Concepts of single highspeed-camera photogrammetric 3D measurement systems

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ABSTRACT:

Highspeed cameras form a central component of photogrammetric 3D measurement systems in applications requiring a high temporal resolution in fields such as fast object tracking or high frequency deformation measurement. Current highspeed cameras offer data rates in the order of 1 Gigabyte per second or beyond, delivering for instance 1000 frames per second at 1000x1000 pixels. Most applications using highspeed cameras for visualization or measurement purposes are still 2D. Highspeed camera stereo systems are rare because of the costs of cameras and the lack of synchronizibility of some camera types.

The paper gives a short overview on single camera 3D measurement system concepts. It presents two concepts of setting up photogrammetric 3D measurement systems based on a single highspeed camera in detail, one based on a single camera with a stereo mirror system and one on based on a camera-projector combination:

- A stereo mirror system in front of a camera generates multiple views on one sensor. These views can be considered virtual cameras of a multi-camera photogrammetric measurement system. The paper presents a flexible quadruple-mirror system to be used in 3D motion analysis applications and discusses geometric modeling and system calibration.
- Photogrammetric surface measurement systems can be configured by a camera and a projector device projecting strip or dot patterns onto a surface. Using the projector as an active element in the system design, dense and accurate 3D surface representations may be generated using coded light approach or phase shift techniques. In the geometric modeling and calibration, the projector can be considered an inverse camera with infinite frame rate. The paper presents results of an accuracy test obtaining a precision potential in the order of $^1/_{50}$ pixel from a standard consumer-grade beamer.

Besides the system design and the geometric modeling of the two concepts, the paper shows results from pilot studies and practical applications.

1. INTRODUCTION

Digital highspeed cameras are often used for a qualitative or quantitative analysis of dynamic events. Typical application fields of quantitative highspeed camera measurements are in fluid mechanics, machine vision, bio-medical motion analysis, automobile industry crash testing or ballistics. Today’s highspeed cameras show a datarate in the order of one Gigapixel per second, corresponding for instance to 1000 images per second at 1000x1000 pixel sensor format. Stereo highspeed camera systems, consisting of two or more cameras, may form rather powerful 3D motion analysis systems. The use of multiple highspeed cameras is, however, often made impossible by the high cost of the devices. Moreover, some types of highspeed cameras cannot be synchronized, which is be an absolute pre-requisite for a stereo system in applications with fast object motion.

For that reason, several techniques have been developed to obtain 3D information from single highspeed camera imagery. The most popular technique is the use of stereoscopic beam splitter systems (chapter 2). In surface deformation measurement applications, a measurement system can also be designed on one camera and a projector. Beyond these approaches, fluid mechanics research has presented a number of techniques based on special illumination techniques or the optical properties of objects.

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2. MULTI-MIRROR STEREOSCOPIC SYSTEMS

The idea of obtaining stereo images from a single camera by a mirror system in front of the camera lens has already been exploited for amateur photography in the time of analogue cameras (Figure 1). In the most simple case, a stereo mirror system consists of two primary mirrors defining the viewing directions and two secondary mirrors directing the two views onto the sensor. Combined in one housing, they can be mounted in front of the camera lens. An obvious disadvantage of beam splitter based stereo systems is the loss of sensor format for each individual view. Moreover, fixed systems are limited in flexibility and precision potential due to their fix geometry. These disadvantages have to be balanced against the advantage of simplicity.

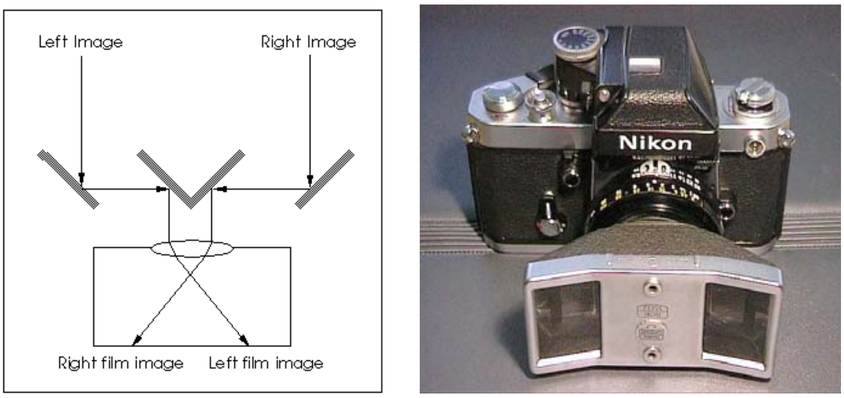

Figure 1: Amateur camera stereo beam splitter

Beyond amateur photography, mirror-based beam splitter stereo systems may depict a rather viable alternative in many professional 3D measurement tasks requiring highspeed cameras to enable a data rate, which is adequate to the dynamic of the scene.

The use of a single digital highspeed camera in combination with a mirror system in car safety experiments is shown by (Hastedt et al., 2005). Their system generates two separate views onto the left and right half of the sensor. With a fix base length of 320 mm, it is only suited for a certain range of applications. At observing distances of more than two meters, the beam intersection angle gets unfavorable and will deteriorate the depth coordinate precision. The system is pre-calibrated, warranting a fix relative orientation of the two views. The limitation to two views excludes the use of the system in measurement tasks, where the reliability issues in automatic data processing require using more than two views (Maas, 1992).

A custom-made compact system generating four stereoscopic views through one lens is shown by (Willneff and Maas, 2000). The system is used to observe particle motion in a very small observation chamber in a sounding rocket under micro-gravity conditions. Multi-ocular image matching forms a pre-requisite for a reliable solution of the task. The optical design of the system uses a lens placed between the primary and secondary mirrors and a 90° angle in the optical path to optimize the compactness of the system. The concept can optionally be used with one sensor or with four identical cameras placed side-by-side (Figure 2).

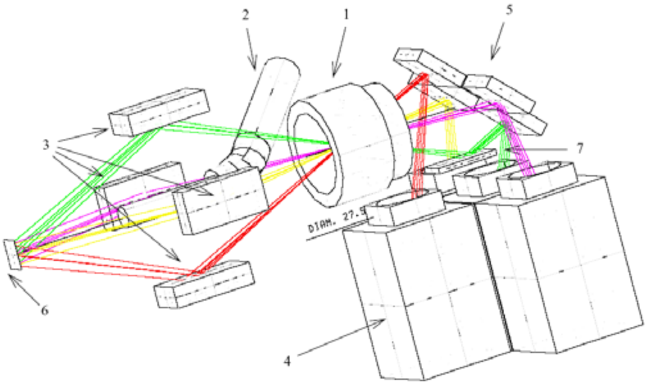

Figure 2: Compact four-view mirror system (Willneff/Maas, 2000)

A flexible four mirror highspeed camera system designed for the use in wind tunnel experiments is shown by (Putze, 2005). The system is used for 3D particle tracking velocimetry image sequence data acquisition, recording small tracer particles marking a gas flow. The complexity of the task of establishing stereo correspondences between a large number of tracers in a gas flow requires the use of four views rather than two (Maas, 1992). The four views cover the four quadrants of the 1000 x 1000 pixel highspeed camera sensor. The secondary mirrors a replaced by a prism. The primary mirrors can be shifted and tilted in order to adapt the system to different imaging distances, observation volumes and precision requirements (Figure 3). In contrast to a fix baseline system, this allows to achieve a favorable beam intersection angle over a wider range of observing distances. The maximum range is defined by the length of the mirror shift mechanism and the primary mirror dimension. The flexible mirror arrangement requires an on-the-job calibration of the system.

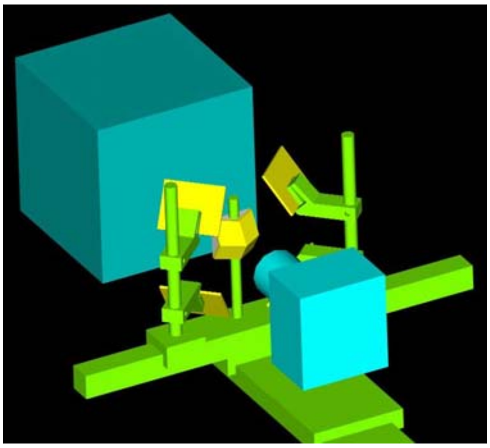

Figure 3: Flexible four-mirror system (Putze and Hoyer, 2004)

Geometric model and calibration:

A geometric camera model has to be developed to enable the use of a mirror-based photogrammetric system for 3D object coordinate determination. In the case of the system shown in Figure 3, this requires modeling the twice-broken paths of the beams from an object point to the four sensor quadrants via the mirrors and the prism. A flexible option in geometric modeling of the system is given by treating the four views as four virtual cameras with the virtual cameras behind the four primary mirrors and the orientation parameters of the virtual cameras depending on the mirror orientation and prism geometry. Using the model of virtual cameras avoids the necessity of handling twice-broken beams and has the big advantage of compatibility with existing photogrammetric software solutions. While lens distortion can be modeled by one set of parameters for all four views, the views will have their principle points in inner corner of their image quadrant.

The orientation parameters of all virtual camera positions, the interior orientation parameters (one camera constant for all views and one principle point per view[1]) and the lens distortion parameters have to be determined in a camera calibration procedure. Conventional self-calibration techniques requiring roll strategies for the reliable determination of the interior orientation parameters may be inapplicable when using a mirror system. (Putze, 2005) used a 3D calibration field with known reference targets to calibrate the system by a single image spatial resection for each virtual camera. Optionally, a self-calibration might be conducted by rotating a calibration field with unknown targets rather than the camera and the mirror system. An elegant option for camera calibration may be given by the moving reference bar approach (Maas, 1999), where a reference bar with two targets at a known distance is moved to some 50 locations/orientations well distributed over the observation volume.

Practical test:

A practical test on the verification of the accuracy potential of a highspeed camera Fastcam Ultima 1024 conducted at Dresden University of Technology is published in (Putze, 2005). In the calibration test, an image coordinate measurement standard deviation of 1/60 pixel could achieved, which is well comparable to the precision potential as usually obtained from standard machine vision cameras. Using a four-mirror system, this figure was reduced by a factor of up to 10. The loss of accuracy has probably to be attributed to effects of unflatness of the large primary mirrors of the adjustable system.

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[1] Strictly spoken, the four principle points are not independent. However, the formulation of the constraints between the individual principle points will be rather complex when using the virtual camera modeling approach.

3. HIGHSPEED CAMERA PLUS PROJECTOR

Optical triangulation techniques depict a versatile and powerful tool for 3D surface measurements. In their simplest form, they consist of a camera and a laser line projector, allowing for the determination of a 3D profile over an object surface. Combined with a mechanism traversing or rotating the object or the measurement system, they allow for a sequential acquisition of dense surface representations. In a following expansion stage, systems may consist of a camera and a LCD projector projecting sequences of strip patterns, such as the well known coded light approach (Altschuler et al., 1979). Due to the necessity of projecting multiple patterns in order to resolve ambiguities in the establishment of correspondences between pixels in the camera image and the projection pattern, these techniques are not suited for dynamic applications.

If ambiguities in the establishment of correspondences can be solved based on a single projection, a camera and a projector projecting a static pattern can be combined to generate a system which is suitable for dynamic applications. A static pattern does not pose requirements to the frame rate of the projector (which is often in the order of 60-85 Hz) and will thus support the full frame rate of a highspeed camera.

One option for the solution of ambiguities is the projection of coded targets (Figure 4). Coded targets include a circular dot allowing for subpixel precision image measurement and a circular affine-invariant code marking a point number. They were first introduced in photogrammetry by (van den Heuvel and Kroon, 1992). Coded targets on the basis of retro-reflective material are frequently used in photogrammetric industrial measurement systems. While the image coordinates and the point numbers of a projected coded target pattern are known from the design of the pattern, the targets can be detected in the images of the camera by relatively simple and fast segmentation techniques, with the point number readable from the target code. In 3D object point coordinate determination by spatial intersection or bundle adjustment, the projected pattern can be treated as an image, with the image coordinates known due to the synthetic nature or the pattern.

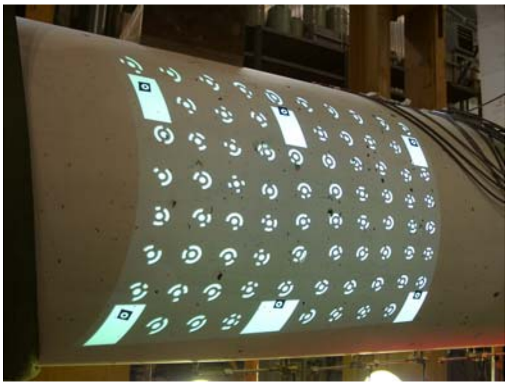

Figure 4: Projected coded targets

Geometric projector model:

Geometrically, a projector can be considered an inverse camera, with the mathematical model of central perspective image formation, extended by parameters to model effects such as lens distortion, applicable in exactly the same manner as for a camera. For practical reasons, most beamers have an asymmetric projection field with the larger part of the projected image above the optical axis (Figure 5). Optically, this is realized by a principle point close to the upper edge of the LCD element rather than in the center.

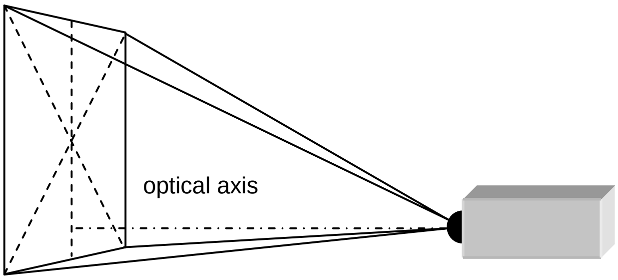

Figure 5: Asymmetric projection field of a standard beamer (Mulsow, 2007)

Accuracy potential of a LCD projector:

In an accuracy test conducted with the goal of evaluating the accuracy potential of an off-the-shelf 3-LCD beamer (EPSON EMP 710) at Dresden University of Technology, (Mulsow, 2007) could show the surprisingly high geometric quality of the beamer. The beamer was used to project 80 coded circular targets onto a test object with two parallel plane surfaces (Figure 6). The projected pattern turned out to be geometrically stable after a warm-up time of 5-10 minutes.

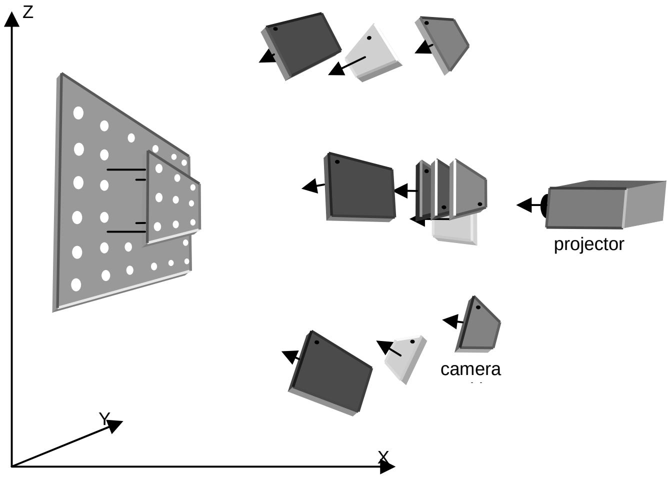

Figure 6:
LCD projector calibration network geometry

11 images of the object were taken by a 3000x2000 pixel mirror reflex camera from different viewing directions, applying roll strategies to strengthen camera self-calibration network geometry. In a self-calibrating bundle adjustment, the 3D coordinates of the projected dots, the image orientation parameters, camera parameters and projector geometry parameters were determined simultaneously. The internal precision of the 3D coordinates was in the order of 10 µm. This is about 1/100’000 of the test object dimension and fulfills the expectations. Treating the image coordinates of the projected dots as observations of an inverse camera, a standard deviation of unit weight of 0.38 µm (0.02 pixel) was obtained for the projector.

Practical test:

To demonstrate the applicability of an LCD projector in combination with a single highspeed camera, a practical test was performed measuring the shape of an activated membrane (Figure 7, Hanusch, 2003). The membrane had a size of approximately 20x20 cm^2. The measurement system consisted of a 1000x1000 pixel highspeed camera Fastcam Ultima and a beamer EPSON EMP 710.

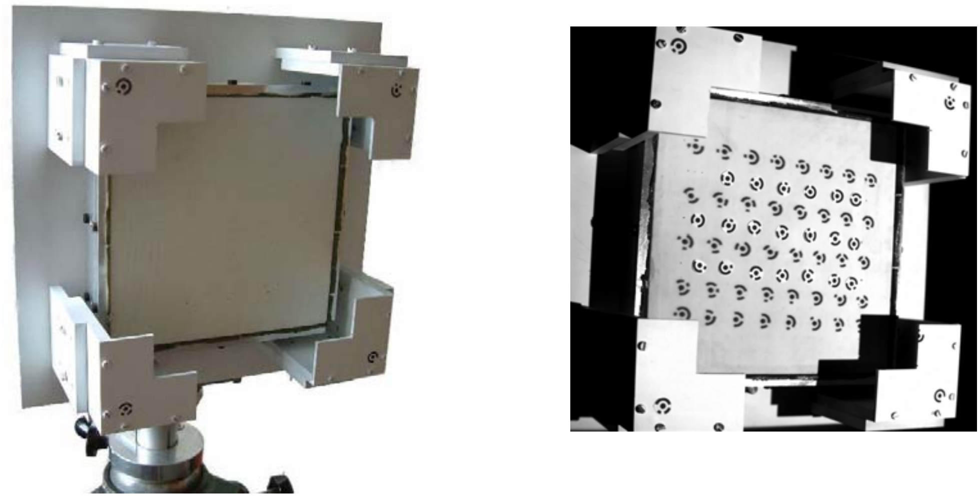

Figure 7: Deformation measurement test membrane, highspeed camera image with beamer-projected coded targets

Obviously, the projected pattern will move relative to the surface during movement of the membrane. Therefore the coordinates of the targets themselves can not be used directly as a result in a deformation analysis test. Instead, the 3D object point coordinates have to be interpolated to a regular grid (or to the locations if the first epoch, alternatively) to allow for vertical surface deformation statements. Depending on the frequency of the projector and the frame rate and exposure settings of the camera, interferences may occur, resulting in stripe patterns on the object surface. These effects may slightly deteriorate the image coordinate measurement precision potential. The standard deviation of the deformation vector components obtained in the study, not regarding possibly degrading interpolation effects, was estimated to be in the order of 20 μm (Hanusch, 2003).

4. CONCLUSION

Although highspeed cameras are often only used for purely qualitative image sequence analysis processes, they may form a valuable tool for quantitative photogrammetric motion analysis systems. The use of multiple cameras in a stereoscopic 3D measurement system is often retarded by the cost of camera devices and the lack of synchronizibility of some camera types. Nevertheless, stereoscopic highspeed camera systems can be configured by the integration of a mirror system into the optical path, imaging two or four different viewing directions onto separate sections of the sensor. Treating the individual mirror views as virtual cameras, the geometry of a mirror-based system can be described in the same way as the geometry of a multi-camera system, and image sequences of a highspeed camera with a multi-ocular mirror system can be processed by standard photogrammetric software tools. The image coordinate measurement precision potential of state-of-the-art highspeed cameras is comparable to the precision obtained from standard machine vision cameras. Using a mirror system, the precision may be reduced significantly as a consequence of mirror unflatness effects.

A passable alternative for surface deformation analysis tasks may be given by a single highspeed camera combined with a projector projecting a dot pattern, where the projector can be treated as an inverse camera, again allowing for the applicability of standard photogrammetric software tools for data processing. In a practical test, a precision potential in the order of 1/50 pixel was verified for an off-the-shelf beamer.

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