PHOTOGRAMMETRIC SYNCHRONIZATION OF IMAGE SEQUENCES

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ABSTRACT:

The three-dimensional photogrammetric analysis of image sequences is a growing field of application. For the analysis of dynamic processes one important precondition has to be guaranteed: The cameras of the acquisition network have to be exactly synchronized, otherwise the results of the object point calculation are affected by asynchronism. In order to obtain synchronous image sequences different methods can be applied. These methods can be divided into three major groups: methods which use hardware components, methods which acquire asynchronously image sequences, but use a hardware component to register the asynchronism and correct the measurements via software in a post-processing step, and methods which acquire asynchronous image sequences and use software algorithms to correct the image measurements within the analysis.

In this article a new method is presented, which can be assigned to the third group. In contrast to already existing methods the new approach has no restrictions concerning the number and the set-up of the cameras in the acquisition network. Furthermore, both the temporal and spatial analysis step are carried out simultaneously and are not divided into two separated parts. Due to these facts, the accuracy of the object point determination from image sequences is significantly improved in contrast to procedures which neglect the asynchronism.

We have implemented the suggested method and have run a number of experiments in the context of vehicle impact testing. These tests confirm the theoretical expectations of the new method. Sequences with a frame rate of 1000 Hz observing an object with a speed of up to 7 m/s and an asynchronism of -0.79 ms were analyzed. The accuracy of the object point calculation could be improved by factor of 10.

1. INTRODUCTION

Digital video and highspeed cameras offer a lot of new areas of application for photogrammetric image sequence analysis. The three-dimensional analysis of a static object scene with a single moving camera and the analysis of a two-dimensional object motion with a single stationary camera have been reported in several applications in the past (Pollefeys et al., 2004; Maas, Hampel, 2006). Recently, several authors described work with a multi-camera set-up for the analysis of three-dimensional object movements. Examples include the analysis of three-dimensional wave surfaces (Santel et al., 2003), three-dimensional particle tracking velocimetry in fluids (Maas, 1992; Willneff, 2003) and gases (Putze, 2004), the analysis of human motion (D'Apuzzo, 2003), the analysis of high-dynamic object movements within vehicle impact tests in the car industry (Raguse et al., 2004; McClenathan et al., 2005) and the analysis of material testing (Schmidt et al., 2005; Maas, Hampel, 2006). All applications use a multi-camera system for the acquisition of the object motion and they all have one common pre-condition: The acquisition of all image sequences has to be done synchronously. Otherwise the results of the photogrammetric analysis suffer from the effects of asynchronism between the acquired image sequences. These effects depend on the object speed, the object movement direction, the frame rates of the cameras and the camera configuration.

Especially for applications with different types of cameras, synchronization is not always guaranteed. For high-dynamic applications, e.g. the analysis of vehicle impact tests, synchronism of the image sequences is indispensable. In a typical acquisition network of an impact test an asynchronism of 0.5 frames between two of the highspeed cameras can lead to a translation of an object point of up to 30 mm. The required accuracy of the object point coordinates for this kind of vehicle impact testing is about 5 mm. Thus, the effects of an asynchronism cannot be ignored.

In the following sections of this paper a new approach for the photogrammetric analysis of asynchronously acquired image sequences is presented. This approach leads to highly accurate results which are not affected by the asynchronism between the cameras. Preliminary results of our work have been reported in (Raguse, Heipke, 2005). The remainder of this paper is organized as follows: In section 2 different methods to obtain a synchronous image sequence analysis are described. The theory of the new approach for the analysis of image sequences is presented in section 3. The results of the practical test are described in section 4. Conclusions and an outlook to future research are given in section 5.

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2. RELATED WORK

In order to obtain synchronous image sequence measurements, several methods have been suggested. They can be divided into three main groups: methods using hardware components, methods using a combination of hard- and software and methods using only software. These three groups are described in the following. The third group, the software methods, is described in more detail, because our new approach belongs to this group.

The methods of the first group use hardware components for the synchronization of the cameras. These hardware components are e.g. hardware trigger boxes or frame grabbers. They send synchronization trigger signals to the connected cameras (Santel et al., 2003). The synchronization accuracy depends on the accuracy of the trigger devices, which generate the synchronization signal. Other methods of this group use mirror systems, e.g. a beam splitter in front of a single camera (e.g. Putze, 2004; Hastedt et al., 2005). With a stereo beam splitter two virtual cameras are simulated which acquire the scene exactly synchronously. An extension of a stereo beam splitter to more than two cameras is not possible, and the available horizontal resolution per image is only 50 %. Through the use of hardware components with a single camera the acquired image sequences are exactly in sync, but the set-up of these systems is fixed.

The methods of the second group use a combination of hard- and software. The image sequences are acquired asynchronously, but the time difference between the image sequences is registered during acquisition through a high precision clock. These values for the asynchronism are then used to correct the measurements of the asynchronously acquired image sequences in a post-processing step. For this method, all cameras of the network have to view the clock. Thus, there are restrictions to the camera set-up.

The methods of the third group use only software to synchronize asynchronously acquired image sequences. Here the cameras do not have to be physically connected to any kind of master system and no special hardware devices are necessary. In some applications the used cameras can have an arbitrary, also varying time offset, e.g. due to different frame rates. The parameters for the asynchronism are determined during the analysis of object points. In some cases the temporal alignment is separated from the spatial alignment and is carried out in a preliminary step.

This third group, the software algorithms, can further be divided into three subgroups (Lei, Yang, 2005). This subdivision depends on the image information which is used for the determination of the asynchronism. The methods of the first subgroup are called intensity-based methods or direct methods. They use the intensities of all pixels of the image for the calculation of the asynchronism (e.g. Caspi, Irani, 2000). The second subgroup contains feature-based methods, which solely use detected features, e.g. points or silhouettes, for the calculation of the spatial and temporal alignment (e.g. Stein, 1998; Caspi et al., 2002; Zhou, Tao, 2003; Carceroni et al., 2004; Sinha, Pollefeys, 2004). A more detailed description of both methods is given by (Irani, Anandan, 2000) and (Torr, Zissermann, 2000). The third subgroup contains methods for cameras which are joined together rigidly, thus the relative orientation between the cameras is fixed during acquisition (Caspi, Irani, 2001; Wolf, Zomet, 2002).

All the above mentioned methods for synchronizing measurements of image sequences with software algorithms have several restrictions. Similar to area-based image matching the methods of the first subgroup are sensitive to changes in brightness. Furthermore, the camera set-up is mostly restricted to two cameras which have to be positioned closely together and the scenes have to be acquired under nearly the same perspective conditions. The methods of the second subgroup are often restricted to two or three cameras, at least if linear spatial alignment functions are used. The main restriction of the methods of the third group is the requirement of rigidly joined cameras. In addition, the spatial and the temporal alignment of the sequences in the methods of all three subgroups are mostly separated into two steps of analysis. This can lead to problems in the analysis, due to the fact that correlations between temporal and spatial parameters cannot be considered.

To overcome all these restrictions, we have developed a new approach. Details of the algorithm and results of practical tests are described in the next sections.

3. NEW APPROACH FOR THE ANALYSIS OF IMAGE SEQUENCES

Our new approach is developed for applications where no possibility of using hardware components is given. In these applications the synchronization can only be achieved using software algorithms. We aim to handle an arbitrary number of different types of cameras which can be positioned anywhere around the measuring volume without any restrictions. Image coordinates of signalized points are used as input values for the algorithm. Thus, it belongs to the subgroup of feature-based methods of the software algorithms.

3.1 Requirements and basic concepts

A reliable and robust algorithm for the solution of the asynchronism problem within the image sequence analysis should be able to handle the following cases (Carceroni et al., 2004):

- unknown frame rates of the cameras,
- arbitrary time shift between the sequences,
- arbitrary object motion and speed,
- unknown user-defined camera set-up and
- no static points in the scene.

These requirements were the basis of the development of the new approach.

The background of our work is the analysis of highly dynamic vehicle impact tests in the car manufacturing industry, keeping in mind that the new approach should be used for tests where the synchronization of the cameras with hardware components is not possible while retaining the same level of accuracy.

To meet all these requirements we have combined the spatial and the temporal alignment and consider them simultaneously within the photogrammetric analysis. The problem of synchronizing image sequences is solved by a mathematical approximation via a temporal correction function which is converted to an interpolation factor in image space. This factor is introduced into the functional model of the bundle adjustment. The parameters of the interpolation factor are considered as unknowns. Note that the same theoretical principle of correction functions is used for the determination of the lens distortion parameters within camera calibration.

3.2 Temporal components of the optical data channel

Like other components of the optical data channel the synchronism between the cameras represents an important factor for the accuracy of the image sequence analysis (Raguse, Wiggenhagen, 2003). This synchronism is affected by the temporal components of the optical data channel. These are different physical effects which are responsible for an asynchronism between the cameras of the acquisition network. The temporal effects can be categorized as follows:

- constant or dynamic time differences between the cameras,
- accuracy and stability of the frame rates,
- accuracy and stability of the exposure times,
- different frame rates of the cameras,
- different exposure times of the cameras and
- object motion (motion blurring effects).

To obtain correct and reliable results in time and space all these effects are considered simultaneously within the photogrammetric analysis, independently of their actual physical reason and are denoted as asynchronism between the image sequences.

The reference for the temporal alignment is always a master time system. This master time system can be an external clock or one of the cameras of the acquisition network. All temporal calibration parameters are calculated with respect to this time reference.

3.3 Modelling the asynchronism via correction functions

In this approach the asynchronism of each camera is modelled by a 2nd order polynomial, which is called the temporal correction function. If the used camera has exactly the same frame rate as the reference frame rate and the frame rate is exactly constant over time, the correction function contains only a time offset. If the frame rate is different from the reference frame rate but constant, the asynchronism can be modelled by a linear correction function. If the camera has furthermore a constant drift in its frame rate, then a polynomial of second order must be used.

For each camera of the acquisition network a separate temporal correction function is introduced. The temporal correction reads:

$$\Delta t(t_i) = \Delta t_{Offset} + (t_i - t_0) \cdot (\frac{f}{f_{ref}} - 1) + (t_i - t_0)^2 \cdot drift \quad (1)$$

where $\Delta t(t_i)$ = asynchronism at time t_i
Δt_{Offset} = constant time offset
t_i = time step i of the image sequence
t_0 = time step of the last synchronization pulse
f = frame rate of the camera to be synchronized
f_{ref} = frame rate of the reference system
drift = temporal drift of the camera to be synchronized

3.4 Inclusion into the bundle adjustment

The consideration of the asynchronism between the cameras of the acquisition network within the photogrammetric image sequence analysis is carried out in image space. The advantage of such a method is that only image coordinates of the signalized features have to be considered. Assumptions about object movement and object speed are not needed.

The correct position of a point in image space is linearly interpolated between the points of the two-dimensional trajectory at different epochs. At least measurements of three successive epochs are needed in each step of the analysis, since it is not clear a priori if the correction has a negative or a positive sign. The required interpolation factor is computed from the correction function. The temporal correction function is introduced into bundle adjustment and the parameters of this function are regarded as additional unknown parameters.

If the asynchronism is larger than the time interval between the acquisition of two images the asynchronism has to be reduced by an integer multiple of the frame time (see eq. (2)). Then, the asynchronism, as a temporal term, has to be converted to a geometrical term in image space to use it for the interpolation in the analysis (see eq. (3)).

$$\Delta t_{red}(t_i) = \Delta t(t_i) - n \cdot \frac{1}{f} \quad \text{with} \quad n = int[\Delta t(t_i) \cdot f] \quad (2)$$

$$\Delta sync(t_i) = f \cdot \Delta t_{red}(t_i) \quad (3)$$

where $\Delta t_{red}(t_i)$ = reduced asynchronism
n = renumbering factor of the asynchronism
$\Delta sync(t_i)$ = interpolation factor of the asynchronism

The use of the interpolation factor of the asynchronism leads to the following temporal correction terms for the image coordinates x and y:

$$\begin{aligned} \Delta x_{sync}(t_i) &= (x_{i+n+sign(\Delta sync(t_i))} - x_{i+n}) \cdot |\Delta sync(t_i)| \\ \Delta y_{sync}(t_i) &= (y_{i+n+sign(\Delta sync(t_i))} - y_{i+n}) \cdot |\Delta sync(t_i)| \end{aligned} \quad (4)$$

These temporal correction terms are added to the collinearity equations in the same way as the correction terms for the parameters of the interior orientation $\Delta x_{Distortion}$ and $\Delta y_{Distortion}$, where X, Y, Z are the object coordinates of the considered point and X_0, …, y_h are the elements of exterior and interior orientation.

$$\begin{aligned} x &= f_x(X, Y, Z, X_0, Y_0, Z_0, \Omega, \varphi, \kappa, c, x_h, y_h) \\ &\quad + \Delta x_{distortion} + \Delta x_{sync}(t_i) \\ y &= f_y(X, Y, Z, X_0, Y_0, Z_0, \Omega, \varphi, \kappa, c, x_h, y_h) \\ &\quad + \Delta y_{distortion} + \Delta y_{sync}(t_i) \end{aligned} \quad (5)$$

In most photogrammetric applications the analysis of image sequences is done in the same way as static photogrammetric applications are analyzed. The analysis is done separately for each time step and the results are combined after the analysis to obtain the temporal information. In this approach the temporal and the spatial alignment of the image sequences are considered simultaneously. Thus, the measurements of all time epochs and of all object points can be analyzed in one step.

3.5 Restrictions of the new approach

The interpolation between the points of the trajectory in image space is carried out by a linear function. Therefore, we assume that the object motion and the object speed are constant within a short time interval, namely from one image to the next of the image sequence. Furthermore, at least measurements of one image point of three successive time steps of the time interval are needed within the analysis to calculate the asynchronism parameters for the reason mentioned above. Also, if the acquisition network consists only of two cameras, it is indispensable that the object motion 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.

4. PRACTICAL TESTS OF THE APPROACH

The described approach has been verified in a practical test series. First results have shown the potential of the approach for the determined accuracy of object point coordinates. With a frame rate of 1000 Hz, an object speed of up to 7 m/s and an asynchronism of -0.8 ms* between two cameras, the accuracy of the object coordinates could be improved by factor of 10 comparing the theoretical standard deviations of object points with and without considering the correction (Raguse, Heipke, 2005). For these tests, images from a circular motion of object points on a three-dimensional test field were acquired with two digital high-speed cameras. All measurements of the circular movement of the object points were used in one analysis. Within one complete rotation of the test field about 910 successive images were available. The described limit of the algorithm in situations where the direction of object movement was nearly within the epipolar plane could be compensated by using the complete rotation.

In the test series of this paper the accuracy of the algorithm is tested empirically. Due to the fact that we do not precisely know the true positions of the objects points at any time step, we analyze the length of a reference distance B12 to C12 on the test field (see figure 1). Note that the centre of rotation does not lie on the line through B12 and C12. Obviously, the length of the reference distance has to be constant in 3d space. We use the differences between the measured length and the reference length to obtain the empirical accuracy of the new approach. Furthermore, in the test series the number of analyzed successive images of the reference distance is systematically reduced to a number which is typical for the later application of this method, the analysis of vehicle impact tests. Thus, we do not use the complete time interval of 910 successive measurements to calculate the asynchronism parameters anymore. Checks are carried out at different positions of the complete time interval. We also analyze positions where the moving direction of the object points of the reference distance is nearly within the epipolar plane.

* The new analysis of the image sequences leads to an asynchronism of -0.79 ms (see section 4.1).

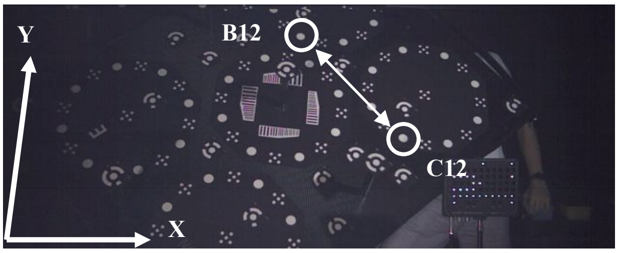

Figure 1. Reference distance between the object points B12 and C12 on the test field

The analyzed image sequences are the same sequences as used in the prior test described in (Raguse, Heipke, 2005) where two digital highspeed cameras with a frame rate of 1000 Hz observe a test field which rotates with a speed of approximately 7 m/s.

4.1 Calculation of a reference value for the asynchronism between the two cameras using a synchronometer

To verify the calculated values for the asynchronism between the two image sequences a reference value for the asynchronism is calculated using a high-precision clock. This clock is a LED panel of superior time accuracy, named synchronometer, which is positioned in the view of the cameras. Counting the lit LEDs of the panel in each image of the sequence gives the current absolute master time of the image.

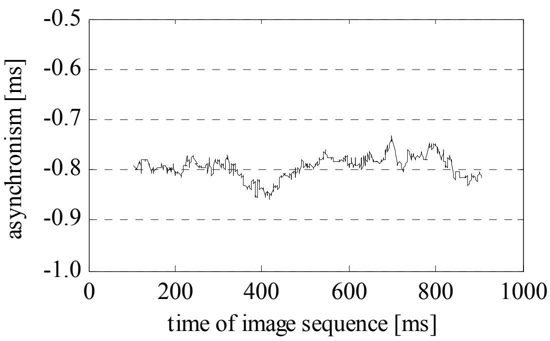

Figure 2. Asynchronism during the analyzed time interval

The temporal resolution of the synchronometer in the used mode is 0.01 ms. The results of the reference measurements are shown in figure 2. The mean value of the temporal offset is -0.79 ms and the standard deviation of each observation is 0.02 ms. We can see that the measurements of the temporal offset are a bit noisy, but the results are good enough to use them to evaluate the results of our algorithm in the following analysis.

4.2 Analysis of a reference distance on the test field

In this section the focus is on the computed length of a reference distance. The analyzed reference distance is defined on the test field between the two object points B12 and C12. The length of this reference distance is calibrated to 520.16 mm with a standard deviation of 0.01 mm. The object coordinates of the two points were calculated for each time step of the image sequence analysis with and without the synchronization term of eq. (5). The results over the complete analyzed time interval of about 910 ms by both types of analysis are shown in figure 3.

The analysis which neglects the asynchronism leads to significant and systematic changes in the calculated length (gray line in figure 3). The maximum changes are up to 14 mm.

The effects of asynchronism on the length of the reference distance with respect to the orientation of the length can be seen in figure 3. Except when the points move perpendicular to the epipolar line, they are somewhat translated in the viewing direction. This translation affects the length in a systematic way (see sine-like gray curve in figure 3). The exact form depends on the camera geometry and the position of the end points relative to the centre of rotation.

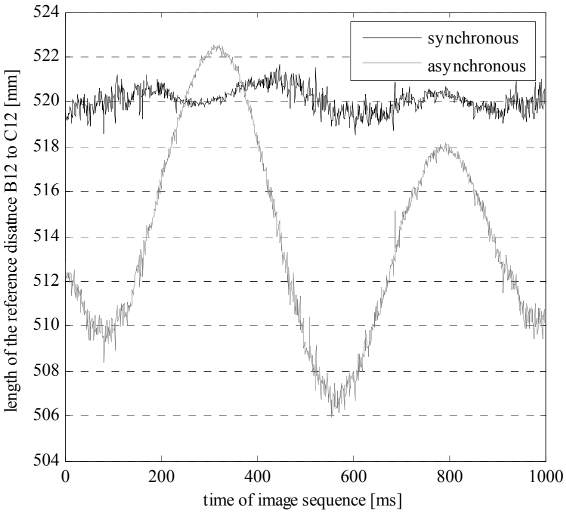

Figure 3. Length of the reference distance B12 to C12 in the analyzed time interval with and without the consideration of the asynchronism

Using the new approach the asynchronism of -0.78 ms with a standard deviation of 0.01 ms is found. Thus, there is no significant difference to the reference value for the asynchronism of -0.79 ms (see section 4.1). The calculated mean value for the length between the two object points is 520.16 mm with a standard deviation of each value of 0.51 mm (black line in figure 3). The difference to the calibrated length is 0.01 mm, which can be neglected. The changes of the length over the analyzed time interval (see figure 3) show a small systematic effect. This effect can possibly be traced back to the temporal offset between the two sequences. This offset seems to be not totally constant (see figure 2).

Due to the modelling of the asynchronism the length of the reference distance B12 to C12 could be calculated correctly. Without modelling the asynchronism the length of the reference distances shows systematic errors of up to 14 mm.

4.3 Reduction of successive measurements

In the prior test series all measurements of about 910 successive time steps were used for the determination of the asynchronism parameters. The aim of this test is to find an upper limit for the necessary number of images to still obtain correct results with respect to the restriction that the object movement is not allowed to be in the epipolar plane. We reduce the number of successive image coordinate measurements of the reference distance B12 to C12 on the test field. The analysis with the reduced number of measurements is carried out at different positions within the time interval. The results of the systematic reduction of the number of successive image measurements are listed in table 1.

No. of images	No. of positions	Δt [ms]		length [mm]	
		min	max	min	max
910	1	-0.78		520.16	
200	40	-0.74	-0.83	519.59	520.33
100	80	-0.73	-0.85	519.17	520.98
50	150	-0.72	-0.86	519.07	521.10
20	450	-0.71	-0.87	518.87	521.32
10	900	-0.70	-0.88	518.68	521.51

Table 1. Results of the reduction of the number of successive image measurements

It can be seen that the results are only slightly worse when reducing the number of measurements. The changes in the calculated asynchronism are in the range of 0.1 ms. The changes of the reference lengths are approximately 1.5 mm.

In this set-up the reduction of the successive measurements to only 10 time steps does not reduce the accuracy of the results significantly because at least one of the two image points of the reference distance always moves outside the epipolar plane. Thus, the critical constellation of a movement direction exclusively within the epipolar plane does not appear.

5. CONCLUSION AND OUTLOOK

In this article a new method is presented which permits the photogrammetric analysis of asynchronously acquired image sequences. The asynchronism is modelled by a 2nd order polynomial and is converted to an interpolation factor in image space. Through the use of the interpolation factor, temporal correction terms for the image coordinates are calculated and introduced in the functional model of the bundle adjustment. This extension of the bundle adjustment leads to a significant improvement of the results of the image sequence analysis. Due to the linear interpolation between the image measurements of one point, we assume that the object movement direction and the object speed are constant within a short time interval, namely between two successive image measurements.

To verify the approach we have analyzed a test set-up with two digital highspeed cameras, acquiring a rotating test field with a frame rate of 1000 Hz. The speed of the test field is up to 7 m/s. The empirical accuracy of the new approach is about 1.5 mm in object space. We have analyzed a reference distance on the test field with the new approach in comparison to a bundle adjustment which neglects the asynchronism. Using the new approach no significant changes of the reference distance were found. The analysis which neglects the asynchronism leads to systematic errors of up to 14 mm. In a second test series the number of used image measurement is reduced systematically to a number which is typical for our application, the analysis of vehicle impact tests. The analysis shows that a reduction to only 10 successive measurements does not lead to a significant loss of quality.

In the future the applicability of the new approach has to be further investigated. Especially test series with different types of cameras will be carried out to analyze experiments where the asynchronism between the cameras is not constant. Further tests will also address the simultaneous determination of the interior and exterior orientation and the asynchronism of a larger number of cameras. Also tests with a varying exterior orientation of the cameras will be carried out. Furthermore, the described method will be applied to real-world applications such as vehicle impact tests.

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