Imaging System Design Approach for Robotic Planetary Exploration

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ABSTRACT

The design of demanding imaging systems for planetary exploration is driven by several challenging aspects. The definition of perspective missions on planets with inhospitable environment, require new design approaches to operate in extreme temperatures, pressure and cosmic radiation. In addition the mass, dimensions and energy budget of the system shall be minimised, whereas the scientific aims and the functionality remain challenging and hence require to apply sophisticated technologies.
The described system is designed to have imaging capability for two different needs: scientific imaging and support rover operation. For the first use the system allows imaging in colour and special wavelength giving to characterise the surface: large-scale roughness of the terrain, rock-size distribution and coverage, surface physical consistency, and surface colour. In support to the operation of a micro-rover, it provides images to reconstruct the whole lander panorama as Digital Elevation Map (to allow planning of the micro-rover motion) and additionally allows to continuously estimate the rover position through optical tracking. The imaging system is basically composed of a stereo camera pair with associated mechatronics and optics subsystems. The mechatronics provides a stable structure for camera mounting and mechanisms for mast deployment and 360° azimuth rotation. The camera pair is equipped with fixed focus wide-angle optics and a large scale Active Pixel Sensor to take images with high resolution over a large field of view.
Finally a light source is included to illuminate the working area, since landing and operation may happen not only in light but also shadow or dark conditions.
The technical approach for the imaging system is presented in detail. Special emphasis will be placed on the description of selected optics, camera and mechatronics components.

REQUIREMENTS DISCUSSION AND DESIGN TRADE-OFF

The design approach of the imaging systems is based on requirements and constraints given in [1]. These requirements have been consolidated and fitted to the technological feasibility and available resources. The dominating development goal was to realise an as far as possible robust and reliable design with minimum power, energy and mass budgets.

The Imaging System (IS) shall enable to characterise the surface at the landing site by creating stereo sets of panchromatic and non-stereoscopic colour and specific wavelength pictures with 360° azimuth and 55° [+10, -45] elevation w.r.t. the surface frame, as well at daylight as in darkness. The IS has to compensate a lander inclination of 20° to the planetary surface (i.e. the vertical of the lander bottom to the planetary gravity vector). The original high positional accuracy requirements for digital elevation map (DEM) reconstruction of the terrain to allow planning of the micro-rover motion have been lowered to acceptable values which allow simple designs and require minimum resources.

The positional accuracy, achievable in a given distance from a stereo camera, depends on the image sensor resolution (pixel size), the focal length of the optics (which is determined by the FOV and the sensor size) and the stereo baseline. The DEM reconstruction software, which in conjunction with a suitable IS delivers adequate performances was described in [2]. There are several possibilities to obtain a high positional accuracy, as enlarging the stereo baseline, increasing the sensor resolution or reducing the active FOV (Field of View) maintaining the sensor resolution.

Each of these measures will have considerable consequences concerning general system feasibility aspects, system reliability, number and complexity of mechanisms, mass and energy budgets and costs. Additionally interface constraints as the downlink to Earth of at most 32 Mbits of imagery after a suitable compression and the maximum dimensions of the IS stowed in the lander have to be considered. System parameters as FOV, respective the lens focal length, stereo baseline, sensor resolution (pixel size) shall be optimised to get a reasonable compromise. Desirable is a fixed vertical FOV of 55°, i.e. without necessity of tilting mechanism, a stereo baseline of lower than 300 mm (stereo camera head width in stowed mode). The following assessment investigates the dependency between positional accuracy and the stereo baseline at various FOV. The proposed camera set-up uses the IBIS 4 Active Pixel Sensor (APS) with following basic parameters:

Horizontal Resolution:	1286 Pixels
Vertical Resolution:	1024 Pixels
Pixel Size:	7 µm
Lens Maximum Vertical FOV:	55°
Focal Length:	6.83 mm

Positional accuracy may be calculated by the empirical formula (1).

$$d_{pos} = d^2 \Delta_{meas} \frac{\left(\frac{s}{f}\right)}{l} \quad (1)$$

where

d_{pos}	- Positional Accuracy
d	- Object distance (in meter)
Δ_{meas}	- Measuring error (in pixel), i.e. in which pixel dimension corresponding stereo points may be calculated
s	- Pixel Size (in µm)
f	- Focal Length (in mm)
l	- Stereo Baseline (in mm)

Fig. 1 shows the positional accuracy versus the stereo baseline for three different vertical field angles, where the 55° field is the proposed and favoured set-up. Field angels of 27,5° and 20° require a double respectively triple vertical scanning, which not only leads to the necessity of a tilt mechanism but also to a dramatic increase of image data to be stored and translated.

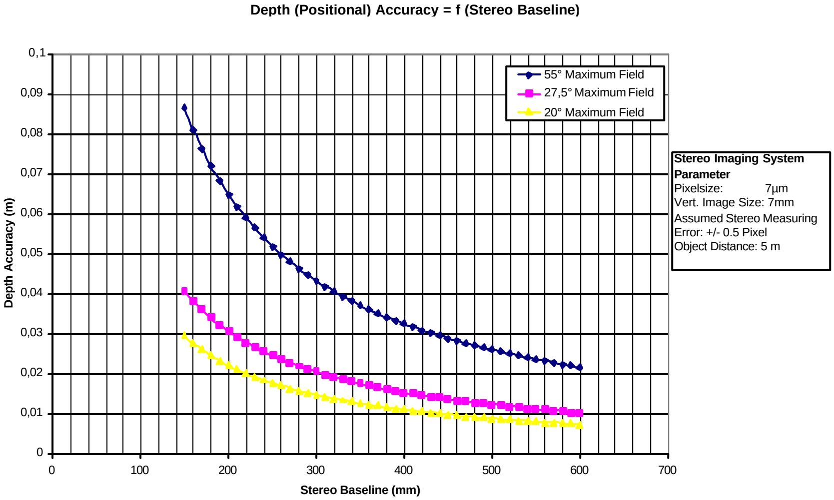

Fig.1. Positional accuracy versus stereo baseline at various FOV

Considering the stereo camera head width constraints (300 mm) and the dimensions of the camera housing, a stereo baseline of 250 mm was determined, which will provide a 50 mm positional accuracy at 5m distance.

From the environmental conditions the operational temperature and the landing shock are the most challenging requirements, e.g. for the night on Mercury the system shall operate on temperatures up to 100 K and during “crash” landing to withstand a half-sine pulse of 200g for some tenth of milliseconds.

SYSTEM CONFIGURATION

The IS is shown in Fig. 2 and consists of following subsystems:

Optical Subsystem
Two identical multiple lens design optics with a wide angle FOV of 88,23° (vertical FOV of 55° and horizontal FOV of 69°) fitted to the image sensor active area of 1024 (V) by 1280 (H) pixels of both cameras.

Camera Subsystem
Two identical camera electronics with an APS Sensor, external 12 Bit A/D converter, FPGA for sensor control and image data acquisition and interface circuits to the lander Digital Processing Unit (DPU). Two camera housings with mechanical interfaces to the camera mast and opto-mechanical interface to the optics. One multicolour illumination device based on a directional multiple LED chip assembly with micro-lenses.

Mechatronics Subsystem
The camera mast assembly mounted to the lander with mechanisms/actuators for unlocking the mast, mast erection, lander inclination correction and 360° camera azimuth rotation including the rotation position sensor. The control electronics as digital controller, command interface level controller, motor controllers, housekeeping unit, analogue multiplexer and A/D converter, is integrated in the bottom of the mast.

Fig. 2. Image System overall view

OPTICAL SUBSYSTEM

The general design approach is a hard focused, wide-angle optical glass objective with parameters given in Table 1.

Table 1. Lens Parameters

Parameter	Value
Focal Length	6.83 mm
Modulation Transfer Function (MTF)	0.4 in the range > 1m ÷ ∞ (at Nyquist frequency)
Transmission with A/R coating reflectivity < 0.01	> 0.9 (460 – 900 nm), > 0.8 (430 – 460 nm)
Focus Range	0.3 m - ∞ (fixed focus)
Resolution in 5 m	11 mm (i.e. textures of 30 mm^2 per sensor pixel)
Straylight	< 10^{-4} of the signal
Dimensions	20 mm diameter, 19 mm length
Mass	17 grams

The lens is designed to operate at an operational temperature range of – 180°C to –160 °C and to withstand total doses of minimum 30 krad without performance degradation. A sectional drawing of the lens is shown in Fig. 3. Lenses are made from different glasses, lens holders and threaded rings are from titanium. Special turning methods during the lens assembly process guarantee high accuracy and stability.

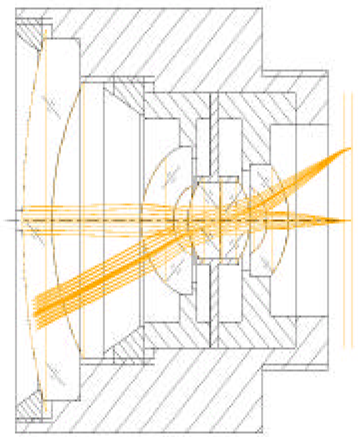

Fig.3 Lens Sectional Drawing

CAMERA SUBSYSTEM

Two camera heads (CH) and an illumination device (ID) are assembled at top of the IS mast (Fig. 2) with a vergence angle of 4° and a fixed tilt angle of 17.5° below the horizontal mast plane. For colour and specific wavelength imaging both sensors at their rims are equipped with different stripe filters (Fig. 4) for daylight operation. The stripe filters are directly coated to the sensor surface and will compensate for a filter wheel mechanism. A multicolour LED illumination device delivers colour imaging capability in darkness. Use of the APS IBIS 4 reduces the camera front-end electronics to a minimum. However, instead of the 10 Bit on-chip ADC a 12 Bit external ADC provides a dynamic range better fitted to the sensor dynamic of almost 11 Bit, considering that dark signal generation, even at integration times of tenth of seconds, may be completely neglected at operating temperatures of 100 K. CHs and ID have simple physical data, command and power interfaces with a minimum of wires. Array of interest readout is implemented to minimise the image data to be transferred. Thus, for day and night stereoscopic imaging and colour imaging at night only the monochrome area of both sensors is read out, whereas for colour daylight imaging only the image windows covered by the stripe filters are translated. The effective LED illumination provides signal to noise ratios >100 in the visible spectrum for distances of 5m on Mercury.
The single CH represents a compact cube manufactured from CFRP with dimensions of $43x43x34mm^3$ and a mass of 86g including lens and a power consumption of 1 W.

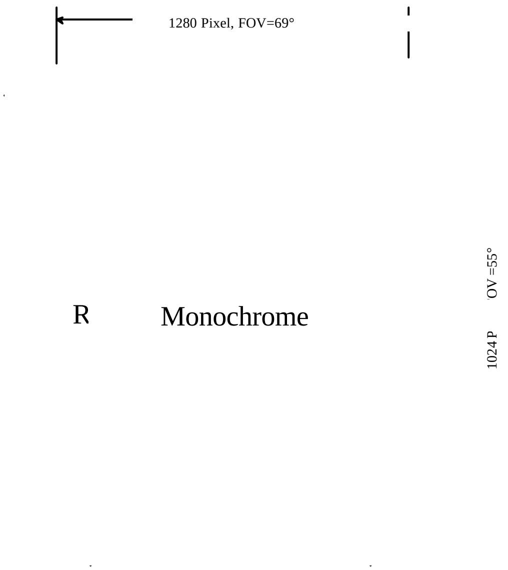

Fig. 4 Image Sensor Colour Stripe Arrangement for a 55° vertical FOV (landscape format)

MECHATRONICS SUBSYSTEM

The mechatronics of the IS provides a stable rotatable structure for precision panorama imaging which is mainly necessary for the accurate rover navigation. Main functional and performance parameters are listed in Table 2.

Table 2 Mechatronics Parameters

Parameter	Value
Azimuth angle positioning accuracy	± 0.5°
Minimum adjustable increment	0.1°
Azimuth movement range	370°
Position measurement accuracy	1 arcminute (i.e. with subpixel accuracy)
Lander inclination compensation	Up to 20°
Minimum number of articulations over lifetime	1000 start/stop cycles

Three actuators are needed for operation of mast elevation, inclination compensation and azimuth angle adjustment. Different mechanisms – i.e. a release rod with a console to hold the mast in the stowed position, turntables for direction and angle adjustment for inclination compensation, turntable for azimuth angle adjustment, the mast with elevation unit driven by compression springs and the traverse at the top of the mast for camera eye distance realisation with the CH and ID adapters – provide the high functionality of the IS. A robust incremental capacitive sensor measures the azimuth angle with the required high accuracy. A RS232 command I/F connects the mechatronics control electronics, which is powered with 5V only, to the lander DPU. The power consumption is lower 3350 mW for all operations and 200 mW in standby. The mass of the subsystem is precisely calculated with 1024 gram.

RESOURCES AND BUDGETS

The decision, if a proposed payload system for planetary exploration may be accepted for a real flight mission, firstly depends on mass (Table 3), power and energy (Table 4) budgets as well as the required data downlink volume to earth.

Table 3. Image System Mass Budget

Subsystem	Mass (grams)
Optical Subsystem (2 lenses)	34.4
Mechatronics Subsystem	1024
Camera SS (2 Camera Heads)	258
Illumination Device	57
Total:	**1373.4**

Table 4 Image System Power and Energy Budgets at daylight and

Budgetary Item	Operation	At daylight		In darkness	
		Stereo	Colour	Stereo	Colour
Power	360° Panorama Imaging	1000 mW	1000 mW	6000 mW	6000 mW
	Deployment, Inclination Compensation, Pointing (in series)	3350 mW	3350 mW	3350 mW	3350 mW
Maximum Current at 5V	Camera "off" during pointing	670 mA	670 mA	-	-
	Camera + Illumination "on"	-	-	1200 mA	1200 mA
Energy	Deployment, Inclinat. Compens., Pointing, Panorama Imaging	3700 Ws	4108 Ws	4177 Ws	5169 Ws
	Imaging without mast deployment/inclinat. compensation	1075 Ws	1495 Ws	1075 Ws	2544 Ws

The resulting image data volumes for panchromatic stereo/colour panorama imaging amount to respectively 201 Mbits/365 Mbits, which requires considerable image compression to meet the at most 32 Mbits of imagery downlink to earth. Acceptable compression rates and useful low-loss algorithms are one of the items to be investigated by means of real images during the following IS breadboard activities.

CONCLUSIONS

A design for an IS for robotic planetary exploration with consolidated performance and functional requirements was proposed. The dominating development goal was to realise an as far as possible robust and reliable design with minimum power, energy and mass budgets. The achieved performance is an acceptable baseline for a realistic mission payload definition.

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