SELF-CALIBRATING BUNDLE ADJUSTMENT WITH RELATIVE ORIENTATION CONSTRAINTS FOR MARS PATHFINDER STEREO IMAGES

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ABSTRACT

The multispectral digital stereo camera IMP (Imager for Mars Pathfinder) was developed to record and survey the landing site of the Mars Pathfinder (MPF). The IMP imagery has been used to control the Mars Rover (Sojourner), to produce panoramic mosaics, orthophotos, topographic maps and digital terrain models, and to derive geological, mineralogical and atmospherical data. The determination of the image orientations is prerequisite to any geometric object reconstruction. In the paper, some features and technical specifications of the IMP stereo camera are described. The orientation of the IMP images is performed by means of a modified version of the bundle adjustment program CAP. In the recently developed latest version, additional constraints regarding the known relative orientation elements of the IMP stereo camera can be introduced.

KURZFASSUNG

Die multispektrale digitale Stereo-Meßkamera "Imager for Mars Pathfinder" (IMP) wurde entwickelt, um den Landeplatz des Mars Pathfinder (MPF) Raumfahrzeugs aufzunehmen und zu vermessen. Die IMP-Bilder wurden bzw. werden benutzt zur Steuerung des Mars Rovers (Sojourner), zur Herstellung von Panoramaansichten, Orthophotos, topographischen Karten und Digitalen Geländemodellen sowie zur Ableitung geologischer, mineralogischer und atmosphärischer Daten. Voraussetzung für jede geometrische Objektrekonstruktion ist die Bestimmung der Orientierungselemente der IMP-Bilder. In diesem Bericht werden zunächst einige technische Spezifikationen und Merkmale der Kamera beschrieben. Die Bildorientierung wird mit einer modifizierten Version des Bündelausgleichungsprogramms CAP durchgeführt. In dieser neu entwickelten Variante der Software ist es möglich, bekannte Werte der relativen Orientierung der IMP Stereokamera als zusätzliche Beobachtungen einzuführen.

1. INTRODUCTION

After a space flight of seven months and 500 Mill. km, NASA's Mars Pathfinder (MPF) landed on the surface of Mars on 4 July 1997, deployed a small rover, and collected data from three scientific instruments, viz. Alpha-Proton X-ray spectrometer (APXS), atmospheric structure investigation / meteorology package (ASI/ MET), and Imager for Mars Pathfinder (IMP) (Golombek, et al., 1997; Golombek, 1998). IMP represents a digital multi-spectral stereo camera of unique design (see following chapter). During MPF's operational period of three months, IMP returned over 16000 partly spectacular images. Besides its own scientific objectives, viz. photogrammetric and remote sensing survey of the surroundings of the landing site, IMP was heavily utilized as monitoring and control instrument for the navigation of the rover and for the other experiments (Smith et al., 1997). The wide range of applications encompassed acquisition of multispectral imagery for geological, mineralogical and atmospheric investigations, multitemporal imaging for the determination of meteorological, photometric and spectrometric features, and of stereoscopic imagery for rover control, exact determination of the lander's position and the production of several panoramas, topographic maps, orthophotos and digital terrain models. In addition, special tasks such as photogrammetry with vertical base line, experiments with super resolution, etc. are envisaged (Dorrer, 1997).

Due to IMP's particular construction principle (see following chapter) the various photogrammetric tasks are rather demanding both from a theoretical and practical point of view. One of the major problems, viz. exact tie between all images of the panoramic block, is nontrivial and requires special attention. However, e.g., a rigorous adjustment of the entire bundle block is prerequisite for the generation of a seamless image panorama. Previous investigations elsewhere have clearly shown the complexity of serious photogrammetric work with IMP imagery. In particular, so far both a purely digital approach for automated image matching and a rigorous panoramic block adjustment could not yet fully be realized (Kirk, et al., 1998; Soderblom, et al., 1998; Oberst, et al., 1998). To a certain extent, the results published so far by the Jet Propulsion Laboratory, the U.S. Geological Survey or the Institute of Planetary Exploration of DLR are still approximate and do not exploit the full potential of the geometric and radiometric information content of the imagery. As NASA will send several more landers onto Mars and ESA is planning to carry out a European Mars mission, all of which will have similar stereo cameras, it is very much worth while and a scientific challenge to search for rigorous photogrammetric solutions for both the bundle block and the panorama generation problem.

2. THE IMAGER FOR MARS PATHFINDER (IMP)

About 30 minutes after cruise stage separation, the space vehicle entered the Martian atmosphere at a velocity of 7470 m/s approximately 5 minutes prior to landing. Parachute deployment, heatshield and lander separation, radar ground acquisition, airbag inflation, and rocket ignition all occurred during the final 134 s. (Golombek, et al., 1997). The lander bounced at least 15 times up to 12 m high, coming to a halt, as hoped, in upright position at 2:58 a.m. true local solar time. The first radio signal (traveling time from Mars was 10 min 35 s) from the low-gain antenna was received some 2 hr and 40 min later, indicating successful landing, properly functioning spacecraft and petal opening (Fig. 1).

Commands were then sent to unlatch the IMP and high-gain antenna. The first images returned from the so-called stowed, i.e. lowest and pre-deployed position of the IMP (Fig. 1, lower end of IMP mast) included a quick panorama, the exact position of the sun for attitude determination of the lander, stereo images of the rover petal, and a partial panorama of the Martian surface and sky. At the end of the second day of operation, the IMP was deployed on its 0.8-m-high mast (Fig. 1). All subsequent images were taken from this position.

The Imager for Mars Pathfinder is a truly digital stereo camera. Its focal plane CCD-array consisting of 512x512 pixels of 23 microns each is simultaneously used by both mono cameras. Fig. 2 schematically shows a cut through the cylindrical stereo camera head. The camera cylinder can be rotated around its axis allowing for the setting of elevation angles. Horizontal angles can be set by the azimuth gimbal assembly. The corresponding stepping motors may be commanded to within 0.5 deg relative precision (Britt, et al., 1997).

The optical system of the stereo camera is clearly shown in Fig. 2. The two "eyes" are 15 cm apart from each other, each constituting a field of view of 14.4 deg horizontally and 14 deg vertically. Light entering the eyes meet the folded mirror assembly and is deviated towards the center of the cylinder. It then penetrates the filter, the camera lens (modified Cooke triplets with aperture 1.04 mm and f/18) and is directed upwards within the optical housing towards a common CCD-array. In order to achieve maximal stereo performance within the 2-to-10-m range, "toe-ins", i.e. convergence was deliberately introduced in the optical train. The focal array system is based on a Loral-CCD of size 512 by 512 with antiblooming and consists of a pre-amplifyer board within the camera head and a reading board mounted in the main MPF housing. Only about half of the IMP focal array is actively used for simultaneous stereo imaging (248 x 256 each), the other half being passive reading and shutter (0.5 ms) zone. The image data are 12 bit digitized. With 23 micron inter-pixel distance, the effective pixel resolution was determined to 0.981 mrad for the left and 0.985 mrad for the right eye, yielding calibrated focal lengths of 23.445 mm, 23.350 mm, respectively. Each optical train contains a wheel of 12 filters from 440 to 1000 nm spectral wavelength.

The camera system is controlled via a time-triggered and in the RAM of the MPF-computer stored uplink command sequence. In these commands details such as exposure time, degree and type of data compression, filter wheel, azimuth and elevation angle settings, etc. are specified. The images are stored in packets in the telemetry buffer after execution and downlinked to Earth.

3. PHOTOGRAMMETRIC PROCESSING OF THE IMAGE DATA

The basic prerequisite to handle IMP stereo images is to calculate orientations, i.e. interior orientation of the camera and exterior orientation of all the digital images. This process can be carried out best by photogrammetric bundle triangulation with constraints. If the orientation parameters are determined, follow-up products such as topographic maps, panoramas and digital terrain models can be derived.

The stereo camera provides rigid yet not exactly known interior orientations (calibration) and relative orientations (pose). In addition, the approximate exterior orientation of the IMP camera head is given. The photogrammetric block consists of a full 360 degree panoramic mosaic. The images overlap each other both in azimuthal and vertical direction. In the overlapping zones between adjacent images, tiepoints can be measured manually or automatically on a digital photogrammetric softcopy

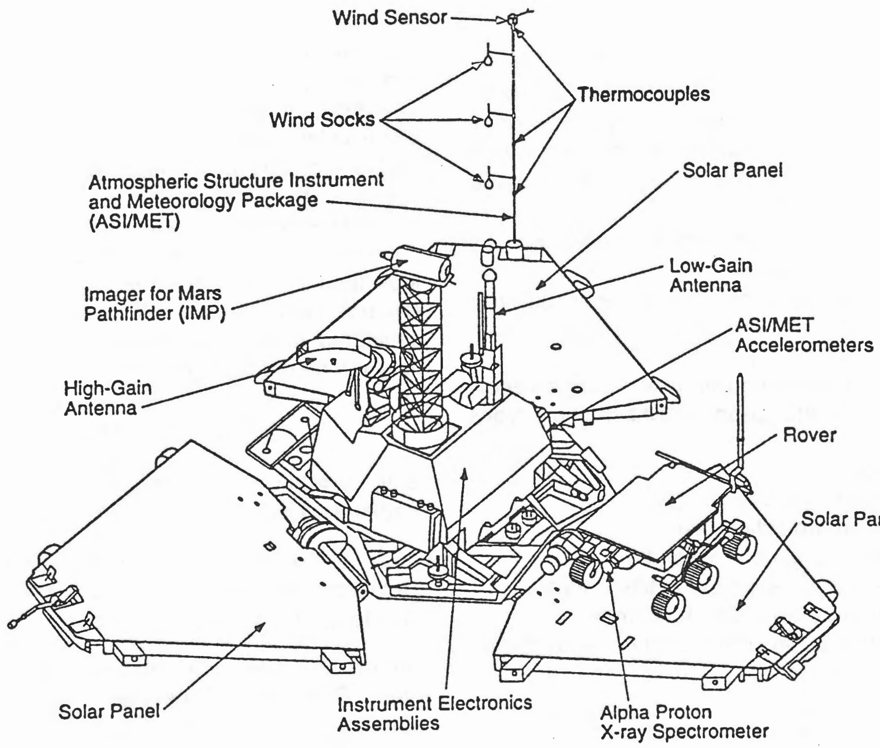

Figure 1 Mars Pathfinder Lander (Golombek, 1997)

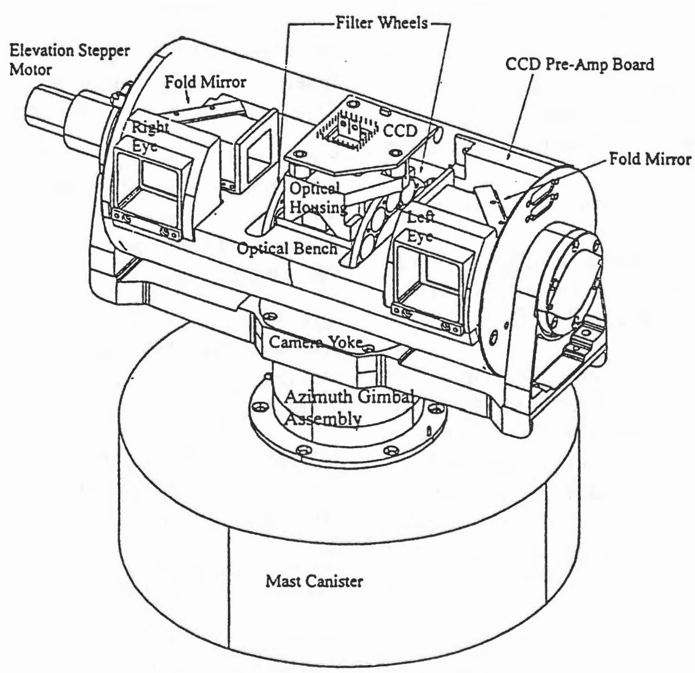

Figure 2 The Imager for Mars Pathfinder IMP (Britt et al., 1997)

workstation. The panoramic block is adjusted simultaneously for all stereo images by means of a modified version of the bundle triangulation program package CAP (Combined Adjustment Program) developed for close range applications (Hinsken et al., 1992; CAP, 1996).

CAP was first introduced in 1988 and has been continuously updated over the last ten years in order to improve the adjustment capabilities and efficiency. The program offers a solution for a series of tasks, mainly

- object reconstruction by 3-d point determination
- spatial orientation of images
- calibration of photogrammetric image acquisition systems.

CAP is capable of combining and processing a variety of photogrammetric and geodetic observation types such as

- image coordinates
- distances between object points
- distances between projection centers
- object coordinates (e.g. control points)
- coordinate differences (e.g. height differences)
- interior orientation parameters of a camera
- exterior orientation parameters: position and rotation of a camera

Each observation can be introduced into the adjustment with its individual weight by assigning the standard deviation a priori to the measurement value.

The parameters of interior orientation of a camera can be derived simultaneously with the 3-d object reconstruction (test field or on-the-job calibration). The following elements are determinable:

- principal distance
- coordinates of principal point
- radial symmetric distortion parameters
- tangential and radial asymmetric distortion parameters
- parameters for affinity and non-orthogonality of the coordinate axes
- parameters for platen unflatness effects and fine tuning parameters to describe systematic image errors (parameter set according to D.C. Brown)

Recently, CAP was modified and extended to meet the requirements of a thorough orientation and calibration of the Mars Pathfinder stereo camera. The program is equipped with the option for handling the relative orientation of multiple stereo image pairs within a simultaneous combined adjustment. For a stereo pair, the following stereo observations with their appropriate standard deviations a priori can be introduced:

- relative base components: bx, by, bz
- relative rotation components: delta_omega, delta_phi, delta_kappa

The efficiency of the modified CAP version was verified by adjusting simulated test data of IMP stereo images.

4. CONCLUDING REMARKS

During the three months of operation, several full and partial panoramic mosaics were acquired (Smith, 1998; Soderblom, et al., 1998). The determination of exterior orientation for each image requires a combined adjustment of all images. Unfortunately, the mutual overlapping regions may be quite irregular and narrow. Therefore, a fully automatic triangulation seems almost impossible. Considering a total of some 1000 images to be processed, this is a rather voluminous task. Obviously, only a step-by-step procedure is appropriate. In order to gain experience, our plans are to process one particular panoramic mosaic. In its smallest version, it still consists of four tiers (strips) of some 35 image pairs each. After testruns with the modified CAP version applied to simulated data, triangulation and adjustment of the real data will be carried out in the near future.

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