Imaging and localisation software demonstrator for planetary aerobots

Barnes, David Preston; Shaw, Andy; Summers, Phil; Ward, Roger; Woods, Mark; Evans, Malcolm; Paar, Gerhard; Sims, Mark

Published in:
Acta Astronautica

DOI:
10.1016/j.actaastro.2005.07.050

Publication date:
2006

Citation for published version (APA):
Barnes, D. P., Shaw, A., Summers, P., Ward, R., Woods, M., Evans, M., Paar, G., & Sims, M. (2006). Imaging and localisation software demonstrator for planetary aerobots. *Acta Astronautica*, *59*(8-11), 1062-1070. https://doi.org/10.1016/j.actaastro.2005.07.050

PERGAMON

Available online at www.sciencedirect.com

SCIENCE DIRECT®

Acta Astronautica 59 (2006) 1062–1070

ACTA ASTRONAUTICA

www.elsevier.com/locate/actaastro

Imaging and localisation software demonstrator for planetary aerobots[☆]

David Barnes[a,*], Andy Shaw[a], Phil Summers[a], Roger Ward[b], Mark Woods[b], Malcolm Evans[b], Gerhard Paar[c], Mark Sims[d]

[a] *Department of Computer Science, University of Wales, Aberystwyth, SY23 3DB, UK*
[b] *SciSys (Space & Defence) Ltd., Bristol, BS4 5SS, UK*
[c] *Institute of Digital Image Processing, Joanneum Research, Graz, A-8010, Austria*
[d] *Space Research Centre, Department of Physics and Astronomy, University of Leicester, LE1 7RH, UK*

Abstract

Aerobot technology is generating a good deal of interest in planetary exploration circles. Balloon based aerobots have much to offer ESA's Aurora programme, e.g. high resolution mapping, landing site selection, rover guidance, data relay, sample site selection, payload delivery, and atmospheric measurement. Aerobots could be used in a variety of configurations from uncontrolled free-flying to tethered rover operation, and are able to perform a range of important tasks which other exploration vehicles cannot. In many ways they provide a missing 'piece' of the exploration 'jigsaw', acting as a bridge between the capabilities of in situ rovers and non-contact orbiters. Technically, a lighter than air (LTA) aerobot concept is attractive because it is low risk, low-cost, efficient, and much less complex than heavier than air (HTA) vehicles such as fixed wing gliders, and crucially, much of the required technology 'building blocks' currently exist. Smart imaging and localisation is a key enabling technology for remote aerobots. Given the current lack of comprehensive localisation and communication systems, it is important that aerobots are equipped with the ability to determine their location, with respect to a planet's surface, to a suitable accuracy and in a self-sufficient way. The availability of a variety of terrain feature extraction, point tracking, and image compression algorithms means that such a self-reliant system is now achievable. We are currently developing a demonstrator imaging and localisation package (ILP) for a Martian balloon. This ILP system will incorporate a unique combination of image based relative and absolute localisation techniques. We propose to demonstrate our ILP using both simulation and a real laboratory based model aerobot. The availability of both simulated and real aerobot data will provide a comprehensive test and evaluation framework for the ILP functionality.

1. Background

For those planets and moons that support an atmosphere, flying robots are likely to provide a practical solution to the problem of extended planetary surface

---

[☆] This work is being funded under the ESA Contract No. 17400/03/NL/CH.

[*] Corresponding author.

E-mail addresses: dpb@aber.ac.uk (D. Barnes), Roger.Ward@scisys.co.uk (R. Ward), gerhard.paar@joanneum.at (G. Paar), mrs@star.le.ac.uk (M. Sims).

0094-5765/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.actaastro.2005.07.050

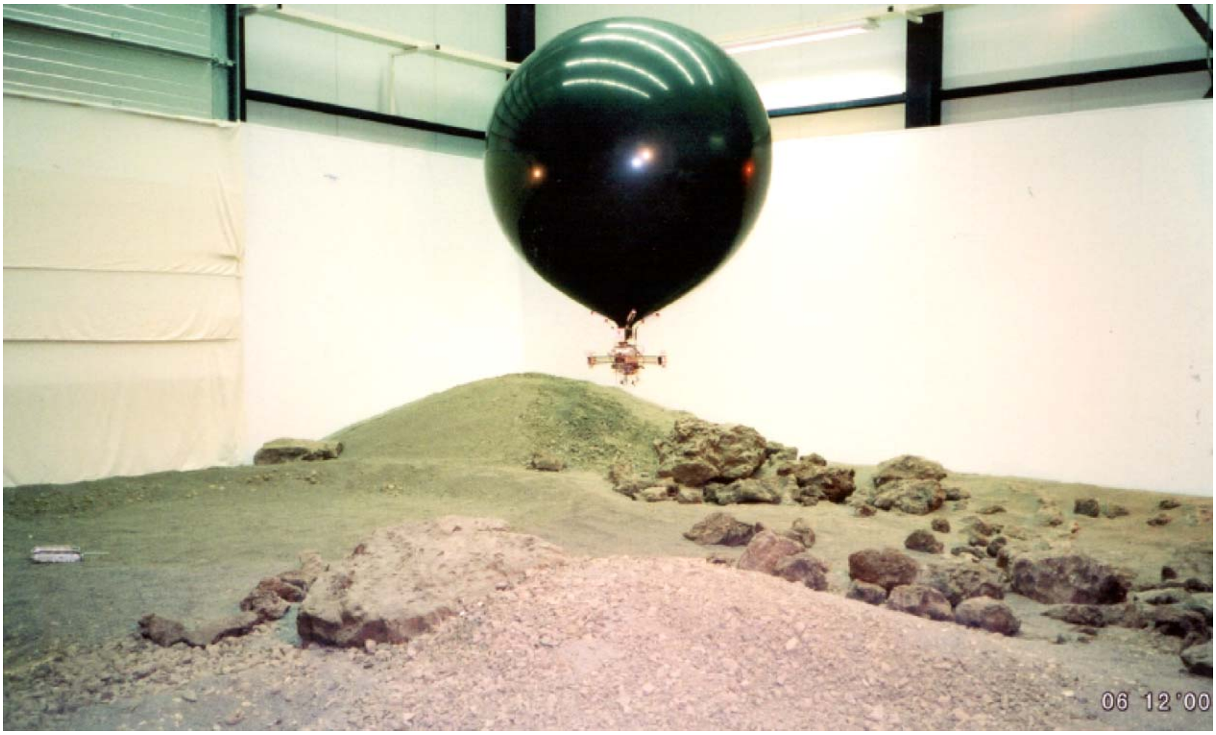

Fig. 1. Prototype ALTAIR-1 being flown at the ESA Planetary Test Bed facility, ESTEC, Noordwijk.

coverage for terrain mapping, and surface/sub-surface composition surveying. Not only could such devices be used for suborbital mapping of terrain regions, but they could be used to transport and deploy science packages or even microrovers at different geographically separate land sites.

Whilst much attention has been given to the use of rovers for planetary exploration, most notably the NASA Jet Propulsion Laboratory (JPL) Mars Pathfinder mission and the Sojourner rover [1], the use of flying robots, or aerobots, for planetary exploration represents a highly innovative concept. Whilst rover technology is clearly competent at facilitating useful science, their application is terrain limited. They are capable of travelling relatively small distances and much of a planet's terrain is impassable to small wheeled vehicles; aerobots in comparison have no such limitations. The technological challenges posed by planetary aerobots are significant [2–5], and we are investigating the design and control of helium filled balloon robots that can fly autonomously to designated landing sites. To study these problems we have constructed ALTAIR-1 [6,7], which is the first aerobot to be designed as part of our ALTAIR (Aberystwyth Lighter Than Air Intelligent Robot) research programme. ALTAIR-1 is a modular laboratory based aerobot designed for rapid prototyping and experimentation within a controlled environment, see Fig. 1. The challenge of flying a planetary aerobot encompasses mobility control and autonomous navigation in a constantly changing 3D environment. Inter-planetary distances prohibit the real-time communication of external meteorological and internal robot state data which would allow human remote control from Earth. An aerobot's long term endurance and ultimate survival can be achieved only if sophisticated autonomous flight control and navigation methods are employed. It is to address these challenges that our research is dedicated.

The main area of interest for balloons in the immediate future, especially on Mars, is planetary ultra-high resolution imaging [8], although later aerobots could carry additional scientific payloads, or provide information for control of surface rovers. Early aerobots, drifting in the vagaries of a Martian wind across its often rugged terrain, will need to be autonomous, communicating with an orbiter as chance permits. With limited resources of memory and power, the main problem will be economic storage and use of acquired images. All unnecessary imagery will need to be suppressed. Perhaps images should be processed to provide the final data required, especially if this processing is a by-product of the aerobot's own needs. Positional data will need to be provided to any scientific package carried. Although other means of navigation could be provided, using already available imagery would be the most economic. Thus our study is designed to investigate localisation to the required accuracy (commensurate with the imagery requirements), economic use of memory to store the vast quantity of images, and the problem of predicting the next communication window with an orbiter, so that the best use of storage can be made to meet the mission targets without loss of any important information. The main outputs of the mission are to be a 3D model of the surface (digital elevation model, DEM), and images of the surface at various resolutions.

This project is to study and design an imaging and localisation package (ILP) for a Martian balloon. The package will allow optimal acquisition of images to reconstruct accurate models of the surface of the explored planet, and accurate localisation of the balloon with respect to the Martian surface. The ILP by means of aerobot mounted cameras and computer vision techniques will:

- acquire and store images of the surface at various resolutions,
- construct and update a 3D model (DEM) of the surface,
- constantly estimate the position (latitude, longitude and altitude) of the aerobot as well as its motion with respect to the surface, and
- decide on the base of the communication budget, of the morphology of the surface and of the information content of the images, which images at which resolution/compression need to be transmitted to Earth.

2. Image acquisition

The image acquisition process must take into account all aspects of camera control—which camera is to be used, its optics (lens, and filtering if required), its parameters (such as integration time, gain, etc.) to obtain the best/consistent image in varying conditions, region of interest, trigger the acquisition at a predefined time, and receive the resultant digital image. Camera selection depends upon the number of cameras used, and what their purpose is. This is primarily a mission dependent decision. The focal length (lens) of the navigation camera(s) will depend on the aerobot height, its maximum speed, and the resolution and FOV required. This may result in a separate camera being required for higher resolution images, or if the aerobot height is expected to vary greatly, different focal lengths for the navigation camera(s). DEMs require the image pairs to be similar but well contrasted. Therefore, with changing planetary conditions, camera exposure parameters may need to be controlled automatically.

An image richness index is also needed to determine the priority to be given to the acquired image to ensure that those of high interest are not lost should the amount of data that could be transmitted to the orbiter become restrictive. The mapping of this index across the image could be used to trigger the acquisition of high resolution images using regions of interest to restrict the memory requirements.

Thus the output of image acquisition is a series of images suitable as input to the subsequent localisation processes and DEM generation.

3. DEM generation

A DEM is a standard data structure for digital representation of a planetary surface. For each x/y coordinate within the represented area a height can be directly derived from the DEM. This makes it a very efficient and straightforward representation for visualisation, map building, structural surface feature detection, navigation, path planning, surface classification and integration into a GIS.

In the aerobot case, DEMs are built using images taken at different positions of the aerobot. For the photogrammetric determination of a distance

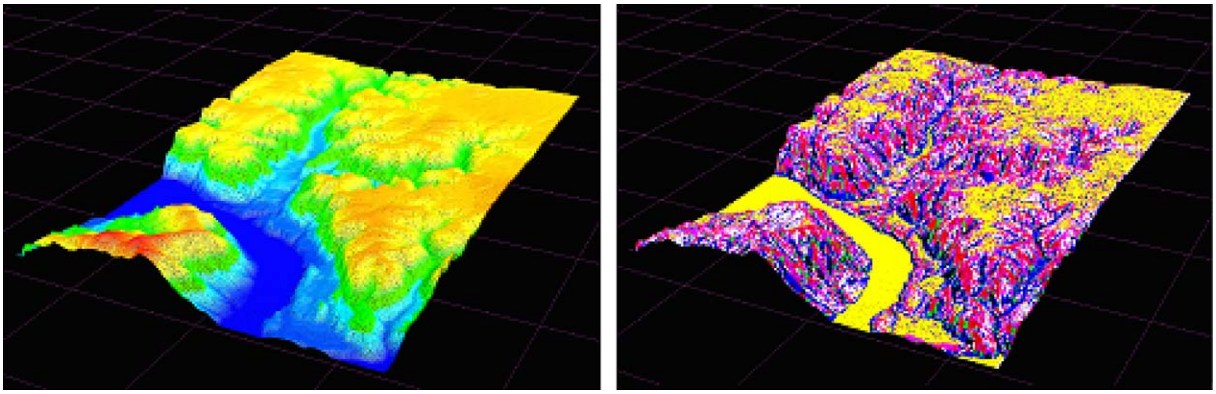

Fig. 2. False height and feature extracted images.

to a certain scene point (without loss of generality in the coordinate system of the temporally first image) the relative orientation between the cameras (pointing and displacement vector) must be known, and the respective scene point must be visible in both images. Consequently, the images involved need to overlap since only within the overlap area a DEM can be generated. Any missing information leads to ambiguities in the resulting DEM data, such as unknown scaling or rotation and displacement with respect to the global coordinate system. Scaling problems can be resolved by one independent distance measurement to a point identified in both involved images (e.g. a laser radar measurement whose direction is known in the camera coordinate system), or the knowledge about the displacement between the stereo images. Integration into the global coordinate system is possible when local DEM landmarks are identified in a global DEM. DEM generation is highly connected to relative localisation since tracking of landmarks in principle is the same process as the stereo matching needed for photogrammetric DEM reconstruction.

4. Localisation—absolute

When conducting experiments in an environment, whether it be image acquisition, atmospheric/surface/subsurface composition analysis, etc., localisation becomes imperative. A problem arises when trying to localise an aerobot on the surface of Mars; this being that preferred localisation systems cannot be used, i.e. global positioning system (GPS) and systems such as rate gyros, accelerometers, flux gate compasses and Sun/star sensors are inadequate by themselves. These systems, therefore, need to be integrated with other sensors such as cameras to provide positional information, which is possible due to recent developments in computer vision. These developments allow the accurate determination of the camera's position with respect to the viewed scene. By matching this viewed scene with a region from a global image, taken either from orbit or during the descent phase, it is possible to derive the aerobot's global position and orientation.

However, the suitability of this approach depends on the relative resolution of target and reference images as problems arise when trying to match images with varying resolutions, i.e. matching low-resolution surface data taken from orbit to high-resolution data taken from the aerobot. There are a number of possible sources of topographical information with global Martian surface data obtained from orbiters, the best of which was gathered from two instruments on board the Mars Global Surveyor (MGS), the Mars Orbiter Laser Altimeter (MOLA) and the Mars Orbiter Camera (MOC) [9].

It is therefore possible to obtain absolute localisation by matching images of a DEM of the region under inspection to regions in the MOLA data [10], see Fig. 2. The accuracy of the position information depends largely on the accuracy and amount of gathered data by the aerobot. The orbiter can also be used to confirm the determined aerobot position occasionally during data upload periods. This method cannot be considered solely for localisation because the position of the aerobot will frequently fall outside the orbital surface trace/track covered by the orbiter.

5. Localisation—relative

Information about position and pointing of the aerobot platform is necessary to spatio-temporally assign each measurement of any sensor on the vehicle. Absolute localisation as described in the previous section would require a DEM generated by the ILP as well as a global reference DEM. DEM generation on the aerobot is computationally expensive and needs morphological landmarks. Conventional localisation sensors may be available but in the standard case they only provide pointing information (star/Sun trackers) or short-term information (gyros, Doppler radar). Therefore landmarks tracking on the images should be used directly for relative localisation. This process fills the gap between short term location sensors and absolute localisation using an orbiter DEM, such that the position and pointing of the aerobot platform is known at any time. The process for relative image-based localisation is based on landmarks tracking on successive images (frames) as displayed in Fig. 3.

The accuracy of relative navigation by image-based 2D landmarks tracking depends on a set of key parameters. They can be divided into system parameters (camera resolution, FOV, camera calibration) and situation dependent parameters which induce a set of different options depending on the availability of information sources apart from the images.

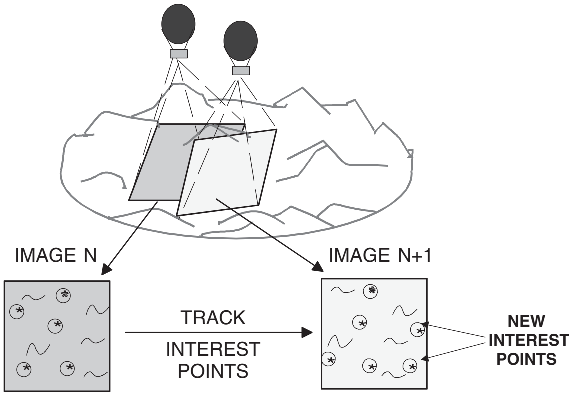

Fig. 3. Principle of relative navigation based on landmarks tracking.

6. Image storage management

Since the time between communications with an orbiter will be variable and doubtlessly long, and the amount of imagery is dependent upon the vagaries of the wind velocity, assuming no area of surface beneath the aerobot is to be lost, image storage management is an important aspect of the study. The image richness parameter is to be used to determine the priority to be given to the image, and possibly the image’s most interesting areas. Because the amount of mass memory is unlikely to be sufficient to hold all images produced before they can be transmitted and then deleted, all unnecessary imagery must be removed. This means that overlap between final stored images should be kept to a minimum, while ensuring that no pixels are lost due to changes in yaw between consecutive images. Reconstruction of the continuous mosaic of images and DEMs must eventually be possible on the ground. This defines the minimum uncompressed imagery required to be stored.

Compression provides a means to greatly reduce and control the actual amount of storage required. Progressive compression techniques (ECBOT wavelet) are to be used to compress the images and DEM data. Such a technique will not only be more resilient against drop out but will allow, for example, the entropy coding to be tailored to meet any data length against image richness profile required by controlling the scaling against signal to noise, resolution, visual quality, or of regions of lesser interest, etc. Since the window of communication will vary as much as the vagaries of the wind, continuous update of the capabilities of the up-link would be required and the compression ratio adjusted to roughly meet the link capability, and the memory storage requirements. However, if the memory storage requirements are not limiting, assuming an acceptable level of compression, then final compression decisions could await the actual beginning of the transmission.

7. Up-link scheduling

Communication links with surface or low-altitude planetary exploration units are usually constrained in terms of frequency, duration and up-link and down-link transmission rates. In addition, real-time commanding is not possible given lengthy RTLT durations. Given that imaging is a data intensive process, the communication link access needs to be optimised by employing intelligent use of available bandwidth and transmission opportunities. Thus the transmissions must be scheduled by predicting the timing and duration of the next up-link of data based on the aerobot's trajectory, the orbit of the relay satellite and the characteristics of the two antennae. During the transmission phase, the link must be acquired, any commands received and confirmed by the aerobot, before its image data can be transferred up to the orbiter, and their correct receipt confirmed. Only then can any images be deleted to make space for the new collection of images. Another aspect that needs to be addressed is signal loss during transmission. What is to be done with the images not transmitted and confirmed, and therefore not deletable as expected? This may need to involve not only the calculation of the next transmission window but the one after that. Thus images are not compressed excessively because the next window is some time off and narrow when the subsequent one is soon after and of much longer duration. A method of dynamically controlling the level of compression without repeating the whole procedure would obviously be a major advantage, since most compression procedures, including wavelet, take considerable computing power in the timescale of image acquisition requirements.

8. ILP demonstrator overview

The ILP demonstrator system proposed requires two distinct modes, a hardware mode that encompasses a real RC balloon plus camera with RF interface and a balloon simulator, both modes being interfaced to a demonstrator shell and associated ILP software.

The use of a simulator as one of the core demonstrator components affords a number of advantages over a hardware-only solution:

- repeatability of experiments;
- simulation of environments that cannot be reconstructed within the laboratory.

Simulators are able to re-construct environments and terrain to a very accurate level whilst still allowing the user to maintain control over the specific parameters. Terrain, weather, atmosphere and hardware devices, such as cameras, can be simulated in a realistic way and noise can be modelled to allow for random fluctuations in the environment or manufacturing tolerances for instruments [11], see Fig. 4. A simulator will be well suited for modelling the flight of a balloon over terrain, experiments cannot always be carried out due to numerous factors and the use of simulation will overcome any of these potential problems.

The trajectory of the balloon would initially be supplied to the simulator, with periodic updates being sent. During periods when the trajectory of the balloon is unknown, interpolation could be used to provide an estimate of the current trajectory. This provides a simplistic but sufficient method, for controlling and modelling the trajectory of the balloon.

A simulator also affords the ability to evaluate algorithms for localisation and control that may be difficult to examine on real hardware in an Earth-based environment. A major factor in the deployment of planetary balloons is the effect the environment and atmospheric conditions have upon the balloon. Although the modelling of haze, clouds and shadows is important, the role that the wind plays is significant. This wind could potentially affect the performance of the ILP and therefore should be modelled to provide as realistic a simulation as is practicable.

Having decided that a dual hardware mode and a balloon simulator mode are required, and identified essential balloon simulator capabilities, one must return to the hardware mode components, and address their requirements. In the first instance, the hardware laboratory environment must be considered. Clearly, this must be large enough to fly an indoor balloon, and allow a terrain model to be created, but it must have sufficient headroom so that a balloon's altitude can be altered whilst gathering terrain image data. The use of the ESTEC Planetary Test Bed (PTB) is proposed as this will provide an ideal real test

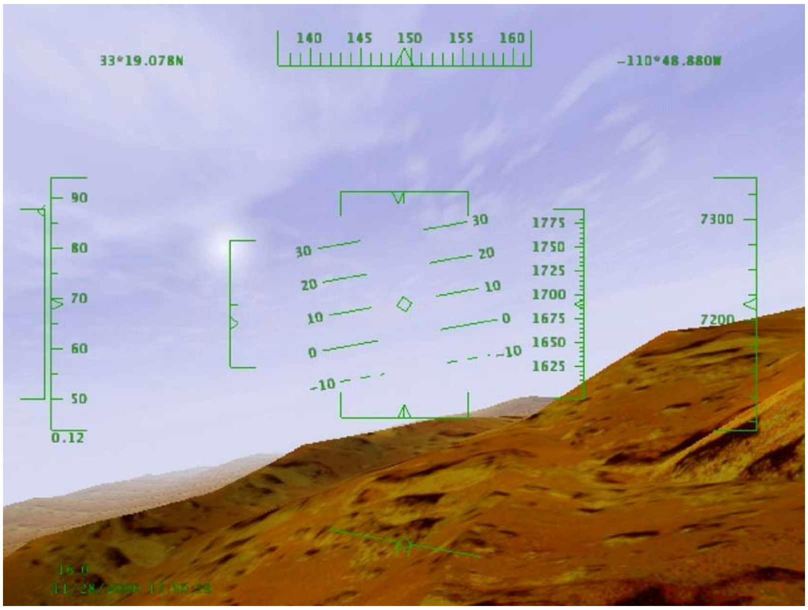

Fig. 4. Screen shot of the aerobot simulator software.

environment. Firstly, its size is compatible for flying a relatively small helium filled balloon and associated ILP hardware. Secondly, the PTB already has a real terrain, which can be used for system demonstration purposes. Thirdly, the presence of heating (from a number of sources including PCs) will ensure that some (albeit small) air currents are present. Even small air currents affect the flight motion of an LTA balloon. UWA has demonstrated its prototype aerobot at the ASTRA 2000 workshop in a laboratory adjacent to the PTB, and are therefore aware of the potential of PTB for real demonstration purposes.

A demonstrator software shell will provide a number of functions, ranging from the control of the balloon hardware and simulator, presentation of data gathered and on to eventual evaluation of the complete system and ILP performance. To this end the demonstrator shell software must encompass enough flexibility to be able to efficiently and effectively perform all these tasks and experiments. The demonstrator shell will need to communicate with both the real balloon hardware, see Fig. 5, and the balloon simulator in order to receive up-linked DEMs and images and to download camera models and balloon trajectory information, see Fig. 6. The shell will allow selection of the demonstration mode, hardware or software, provide an interface to allow selection and upload of camera, antenna and terrain models and enable the user to define the communication window function. The ability to create a demonstrator configuration and save this for later use would also be desirable. The provision of simulator control functions is also part of the requirements for the demonstrator shell. The user will be able to start, stop and pause the simulation at will. Another function afforded by the demonstrator shell is the display of demonstrator software status. This will consist of the data provided to the demonstrator shell by the balloon simulator and the data produced by the ILP demonstrator. A graphical interface will be used to display this data in a clear and concise form. The presentation of this ILP data will incorporate the display of image mosaics. This implies that the demonstrator shell must be able to reconstruct the sequence and determine the placing of the individual images within these mosaics. It must also be possible to display the DEM data received by the demonstrator shell. This DEM data should be presented in a format suitable for easy visualisation. The rendering of either a perspective, top-down or orthographic view of the DEM data could achieve

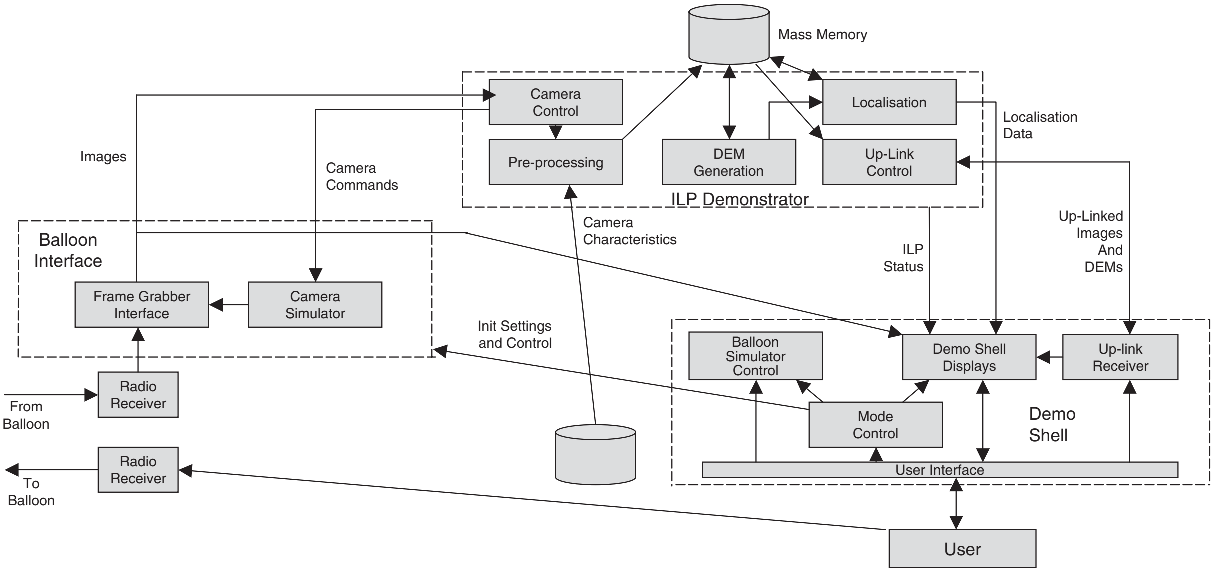

Fig. 5. Schematic of our ILP demonstrator system with balloon interface (not all data exchanged by different elements are included).

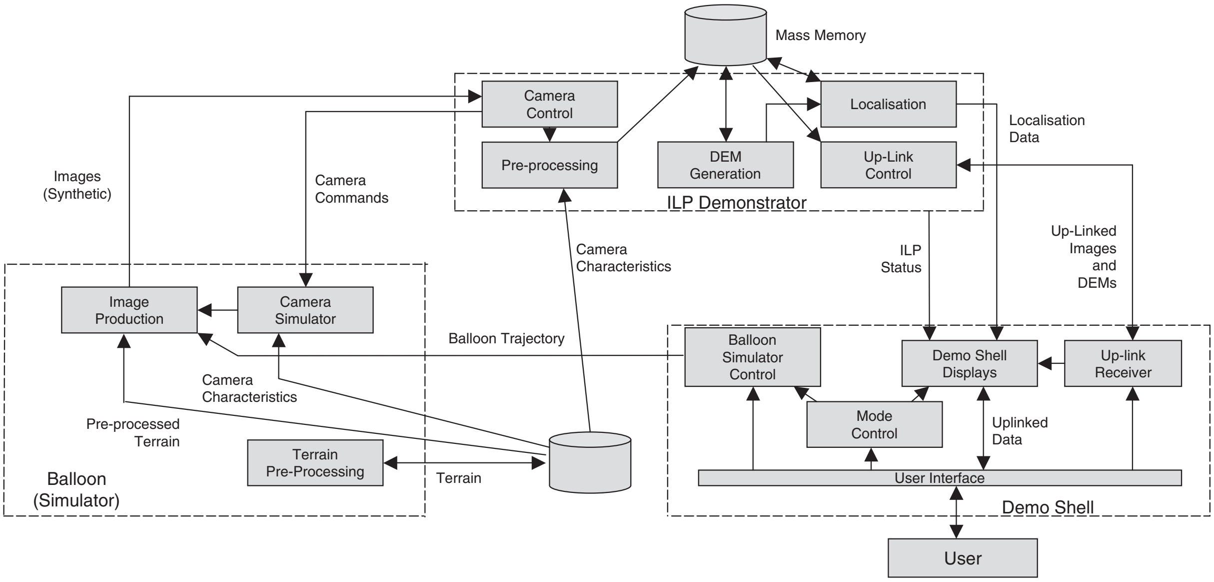

Fig. 6. Schematic of our ILP demonstrator system—software mode only (not all data exchanged by different elements are included).

this. Additionally, functionality should be provided to perform measurements on the said DEMs such as the co-ordinates of individual points and the distance between selected points. The majority of this functionality is already available within software produced by Joanneum Research. Furthermore, the demonstrator shell will allow the performance of the ILP system to be measured, perhaps by providing a representation of where the ILP thinks the aerobot is in relation to where the aerobot actually is. The demonstrator shell must communicate to and receive communications from both the real hardware and the software simulator. To this end all communications to either of these devices should take place via an interface module. This module must present a common interface to the demonstrator shell to enable seamless integration and selection of both hardware and software modes.

9. Conclusion

We have begun a study to design and implement an Imaging and Localisation Package (ILP) for a Martian balloon. An overview of the rational for sending an LTA aerobot to Mars has been presented. Whilst there are many challenges, we believe that the technology 'building blocks' are available to launch a planetary exploration robotic balloon to Mars within the next launch opportunity windows (2005, 2007, 2009). We are proposing a novel combination of imaged based relative and absolute localisation techniques. We propose to demonstrate our ILP using both simulated and real aerobot data, and thereby provide a comprehensive test and evaluation of the ILP functionality. We will report on this work in future literature.

Acknowledgements

The authors would like to thank G. Visentin (ESA D/TOS), Head of Automation and Robotics Section, and C. Hansen (IMT-CTM), Contracts Officer, for their collaboration with this work.

References

[1] H.W. Stone, Mars Pathfinder Microrover a Small, Low-cost, Low-power Spacecraft, Jet Propulsion Laboratory, 1996.

[2] J.A. Cutts, K.T. Neck, J.A. Jones, G. Rodriguez, J. Balaram, G.E. Powell, S.P. Synnott, Aerovehicles for planetary exploration, IEEE International Conference on Robotics & Automation, 1985.

[3] J. (Bob) Balaram, R.E. Scheid, P.T. Salomon, On-Board Perception System for Planetary Aerobot Balloon Navigation, 23rd AUVSI, Orlando, FL, 1996.

[4] K.T. Neck, J. Balaram, M.K. Heun, S. Smith, T. Gamber, Mars 2001 Aerobot/Balloon System Overview, AIAA 97-1 447, 1997.

[5] M.K. Heun, J.A. Jones, J.L. Hall, (JPL, Pasadena, CA), Gondola design for Venus deep-atmosphere aerobot operations, AIAA, Aerospace Sciences Meeting & Exhibit, 36th, and 1998 ASME Wind Energy Symposium, Reno, NV, 1998.

[6] D.P. Barnes, P. Summers, A. Shaw, An investigation into aerobot technologies for planetary exploration, 6th ESA Workshop on Advanced Space Technologies for Robotics and Automation, ASTRA 2000, December 2000, pp. 3.6–5.

[7] A. Shaw, P. Summers, E. Geneste, D.P. Barnes, ALTAIR-1: a laboratory based aerobot for planetary exploration experiments, Proceedings of EUREL European Advanced Robotics Systems, Masterclass and Conference, Salford, UK, April 2000.

[8] M. Heun, H.M. Cathey Jr., R. Haberie, Mars balloon trajectory model for Mars geoscience aerobot development, AIAA, International Balloon Technology Conference, San Francisco, CA, 1997.

[9] <http://mars.jpl.nasa.gov/mgs/>, Mars Global Surveyor (MGS).

[10] A.J. Shaw, D.P. Barnes, Landmark recognition for localisation and navigation of aerial vehicles, IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Las Vegas, October 2003.

[11] <http://www.flightgear.org/>, The Flight Gear Flight Simulator.