DESIGN AND CALIBRATION OF A FOUR-HEADED CAMERA SYSTEM FOR USE IN MICROGRAVITY RESEARCH

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ABSTRACT

In a cooperation of the Swedish Space Corporation, the Microgravity Research Center of the Université Libre de Bruxelles and the Institute of Geodesy and Photogrammetry at ETH Zurich, a system for the measurement of three-dimensional particle motion field in an experimental vessel under micro-gravity conditions has been designed and constructed. The system consists of four CCD cameras and a mirror system allowing a good photogrammetric network quality in combination with an extremely compact design. The paper shows the basic design of the system, discusses a calibration strategy and presents first results. The experiment unit was made for the MASER 8 sounding rocket JET experiment with the aim of a first direct observation of the so-called chemojet motion of free flying small growing crystals. It takes place in a reactor chamber with a dimension of 10x11x14 mm^3, into which several hundred particles are injected during the flight. The particles are imaged by four synchronized CCD cameras. The chamber is illuminated from the backside via a milk-glass window. The front wall of the chamber is an observation window used for imaging the particles. According to the reliability requirements of 3-D particle-tracking-velocimetry (3-D PTV), the reactor chamber has to be imaged from at least three different directions. A fourth camera was added to enable the discrimination of two different particle substances via a special illumination in combination with a filter.

1 INTRODUCTION

3-D PTV has been developed as a versatile photogrammetric tool for the determination of 3-D velocity fields in flows marked by a large number of neutrally buoyant tracer particles (Papantoniou/Maas, 1990; Maas et al., 1993). The suitability of the technique for measurements under micro-gravity conditions has been discussed in (Maas et al., 1997). Based on these results, 3-D PTV was chosen as measurement technique for the examination of chemo-jet phenomena (Vedernikov/Melikhov, 1994; Melikhov/Vedernikov, 1995) on the MASER 8 sounding rocket experiment performed by Swedish Space Corp. in cooperation with the Microgravity Research Center of the Université Libre de Bruxelles and the Institute of Geodesy and Photogrammetry at ETH Zurich (Figure 1). Launched to a height of 260 km, this rocket offers 6 minutes and 18 seconds of micro-gravity conditions. During this time, 500 liquid crystal particles are released into an observation chamber of 10x11x14 mm^3. Due to the chemo-jet effect, the motion of these particles is supposed to deviate from random motion. As a proof, another 500 neutral particles are added. To enable optical differentiation between active and neutral particles, the latter ones were chosen as gold plated hollow glass spheres. The 3-D particle trajectories are determined by a 4-camera 3-D PTV system, with a filter to discriminate the two particle substances in the optical path of one of the cameras. Detailed information about the JET growth motion in aerosol experiment module can be found in (Lockowandt et al., 1999; Dupont et al, 1999). In the following, the design and calibration of the observation system is described. A discussion of the experiment itself will follow as soon as data processing has been finished.

Figure 1: Launch of sounding rocket

2 DESCRIPTION OF THE FOUR HEADED CAMERA SYSTEM

The available space to accommodate the reactor chamber as well as the illumination and imaging modules is limited to the diameter of the sounding rocket, which is 0.4 m. For this reason the experiment unit had to be designed as compact as possible. The image acquisition system is based on one single almost distortionfree objective that collects light coming from different viewing directions via four mirrors and transfers it to the four CCD-cameras via another four mirrors. Image quadruplets from these cameras are grabbed simultaneously, intermediately stored and then written to a compact analogue storage device via a multiplexer. Compactness of the system is furthermore achieved by a 90-degree angle in the optical path. To be able to apply the standard photogrammetric model of 3-D PTV based on the collinearity condition, multimedia geometry and additional camera calibration parameters, the optical paths for the four cameras were 'unfolded' for further processing, leading to a configuration with four virtual projection centers and virtual camera positions with a convergent arrangement.
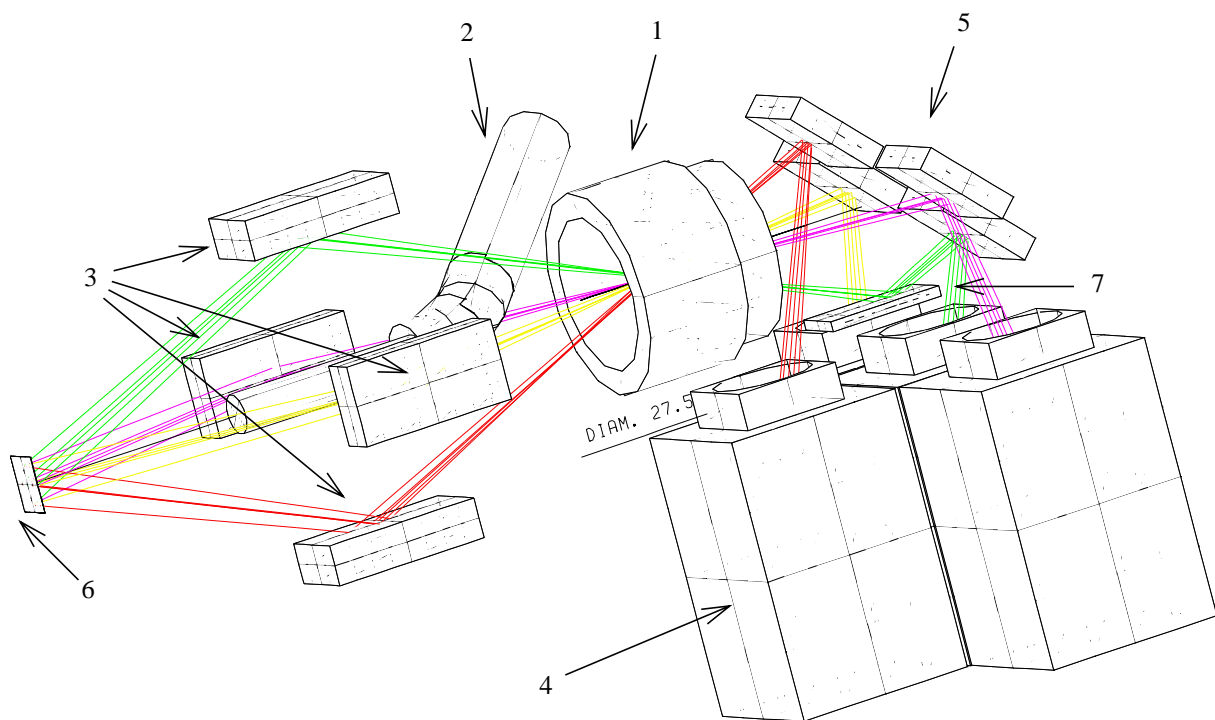

Figure 2: Mechanical design of the imaging head: 1, objective; 2, front illumination; 3, mirrors; 4, CCDs; 5, mirrors; 6, Reactor Chamber; 7, additional mirror

3 CALIBRATION OF THE IMAGE ACQUISITION SYSTEM

To be able to establish correspondences between particle images and to compute 3D particle coordinates, the (virtual) orientation and calibration parameters of the system have to be determined in a calibration procedure. The calibration is being performed using images of a 3-D reference body with discrete targets, which is inserted into the reaction chamber before and after the experiment. Using the mathematical model of spatial resection, the orientation and calibration parameters of a camera can be determined from one single image of the calibration reference body under suitable illumination, if the 3D coordinates of the targets are known. Based on this calibration facility, particle tracking with micron-accuracy becomes possible.

3.1 Calibration body

The calibration reference body was fabricated by spark erosion techniques in aluminum with 48 mechanically generated reference points in an anodized surface with a precision in the order of one micron. The reference body used for the calibration is shown in Figure 3. To calibrate the system in its actual configuration the calibration body should be put into the experiment cell immediately before launch. The reference body is used to define the coordinate system. The X-Y-plane is chosen identical with the inner side of the front glass plate. The Z-axis is perpendicular to the front glass plate and has its positive direction away from the observation volume. The origin and the

Figure 3: 3-D calibration reference body

directions of the X- and Y- axis is depending on the placement of the calibration body. Due to the fact that there is no fixation for the calibration body the orientation of the X- and Y-axis and the origin of the coordinate system depends on the actual position of the calibration body during the aquisition of the calibration images. This is irrelevant due to the relative character of the particle motion. For the experiment it was assumed that the arrangement is stable during the flight.
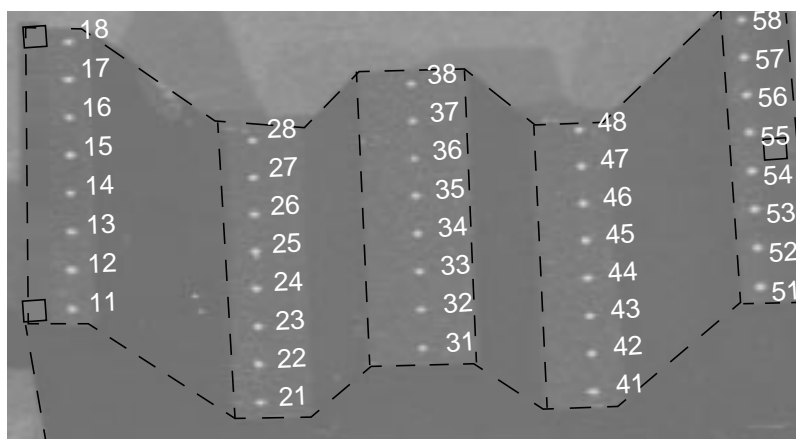
3.2 Image quadruplet used for the calibration

The time delay between the acquisition of the images used for the calibration and the actual experiment should be kept to a minimum to reduce the influence of temporal changes of the configuration. The images have a more or less dark background and the reference points appear as bright spots. After a high pass filtering the location of the imaged reference points is calculated as the gray value weighted centre of gravity. From each calibration image, at least 20 points of the reference body were detected and used for the determination of the photogrammetric parameters. Due to the convergent setup and the depth of the observation chamber, the common viewing volume of all four cameras is relatively small. The image quadruplet used for the calibration with the detected image positions of the points of the reference body is shown in Figure 4.
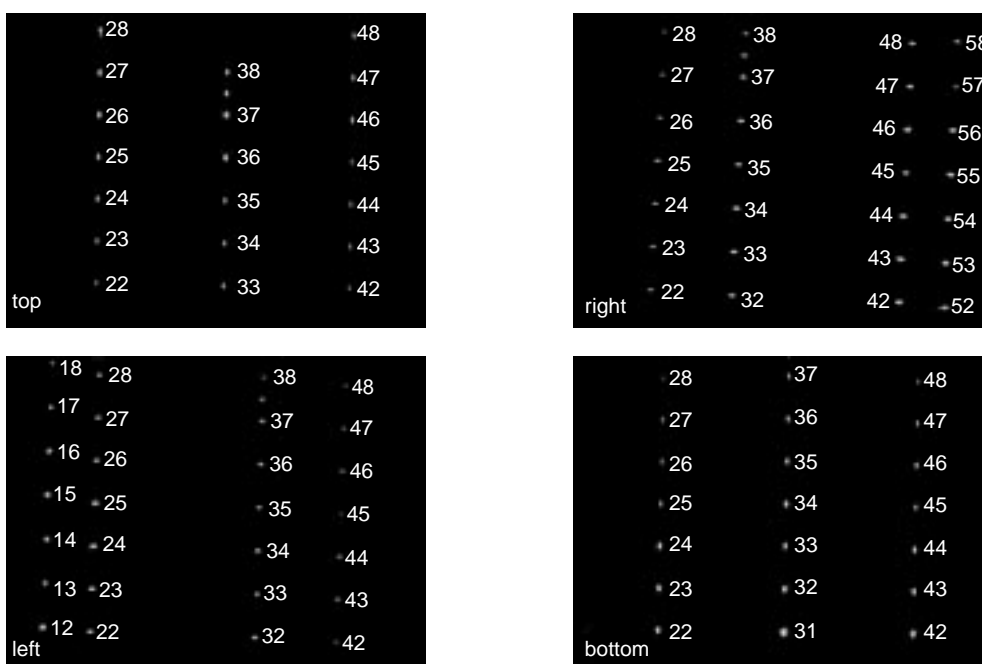

Figure 4: Views of the calibration body by the four-camera system

3.3 Results of the calibration

The four-camera system was calibrated by spatial resection. As the mathematical model does not contain mirrors, the optical paths were 'unfolded' for further processing, leading to a configuration with four virtual projection centres and four virtual camera positions with a convergent camera arrangement and principal point coordinates deviating strongly from the centre of the image. The calibration yielded the following results:

- The standard deviation of unit weight was between 2.39 - 4.94 microns for the four images. This is certainly suboptimal, but has to be contributed to the micro-structure of the targets plus illumination effects.

- The camera constant could not be determined. This is due to the extremely narrow opening angle, which leads to high correlations between parameters of exterior and interior orientation. The mathematical model depicts an over parameterisation to the chosen configuration. Therefore the camera constant can be introduced as a fixed parameter with a value of 108.83 mm computed from the parameters of the optical system, and the effects of deviations from this value are covered by parameters of the exterior orientation.

- The principal point is turned outward between 25 and 42 mm for the four cameras and is thus lying far outside the actual sensor format.

- No other significant parameters could be determined.

The results of the calibration are listed in Table 1 and Table 2.

Camera	Number of measurement reference points	Principle distance c [mm]	Principle point X_h/σ_{Xh} Y_h/σ_{Yh} [mm]	Standard deviation of unit weight [µm]
Top	20	108.83 (fixed)	-0.70 ± 0.18 41.15 ± 0.19	2.39
Bottom	28	108.83 (fixed)	-0.56 ± 0.23 -42.45 ± 0.24	3.15
Right	28	108.83 (fixed)	26.73 ± 0.47 -0.07 ± 0.47	4.92
Left	21	108.83 (fixed)	-25.72 ± 0.49 0.43 ± 0.49	4.94

Table 1: Camera calibration data

Camera	Projection Center [mm]			Rotation angles [gon]		
	X/σ_X	Y/σ_Y	Z/σ_Z	ω/σ_ω	φ/σ_φ	κ/σ_κ
Top	4.93 ± 0.12	67.99 ± 0.13	164.78 ± 0.13	-0.46 ± 0.09	0.51 ± 0.09	1.14 ± 0.03
Bottom	8.99 ± 0.15	-64.66 ± 0.16	163.03 ± 0.17	1.42 ± 0.11	1.00 ± 0.11	1.32 ± 0.03
Right	69.51 ± 0.16	3.69 ± 0.12	154.07 ± 0.23	0.84 ± 0.25	9.32 ± 0.24	3.03 ± 0.07
Left	-56.33 ± 0.16	-0.28 ± 0.12	155.50 ± 0.23	1.29 ± 0.26	-9.24 ± 0.25	2.71 ± 0.07

Table 2: Exterior orientation data

4 PROCESSING OF IMAGE SEQUENCE DATA

The experiment was performed successfully and the JET module functioned nominal during the flight. During the flight of MASER 8 an image sequence of around 7 minutes was recorded and the movement of the particles could be observed. In total ca. 1500 time steps were analysed. This refers to the first five minutes, the last two minutes were not evaluated because no particle movement could be detected. After a preprocessing of the image sequence data the particles appear as bright spots before a more or less dark background. These images are suitable for the processing with 3D-PTV. The system orientation and calibration parameters as determined in chapter 3.3 were used for the processing of the data. The imaged particles are detected by thresholding, and their location in image space can be determined with subpixel accuracy by a centroid operator. To compute 3D particle coordinates, a spatial intersection has to be performed with corresponding image coordinates. The establishment of those correspondences poses some problems. The particle images do not show any characteristic features, which could allow a reliable distinction of particles. The only criterion which can be applied is the geoemetric constraint of the epipolar line: Knowing the orientation of the cameras from the calibration procedure, proceeding from a point in one image an epipolar line in an other image can be calculated, on which the corresponding point has to be found. Its length can be restricted by the kowledge of the depth range in object space. In this case the depth range in limited by the glass front and back of the reaction chamber.

In the next step the 3-D coordinates of all particles can be determined by spatial intersection. The redundant information provided by the measurement of three or four times two image coordinates for the determination of three object space coordinates allows to perform a least-squares adjustment for each individual point, thus providing additional precision estimates. The standard deviations of unit weight was between 7 up to 12 microns, the standard deviation of the 3-D coordinate determination by spatial intersection was between 0.007/0.007/0.017 and 0.012/0.012/0.032 mm in X/Y/Z. These standard deviations are also influenced by the precision and stability of the orientation parameters, as well as by the irregular shape of particles and sub-optimalities in illumination. As these effects will show a high correlation on successive positions of the particle trajectory, the precision of the velocity vector components can be assumed to be significantly better.
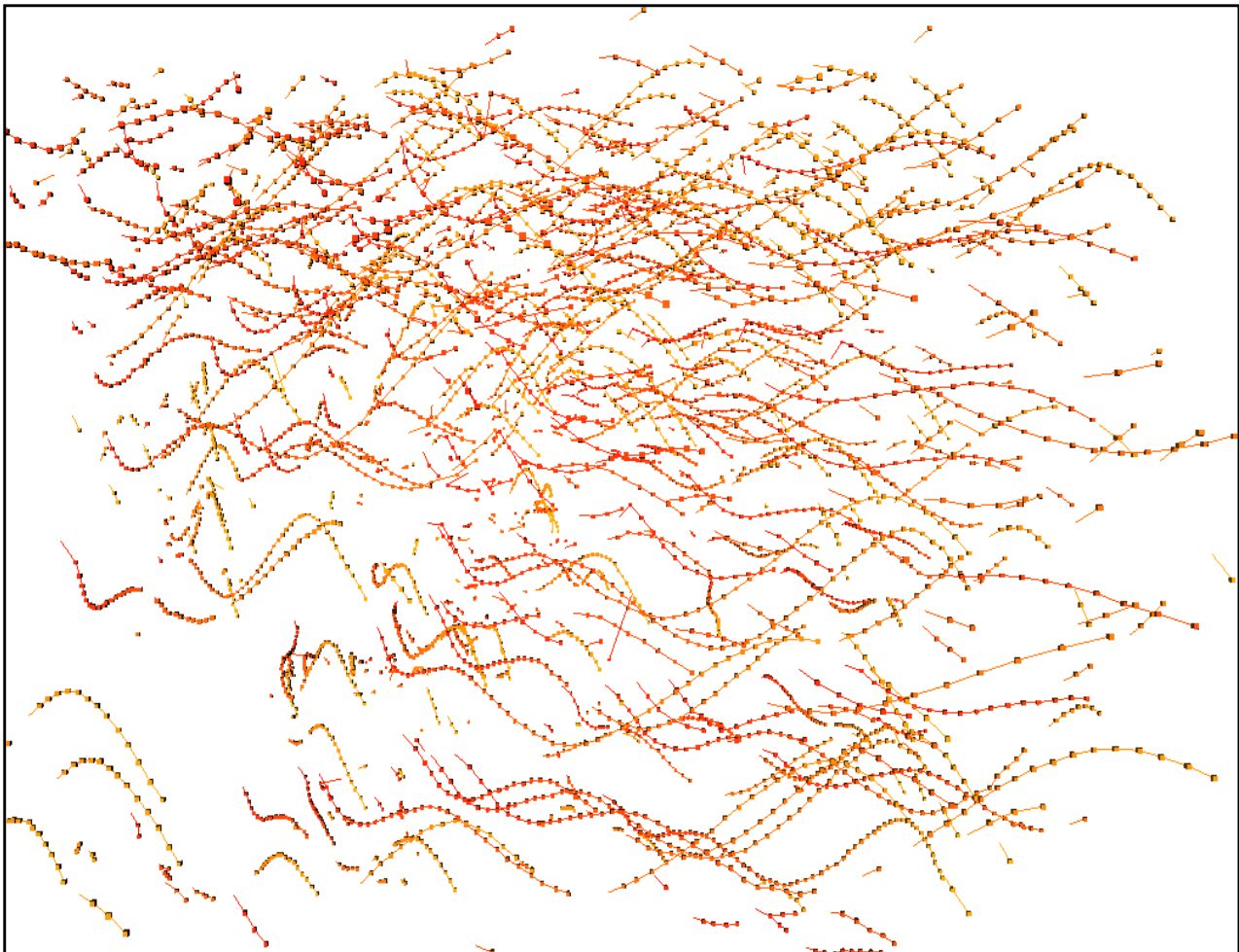

Figure 5: Velocity field (visualization of results)

After the calculation of the 3-D coordinates of every time step the tracking procedure is applied to get trajectories in the velocity field. A visualization of the results is shown in Figure 5. These results can be used for a further analysis of the movement of the particles.

The planned classification of the particles in two groups (reference and crystals) was performed as a simple binary decision. The fourth camera should enable the discrimination of two different particle substances via a special illumination in combination with a filter. If a particle is detected on the images of the decisive camera then it is classified as a reference particle. Due to the reason that the crystal particles were also visible and detectable on the images of the decisive camera acquired during the flight no reliable classification is possible with a binary decision. Perhaps further analysis of the results could solve this problem.

5 CONCLUSIONS

A four-camera photogrammetric system for 3-D particle tracking velocimetry measurements under micro-gravity conditions has been designed and tested. To achieve the compactness required by the installation in a sounding rocket, the system consists of four camera heads viewing the observation chamber through one common lens via a system of mirrors. To warrant compatibility with existing software packages, the optical paths of the four cameras are unfolded, leading to virtual camera positions. The results of the calibration and the first processing of experimental data show the proper function of the system. Although the precision potential of close-range photogrammetry could not fully be achieved as a consequence of the extremely small observation volume, the system provides a basis for micrometer-accuracy for of the determined 3-D particle trajectories.

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