-frame synchronization *events* that enable us to find parameters of an affine synchronization model. The differences of the synchronized time at *events* that should be ideally 0 are in range from 0.3 to 0.5 milliseconds. We validated the synchronization method by interpolating a puck position between two frames in one camera and checking against the real position in other camera.

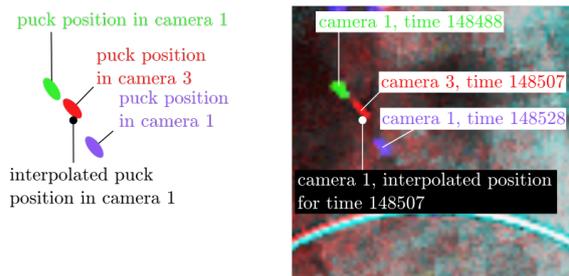


Figure 10: Synchronization validation. Moving blurred puck is visible in two synchronized cameras. We show three overlaid images of the same puck: two consecutive frames in the camera 1 and single frame in the camera 3. The acquisition time of the puck for all 3 frames was computed considering frame f and row r of the puck centroid. Knowing the puck acquisition times it possible to interpolate a position of the puck in the camera 1 for the time of acquisition in the camera 3. The interpolated puck position in the camera 1 and the real position in the camera 3 should be equal. The situation is redrawn on the left, on the right are the image data visualized in green and blue channels for the camera 1 and in the red channel for the camera 3. The interpolated position in the camera 1 is depicted as a black circle on the left and a white circle on the right. The interpolated position and the real position in the camera 3 are partially overlapping.

We published³ the synchronization code as an easy to use Python module and the paper itself is available in an executable form that allows anybody to reproduce the results and figures.

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³http://cmp.felk.cvut.cz/~smidm/flash_synchronization

Table 1: Synchronization parameters and errors for a system of four cameras. The camera 1 was selected as the reference camera c_{ref} and the cameras 2, 3 and 4 were synchronized to the reference camera time. The found parameters of the synchronization transformations (Eq. 2) are presented in the table below. The *time per image row* for the reference camera is 0.0154 ms. The clock drift is in column three presented as a number of rows per second that need to be corrected to maintain synchronization. The standard deviation of the synchronized time from the reference time for the *synchronization events* is presented in the last column.

camera c_{ref}, c	1 - clock drift	drift (in lines/s)	shift (in ms)	T_{row}^c (in ms)	std error (in ms)
1 2	8.39×10^{-6}	-0.56	6066.7	0.015	0.49
1 3	-3.12×10^{-6}	0.08	-37500.2	0.0394	0.44
1 4	-8.35×10^{-6}	0.2	-23858.7	0.0414	0.44

Table 2: Synchronization parameters and errors for independent pairs of cameras. For detailed description see Table 1.

c_{ref}, c	1 - clock drift	drift (in lines/s)	shift (in ms)	$T_{\text{row}}^{c_{\text{ref}}}$ (in ms)	T_{row}^c (in ms)	std error (in ms)
1 2	8.47×10^{-6}	-0.57	6067.49	0.0159	0.0148	0.45
1 3	-8.55×10^{-6}	0.22	-37500.7	0.0158	0.0396	0.42
1 4	-7.04×10^{-6}	0.17	-23859	0.0151	0.0417	0.39
2 3	-14.52×10^{-6}	0.37	-43567.9	0.0149	0.0397	0.39
2 4	-17.37×10^{-6}	0.42	-29926	0.015	0.0416	0.33
3 4	-10.12×10^{-6}	0.2	13642.3	0.0477	0.05	0.27

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