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PHOTOGRAMMETRIC METHODS FOR MEASUREMENTS IN FLUID PHYSICS EXPERIMENTS IN SPACE†

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Abstract—Methods of digital close-range photogrammetry allow for manifold real 3-D measurements in dynamic processes. Based on the acquisition of multi-camera digital image sequences, image analysis with subpixel accuracy image measurement operators, photogrammetric multi-image matching and point determination techniques, strict geometric modeling of complex environments and thorough system calibration techniques, time-resolved accurate 3-D coordinates of a large number of objects in a scene can be determined fully automatically. The paper will first give a short review on basic principles of digital photogrammetry and discuss the application and accuracy potential. After that, practical examples will be given from several breadboard experiments conducted in the frame of the ESA Technological Research and Development Programme to show the applicability of the technique to typical experiments in the field of fluid physics. These experiments focus on the investigation of experiments on Marangoni convection; they include the determination of 3-D velocity fields near a hanging drop within a fluid matrix and the observation of the tangential tension on the boundary surface by measuring changes in shape and/or position of liquid bodies like drops, bubbles or liquid columns in a fluid matrix. © 2001 Published by Elsevier Science Ltd.

1. INTRODUCTION

Compared to Earth's environment, microgravity is a challenging chance offered , to basic science for achieving a deeper understanding of fundamental physical phenomena, and to technology for improving several technologically oriented processes. The investigation of liquid flows due to thermal gradients in a fluid matrix is of great importance in the study of heat and mass transfer processes, for both fundamental research and technology. One example is the analysis of thermocapillary flows: While on Earth the thermocapillary effect is covered by buoyancy, in microgravity it can play a leading role. From the industrial point of view, several processes can benefit from the buoyancy-absent Space environment: Material production processes and solidification front dynamics can be improved, leading to products of higher quality than those produced on Earth.

To be able to analyze fluid physics phenomena quantitatively, measurement techniques have to be applied with the aim of determining shape and motion parameters. Due to the three-dimensional dynamic character of many phenomena, these measurements should preferentially cover the whole experimental volume at once. Methods of digital

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photogrammetry offer themselves for such tasks, as they allow for the determination of accurate three-dimensional information simultaneously at many locations of an observation volume in a non-contact manner and without the risk of disturbances as created by mechanically driven scanning devices.

To be able to judge the potential of digital photogrammetric techniques in the field of fluid physics measurements, two studies were performed on photogrammetric methods applied to fluid motion visualized by tracers and on liquid bodies. In the course of the studies, breadboards were developed for two experiments: In an experiment on thermocapillary convection in a liquid around a gas bubble, 3-D velocity vectors and trajectories of several hundred flow markers were determined simultaneously using a four-camera imaging system. Another breadboard was built for the measurement of position and shape of liquid bodies as a function of time. Investigations concentrated on the development of a compact and exchangeable multi-camera observation module and an imaging chain for the data flow concerning photogrammetric measurements on microgravity experiments.

2. DIGITAL PHOTOGRAMMETRY

With the development of solid state sensor imaging devices and powerful computer platforms, new image-processing-based solutions for a large number of 3-D measurement tasks have become possible in the past two decades. While computer vision does often deal with more qualitative image understanding tasks and machine vision is mainly to be seen in the context of industrial production line applications, digital photogrammetry aims at the derivation of accurate 3-D metric information from multiple digital images.

Besides subpixel accuracy image measurement operators, strict geometric modeling and a thorough system calibration provide the basis to achieve high accuracies in 3-D space with vision systems based on off-the-shelf vision hardware components. The basic equation of photogrammetric 3-D coordinate determination is the collinearity equation (see e.g. [1]) which simply states that object point, camera projective center and image point lie on a straight line. This mathematical formulation has to be extended to meet the physical realities. Effects caused by lens distortion and A/D conversion are usually compensated by a set of additional parameters, which have to be determined in the system calibration together with the parameters of exterior and interior orientation of the cameras. Lens distortion is often compensated by a set of five additional parameters modeling radial and decentering distortion [2]. For the compensation of electronic effects, especially the often a priori unknown difference between the pixel rate of a camera and the clock rate of a framegrabber, an additional transformation with two parameters of an affine transformation [3] is often adjoined. These parameters have to be determined in a system calibration before, during or after the image acquisition of an actual measurement task. The most flexible way of determining these system parameters is self-calibrating bundle adjustment [4], in which 3-D object coordinates, camera orientation data and camera calibration parameters are determined simultaneously, based only on image coordinate measurements and at least one scale information in object space. To warrant good determinability of all parameters, the acquisition of multiple images of the scene with each camera under different orientations is required. Besides this, multiple images are also useful for the improvement of the precision of the object point coordinates and the capability of self-diagnosis (control of the quality of measurements and results based on redundant information in the least-squares estimation process). For applications in fluid physics experiments, the collinearity equation has to be extended to meet the reality of objects in a liquid which are imaged through a transparent window, thus causing multiple twice-broken beams to be intersected for 3-D object point coordinate determination. These twice-broken beams can be handled with a strict geometric modeling contained in a multimedia module [5]. The module also allows for the handling of multiply broken beams as caused by multi-containments.

Due to the nature of digital images, automation is an inherent characteristic of digital photogrammetric data processing as well as real-time or on-line processing aspects, thus making it well suited for dynamic applications. Using standard image acquisition devices like standard videonorm CCD cameras ($\sim$ 768 $\times$ 576/480 pixels, 25/30 images/s), subpixel operators measuring the image coordinates of features with a precision of 1/10–1/50 pixel and appropriate system calibration techniques, relative precisions in the order of 1:20,000 of the object space dimensions can be achieved in dynamic applications. This potential allows for the substitution of film-based cameras by solid state sensor cameras, which has to be considered an enormous improvement concerning Space instrumentation. Quantitative image data will be available via the communication link, an absolute prerequisite concerning an intensive use of the International Space Station. With large format solid state cameras and the acquisition of a large number of images of a static object, an accuracy potential of better than 1:100,000 has been achieved. A detailed review of the historical development of digital close range photogrammetry and a number of application examples in different fields is given in [6].

3. THREE-DIMENSIONAL PARTICLE TRACKING VELOCIMETRY

Techniques of digital photogrammetry are suitable for static applications as well as for 3-D measurement tasks in dynamic processes. A typical application field of digital photogrammetric techniques in dynamic processes is 3-D particle tracking velocimetry (PTV). 3-D PTV is based on tracking a large number of discrete flow markers in multi-camera image sequences and depicts a robust and accurate technique, which is capable of delivering truly 3-D velocity field information (i.e. all three vector components in a 3-D observation volume) at a high spatial and a sufficient temporal resolution. It is based on the acquisition and processing of stereoscopic image sequences of moving particles.

Figure 1 shows the data flow of 3-D PTV data processing. The first step in the fully automatic data processing chain is a high-pass filtering of the images in order to eliminate global image contrast and to remove some non-uniformities of the background intensity introduced by effects of the illumination. After that, particles can be detected by thresholding, and their location in image space can be determined with subpixel accuracy by a centroid operator [7].

The most critical step of automatic 3-D PTV data processing is the establishment of stereoscopic correspondences between particle images as a prerequisite for 3-D coordinate determination. Particle features (like size, shape, color) do not usually allow for a reliable distinction between matching candidates, the more so as these features are furthermore influenced by the imaging process. Thus, the only information that can be used for the establishment of correspondences is the geometric information provided by the epipolar line: Knowing the orientation parameters of the cameras from a calibration procedure, the search space for corresponding points can be reduced to a line plus tolerance in image space. However, this search on epipolar lines will produce ambiguities in applications with dense tracer seeding. These ambiguities can be solved by using three or four synchronized

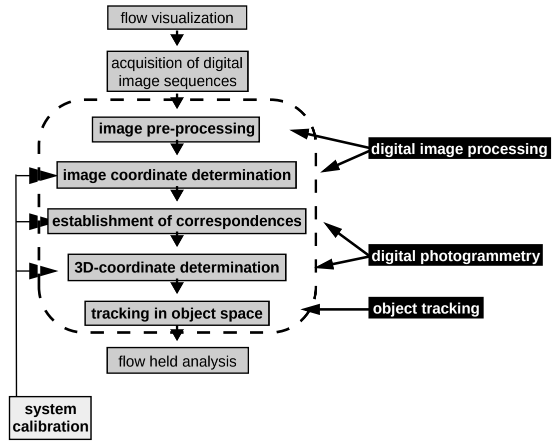

Fig. 1. Dataflow scheme for 3-D PTV data processing.

cameras rather than two and applying trinocular or multiocular vision techniques [7].

In the next processing step the 3-D coordinates of all particles can be determined by spatial intersection, taking into account the beam deflections caused by the glass window on the optical path. The redundant information provided by the measurement of three or four times two image coordinates for the determination of three object space coordinates increases the precision and allows to perform a least-squares adjustment for each individual point, thus providing additional precision estimates.

For a more detailed description of data acquisition system configurations, image processing, establishment of multi-view correspondences, geometric modeling and system calibration see [8].

As less ambiguities can be expected when tracking is performed in 3-D space, the establishment of temporal correspondences is the last step in the processing chain as outlined here. The tracking is based on principles that are rather similar to the treatment of ambiguities during the establishment of multi-image correspondences, solving possible ambiguities by the propagation and verification of possible links between two time instances into a third time instance under assumptions on the maximum Lagrangian acceleration [9].

Using four CCD cameras and an image format of only 512 × 512 pixels, the method allows for the determination of velocity vectors of more than 1000 particles per time instant. The relative accuracies of the vector components are approximately 1:4000 (standard deviation of X and Y coordinates over field of view) with the accuracy of the depth component Z being typically by a factor of two to three worse than the components perpendicular to the main viewing direction. For a cubic volume of

1 l that means 0.025 mm in X and Y directions and 0.060 mm in Z direction; this is compatible with the requirement for spatial resolution of 0.1 mm given for the diagnostic tools of the Fluid Science Laboratory (FSL). These figures are valid under controlled conditions; suboptimal illumination conditions, complex flows, temperature gradients or image noise may lead to a severe degradation of the potential. In addition to the 3-D vector fields, PTV is also capable of determining long particle trajectories, if storage capacity for image sequences is available. In practical experiments, particles could be traced over several hundred frames when the number of particles in the observation volume was kept small [10].

The unique features of the technique and its unrivaled suitability for 3-D velocity field measurements provide a solution to a number of measurement tasks which could so far not be realized.

4. APPLICATION OF 3-D PTV IN THERMOCAPILLARY CONVECTION EXPERIMENTS

To verify the potential of 3-D PTV for the solution of fluid physics measurement tasks, a breadboard experiment on the determination of 3-D velocity fields in the vicinity of a gas bubble (Marangoni convection) was set up [11]. The experiment setup is a replica of an experiment described in [12].

The mechanism of Marangoni convection is outlined in Figs. 2 & 3: At the interface between two immiscible fluids a curved surface will be generated by the surface tension. Local variations of this surface tension, caused by temperature gradients, induce a capillary convection parallel to the surface. The interaction between this surface-tension-driven convection and gravity-driven convection leads to a complicated flow field, which is to be examined over time in all three dimensions.

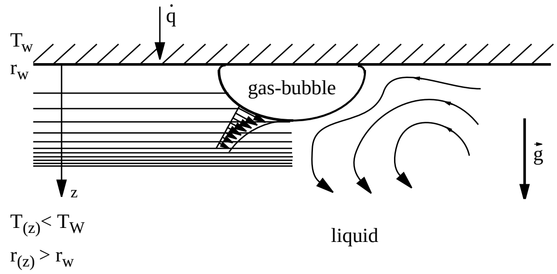

Fig. 3. Mechanism of thermocapillary convection in the surrounding of a bubble under a heated horizontal wall.

To generate and observe Marangoni convection effects around a gas bubble in silicon oil, a top heated fluid cell has been designed and constructed similar to the one described in [12]. It consists of a cubic cell with inner dimensions of $90 \times 90 \times 90$ mm^3 and glass walls for optical access of a photogrammetric multi-camera module and a tracer illumination device. Top and bottom plates are designed for heating and cooling, fluid supply and drainage; they contain several temperature probes and facilities for the generation and adjustment of a gas bubble. The liquid in the cell is seeded with neutrally buoyant tracer particles, which are suitably illuminated and imaged by a system consisting of four CCD cameras (Fig. 4).

The observation system was calibrated before and/or after an experiment by imaging a 3-D reference body covering the observation volume with a large number of targets with known coordinates. This calibration procedure using 3-D reference avoids the necessity of the acquisition of multiple images with each camera as required by self-calibration techniques; it allows for the determination of the parameters of camera orientation as well as parameters describing the camera model, lens distortion and other disturbances. Using the

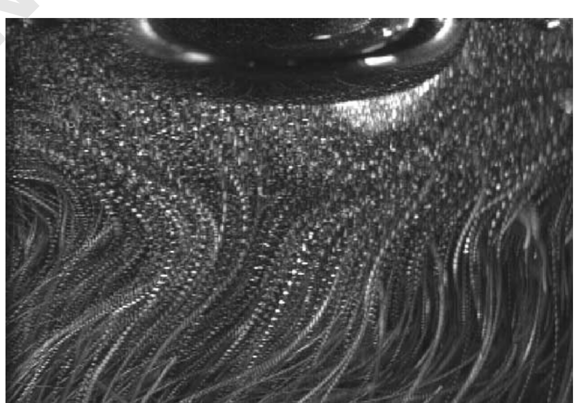

Fig. 2. Section of an accumulated particle image (Marangoni convection experiment).

Fig. 4. Four-camera 3-D PTV arrangement, fluid cell with calibration body.

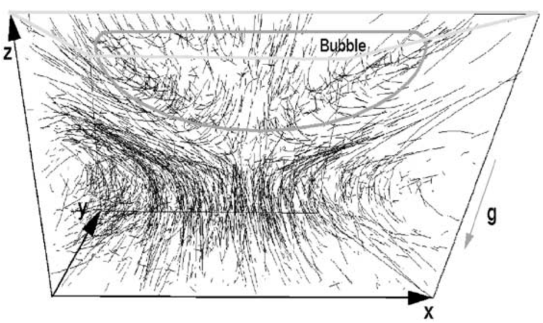

Fig. 5. 8000 out of 100,000 3-D velocity vectors in sub-volume of $10 \times 8 \times 6$ mm^3 of a Marangoni convection experiment (Ma = 600), recorded at 400 time steps over 20 min.

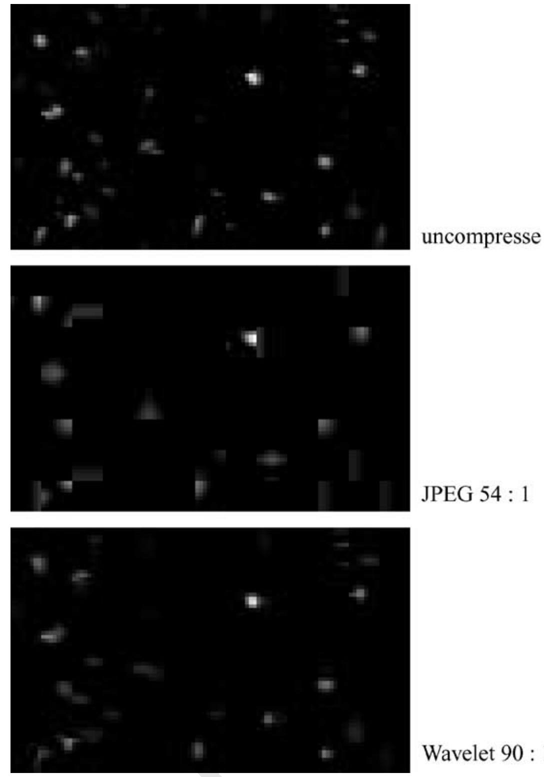

Fig. 6. Effects of high compression ratios to particle images (104×80 pixel image region).

calibration parameters and the data processing chain as outlined in Fig. 1, 200–500 velocity vectors per time instant could be determined in an observation volume of $20 \times 14 \times 14$ mm^3 centered around the gas bubble. A sample of a velocity field is shown in Fig. 5.

The precision of the velocity vector components within the observation volume was estimated to be in the order of 5–10 μm for the two lateral components (X, Z) and 20–30 μm for the component in camera viewing direction (Y).

The high data rate of techniques based on image sequence processing poses severe requirements to data storage systems. if data cannot be processed in real time. As an option to reduce the amount of data to be stored intermediately, advanced transform coding based compression algorithms for lossy image compression were quantitatively examined in order to be able to evaluate the ability of different algorithms to preserve the image information which is relevant for the photogrammetric application when high compression factors are required. In particular, the Discrete Cosine Transform based JPEG standard and the Discrete Wavelet Transform based EZW scheme were examined. The results indicate that for particle images a compression factor of 10–15 can be achieved at an acceptable loss of data quality, leading to a proportional reduction of data transmission bandwidth requirements and extension of recording time.

For these compression ratios no significant difference could be detected between JPEG and wavelets. As much higher compression factors (90–120) have to be applied for telescience purposes, the influence of the two compression techniques was also tested at those qualitative images. Here JPEG fails and leads to unacceptable blocking effects, while images compressed/decompressed with the wavelet-based technique still show details of the convective currents, which is a must for telescience (Fig. 6).

The study has shown that the advantages of 3-D PTV as a non-invasive, simultaneous, accurate, unbiased, truly three-dimensional technique for the determination of a large number of velocity vectors and trajectories in combination with strict geometric and statistical modeling including the capability of determining the precision of the delivered information and detecting deviations from the mathematical or the statistical model qualify the technique for the use in complex flow measurement applications.

On the basis of the promising results gained through the investigation of thermocapillary convective flows around a hanging drop in a fluid matrix using 3-D PTV, another project is currently in progress, whose aim is to determine, presently on Earth, velocity fields in smaller and more complex fluid volumes, like liquid bridges under mechanical and thermal stress.

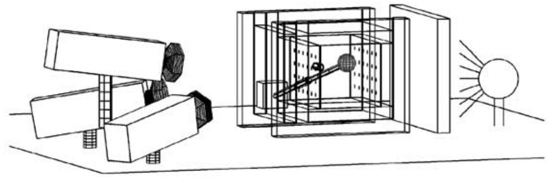

Fig. 7. Breadboard for liquid body measurement.

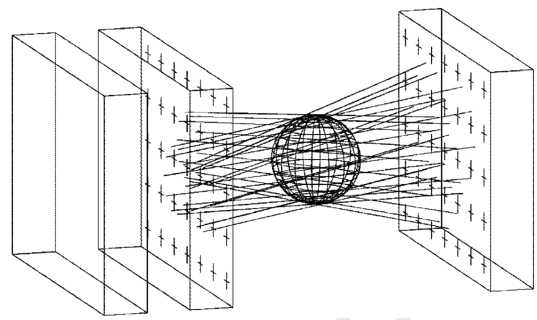

Fig. 8. Tangent lines between reseau planes.

5. EXPERIMENT ON MEASUREMENT OF POSITION AND SHAPE OF LIQUID BODIES

For the observation of tangential tension on the boundary surface between two media it is necessary to determine the velocity of liquid bodies, e.g. drops and columns, within a fluid matrix and/or their change of shape in time. To demonstrate the performance of photogrammetric methods concerning the study of those phenomena, a demonstration breadboard of a photogrammetric diagnostic tool has been developed and built [13].

This breadboard developed for ESA/ESTEC [14] consists of the fluid cell, a motion device, the drop and column dummies and the photogrammetric front end. The photogrammetric front end consists of three CCD cameras, which form a compact setup in front of one observation window of the fluid cell, and facilities for the calibration of this photogrammetric measuring unit (Fig. 7).

The dimension of the fluid cell and the fluid body chosen are representative of typical microgravity experiments [15]. The objects can be moved within the fluid cell with an inner size of $50\times50\times70$ mm^3. A double-walled window has been chosen to represent the thermal insulation of a typical cell, and a window thickness of 10 mm is representative in case interferometric methods are also applied. A reseau grid is placed on the inner sides of the front and back windows of the fluid cell. Top and bottom windows are also made of glass to be able to use additional observation techniques. The objects are inserted into a silicone oil fluid matrix. The drop and the fluid column dummies representing the model scene are manufactured from solid transparent materials. To simulate different sizes of the drops high-precision glass balls with diameters from 2 to 20 mm can be attached to a moveable rod; to simulate the column bodies three different objects with cylindrical, spheroidal and hyberboloidal shape are manufactured from Plexiglas and can be mounted instead.

The three cameras of the photogrammetric observation module are fixed on a common frame with their relative positions chosen with respect to the size of the observation window and the depth of the scene to be observed. Such a photogrammetric observation module can be used for measurements on different types of experiments. It can be exchanged with other diagnostic tools and because it is applied from one side only it can even be used simultaneously with other diagnostic tools like interferometry for example.

Instead of the fluid cell, a testfield can be mounted in front of the measuring head for a precise automatic calibration of the camera setup. This concept of exchangeable, reconfigurable measuring heads together with exchangeable experiment cells gives highest flexibility concerning the different types of experiments to be expected.

The calibration of the camera head can be performed prior to the actual measurement with a testfield calibration procedure [16]. Instead of a strict geometric modeling of the optical path, correction parameters due the multi-media path can be calculated by observing a grid of reseau crosses on the inner sides of the front and back observation windows and comparing to the known grid mesh values. This way even local deviations of the refractive index in the fluid due to temperature gradients can be corrected. This calibration of the multi-media path can be performed before the actual image sequence in a thermally balanced state of the experiment or on-line at each step of the image sequence.

For the reconstruction of the liquid bodies the edges are measured with subpixel accuracy in the digital images. The connections of the interpolated edge points in the two reseau planes form tangents lines to the liquid bodies (Fig. 8). The evaluation procedure for the liquid bodies is a least-squares adjustment with the tangent lines as observations and different basic distance functions describing the liquid bodies as unknown parameters.

Results of the evaluation of typical bubble sequences and column movements showed accuracies of the position and shape of the liquid bodies in the order of 20–30 μm.

In a second part of the study work will focus on the measurement of shape changes of arbitrarily shaped liquid columns and the investigation of the influence of different compression techniques on the measurement results.

6. CONCLUSION

The results of the breadboard experiments, achieved with relatively compact, stable and economic measurement systems, show the suitability of photogrammetric techniques for applications in fluid physics experiments in space. Although the breadboards were primarily designed for laboratory use, much effort was made to design the photogrammetric observation modules with respect to the specific needs of fluid physics experiments under microgravity conditions onboard a Space station.

Beyond the experiments performed within the studies, the technology of melt processes and crystal growth could also benefit from these achievements. If it is demonstrated that also very complex flow phenomena, like oscillating liquid bridges, can be analyzed through photogrammetric techniques, as for both the velocity field of tracers inside the column and the changing shape of the column itself, this optical method will have a good chance to become a multi-user diagnostic tool, simplifying Space facilities.

7. UNCITED REFERENCE

[17]

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