PHOTOGRAMMETRIC ANALYSIS OF ASYNCHRONOUSLY ACQUIRED IMAGE SEQUENCES

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Abstract: The three-dimensional photogrammetric analysis of dynamic processes using image sequences represents a growing field of application for digital photogrammetry. An important precondition is the use of accurately synchronized cameras. In most applications the synchronization of the cameras is realized by external master clocks. Other approaches use stereo-beam splitting for the synchronous acquisition of image sequences.

In this article a new method for the synchronization of measurements of asynchronously acquired image sequences is presented. In contrast to the other mentioned procedures our approach models the asynchronism within the photogrammetric analysis instead of using additional hardware components. We model the asynchronism with a linear approach. The constant part is called time-offset and the linear part is called temporal drift. These two parts are combined and converted to an interpolation factor. This factor is included in the functional model as a temporal correction term and is regarded as an unknown parameter in an extended bundle adjustment. Due to the temporal interpolation, measurements from successive epochs are needed. Because of modeling the asynchronism terms in the analysis, the accuracy of the three-dimensional object point determination from image sequences is significantly improved in contrast to procedures which neglect the asynchronism. Also, using the suggested method image sequences of cameras, which due to technical reasons cannot be synchronized by external hardware, can be processed.

We have implemented the suggested method and have run a number of experiments in the context of vehicle impact testing. The test series confirm the theoretical expectations of the new method. With a frame rate of 1000 Hz, an object speed of up to 7 m/s and an asynchronism of 0.8 ms the accuracy of the object coordinates can be improved approximately by the factor 10.

1. Introduction

The three-dimensional photogrammetric analysis of dynamic processes represents a growing field of application for digital photogrammetry. An important precondition is the use of accurately synchronized cameras. Like some other components of the optical data channel the synchronism of the camera systems represents an important influence factor for the accuracy

of three-dimensional point determination from image sequences [5]. The determination of three-dimensional movements from image sequences is used in different areas of application, e.g. for the dynamic determination of wave surfaces [7], for the analysis of car and passenger movements in the context of vehicle impact testing [6], for human body motion capture from multi station video sequences [1] and for the so called Particle Tracking Velocimetry in liquids [3], [9] or gases [4].

For the synchronization of the camera systems two different procedures have mainly been used in recent years. In most applications the synchronization of the cameras is guaranteed by an external continuous synchronization trigger signal. With this signal all starting points of exposure time of the cameras are controlled. The accuracy of this synchronization method depends on the internal time delay of image acquisition in the individual camera systems. The second possibility of producing synchronous image sequences is the use of a beam splitting device in front of the lens of the camera. [2] use a stereo beam splitter for the acquisition of three-dimensional object movements in pedestrian protection testing in the car industry. In [4] a beam splitter which simulates four virtual camera positions is used for Particle Tracking Velocimetry in gases. The benefit of a beam splitter in front of the lens is that exactly synchronous cameras are simulated, however, with the disadvantage that per image sequence only the half or a fourth of the sensor size of the camera is available. A further disadvantage of a beam splitting system is the fixed camera setup: The configuration is specified by the mirror setup of the beam splitter.

Apart from using hardware components to obtain synchronous image sequences there are also some approaches to synchronize the measurements of asynchronously acquired image sequences in the analysis. [8] use the silhouettes of moving objects. The basic concept of this approach is to determine the tangent envelope of the moving object and then finding corresponding tangents in the image sequences. The result is the temporal offset between the two cameras. The method is used within a multi-camera shape-from-silhouette system. Another approach [10] exploits the correlation of space-time interest point distribution in different image sequences of the same scene and achieves synchronization without any image feature correspondence. The approaches [8] and [10] deal with non-convergent camera constellations. They also do not handle the temporal drift. Only the constant part, the temporal offset is calculated.

In this article an alternative possibility for the photogrammetric analysis of asynchronously acquired image sequences is presented. Instead of using hardware components, the synchronization is embedded into the photogrammetric analysis of the asynchronously acquired image sequences. The asynchronism of the camera systems is regarded as an unknown parameter in an extended bundle adjustment. This new method was developed for the photogrammetric analysis of high dynamic processes. The main applications are the analysis of vehicle impact testing and pedestrian protection testing for car development. The scenario is imaged with up to eight digital high-speed cameras in a circular setup around the measuring area. The cameras acquire image sequences with a frame rate of 1000 Hz and the testing objects move with a speed of up to 18 m/s [6]. The work flow of such a synchronization method and experimental results are described in detail in the following sections.

2. New approach for the analysis of image sequences

2.1. Requirements and basis concept

Due to the intended area of application for this method, there are some requirements for the analysis of image sequences:

- suitable for high dynamic applications,
- no use of hardware components for the synchronization,
- same accuracy level as the analysis obtained when using hardware components for the synchronization,
- user-defined camera acquisition network and
- use of different types of cameras in one network.

To meet all these requirements the synchronization of the measurements of asynchronously acquired image sequences is carried out within the photogrammetric analysis. Thus, the problem of the synchronization of the cameras is solved by a mathematical approximation with correction functions. Note that the same theoretical principle is used for the determination of the distortion parameters within a camera calibration.

In this approach the asynchronism is considered in form of an interpolation factor and introduced as an unknown parameter in the bundle adjustment.

2.2. Temporal components of the optical data channel

Different effects of the optical data channel are denoted as temporal components. With respect to the different cameras these are constant time differences between the times of acquisition, different time delays during signal transmission, different exposure times and different frame rates. Independent of the actual reasons all these effects will be considered as part of the term asynchronism.

For modeling the asynchronism a linear approach is used. The constant part is called time offset and the linear part is called temporal drift. These two values are determined for every camera and indicate the time difference to a reference system. The reference system can be an external time measuring system or one of the cameras of the camera network, which should be synchronized.

2.2.1. Time-offset

The effects of different exposure times and other constant time differences between the cameras are denoted as time-offset of an imaging system. The time-offset is a value, which is indicated for each imaging system relative to the reference system and is constant over the analyzed time interval. This offset often constitutes the main part of the effects of the temporal components.

2.2.2. Temporal drift

The temporal drift is the part of the temporal components, which changes with increasing recording time and causes a change of the asynchronism. This factor can be traced back to differences in the quartz frequencies, which are responsible for clocking the imaging systems. It is assumed that each individual quartz frequency is constant over the entire time interval. Therefore the effect of the temporal drift can be modeled as a linear function, dependent on the time since the trigger signal for the synchronization was started:

$$\Delta t_{Drift} = \frac{1}{f_{Ref}} - \frac{1}{f} \qquad (1)$$

Δt_{Drift} Temporal drift of the camera [sec]

f_{Ref} Frame rate of the reference system [Hz]

f Frame rate of the camera to be synchronized [Hz]

2.2.3. Asynchronism

The time offset und the temporal drift can be combined to yield the asynchronism:

$$\Delta t(t_i) = \Delta t_{Offset} + (t_i - t_0) \cdot f \cdot \Delta t_{Drift} \qquad (2)$$

$\Delta t(t_i)$ Asynchronism of the camera [sec]

Δt_{Offset} Time offset of the camera [sec]

t_i Time step i of the imaging sequence [sec]

t_0 Time step of the last synchronization pulse [sec]

2.3. Modeling of the temporal components within the photogrammetric analysis

2.3.1. Basic concept

If the image recording devices acquire accurately synchronous image sequences, the analysis of the image sequences can be done analogue to the analysis of static photogrammetric images: For each epoch the images can be analyzed separately and the three-dimensional object coordinates are then calculated. In the presence of asynchronism, however, this method leads to wrong results. In the presented approach the asynchronism is modeled by interpolating between the measurements of signalized points in different epochs. Therefore, measurements of different epochs are needed for the analysis of one time step. The required interpolation factor is regarded as an unknown parameter and is introduced as a temporal correction term in the functional model of the extended bundle adjustment.

The consideration of the temporal components in the photogrammetric analysis is carried out in image space. The benefit is that only the measurements of the signalized points in image space are needed. No assumptions about object speed or moving direction must be made.

2.3.2. Extension of the functional model of the bundle adjustment

The functional model of the central perspective projection is extended for the integration of the temporal components. The basic structure of the functional model is still valid, however. By considering the temporal components, measurements of different epochs are processed simultaneously.
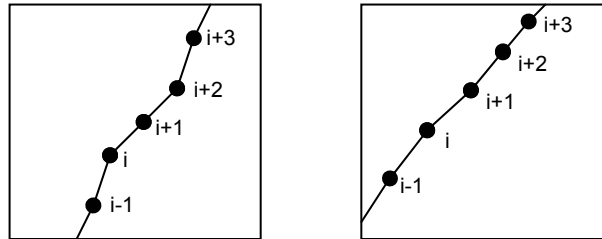

Figure 1: Subsets of two image sequences with a point imaged at different epochs *i-1*, *i*, *i+1*, etc. and the corresponding trajectories. (left: camera 1; right: camera 2)

For the following explanation we only consider two image sequences, keeping in mind that the method can be extended to any arbitrary number of image sequences just like conventional bundle adjustment. The left image subset of figure 1 is regarded as the reference system in our example. If both image sequences are exactly synchronous, the image points at epochs i-1, i, i+1, etc. in the two subsets are corresponding points. The asynchronism between the two cameras leads to a deformation of one trajectory with respect to the other. Therefore, the corresponding points in the right subset are interpolated with respect to the asynchronism between the two cameras. Because of the very small distances between two points of the trajectory a linear interpolation can be employed. For the interpolation the asynchronism is converted into a geometrical term in image space which can be used in the analysis:

$$\Delta t_{red}(t_i) = \Delta t(t_i) - n \cdot \frac{1}{f} \quad \text{with} \quad n = \text{int}[\Delta t(t_i) \cdot f] \tag{3}$$

$$\Delta sync(t_i) = f \cdot \Delta t_{red}(t_i) \tag{4}$$

$\Delta t_{red}(t_i)$	Reduced asynchronism [sec]
n	Renumbering factor of asynchronism
$\Delta sync(t_i)$	Interpolation factor of asynchronism

First, if necessary, the asynchronism has to be reduced by an integer multiple of the exposure interval (see formula 3). Through the reduction, the numbering of the corresponding image points is adapted by the renumbering factor n and the image point i of the reference system corresponds to the image point i+n in the other system. The use of the interpolation factor of the asynchronism leads to the following temporal correction terms for the image coordinates x and y:

$$\Delta x_{Time}(t_i) = (x_{i+sign(\Delta sync(t_i))} - x_i) \cdot |\Delta sync(t_i)|$$
$$\Delta y_{Time}(t_i) = (y_{i+sign(\Delta sync(t_i))} - y_i) \cdot |\Delta sync(t_i)| \tag{5}$$

Analogous to the correction terms of the interior orientation $\Delta x_{Distortion}$ and $\Delta y_{Distortion}$ the temporal correction terms $\Delta x_{Time}(t_i)$ and $\Delta y_{Time}(t_i)$ can be introduced into the collinearity equations, where X, Y, Z are the object coordinates of the considered point and X_0, …, yh are the elements of exterior and interior orientation.

$$x = f(X, Y, Z, X_0, Y_0, Z_0, \Omega, \varphi, \kappa, c, xh, yh) + \Delta x_{Distortion} + \Delta x_{Time}(t_i)$$
$$y = f(X, Y, Z, X_0, Y_0, Z_0, \Omega, \varphi, \kappa, c, xh, yh) + \Delta y_{Distortion} + \Delta y_{Time}(t_i) \tag{6}$$

The results of the extended analysis of the situation depicted in figure 1 are shown in figure 2. The red points in the right subset are the image points of the asynchronously acquired second image sequence. The image points i-1*, i*, i+1* are interpolated by using the presented approach to eliminate the effects of asynchronism between the two used cameras.
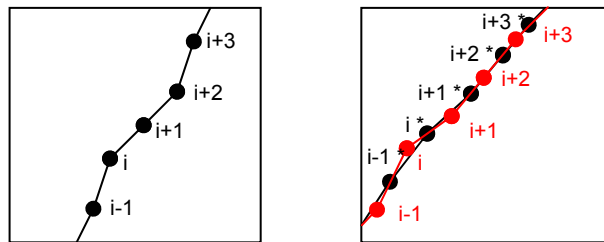

Figure 2: Subsets of two image sequences with the corrected image points of the trajectory

2.4. Preconditions of the approach

There are some preconditions of the new approach: The frame rate of every camera has to be constant over the analyzed time interval. Furthermore the object movement and the object speed have to be constant within a short time interval due to the employed linear interpolation. If the camera network only consists of two cameras, it is indispensable, that the object movement does not occur in the epipolar plane, because otherwise the asynchronism results in a systematic point shift in that plane since the two image rays still intersect. Furthermore it is necessary to measure one image point in successive images. Therefore the measurements of at least three successive time steps of the time interval have to be available for the analysis.

3. Experimental Results of the new approach

3.1. Test equipment and test conditions

The goal of these first tests is to demonstrate the suitability of the proposed new approach. For safety and cost reasons a rotating three-dimensional stable test field was used in the tests. The object points on the test field have a maximum speed of 7 m/sec. They were observed by two NAC Hi-DCam II high-speed cameras which acquire image sequences with a frame rate of 1000 Hz. Each camera has a usable sensor size of 1280 x 512 pixels and a pixel size of 12 μm. The used focal lengths were about 16 mm, the stereo base is about 28 cm and the distances between the cameras and the rotating test field were about 1.9 m. Out of these test properties and the assumption of an image measuring accuracy of 0.05 pixel a mean theoretical standard deviations of $\sigma_x = 0.1$ mm, $\sigma_y = 0.5$ mm and $\sigma_z = 0.8$ mm for the object points on the test field were calculated. For the definition of the coordinate system see figure 3 and 4. The viewing directions of the cameras are tilted about 30° to the Z-axis of the coordinate system, the stereo base is parallel to the X-axis and the base-to-distance ratio amounts to 1:7. The coordinate system is aligned in the way that the rotation axis of the test field is parallel to the Z-Axis of the coordinate system.

The interior orientation of the camera had been determined within a test field calibration and the exterior orientation was calculated with the help of a non-rigid test field before the test. Both orientations are assumed to be constant over the analyzed time interval. Each of the targets on the test field was then measured with automatic target detection algorithms. So for each object point on the test field a 2D-trajectory in the images is available. For the following explanation of the analysis the focus is set to three special positions on the 2D-trajectory of object point C12 which is representative for the whole setup (see figure 3). The three selected positions are marked in the figure 3 and denoted as *top*, *middle* and *bottom*. Due to the alignment of the test field with respect to the coordinate system, the Z-component of the object point C12 is not changing over the analyzed time interval. The movement of the object point is only in the X-Y level.
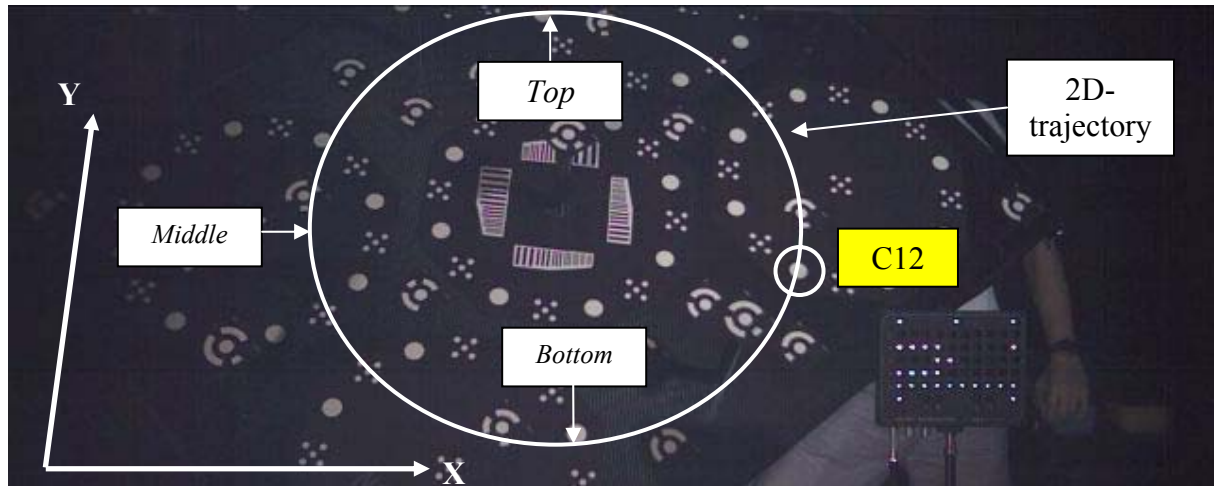
Figure 3. Image sequence – 2D-trajectory of object point C12 of the test field.

3.2. Analysis of the test without modeling the asynchronism

First, the object space coordinates of point C12 resulting from a conventional bundle adjustment, which neglects the asynchronism between the two cameras, are analyzed. The analysis is done for each time step separately and subsequently, three-dimensional trajectories of the object points are computed. The effect of the asynchronism on the three-dimensional point determination depends on the moving direction of the object point. If the object point moves in the epipolar plane, the asynchronism results in a translation of the object coordinates within this plane (see above). If the object point moves in another direction, the asynchronism results in higher standard deviations of the object coordinates. The translation effects are shown in figure 4.
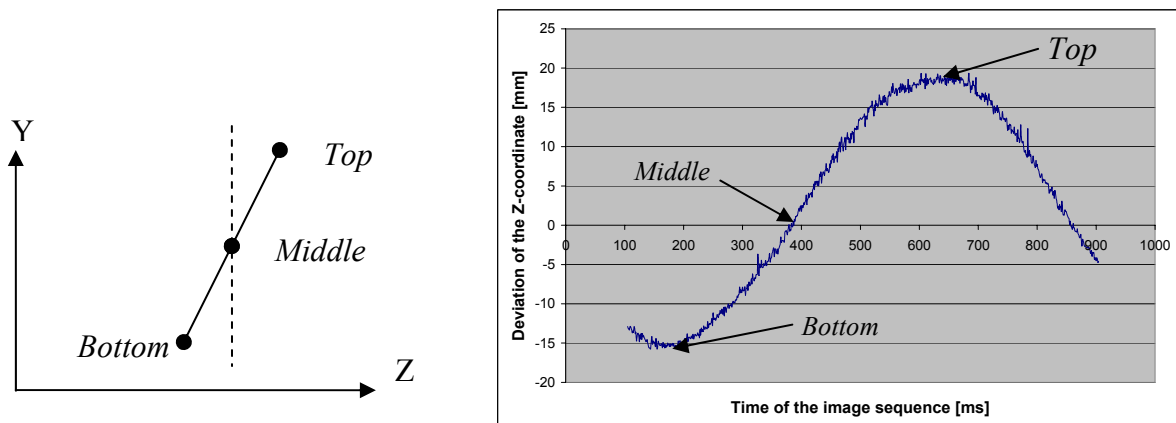

Figure 4. Translation of the object point due to the effect of the neglected asynchronism in the analysis; theoretical situation (left), analysis results (right)

At the trajectory positions *top* and *bottom* the object point moves in the epipolar plane. At these positions the asynchronism leads to a translation of the object point in viewing direction. Depending on the moving direction the calculated positions of the object point are in front of the real position or behind the real position (see positions *top* and *bottom* in figure 4). In this case the asynchronism is about 0.8 ms and the object point C12 moves with a speed of 2.9 m/s. Thus, the effect of the asynchronism parallel to the viewing direction is about 2.3 mm. At the position *bottom*, this results in a translation of about 16 mm in viewing

direction. Due to the tilt of the viewing direction with respect to the Z-axis of about 30°, the translation affects the Y- and Z-component of the object coordinates. Thus the correct position is translated about 14 mm in Z-direction and 8 mm in Y-direction (see figure 4).

The dotted line in the left part in figure 4 shows the plane in which the object point C12 is actually moving. At the trajectory position *middle* the object point moves in a direction perpendicular to the epipolar plane. At this position the asynchronism results only in an increasing standard deviation of the object point coordinates. The calculated position of the object point, however, is correct.

3.3. Analysis of the test with modeling the asynchronism

In contrast to the analysis, which neglects the asynchronism, the new approach with the extended functional model of the bundle adjustment is now used. The results of the analysis are shown in figure 5. The calculated position for *top*, *middle* and *bottom* lie all on the plane (see left part of figure 5). The remaining deviation of the Z-component is caused by the rotation of the test field, which is not perfectly straight.
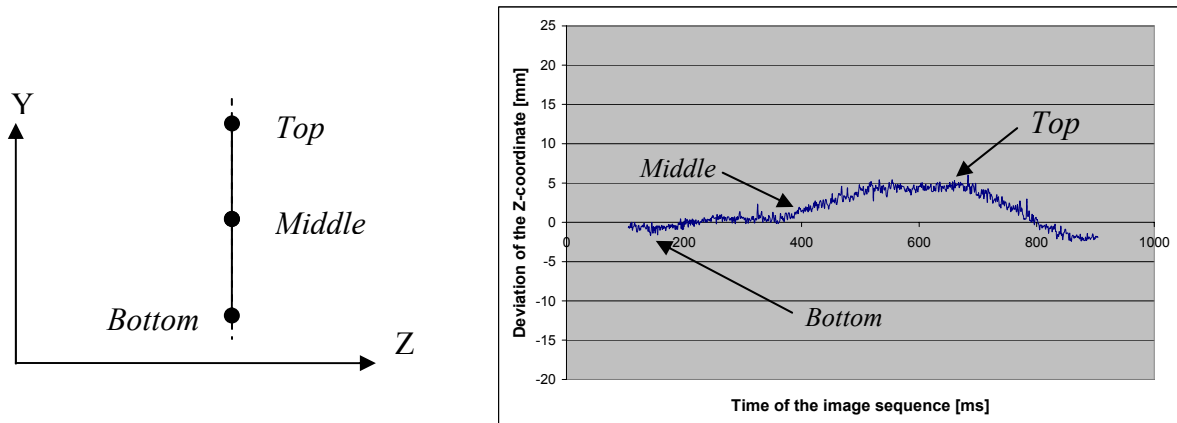

Figure 5. Accuracy of the analysis with modeling the asynchronism;
theoretical situation (left), analysis results (right)

3.4. Comparison of the results and verification of the new approach

For the position *middle* the results of the analysis are presented in table 1. It can be seen that modeling the asynchronism in the described way resulted in an improvement of the theoretical standard deviation of the coordinates of point C12 by factor 10. Furthermore, the theoretical expectations are met.

Object point C12 on the test field		Theoretical values	Analysis without modelling the asynchronism	Analysis with modelling the asynchronism
Asynchronism		0.8 ms	./.	0.79 ms
Middle	σ_x	0.16 mm	1.82 mm	0.17 mm
	σ_y	0.45 mm	5.23 mm	0.49 mm
	σ_z	0.70 mm	8.17 mm	0.77 mm

Table 1: Comparison of the standard deviations of the coordinates of both types of analysis

The differences between the calculated coordinates in both types of analysis are shown in figure 7. They correspond to the theoretical values for the translation with an asynchronism of 0.8 ms and an object speed of about 2.9 m/s. The linear correlation between the asynchronism and the translation of the object coordinates in viewing direction does only appear in a test setup with two cameras as in our experiments. If image sequences of more than two cameras are used for the analysis the asynchronism results in an increase of the standard deviation of the calculated object point coordinates, as can be shown using epipolar reasoning, and as additional experiments have actually demonstrated. In our test setup the modeling of the asynchronism leads to an increasing accuracy of the object coordinates and to the correct determination of the object coordinates.
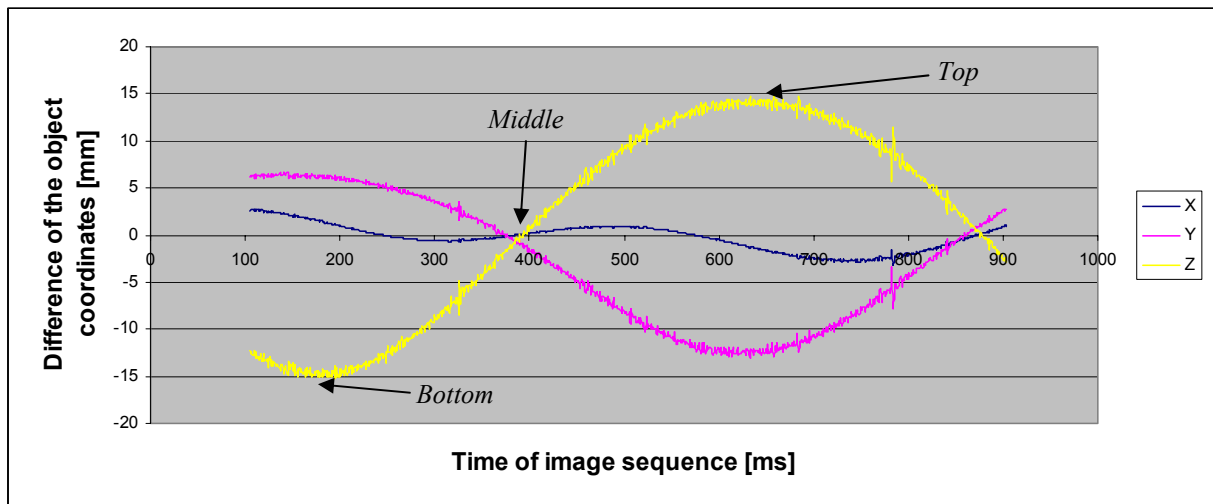

Figure 7: Differences of the object coordinates over the analyzed image sequence caused by the different types of analysis

The verification of the determined asynchronism is carried out by an external time measuring system (see figure 3; below the yellow box labeled "C12"). From the lit LEDs the time of image capture can be derived. The image of the left camera was acquired at time 43.3 ms and the image of the right camera was acquired at time 44.1 ms. Thus, from this time measuring system an asynchronism of 0.8 ms is computed between the two cameras. This is about 80 % of the exposure interval of the used cameras. In the analysis an asynchronism of 0.79 ms was obtained. The resolution of the external time measuring system is restricted to 0.1 ms in the used mode, the accuracy is a few orders of magnitude better. Therefore, the estimated value of the analysis and the calculated value for the asynchronism of the time measuring system can be regarded as equal.

4. Conclusion and Outlook

In this article a procedure is presented, which permits the photogrammetric analysis of asynchronously acquired image sequences. The asynchronism is modeled with a linear approach and is then converted to an interpolation factor. With this interpolation factor temporal correction terms for the image coordinates are calculated. The modeling of the asynchronism as a temporal correction term in the functional model of the bundle block adjustment leads to a significant improvement of the results.

At the current state of work there are some preconditions for the successful application of this new approach for the photogrammetric analysis of image sequences. All cameras must have a

constant frame rate over the analyzed time interval. This precondition corresponds to the linear asynchronism model. Furthermore and for the same reason, the object movement and the object speed have to be constant within a short time interval.

In our experiments two image sequences of a rotating three-dimensional test field are analyzed. For the first test the asynchronism is only modeled with the constant part of the asynchronism, the time-offset. The use of this reduced approach leads to a correct determination of the object coordinates and to an improvement of the object point accuracy of factor 10 in contrast to the analysis, which neglects the asynchronism. The calculated accuracy also corresponds to the theoretically estimated values. The determined asynchronism is 0.79 ms, which corresponds to the external determined asynchronism of 0.8 ms.

In following test series the applicability of this new approach has to be further investigated. At the current state of work some of the mentioned preconditions are indispensable. Further investigations will show if some of them can be relaxed under special conditions. In addition the described procedure will be applied to real-world applications such as vehicle impact tests. Also, experiments with more than two cameras and with different types of cameras will be carried out, and the simultaneous determination of the interior and exterior orientation of the cameras and the asynchronism will be investigated.

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