Configuration of multi mirror systems for single high speed camera based 3D motion analysis

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Abstract

The use of multi camera systems to determine 3D object coordinates is a common approach in close range photogrammetry. The paper discusses system configurations based on a single camera and mirror systems to generate a virtual multi camera system. The two main advantages of mirror-based multiple-view vision systems can be seen in the lack of synchronisation requirements and the costs of only one camera. The latter applies especially if high speed cameras are required to capture the dynamics of an application. These advantages have to be weighted against the disadvantages of a reduced active image format per view and the restrictions to the imaging geometry.

In the paper we present two different systems used for motion analysis applications: A fixed two mirror system is used to analyse pedestrian protection testing in the context of vehicle safety development, and a flexible four mirror system is used to capture 3D velocity fields of particles visualising gas flows in a wind tunnel. A geometric model for multi-mirror stereoscopic systems has been developed, representing the mirror system by multiple virtual cameras in order to warrant compatibility with existing photogrammetric stereo data processing software solutions. The accuracies achieved in practical tests are almost comparable to those obtained with multi camera systems.

1. Introduction

Motion analysis applications require 3D data with high spatial and temporal resolution. Spatially resolved 3D data can be obtained through multi-camera photogrammetric systems. Recent high speed cameras offer a temporal resolution far beyond 1000 images per second. High speed cameras are, however, cost intensive. Hence, the availability of several high speed cameras is not always granted. In addition, proper synchronisation between multiple high speed cameras, especially between different types, is still a problem, which is not fully solved.

In general, 3D dynamic processes have to be observed with a multi camera system. Single camera systems can only be used if previous knowledge is available, e.g. surface parameters to reduce the motion to a 2D problem, or if control points are available to determine the unknown parameters through 6 DOF [5], or if an active projector [3] or a so-called 3D Camera [9] are used. These technologies are developed with respect to special applications and cannot be used in general.

In dynamic processes a multi camera system with synchronous image capturing is essential to obtain correct results. The coordinate error caused by a time delay of one camera in a stereo system depends on the velocity of the object, the object movement, the frame rate of the camera system and the stereo imaging geometry [12]. It is shown that high speed applications are susceptible to synchronisation bias. If the acquisition network only consists of two cameras and the object is moving in the epipolar plane parallel to the camera basis, the translation of the object in moving direction x and in viewing direction y can be estimated by equation (1). A delay of 0.5 ms (1/2 frame at 1000 fps) and an object velocity of 10 m/s means that the recorded object moves 5.0 mm in object space between the images of the two cameras. The determined object point coordinates are shifted systematically about 2.5 mm in moving direction and 15.0 mm in viewing direction (basis length 2.5 m, object distance 7.5 m). This systematic point shift due to an asynchronism of the cameras cannot be ignored.

$$dx = \frac{dt \cdot v}{2} \qquad dy = dx \cdot \frac{2 \cdot y}{b} \tag{1}$$

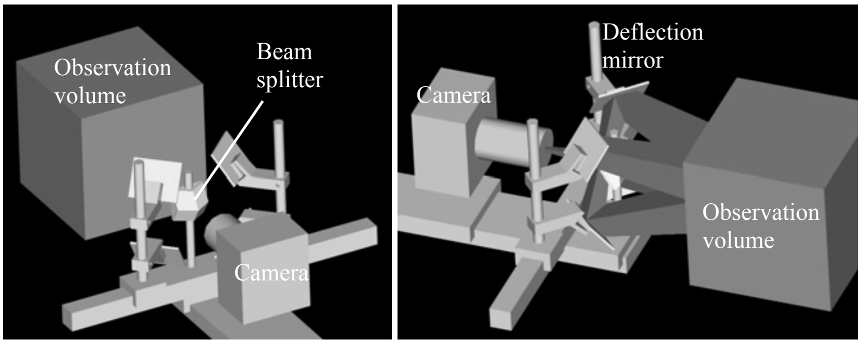
A possibility to obtain 3D object coordinates with a single camera system avoiding synchronisation bias is the use of a mirror system, which simulates a virtual multi camera system. This usage of a camera mirror system has advantages and disadvantages which have to be weighted [11]. On the one hand only one camera is required and the synchronisation between the virtual cameras is inherently granted. On the other hand there is a decrease of active image format, flexibility and accuracy in contrast to fully-fledged cameras.

Possible applications for camera mirror systems are small test systems in the context of vehicle safety development [4][12], 3D liquid or gas flow analysis [10][11], bio-medical or sports-medical motion analysis [2] or conveyor belt quality control [8].

2. Configuration of mirror systems

The use of mirror systems to obtain stereo images with a single camera is known since many years. For non-metric applications beam splitter lenses for SLR cameras are available. Here, the basis of the two virtual cameras is nearly as long as the eye distance of human beings, which makes a stereoscopic view possible. In [14] a mathematic approach for the geometric model of an optical beam splitter is characterised. The use of mirror systems for metric applications in huge volumes requires a more specific configuration than the beam splitter lenses for SLR cameras. A convergent camera set-up and a large base length between the virtual cameras are obligatory to achieve a high accuracy.

The basic construction of the developed mirror systems consists of a beam splitter directly in front of the lens (see figure 1(a)). The image rays are divided into two or four equal bundles and are deflected orthogonal to the viewing direction by the beam splitter. In the corners of the system, approximately at the positions of the virtual cameras, huger deflection mirrors are positioned to adjust the ray bundles into the observation volume (see figure 1(b)). The base-distance ratio depends on the distance between the deflection mirrors and their incidence angle.



(a) (b)

Figure 1: Scheme of a 4-fold beam splitter without (a) and with (b) image rays

2.1. Fixed two mirror system

The use of a single camera system and two mirrors in a fixed arrangement eliminates two major problems. Hereby the synchronisation problem as shown before is solved. Furthermore, the determination of the orientation parameters of these virtual cameras is simplified. Normally, control points have to be signalised in the observation volume to determine the parameters of exterior and interior orientation. Using separate cameras the determination of these parameters is carried out in the factory floor with industrial environment so that the availability and the stability of control points can not be ensured. The camera mirror system used at Volkswagen has a stabile relative and interior orientation of both virtual cameras. Camera, prism and mirrors are rigidly mounted in a robust metal box (see figure 2) with a basis length of 32 cm. Through a pre-calibration the required parameters can be determined in a prior phase of the test. Thus, the measurement system is ready to use in the crash test laboratory. The obtained object coordinates are given in the stereo mirror coordinate system.

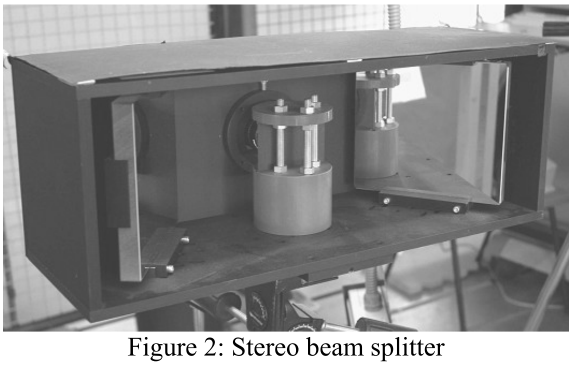


Figure 2: Stereo beam splitter

Due to the fact, that the stereo beam splitting device is specially developed for this type of application the disadvantages such as the reduced image format or the imaging geometry are not relevant. The used high speed camera has a very oblong image format (see figure 3) so that the images of each virtual camera are nearly equal to the typical used image format ratio of 4:3.

Figure 3: Single image with two parts

The observation volume in this type of application is about 1.2 x 1.0 x 0.5 m³ and the mean distance between camera mirror system and object is approximately 2.5 m (see figure 4). The set-up of the mirrors, the prism and the camera is optimized with respect to these requirements.

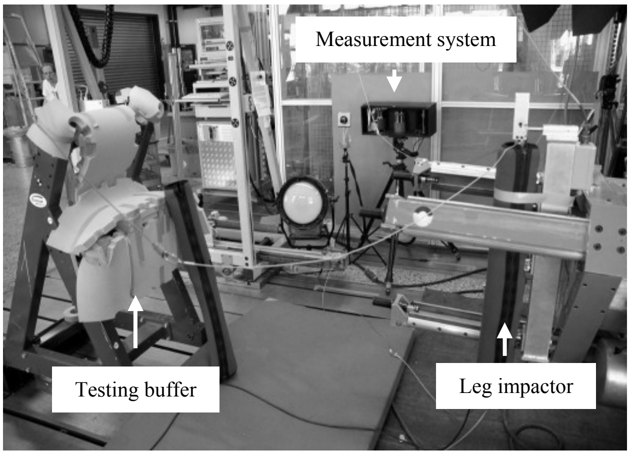
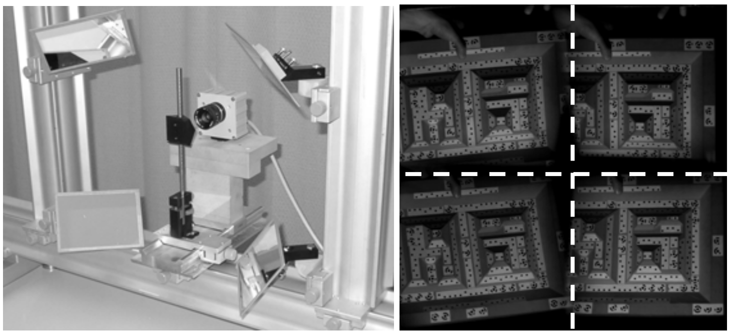


Figure 4: Experiment construction

2.2. Flexible four mirror system

In applications with a high density of targets or obstacles in the observation volume, more than two cameras are required to solve the matching of image points reliably [7]. The used mirror system, developed in cooperation with ETH Zurich, generates a flexible virtual four camera system.

Figure 5(a) shows the set-up of the four mirrors and one prism in front of the camera. All parts are mounted flexibly on a rail system so that several base lengths (0.2 m to 0.9 m), depending on the deflection mirror size, can be realised [10]. This system is mainly used for 3D Particle Tracking Velocimetry (3D PTV) in gas flow. This means that it is used in a laboratory environment in the wind channel. The focus is set to high accuracy and to the measuring task. By means of the rail system and the exchangeable mirrors the size of the observation volume can be easily diversified. The orientation parameters are determined during a special calibration process before and after the measurement. Thus, changes caused by the flexibility of the system, especially by the mounting of the mirrors, can be detected. The active image format for each virtual camera is one quarter of the quadratic image format of the used camera (see figure 5(b)).



(a) (b)

Figure 5: (a) Flexible mirror system with single camera and four deflection mirrors on a rail system (b) Single image with four parts, each from one virtual camera

2.3. Analysis approach

There are several strategies to handle and analyse the images. One uses the full image size with only one half/quarter of the sensor area containing information (see figure 6(a)). In this case, the principal point is approximately in the image centre. Another strategy uses only one half/quarter of the image format (see figure 6(b)). This strategy saves memory capacity but the principal point of each virtual camera is in one corner of the image or sometimes even outside the image. The mathematical conditions are equal for both strategies. Due to the reduced active sensor format in the second strategy the focal length seems to be doubled. This should be considered for the control point field construction [11].

The distortion parameters for each virtual camera are composed of parameters of the lens, which are equal for each virtual camera and of parameters of the mirrors, which are different for each virtual camera several. There are lots of combinations of correlated and uncorrelated parameters for lens and mirrors. The used approach contains for each virtual camera one set of Brown distortion parameters [1].

The used mirrors are front surface mirrors made of float glass. The substrate has very small systematic irregularities. But the major curvature caused by the fabrication affects only in one direction and is comparable in size and direction to an affinity of normal camera lenses (e.g. $c1 \approx 10^{-4}$). So the effect of these irregularities can nearly be modelled with the affinity approach (c1) of the Brown distortion parameters.

The calibration procedure is based on the previously split images, one image for each virtual camera. Further on, each virtual camera is handled as a single independent camera and the calibration procedure is separately carried out for each one. Thus, the results are independent interior and exterior orientation parameters for each virtual camera. In the further analysis the images of the virtual cameras are used in the same way as the images of four single cameras were used.

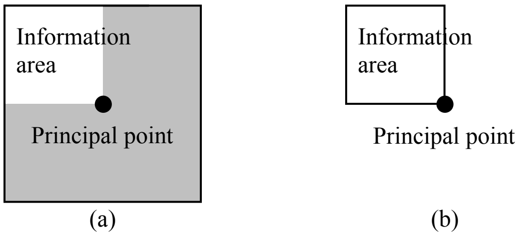


Figure 6: Possible image handling strategies

3. Applications

3.1. Pedestrian protection testing

For the development of vehicle safety components within the development of cars several crash tests are carried out. In a typical impact test a car is crashed with a speed of approximately 18 m/s and is observed by a circular set-up of up to eight digital high speed cameras. Besides vehicle impact test, which are used for the development of safety components for the passengers of the cars, also tests for the improvement of the safety of pedestrians are carried out. Within these tests a leg impactor, which represents the leg of a pedestrian, is shot at the front of a car. This constellation represents a typical accident between a pedestrian, who is crossing the street, and a car. To obtain representative and comparable results of the test, several requirements to the carrying out of the test are defied in a European guideline. These requirements are the orientation angles, the impact angles and the impact speed of the leg impactor. The impact speed has to be 11.1 m/s.

During the analysis of the pedestrian protection test the required values, which are defined in the European guideline have to be calculated. The aim of this part of the analysis is the determination of reliable and comparable results. A second aim of the analysis is the calculation of the distance the leg impactor dents the front of the car. The testing engineer need to know how much space is still remaining to the next hard component of the car, as e.g. the engine.

3.2. Particle tracking in gas flow

For the development of new methods of 3D PTV several experiments are carried out in a draw channel within its profile of 60 x 60 cm^2. Two boundaries are made of plexiglass as optical interfaces. Inside the channel different objects are placed to analyse their effects on the flow field. The illuminated observation volume is 30 x 20 x 30 cm^3.

3D particle tracking in gas flow makes high demand to the used hardware [10]. For the analysis of a flow velocity of about 7 m/s, a high speed recording system is required. To determine the flow comprehensively a high number of targets, called tracers, has to be seeded in the observation volume. The used tracers are white Styrofoam particles with a diameter less than 1 mm. All these requirements lead to the used camera mirror system. The required accuracy is as high as possible. The velocity vector results from the difference between two corresponding coordinate triples.

Hence, the point error amplifies the velocity error. The ratio between the lengths of the velocity vector and of the point error vector has to be as large as possible to obtain reliable results. The smoothing of a large trajectory corrects only errors orthogonal to the main direction.

Another application is a large scale flow in the “Ilmenauer Fass” [13]. There, a smoothing algorithm allows the determination of suitable results. Here, the point accuracy is not getting the main focus. The large observation volume up to some cubic metres requires the flexibility of the mirror system. In this experiment, the used tracer particles are soap bubbles filled with helium [6], which have a diameter of about 1 cm.

4. Results

4.1. Pedestrian protection testing

To measure the required values for the orientation and the position of the leg impactor, it has to be signalised with markers. The positions of these markers have been measured in the coordinate system of the leg impactor in a prior phase of the test. It is essential that these marker positions are stable during the test. The outside of the impactor cannot be used for the signalisation, because it is made of special foam which can slip during the test. However, the interior of the impactor is a steel cylinder. Thus, the markers have to be connected to the steel cylinder. Therefore two positions, one at the top of the impactor and one at the middle can be used (see figure 7). The coordinates of these five markers were analysed during the test.

Regarded the distribution of the markers on the leg impactor and the required values from the European guideline, the required accuracy for the coordinates of the markers can be estimated [12]. The accuracy of the object coordinates perpendicular to the viewing direction has to be lower than 1 mm and the accuracy in viewing direction has to be lower than 5 mm.

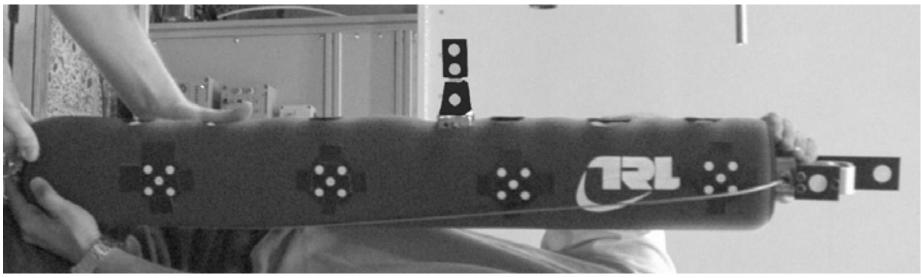


Figure 7: Leg impactor with markers (image flipped)

The used camera is a NAC HiDcam II, which observes the scene at a frame rate of 1000 Hz. The sensor size using this frame rate is 1280 x 512 pixel with a pixel size of 12 µm. The used focal length is 12.5 mm and the object distance is about 2.5 m. The acquired image sequences consist of 35 images which are analysed using the prior calculated interior and exterior orientations. The object coordinates of the five markers are determined by spatial intersection [4]. Table 1 shows the results of the object coordinate calculation of the two test series. The requirements to the accuracy of the object coordinate determination are always fulfilled.

Using the determined object coordinates of the markers the required parameters for the orientation and position of the leg impactor at impact time can be calculated with the required accuracy.

test	σ_x [mm]	σ_y [mm]	σ_z [mm]
T1	< 0.7	< 3.3	< 0.5
T2	< 0.6	< 4.1	< 0.5

Table 1: Results of the analysis of the pedestrian protection tests

4.2. Particle tracking in gas flow

During the 3D PTV experiments in gas flow thousands of epochs with hundreds of particles have been processed. Thus, the determined accuracies show reliable values for the used measurement system. The image point measurements of the tracer particles (Styrofoam or soap bubbles) are carried out with a centroid operator. [11] shows that the image point measurements are not affected by the mirrors, as for example through an unevenness of the mirror surface.

experiment	flow	tracers	mean distance [m]	basis-depth ratio
A	wind tunnel	Styrofoam	1.3	1:3
B	wind tunnel	Styrofoam	1.8	1:4
C	Ilmenauer Fass	soap bubbles	1.9	1:5

Table 2: Experiment definition

Three different arranged experiment configurations (see table 2) have been analysed. In experiment A and B the high speed camera Fastcam ultima 1024 with a pixel size of 12 µm and a frame rate of 500 Hz was used. The third experiment C was realised with a machine vision camera DMK 41 AF02 with a pixel size of 4.65 µm and a frame rate of 15 Hz. The mean distance between camera and object was about 1.5 m.

The object coordinates have been determined by intersection of four virtual cameras. The mean value of the standard deviations of unit weight is about ¼ pixel in all three experiments. It can be seen in table 3 that the standard deviations in object space of experiment A and B are less than 1 mm. Caused by the grinding image rays the depth component (Z-value) is worse by factor 3 to 5. In spite of the configuration of the mirror system and the non ideal targets the results are suitable.

experiment	$\sigma_{x/y}{}^1$ [mm]	$\sigma_z{}^1$ [mm]	$\sigma_{xyz}{}^1$ [mm]	$\sigma_0{}^2$ [mm]
A	0.13 / 0.14	0.40	0.44	0.0035
B	0.18 / 0.14	0.74	0.77	0.0035
C	0.47 / 0.34	1.25	1.38	0.0012

[1]: standard deviation of object coordinates

[2]: standard deviation of unit weight

Table 3: Accuracy values of intersection with a virtual four camera system

5. Conclusions and future work

In this article we discussed the application of camera mirror systems to analyse highly dynamic 3D processes, as e.g. pedestrian protection testing in the car industry or 3D PTV in gas flow. Such measurement systems are a suitable solution for problems caused by the use of multi camera systems. A set-up of mirrors in combination with a single camera is cheaper and requires no synchronisation. The additional expenses to handle the virtual cameras are negligible and can be automated.

The configuration and the achievable results are up to the practical demand. The method is established both in industrial and research applications. In future, the camera mirror systems will be adapted to other applications and huger volumes. The applicability of a camera mirror system on the analysis of pedestrian protection testing has been shown in this paper. The configuration of the current system is optimised to this type of testing and cannot be easily adapted to other applications. Currently, at Volkswagen the applicability of such a system for different other vehicle safety tests, as side pole test or whiplash tests, is intended.

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