GEOMETRIC MODELLING AND CALIBRATION OF A VIRTUAL FOUR-HEADED HIGH SPEED CAMERA-MIRROR SYSTEM FOR 3-D MOTION ANALYSIS APPLICATIONS

Torsten Putze
Institute of Photogrammetry and Remote Sensing
Dresden University of Technology
Torsten.Putze@mailbox.tu-dresden.de
Tel: 0351-463-39701

Abstract: The present paper gives an overview of the potential of using a mirror system to generate virtual cameras. This enables the determination of 3-D object coordinates using only one camera. Advantages of this strategy are economical aspects and the elimination of the necessity of synchronisation. Obvious disadvantages are in decreasing the active sensor area. To determine highly dynamic processes a high speed camera is compulsory. The integration of such a camera in a mirror system forms an economic tool to determine 3-D motion of dense target fields. The paper describes a 3-D motion analysis data capture tool based an one high speed camera and a four-headed mirror system and presents practical data handling as well as calibration results.

1. Instruction

The observation of static objects with photogrammetric techniques can be performed with only one camera taking images sequentially. In contrast, dynamic processes have to be tracked with a synchronized stereo camera system to ensure that homologous image points are captured at the same time. Standard applications in slow dynamic processes and with low point density can be solved with two industrial machine vision cameras. Complex tasks with a high image point density or occlusions are more demanding concerning hardware efforts. Ambiguities in multi-image matching caused by a high image point density may be solved using a third or fourth camera, as shown in [2].

In case of highly dynamic processes, industrial machine vision cameras with a frame rate of 30 frames per second (fps) are insufficient. High speed cameras offer imaging rates of 1000 fps and beyond, but at made higher prices as compared to off-the shell machine vision type cameras. A stereo mirror system forms a viable alternative to create a 3-D particle tracking system on the basis of only one high speed camera.

3-D Particle Tracking Velocimetry (PTV) is a flexible technique for the determination of velocity fields in liquid or gas flows. Therefore, a flow is densely visualised by particles and recorded by a multi high speed camera system. In contrast to other methods, such as PIV, LDA or HDA, which determine flow characteristics at limited spatial or dimensional resolution, 3-D PTV generates full 3-D trajectory information of the observed 3-D flow volume. This information is obtained from tracer particles, which represent the flow.

The tracers are detected in all images in all epochs. This leads to 3-D coordinates for each tracer particle at each epoch. The velocity information results from the linking of successively tracked point clouds in consideration of the used camera frame rate. The results of 3-D PTV are not only 3-D velocity vectors in object space with certain temporal resolution, but also 3-D trajectories plus information on the particle distribution and the temporal behaviour.

The method of 3-D PTV can be used in a wide range of applications. While tracer particles in liquid or gas are used as additives to describe the flow, in some industrial applications the focus is set on the flight path or trajectories of the objects themselves.

2. System

In order to determine 3-D object coordinates, two or more images taken at the same time step are necessary. In dynamic processes a multi camera system with synchronous image capturing is essential. In case of fast gas flow, a high speed camera system is compulsory due to the velocity spectra. In practical applications, four high speed cameras would be expensive and are often not synchroniseable. As shown in [6], the impact of a non synchronised camera system is essential and has to be corrected. A bias of 0.5 ms (0.5 frames at 1000 fps) and a flow velocity of 10 meters per second mean a tracer movement of 5 mm between the two recordings.

If there is a high density of tracer particles or occlusions of targets, more than two cameras are required to solve the matching of image points reliably [3]. If the density is even higher, a four camera system is mandatory to solve the ambiguities of image point matching reliably. With a mirror system it is possible to generate virtual cameras. In our case four cameras convergently arranged cameras are generated by using only a single camera and 8 mirrors.

2.1. Camera

There are specific camera requirements necessary in order to verify dynamic processes. In addition to the sensor format and quality, the temporal resolution is most important. Successive temporal matching depends on the relation between velocity, camera frame rate and observation area.

Figure 1: FASTCAM ultima 1024 (control panel, head and memory)

In our case a CMOS high speed camera *FASTCAM ultima 1024* (Figure 1) is used. Its image size is 1024 x 1024 pixel with a frame rate up to 500 fps or 512 x 512 pixel with a frame rate of 1000 fps. The camera memory continuously saves image sequences of 1000 or more frames, depending on the resolution. CMOS technology offers a flexible reduction of the active senor area in order to increase frame rates. The accuracy of the used CMOS camera can be compared to high quality industrial cameras (see chapter 2.4.) or SLR cameras. Beside that there is no impact of frame rate to the accuracy of the high speed camera (Table 1).

	60 fps	125 fps	250 fps	500 fps	1000 fps
σ_{IPM} [1] [µm]	0,23	0,25	0,24	0,27	0,29
σ_0 [2] [µm]	0,28	0,30	0,22	0,27	0,39
σ_{XY} [3] [µm]	4	8	5	4	9
σ_Z [3] [µm]	8	30	17	8	42

[1]: standard deviation of image point measurement
[2]: standard deviation of unit weight
[3]: standard deviation of object point coordinates

Table 1: Accuracy of FASTCAM ultima 1024 (1000 fps with ¼ sensor area)

Furthermore, the illumination is very important to get useful results. In most cases especially in gas flows the particles are very small. In order to follow the flow, high frame rates necessitate short exposure times. To be able to detect tracers in the observation area, a concentrated illumination in the whole observation volume is essential.

2.2. Mirror system

In amateur applications stereo lens modules for SLR cameras have been established for many years. Here, the basis is nearly the eye distance of human beings. For measurement applications the mirror system has to allow convergent views at a much larger base. They are used for instance in the automobile industry [7] or in application areas with limited space [5].

The mirror system developed in cooperation with ETH Zurich generates a four camera system. Figure 2 shows the arrangement of four adjustable mirrors and one fix prismatic mirror in front of a camera. All parts are mounted flexibly so that several base lengths and designs may be realised [4]. The obtained image (Figure 3) is split. The results are four images of four virtual cameras. Hence, all images are captured at the same time. Besides this advantage, the system is more economic instead of using four cameras. The disadvantage is that one virtual camera consists of only one fourth of the active sensor area.

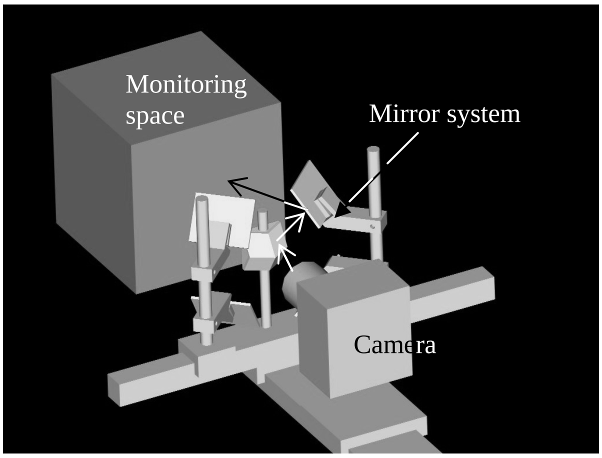

Figure 2: Mirror arrangement (K. Hoyer, ETH Zurich)

2.3. Modelling and calibration

The calibration procedure for the virtual camera system delivers virtual camera orientation parameters. There are several possible strategies for calibrating this system: One uses the original image size (Figure 4) with only one fourth of the sensor area containing information and the principal point in the image centre (Figure 3 - left). Another one uses only one fourth of the image size with full information, but with the principal point in the appropriate corner (Figure 3 - right).

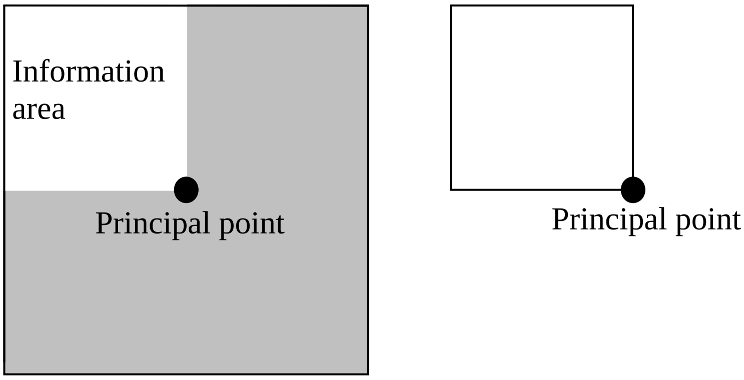

Figure 3: Image handling

An additional option is in the handling of the lens distortion parameters. The first method handles each of the four image parts as taken with an individual virtual camera and the according mirror. The second method presumes that all four image parts are taken with one camera (one set of inner orientation parameters), but different mirrors. While the latter one is more rigorous in the restriction of the number of parameters, the first one offers the advantage of being able to partly compensate for effects introduces by mirror surface irregularities.

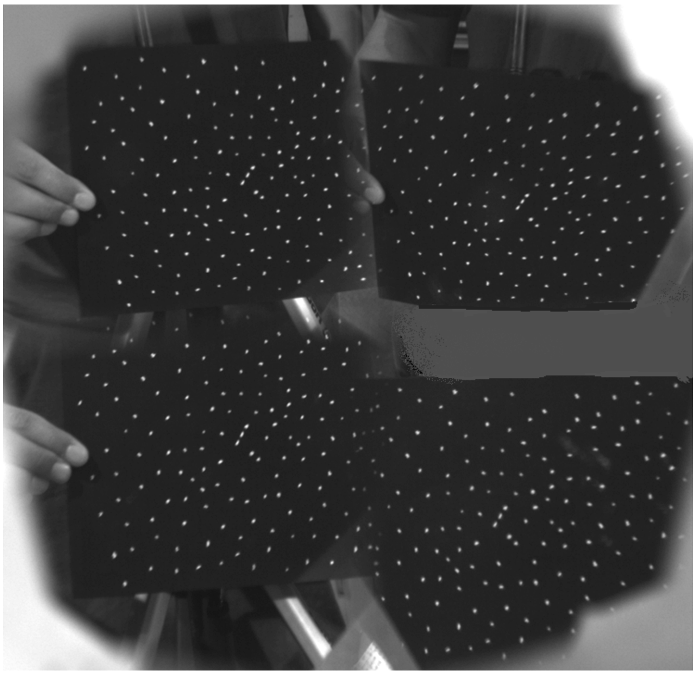

Figure 4: Image taken from 4 virtual cameras

The accuracy that can be obtained depends on different parameters. On the one hand there are hardware components with different qualities, e.g. mirror quality, on the other hand there are the influences of the calibration model and the used calibration field. Due to weaker geometry caused by the reduced active sensor area, the calibration field has to support and compensate this instability. The calibration field has to contain a high number of targets spread out over the whole field and a good amount of depth information.

2.4. Accuracy analysis

The accuracy of the used CMOS high speed camera is comparable to high quality industrial cameras. This was proven in a calibration test with different configurations and analysis models. The comparison contains camera calibrations in single mode, which is a common camera calibration, and in multi mode, which integrates the mirror system. The latter comparison includes two strategies, which take different positions of the principal point into account (see chapter 2.3.). These three modes are tested with different frame rates.

In order to generalise the calibration results, three different calibration fields were used. Besides the camera parameters, the 3-D point coordinates of these three calibration fields are calculated using a bundle adjustment. The analysis software AICON DPA Win and 3D-Studio were chosen, as they support these strategies. The analysis delivers standard deviations of unit weights, image point and object point measurements.

In order to assess the geometric image quality of the high speed camera system, the obtained results are compared to the calibration information of two reference cameras: a Sony X 700 industrial camera [1] and a Nikon D100 SLR camera (Table 2).

	FASTCAM ultima 1024	Sony X 700	Nikon D 100
Pixel size (µm)	12,0	6,5	7,8
Sensor size (pixel)	1024 x 1024	1024 x 768	3008 x 2000
σ_{IPM} [1] [µm]	0,26	0,11	0,18
σ_0 [2] [µm]	0,27	0,12	0,15
σ_{XY} [3] [µm]	6	6	5
σ_Z [3] [µm]	16	12	13

[1]: standard deviation of image point measurement
[2]: standard deviation of unit weight
[3]: standard deviation of object point coordinates

Table 2: Camera features and results of comparative calibrations in single mode

Table 3 shows an overview of the results of the different tests. Comparing the standard deviations in Table 3, it can be concluded that the high speed camera operates in the same accuracy range as the reference camera. The obvious difference of standard deviations in object space between a single mode camera and a virtual camera probably has to be attributed to the mirror quality and the absence of an additional mathematic model of the mirror. Further on, the quartering of the active sensor area has a similar effect to the projection geometry as the doubling of the focal length. It means a degreasing of the camera angle. This has a negative impact to the resection results.

	FASTCAM + mirror		X700 + mirror		FASTCAM (half distance)		X700 (half distance)	
	(µm)	(Pixel)	(µm)	(Pixel)	(µm)	(Pixel)	(µm)	(Pixel)
σ_{IPM} [1]	0,38	1/30	0,15	1/40	0,40	1/30	0,15	1/40
σ_0 [2]	2,0	1/6	0,7	1/10	0,21	1/60	0,11	1/60
σ_{XY} [3]	40		40		4		4	
σ_Z [3]	60		60		30		20	

[1]: standard deviation of image point measurement
[2]: standard deviation of unit weight
[3]: standard deviation of object point coordinates

Table 3: Results of comparative calibrations

During experiments with different mirror qualities the positive influence of high quality mirrors could be shown (Table 4). Because of the disadvantages caused by the reduced active sensor area it is inevitable to use front surface mirrors.

	Single mode		Back surface mirror		Front surface mirror	
	(µm)	(Pixel)	(µm)	(Pixel)	(µm)	(Pixel)
$\sigma_{IPM}{}^{1}$	0,11	1/55	0,12	1/50	0,10	1/30
$\sigma_{0}{}^{2}$	0,12	1/55	0,51	1/13	0,32	1/60
$\sigma_{XY}{}^{3}$	6		40		17	
$\sigma_{Z}{}^{3}$	12		60		50	

[1]: standard deviation of image point measurement
[2]: standard deviation of unit weight
[3]: standard deviation of object point coordinates

Table 4: Sony X700 with different mirror quality

3. Conclusions and outlook

This article showed that it is possible to use only one camera supplemented by a mirror system in order to get a virtual multi camera system for high speed 3-D PTV applications. Besides economic advantages, geometric disadvantages have to be taken in account. If one can or has to accept the compromise, it is a possibility to design a multi camera system. The accuracy of modern CMOS high speed cameras is comparable to high quality industrial cameras or SLR cameras. So highly dynamic processes can be determined with the same accuracy as slow motion processes can be. The 3-D precision potential of a mirror-based system is decreased by the reduced sensor format and the geometric surface quality of the mirrors.

4. Acknowledgement

The work presented in the paper was supported by “Deutsche Forschungsgemeinschaft” (DFG) within SPP 1147. My gratitude also goes to Dr. K. Hoyer (IHW, ETH Zurich) for producing hardware components of the mirror system and to the “Institut für Luft- und Raumfahrttechnik” for supporting some experiments.

5. References

[1] Hollow, G., “Infrared cameras enhance machine-vision systems”, Vision Systems Design – Worldwide Industrial Camera Directory Vol. 9, ADT Publishing Services, England, 2004, pp. D14 – D 43.

[2] Maas, H.-G., “Complexity analysis for the determination of image correspondences in dense spatial target fields”, International Archives of Photogrammetry and Remote Sensing, Vol. 29, Part B5, pp. 102-107, 1992.

[3] Maas, H.-G., Grün, A., Papantoniou, D., “Particle tracking in threedimensional turbulent flows” Part I: Photogrammetric determination of particle coordinates. Experiments in Fluids Vol. 15, pp. 133-146, 1993

[4] Putze, T., ”Einsatz einer Highspeedkamera zur Bestimmung von Geschwindigkeitsfeldern in Gasströmungen”, Publikationen der Deutschen Gesellschaft für Photogrammetrie, Fernerkundung und Geoinformation, Band 13, Ed. Eckhardt Seyfert, 2004, pp. 325 – 332.

[5] Willneff, J., Maas, H.-G., “Design and calibration of a four-headed camera system for use in microgravity research”, International Archives of Photogrammetry and Remote Sensing, Vol. 33, Part 5B, pp. 894-899, Amsterdam, 2000.

[6] Raguse, K., Heipke, C., “Photogrammetrische Auswertung asynchroner Bild-sequenzen”, Photogrammetrie Laserscanning Optische 3D-Messtechnik, Beiträge der Oldenburger 3D-Tage 2005, Wichmann, Heidelberg, 2005.

[7] Luhmann, T., “Zum photogrammetrischen Einsatz von Einzelkamers mit optischer Stereostrahlteilung”, PFG, 2/2005, pp. 101-110, E. Schweizerbart’sche Verlagsbuch-handlung Stuttgart, 2005.