Near range stereo for Mars landing site reconstruction

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ABSTRACT

Within the European Mars Express Mission to be launched 2003 the Beagle2 Lander will foresee the access to stereoscopic views of the surrounding Martian surface after touchdown. For scientific purposes the necessity for a high resolution three dimensional (3D) reconstruction of the landing site is evident. A lander vision subsystem capable of reconstructing the landing site and its vicinity using a stereo camera mounted on the robotic arm of the lander is used therefor. Knowledge about the geometric camera features (position and pointing with respect to each other, position and pointing with respect to the lander, intrinsic parameters and lens distortion) are determined in a calibration step on ground before takeoff. The 3D reconstruction of the landing site is performed after landing by means of stereo matching using the transmitted images. Merging several stereo reconstructions uses the respective robotic arm states during image acquisition for calibration.

This paper describes the full processing chain consisting of calibration of the sensor system, stereo matching, 3D reconstruction and merging of results. Emphasis is laid on the stereo reconstruction step. A software system configuration is proposed. Tests using Mars Pathfinder images as example data show the feasibility of the approach and give accuracy estimations.

Keywords: Space Exploration, Stereo Reconstruction, Photogrammetry

1. INTRODUCTION

The Beagle lander of the Mars Express mission[1] contains a set of cameras that will be used for sensing the environment of the lander after landing. A panoramic camera is used for wide angle image acquisition. To get three dimensional information about the near range environment, a stereoscopic camera is used. This stereoscopic camera is mounted on a robotic arm which enables enough degrees of freedom to provide views of at least 180 degrees field of view, from a distance of some centimeters to infinity.

A set of experiments, mainly performed using the robotic arm, needs accurate 3D information about the environment. The only sensor that is available for this task is the stereo camera. Expertise and operational software for the 3D reconstruction using stereo images has been developed at the Institute of Digital Image Processing of JOANNEUM RESEARCH, Austria, during the past seven years. Using the existing technology under consideration of the technical requirements has been the basic idea of this Austrian contribution which proposes to provide a software solution for the following tasks:

- Support the development team in terms of camera arrangement and design
- Geometrically calibrate the Beagle2 cameras
- Develop software to generate a digital elevation model (DEM) from Beagle2 lander stereo camera images
- Perform the ground segment for DEM generation shortly after Beagle2 touchdown

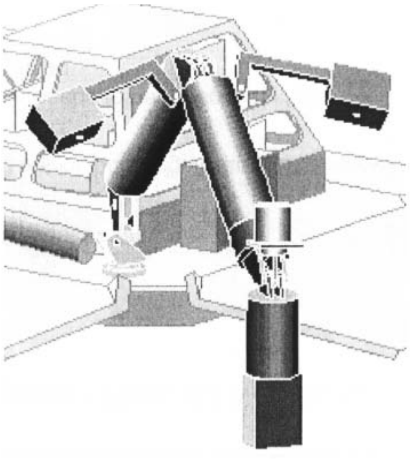
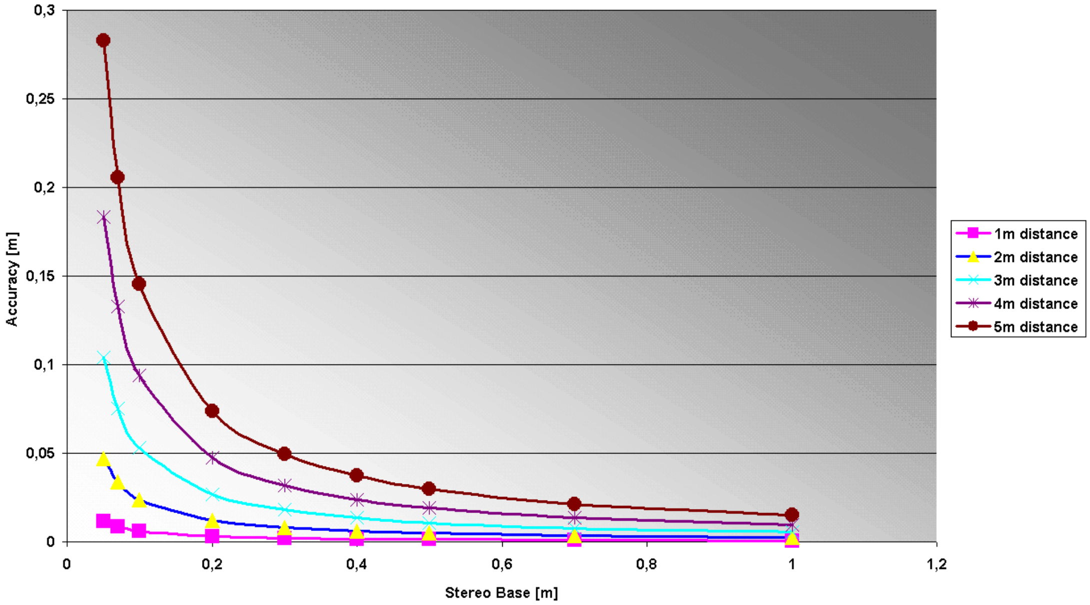


Figure 1. Beagle2 panoramic stereo camera and robotic arm concept

Table 1. Stereo reconstruction accuracy depending on viewing distance and stereo baseline (matching accuracy: 0.3 pixel; focal length: 10mm, pixel size on CCD: 10 μm). A larger focal length would linearly improve the accuracy.



2. CAMERA GEOMETRY

The Beagle2 Lander will contain a stereoscopic camera pair with a medium field of view (FOV), mounted on the robotic arm (Figure 1), and a wide angle camera with a large FOV mounted on one corner of the lander. Hence, the stereoscopic camera can be moved with at least 3 degrees of freedom, whereas the wide angle camera is fixed. Stereo reconstruction accuracy decreases quadratically with increasing scene distance. The base length (distance between the left and right camera part) has a linear influence on the accuracy.

Table 1 gives an idea about this relationship. It depends therefore very much on the accuracy requirements at a certain range, which minimum baseline and focal length should be chosen. The parameters on Table 2 are essential in this selection.

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Table 2. Essential parameters for the selection of camera setup

Parameter	"Negative" influence on	"Positive" influence on
High focal length	Number of frames required (amount of data): quadratic	Accuracy: linear
High stereo base	Mechanical stability; matching robustness at very near range	Accuracy (quadratic)
Number of CCD pixels	Data rate; HW complexity	Number of different views: linear

In principle the foreseen camera setup will be very similar to that used in the Mars Pathfinder mission.[2] The same team which developed the Mars Pathfinder Lander stereo camera will be involved in the development of the Beagle2 Lander cameras as well. An important difference is that the camera will not use just one but two CCD arrays.

An important consideration for enhancing the reconstruction accuracy of the far-range (several meters) vicinity of the lander could be the incorporation of the wide-angle camera into the stereo reconstruction process. It is possible to use one component of the stereo camera pair together with the wide angle camera as second component. This would increase the stereo baseline, whereas decrease resolution. Since the accuracy decreases quadratically with stereo base and just linearly with resolution (=focal length), at a certain distance the usage of the wide angle camera would yield an improvement of accuracy.

Another consideration is the selection of calibration targets for on-site verification and/or improvement of the camera calibration. Although the cameras and robotic system are calibrated on ground before launch, the setup might change due to strong mechanical and thermal influences during take-off and landing. Therefore it must be assured that parts of the lander itself can be made visible after landing from both the stereo camera pair and the panoramic camera.

3. CAMERA CALIBRATION

3.1. Pre-Launch Calibration

Geometric camera calibration is the geometrical description of a lens-camera system with respect to the outside world. If focused correctly, each pixel of the camera CCD array is viewing along one straight line towards the scene to be observed. To get a relation between the CCD pixel position (=image coordinate) and this straight viewing line, a perspective transformation[3] is the most commonly used model for digital frame cameras. The parameters for this relation can be split into the following classes:

- Interior orientation: Focal length, lens distortion parameters (typically 4-8), principal point (image coordinate of lens center projection). They describe the geometrical features of the lens-camera setup regardless of its position with respect to the outside world. It should not change after calibration on ground.
- Exterior orientation: Position of the principal point (x, y, z in world coordinates), pointing of the camera (ω, ϕ, κ: The rotation of the image coordinate system with respect to the world coordinate system). The exterior orientation is depending on the state of the robotic arm which holds the cameras, and the position and pointing of the lander frame. In addition, for a stereo camera setup it is necessary to describe the
- Relative orientation: Position and angles of the two stereo cameras with respect to each other. It should not change once the cameras have been unfolded.

The following steps are recommended to perform a calibration of the cameras (for each filter state individually):

1. Acquire many images of a calibration target from different distances using the same camera, lens, frame grabber and software as in the target system. Best would be to keep the system in a constant temperature which is varied for new sets of data (e.g. three different temperatures to be able to determine the sigma and linear variation).

2. Calibration using off-the-shelf software[4] for calculating the interior orientation for each camera independently.
3. Correct the lens distortion and perform a relative orientation parameter adjustment for the stereo setup. This gives the relative orientation between the left and right stereo camera components.
4. The exterior orientation depends on the robotic arm state. The relation between robotic arm state and exterior orientation of the stereo camera can be described by a physical model of the robotic arm and the camera rotation and orientation with respect to the robotic arm actuators.[5] Each actuator induces a separate transformation matrix. The components of the matrix can be determined by calculating the exterior orientation for a set of tie positions, variating just the respective axis. To get the exterior orientation from the robotic arm state, the axe- specific matrices have to be multiplied. An alternative would be to first identify all necessary states of the robotic arm to fulfill the requirements for mapping, and then calibrate each of the positions separately once the arm and camera has been assembled. Between the "discrete" states an interpolation is sufficient.

The easiest way would be if the robotic arm kinematics (position of distinct points on the robotic arm with respect to the actuator state) are given by the producer.

3.2. On-Line Calibration After Landing

The validity of the calibration done on ground has to be checked after touchdown. That can be done using distinct points on the lander or the robotic arm that are visible within the field of view of both stereo cameras, for example fiducial marks on the microscope head which is connected to the robotic arm. The latter can be used for verifying the relative orientation between the two cameras. If there exists a distortion of the robotic arm mechanical setup this will result in a change of coordinate transformation between robotic arm and lander co-ordinate system. Since almost every action depending on the accurate DEM is done by the robotic arm itself, such a distortion might be not relevant at all (unless major angular distortions are involved).

Not all influences that can lead to a mechanical distortion of the initial calibration can be modeled just from the images. Therefore, if every attempt to automatically recalibrate a mechanically distorted system fails, the possibility to manually calibrate each stereo pair must be possible within a few hours to be able to merge a set of stereo reconstructions. The key features of this module are:

- Manually select tie points on each of the images to be merged (in the overlapping areas, see Section 4.3). This process can be done semiautomatically using correlation methods.
- The selection of tie points should be possible both on the input stereo images and on the DEM (Section 4.2)
- Use the erroneous calibrations as starting point and correct it (or the erroneous DEM) with respect to the tie points.
- Enable the user to manually variate the basic parameters of the calibration and repeat any reconstruction without great additional manual effort.

4. STEREO RECONSTRUCTION

Stereo reconstruction is based on the same principle as the human visual system uses for depth recovery. Two cameras viewing the same scene from a different position produce slightly different views. Each scene point is projected on slightly different locations of the two sensors and can therefore be localized with respect to the stereovision sensor using this difference, which is called *disparity.* The search for corresponding points on two images is called *stereo matching*,[6] which is the core process involved in stereo reconstruction. If the relative orientation and the exterior orientation of the stereoscopic system is known, not only the distance to a matched point can be determined, but also the exact position within 3D space.[7] If all points of the stereo images are used, a dense grid of disparities and further a dense DEM can be generated (Figure 2).

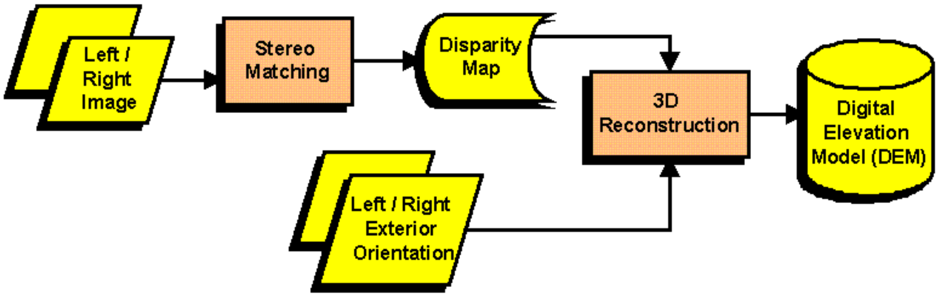

Figure 2. Basic steps and data for 3D stereo reconstruction

4.1. Stereo Matching

Finding corresponding points in two stereo images is a non-trivial task. However, a set of commercial products is available on the market, especially for remote sensing applications.[8,9] These tools are in most cases designed for the image acquisition geometry that occurs in aerial photogrammetry, which means a viewing direction almost orthogonal to the area to be mapped. In the case of Beagle2 landing site mapping the viewing angle is very flat, almost parallel to the surface. Therefore we recommend to use methods that have been proven to work on this kind of geometry. One of these methods was developed at in the frame of an ESA contract[10] between 1991 and 1995. HFVM (Hierarchical Feature Vector Matching) can be adopted to special imaging geometries and scene classes, since it has a flexible matching core, using dedicated local features for matching.[11] A test using Mars Pathfinder data showed that this stereo matching method is well usable for the case of a stereo camera mounted at a rather deep position on a Mars lander (Figure 3). The basic properties of HFVM are summarized in Table 3.

Table 3. Hierarchical Feature Vector Matching: Properties

Property	Value	Comment
Matching Methods	Image pyramid, local features	Feature set can be optimized[12]
Matching density	Every pixel	+consistency left-right, right-left
Necessary HW	HW independent	Source Code Library existing
Matching speed (256 x 256 pixels)	6 sec	On PentiumII 300 MHz
Matching accuracy	< 0.4 pixels	On rocks and rough sand
Geometrical Constraints	Image Rotation $< 20°$, Scale Difference < 20 %	
Maximum search space	Unlimited	Due to pyramid approach

4.2. 3D Reconstruction

The disparities as depicted on Figure 3 only describe correspondences between the stereo images, without any additional geometric issue. These correspondences can be used for 3D reconstruction as soon as the calibration data (Section 2) is known. Using the simple spatial forward intersection principle gains a 3D position for each scene point that describes a correspondence in both stereo images (i.e. is visible and identified as the same scene point in each image). In principle, all the correspondences build up a cloud of 3D points which has to be stored in a dedicated scheme. One straightforward and efficient method is a Digital Elevation Model (DEM, Figure 4).

Other approaches than the forward intersection method (=getting a 3D point and putting it on a discrete position in the DEM) could better fit to the current Mars lander scenario, since the flat viewing angle makes it very sensitive to noise, and interpolation of the result is necessary. The so-called *Locus Method*[13,14] at each DEM pixel looks for an elevation making use of the dense disparities provided by HFVM, which makes it very flexible in terms of DEM

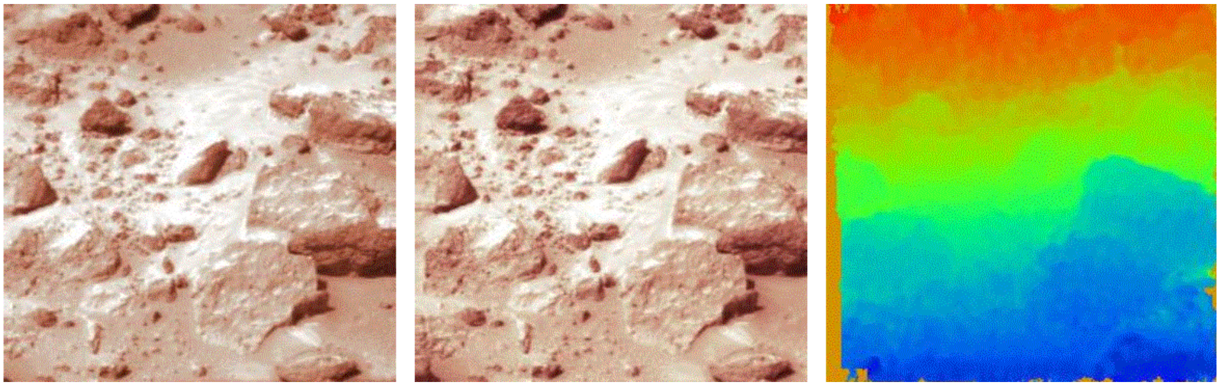

Figure 3. *Left, center*: Mars Pathfinder landing site stereo images. *Right*: HFVM Disparity image (false color)

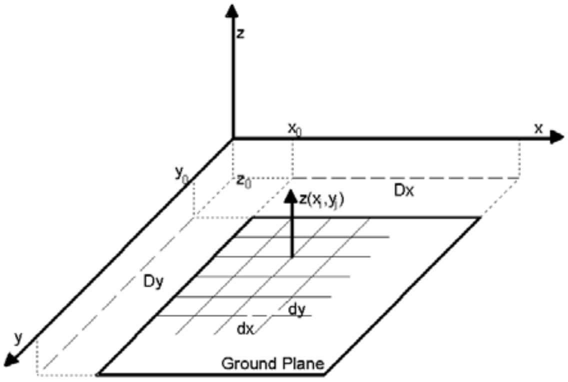

Figure 4. Geometry of a Digital Elevation Model. The DEM is stored in a raster image with $C = D_x/d_x$ columns and $R = D_y/d_y$ rows.

resolution and the region to be reconstructed. Furthermore the Locus Method allows the detection and evaluation of calibration misalignment. This data can be used for correction of calibration if a mechanical distortion occurred during touchdown. The 3D reconstruction from HFVM disparity results was again verified using Mars Pathfinder data. The results of such a reconstruction is displayed on Figure 5. Additional to the DEM an *Ortho Image* is the result of projecting the grey levels of the original images on the DEM.

4.3. Merging of Results

One stereo pair only covers a small portion of the entire lander environment. To get a result as displayed on Figure 6, the stereo pairs must overlap and the individual exterior orientations have to be rather accurate (especially the pointing vectors). To correct problems at overlapping areas, one possibility is to manually improve the calibration: Misalignment between neighboring reconstructions is detected easily by evaluating the difference in the overlapping area, both in elevation and ortho images (texture comparison).

5. ENHANCEMENT OF INPUT IMAGES AND RESULTS

Particularly in space exploration input images and results can suffer from artifacts caused by various reasons. A list of possible artifacts is given on Table 4. It shows that interpolation and masking are the most important tools to suppress artifacts. A toolbox that enables the interactive processing of input and output images much quicker than the receiving image data rate is necessary during ground control.

An important issue is lossy image compression. A short evaluation resulted in the evident fact that DEM noise increases gradually with increasing compression factors. For JPEG images this effect is demonstrated on Figure 7.

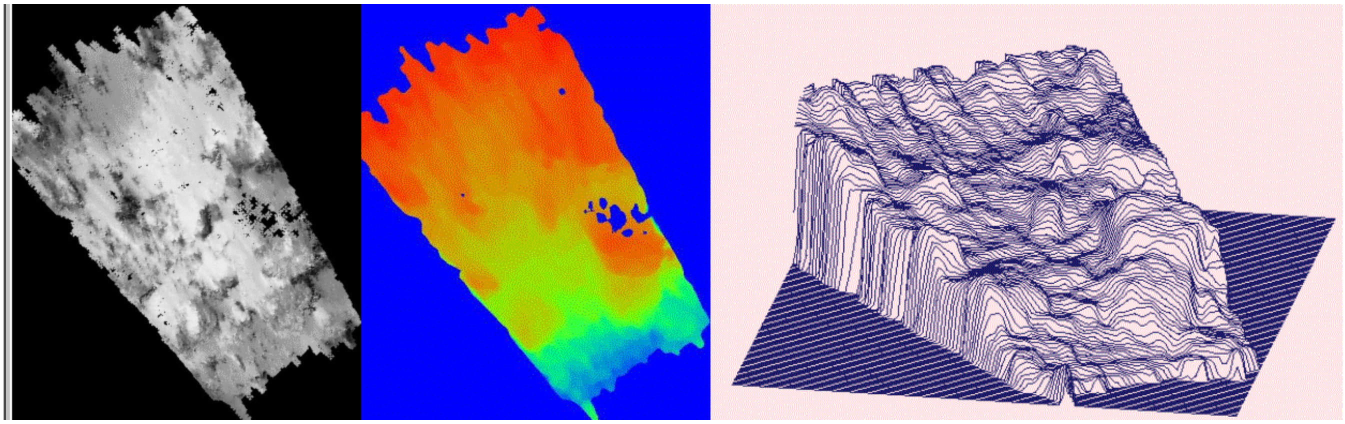

Figure 5. Ortho Image, DEM (false color) and 3D plot of Mars Pathfinder stereo reconstruction (one image pair)

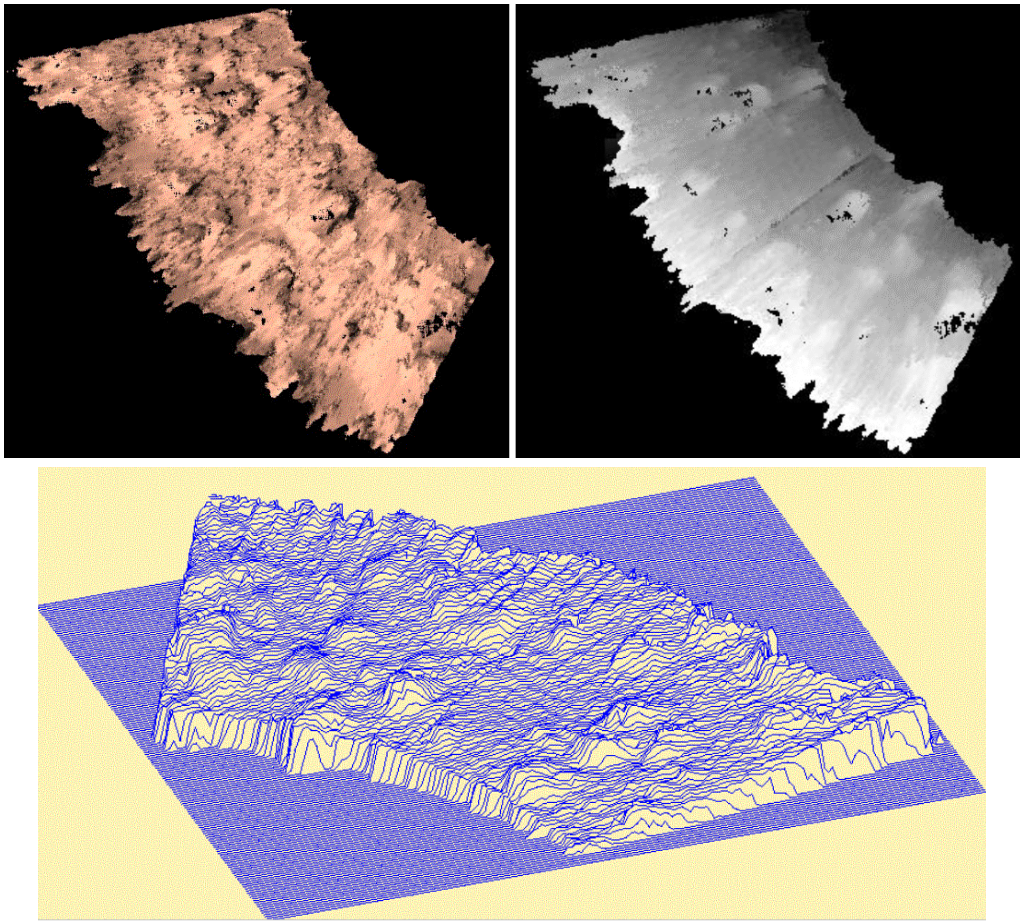

Figure 6. Result of merging four different adjacent stereo reconstructions (Pathfinder data): *Top left*: Ortho image, *top right* DEM. Higher regions are coded bright. The individual stones can be easily detected. *Bottom*: 3D plot. The region has a size of 3 x 3 m.

Table 4. Possible Artifacts (among others)

Artifact	Occurs on	Reason	Enhancement method
Missing data (stripes)	Input images	Transmission problems	Interpolation and / or masking
Low contrast or brightness	Input and ortho images	Bad illumination	Contrast stretch
DEM noise and wrong matches	DEM	Matching problems	Manual masking, interpolation
Blind pixels	Input images	CCD failure	Interpolation
Vignettation	Input images	Optical design problem	Adaptive contrast stretch
Invisible (occluded) areas	DEM	Shadowing objects	Interpolation (only recommended for small occluded areas)
DEM noise	DEM	Lossy image compression on input images	Acquiring important images again without lossy compression

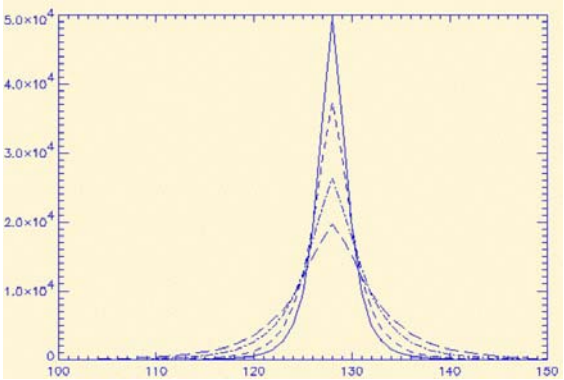

Figure 7. Disparity noise depending on compression factor on the stereo images. The diagram shows histograms of the disparity differences between "ideal" stereo images and stereo pairs compressed and decompressed using the JPEG standard. A value of 128 corresponds to 0 difference (i.e. the disparities are "perfect"), one pixel disparity corresponds to 16 units in x direction. Y represents the number of pixels. Compression rates 3,5,7 and 10 are displayed.

6. VISUALIZATION OF RESULTS

Once a DEM has been generated, it can be used as data source for various visualization tools. Generating a 3D point cloud that contains color grey levels is one straightforward method. Other possibilities include the usage of off-the-shelf rendering tools (e.g. by SGI) or simple contour plots like provided by the interactive data language IDL. For an example, see Figure 6, right. The most important application for the near vicinity DEM is the location of objects to be sampled by the robotic arm. An interactive visualization tool must provide the 3D coordinates of visually identified objects on the DEM. A straightforward solution is shown on Figure 8 where the coordinates are read from the DEM when clicking on the respective object in the Ortho image.

Visualization however will not be content of the specific technical development for Beagle2 DEM generation. It is rather intended to provide a sufficient set of export functions for the generated data, since during the next years commercially available visualization techniques will be a hugely evolving field.

7. DEVELOPMENT ISSUES: TESTING AND SIMULATION

During the different stages of development it is necessary to test individual functions as well as the whole system. To enable a laboratory testing of the whole 3D reconstruction processing chain including the on-line calibration

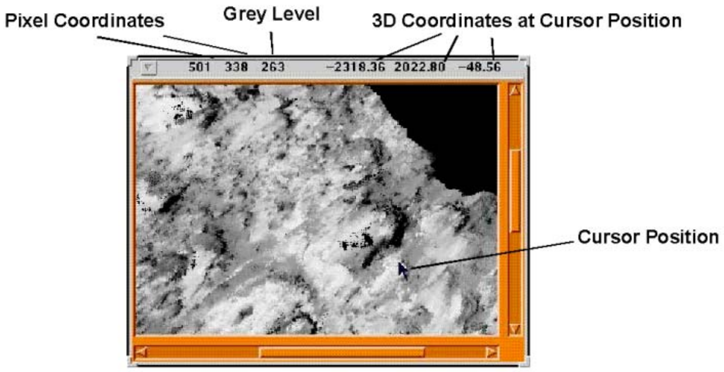

Figure 8. User interface for reading 3D coordinates from DEM

and enhancement mechanisms, a laboratory mockup of the Martian surface (sand and stones) will be generated. A robotic head (CamRobI,[15] Figure 9) with some degrees of freedom can be used to simulate at least one angular motion of the Beagle2 robotic arm.

Table 5. Tests

To be tested	Necessary Test data / System components
Calibration functions	Laboratory image data of calibration target
Robot Arm Interface	Robot arm: Real motions and images of a test target
Calibration concept and performance	Robot arm and final camera + filters: Real motions and images of a test target
Stereo matching enhancements	Laboratory image data of Mars mockup (1 x 1 m)
Visualization	Laboratory image data, CamRobI state
Full Ground Control	Robot Arm+kinematics, mockup, all components

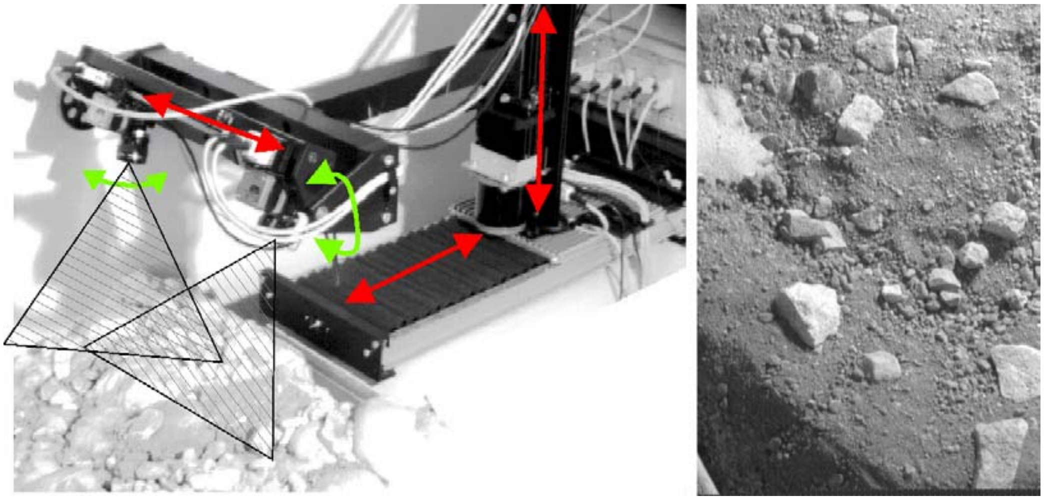

Figure 9. CamRobI camera mounting device and Mars mockup at JOANNEUM RESEARCH

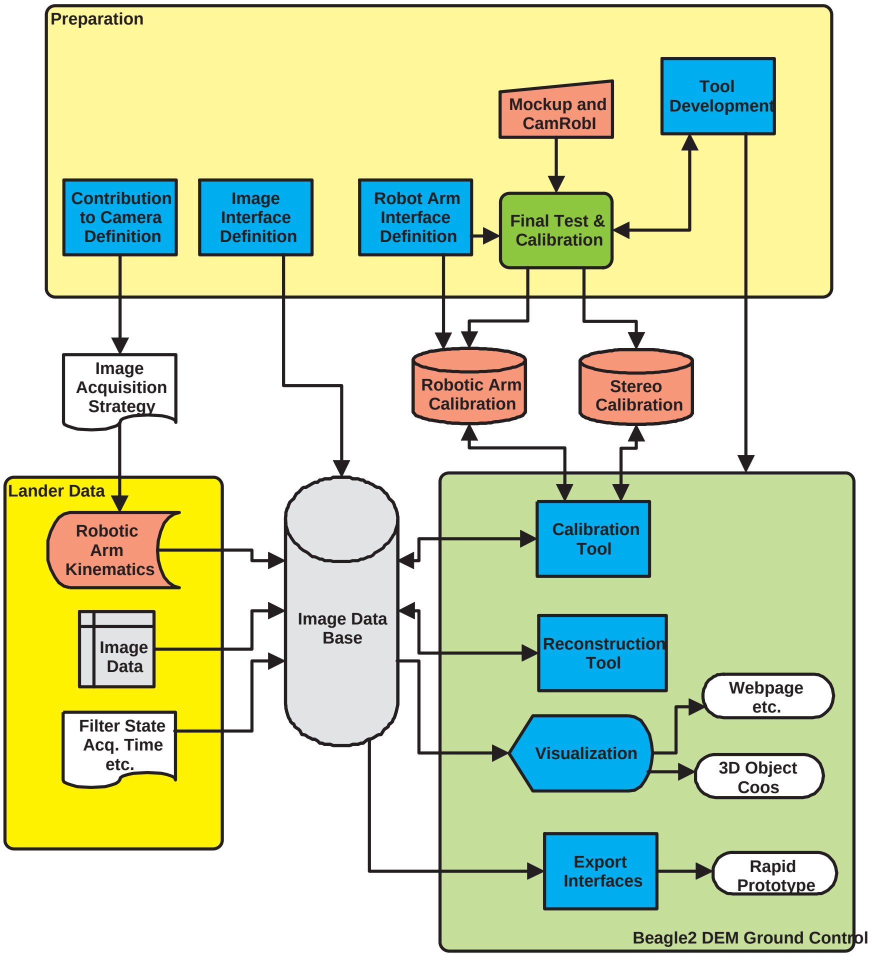

Figure 10. Overview of Beagle2 DEM System and logical components

8. BEAGLE2 DEM GROUND CONTROL AND DEVELOPMENT CONCEPT

Figure 10 gives a rough overview of the Beagle2 DEM System. It is split into the preparation and a ground control part. An essential interface between Ground Control and Lander Data is a sophisticated data base both for input images and output DEM data.

The preparation part uses a mockup and CamRobI for testing. Interfaces to the other teams consist mainly of the image interface and the robotic arm definition. In addition contributions to the camera definition give impact on the image acquisition strategy. Result of the preparation phase is the toolbox to be used for ground control, as well as the calibration of the stereo camera and the robotic arm (in part). The ground control will use the tools (calibration, reconstruction, visualization and data export) to maintain the Image Data Base. Final outputs will be source data for a webpage, individual 3D object coordinates for scientific purposes and the DEM for scientific purposes, rapid prototyping and robot arm path planning.

One issue to be encountered during development is the relatively long time between software delivery (acceptance test during final ground control simulation) and the application period of the result. For that reason a continuous update phase is necessary to ensure operation in possible new environments (platform and operating system). Well documented test cases will serve as data basis for verification of intermediate and final results.

9. SUMMARY AND CONCLUSION

In this work we have presented the concepts and structure of an operational stereo-vision system which is designed to be part of a Mars probe. The preliminary system design covers important hardware on the lander itself as well as software requirements and algorithms for postprocessing of data on ground. We have demonstrated that the necessary technologies for imaging, image processing, stereo matching, 3D reconstruction and visualization are already available. The combination of standard software packages together with thoroughly tested and mature image processing tools developed in recent ESA projects allows for efficient and flexible processing of lander data. Due to the already wide fields of application of the proposed algorithms the system gains robustness in operation since for each individual processing step different strategies can be applied. A development and simulation framework was presented which will enable a straightforward implementation of the proposed concepts, aiming in an operational stereo vision system on Beagle2.

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