EMBEDDING SENSOR VISUALIZATION IN MARTIAN TERRAIN RECONSTRUCTIONS

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ABSTRACT

The PASTEUR payload on the ESA ExoMars Rover 2018 contains a panoramic imaging system (PanCam) specifically designed for visual characterization of the Rover's surroundings and remote detection of potential sample sites. PanCam with its wide angle stereo camera pair WAC (Wide Angle Camera) and the narrow angle HRC (High Resolution Camera) provides data for 3D reconstruction of the Rover's environment which is fed into a real-time rendering suite to allow virtual representations for scientific investigations and planning. One of the other PASTEUR sensors is WISDOM (Water Ice and Subsurface Deposit Observation On Mars), a ground penetrating radar that will allow the definition and representation of suitable drilling locations.
This paper describes major exploitation modes of PanCam 3D vision and its virtual 3D data presentation tool PRo3D, in cooperation with the WISDOM Team. The PanCam visual data presentation tool PRo3D is able to include 3D visualizations of WISDOM data for a joint presentation in a unique coordinate frame. We report on the necessary data scheme for real-time multi-resolution rendering. The workflow of PanCam-to-WISDOM data fusion is sketched, and the operations, interactions and data assessment tools available in PRo3D are described. An example is given from a joint ESA-initiated test campaign in Chile in 2013 (the SAFER Campaign).

1. INTRODUCTION

The ExoMars 2018 Rover Mission contains the panoramic scientific camera system PanCam [3], which is designed to provide stereo imaging capabilities. For geologic medium range survey, scientific target determination and operations purposes the Rover's environment is reconstructed in 3D, making use of a 3D Vision processing chain [6] that is able to generate a textured 3D surface model, to be properly presented to the interpreting & planning scientists and engineers.

One aspect of this framework is a virtual environment that allows to interactively explore the virtual Martian terrain reconstructed from PanCam stereo imagery: PanCam is a part of the ExoMars on-board scientific sensors' suite PASTEUR [2]. Based on PanCam-provided 3D models in the context of the PASTEUR data exploitation it is possible / necessary to simultaneously visualize different sensors' data within the 3D scene in joint consistent geometry. This preserves the geospatial context and enables a combined perception of topographic and physical properties, thereby providing a valuable additional tool for in-depth scientific analysis.

In particular, data from the WISDOM (Water Ice Subsurface Deposit Observation on Mars, [10]) ground penetrating radar (GPR) was considered for this kind of embedded visualization. WISDOM is designed to investigate the near-subsurface down to a depth of ~2-3 m, commensurate with the sampling capabilities of the ExoMars Rover's drill.

2. 3D DATA REPRESENTATIONS

2.1. PanCam 3D Vision Products for Visualization

ExoMars PanCam provides wide angle multispectral stereoscopic panoramic images (~34° FOV, 50cm stereo base) at a resolution of 1024x1024 pixels. Typical 3D vision products derived from PanCam data are distance maps giving detailed information on the Martian surface topography from the Rover's perspective. Depending on the parametrisation used for processing distance accuracies down to 3mm can be achieved in 2m distance to the Rover (~20mm in 5m distance, ~70mm in 10m distance). The 3D surface data are complemented by texture information, varying from single to multi-channel data. The combination of high resolution texture and 3D surface information simplifies the identification and selection of scientific targets.
The distance maps are generated by a stereo processing chain. Image pairs are matched to get the disparities as relative depth information for each image point. Together with the orientation information of the left and right camera the 3D surface model typically is reconstructed with the PanCam's position as center for a spherical projection – depending on GNC information

provided this can be in the Rover, Lander or Planet coordinate system. Depending on the number of available stereo image pairs taken at the same Rover position, a variety of neighboured distance maps can be combined in a mosaicking step, resulting in a full 3D reconstruction e.g. by means of a Digital Elevation Model (DEM) up to 360° around the Rover.
Distance maps for larger distances up to several hundred meters from the Rover are processed from two overlapping images captured at different Rover positions to realize a wider base line (forced by the distance accuracy that shall be reached).
Regardless of imaging geometry the output format of the panoramic stereo reconstruction is in *generic point cloud* format (*GPC*) consisting of an xml file that refers to the 3D geometry data file and the orthographic image, typically a grid in spherical coordinate space centered by the sensor (middle point between cameras).
In addition to these basic point cloud data the GPC is capable of holding further attribute layers, e. g. multispectral texture.
For visualization purposes the GPC is converted to an *OPC* (Ordered Point Cloud) format which contains the 3D data in different pre-processed resolutions to facilitate level-of-detail rendering in the PRo3D viewer. By special ordering of points used in the OPC a mesh structure is implicitly given. Each OPC is split into one or more patches (see Figure 1), each patch containing all the data that is valid within a square section of fixed size (e.g. 256x256). For each patch the following data is maintained:

- The array of 3D positions of OPC points
- The index array of (non-planar) quads that make up the OPC
- One or more parts of the texture that are valid for the patch geometry.

For each image part the following data is maintained:

- The image part (texture)
- The texture coordinates for mapping the image part onto the patch.

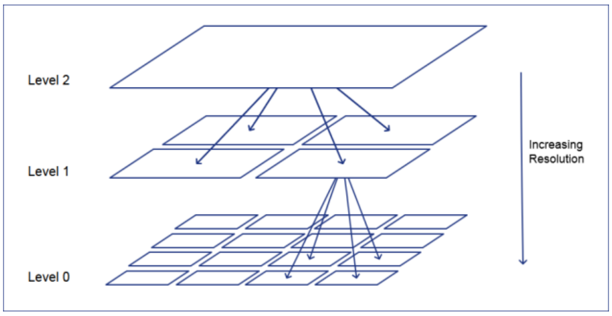

Figure 1: Hierarchical OPC data structure

2.2. WISDOM 3D DATA FOR VISUALIZATION

The WISDOM ultrawideband ground penetrating RADAR yields insights on the Martian subsurface at centrimetric resolution up to a depth of 3 meters below the ExoMars Rover. This data is not only of interest from a scientific point of view but also for operational aspects as it allows the identification of interesting drilling sites and possible hazards to the drilling process. For these purposes three kinds of data products are provided for the joint visualization representing subsurface structures and information:
1. A WISDOM subsurface contrast profile as a 1D-dataset for each given measurement position being equivalent to the normalized measured RADAR signal in time domain, but with depth correction considering an estimated effective permittivity. Brightness values between 0 and 1 are given for subsurface points within the footprint of the WISDOM antennas.
The subsurface contrast profiles along the rover path can be combined and visualized as so-called radargrams (see Figures 7 and 9).
2. The WISDOM subsurface interface data stores the geometry and normalized brightness values for a detected interface for a specific estimated dielectric permittivity and permittivity contrast between two subsurface layers being separated by this interface.
3. A WISDOM subsurface object depicts minimum and maximum surface representations of buried scatterers with associated probabilities.
The data is given in VTK xml format for point meshes and unstructured meshes. Along the actual subsurface data, metadata on the measurements and processing steps is provided as well.

3. PRO3D: PLANETARY ROBOTICS VIEWER

3.1. Scientific rationales for visualization

Scientists will be able to explore 3D reconstructions of the planetary surface captured by PanCam from various viewpoints with an interactive viewer, *PRo3D*. In contrast to other existing tools PRo3D addresses special requirements from the planetary science community, especially geologists. Such requirements are:

- Explore and analyse the surface structure, especially investigating outcrops from various viewpoints, in different scales
- Measure dimensions, distances and inclination of sedimentary layers
- Watch sensor values in geospatial context, including in particular subsurface WISDOM data
- Annotate in a geological sense.

PRo3D focuses on exploration and analysis of reconstructions of planetary terrain. The tool 3DROV [1] also provides a visualization component based on surface reconstruction. However the focus is on showing simulation results of Rover operations and planning.

PRo3D allows geologists to zoom within a broad range of scales to study structures from a large distance but also from close-up. As an example, Figure 2 shows a total view of a rock outcrop and in Figure 3 a zoom into it is displayed, to reveal surface details. This demands a high geometric accuracy and sophisticated data structures to access them in an interactive way in real-time.

Figure 2: Total view of rock outcrop (real diameter: about 5 meters).

Figure 3: Close-up showing surface details (real diameter of surface patch: about 50 millimeters).

3.2. PanCam Visualization in PRo3D

Like with computer games, in PRo3D users can virtually walk or fly through the 3D scene to investigate the environment, make measurements and inspect sensor data displayed at corresponding locations. The main difference to games is the accuracy of the virtual reconstructions. The geometric resolution is much higher and needs to be sufficient for scientific analysis.
Sophisticated real-time rendering techniques were applied to enable this high accuracy in an interactive viewer. The reconstructed terrain is represented in different levels of detail (LOD) [4] [5]. The viewer automatically sets the appropriate level depending on the distance from the viewpoint. This is done independently for different patches of the terrain such that close-by areas are shown in more detail than those further away. LODs also allow a seamless zoom within a broad range of scales, such as from orbital views to close-up details on the surface. Figure 4 illustrates the LOD technique.

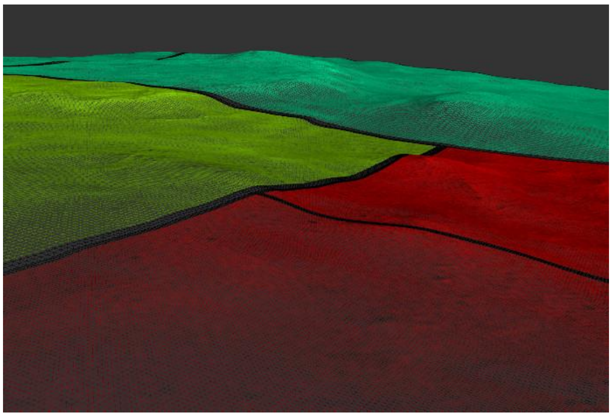

Figure 4: Surface patches (Example: HiRISE DTM in the vicinity of MER-A Home-Plate) with different LODs (Red: Most detail, blue: least detail).

Sensor data can be displayed within the 3D scene at the appropriate location, where measurements were performed. This is achieved by combining 3D *information visualization* methods [8] with *real-time rendering* [7]. Extra 3D objects and false colour textures are added to the scene to display numerical sensor values. The advantage of this combination is that the geospatial context of sensor values is preserved. Scientists are able to simultaneously investigate topographic and physical properties, which supports to discover correlations and to gain the overall picture. Section 3.3 explains how radar data from the WISDOM instrument is visualized in this way.
To be able to measure the geometric relationships between surface and underground features the viewer provides interactive tools for various types of measurements in 3D space. Scientists can inquire exact geo-coordinates of selected surface points. They can measure the distance from the viewpoint to a selected surface point or the distance between two such points (see Figure 5). Besides line-of-sight (or linear distance) the way length on the surface between two points can be calculated (projected line-of-sight). An additional tool allows to specify a path on the terrain consisting of several points. The length of these paths are calculated. This polyline tool can also be used to mark regions of interest and thereby annotate the scene (see Figure 6). Furthermore, users can load 3D objects (e.g. scale bars, Rover models). 3D data interfacing is done via commonly available schemes such as the Visualization Tool Kit *VTK*, which is exploited also for WISDOM data import.

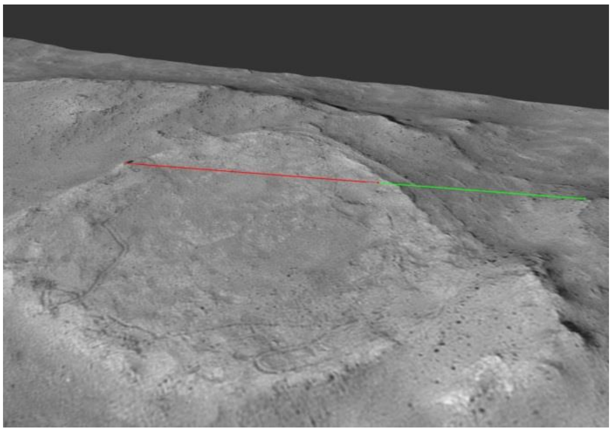

Figure 5: Measuring the distance between terrain points (Credits: Tao and Muller, EPSC, 2014).

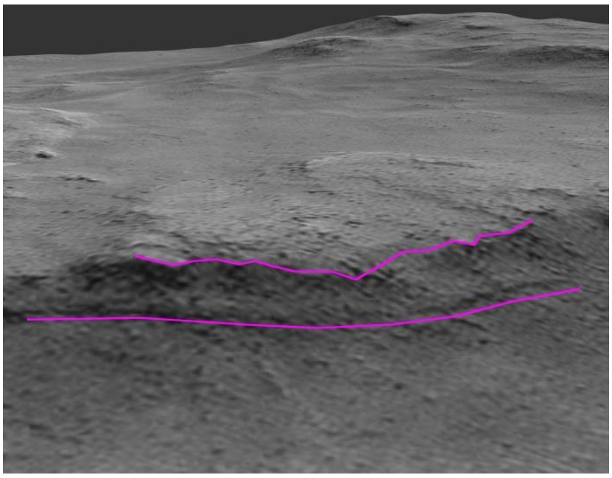

Figure 6: Drawing a polyline to mark and measure a region of interest.

Measurement tools allow to get actual dimensions of the reconstructed terrain, which is especially important for geological assessments. Geological features can be quantified and compared. For example faces of sedimentary layers can be delineated and the inclination of beds can be estimated.
Physical properties can also be quantified in relation to geological features by using measurement tools. Concerning WISDOM the spatial extent of radar data becomes apparent, especially the achievable depth.

3.3. WISDOM Visualization in PRo3D

To compare surface characteristics with subsurface structures it is important to visualize both WISDOM and PanCam products in the correct geospatial context.
For each geo-referenced location of single sounding, WISDOM will provide the location and depth of buried reflectors. Several of such measurements performed along a path of the Rover can be visualized by a sweep at the correct geo-referenced position. Radar values reflected from different depths are displayed as false colour dots along a vertical line. A mesh is created between these lines and a texture is derived by interpolating the measured values of the dots. Figure **7** for an exemplary GPR data set shows both single lines at actual measurement locations as cylinders and a mesh representing a measurement path with colour coded interpolated values.
The data exchange between processed WISDOM readings and the viewer is managed via standard VTK [9] files, see Section 2.2.

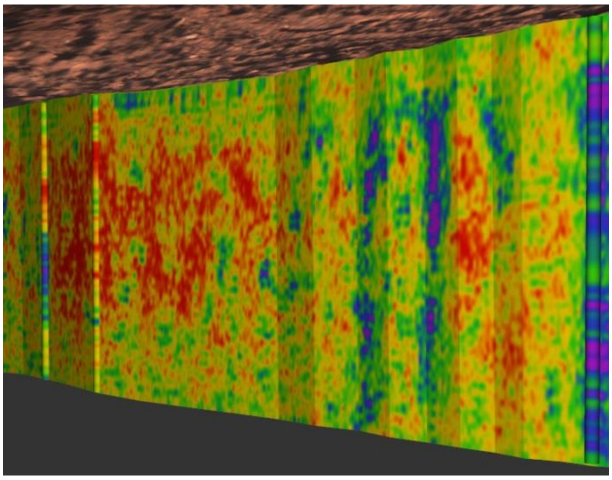

Figure 7: Visualization of GPR data.

3.4. PANCAM AND WISDOM DATA FUSION

The global data flow from data capture to sensor fusion in PRo3D is depicted on Figure 8. Products from PanCam and WISDOM are independently processed and georeferenced, and loaded into PRo3D.

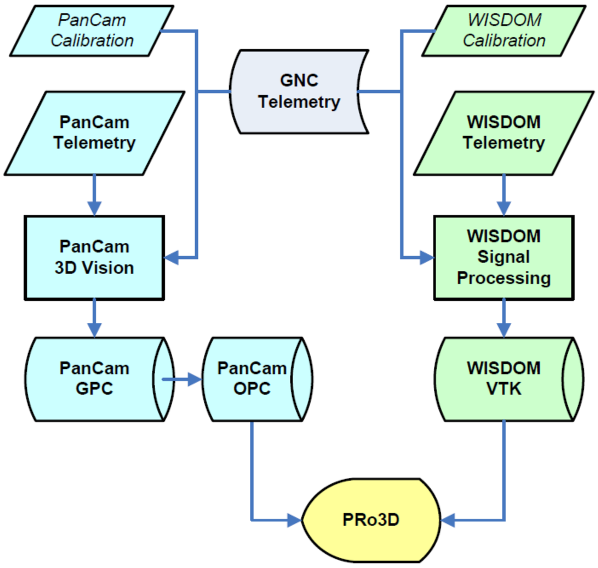

Figure 8: Global data flow for PanCam-WISDOM fusion within PRo3D.

For unified geometric context of PanCam-provided 3D surface models and WISDOM scans it is necessary to know the position and orientation of the involved sensors with respect to the Rover, based on joint calibration during Assembly, Integration and Test (AIT). A practical approach thereto is to use white metal disks with 5 to 10 cm diameter. These should show good contrast in PanCam images as well as WISDOM data. For in-flight calibration check, features on the landing platform could be used before / during the rover's egress.

To get the global position and orientation of the sensor data one needs to know the global position and orientation of the Rover at data capturing time. These are determined by the Rover Guidance, Navigation and Control (GNC) system: The GNC periodically updates the position and orientation of the Rover based on data from the Inertial Measurement Unit (IMU) and the odometer. For proper fusion of several PanCam and WISDOM data sets a synchronized GNC data set has to be attached to each of the sensor data sets.

4. PANCAM & WISDOM AT SAFER TRIALS

The Mars Rover mission simulation campaign SAFER (Sample Acquisition Field Experiment with a Rover, [12]) led by RAL and supported by ESA, took place in the Atacama Desert in October 2013. The main purpose of the project was to simulate as accurately as possible an actual Rover mission (very similar to the forthcoming ExoMars Rover mission) that would look for interesting places to collect samples of the shallow Martian subsurface. Indeed, three development models of ExoMars instruments (PanCam, WISDOM and CLUPI) were accommodated on-board a prototype of the ExoMars Rover chassis model provided by Airbus Space & Defence, UK. The field experiment in Chile was remotely controlled from an operation center located at Harwell, UK. During the six days of the trial, the decisions made by the remote control team were essentially based on data collected in Chile (images by PanCam and CLUPI mock-ups, and radargrams of the shallow subsurface built from WISDOM mock-up data [11]) since no direct interaction between the remote center team and the field team was possible. This remote configuration made the need for visualization extremely important in order to make the best decision for the Rover and drilling operations, namely choose the Rover path for the next day and identify a location where to drill. A large video wall was used to display the images of the surface as well as the radargrams of the subsurface in the same 3D environment.

During this SAFER experiment, a prototype very similar to the future WISDOM flight model has been used to collect data. A total of more than 3000 soundings were performed by WISDOM covering a distance of approximately 200m over the 6 days of the trial. For each of the soundings, the 3D location of the WISDOM antennas mandatory to build the radargrams were provided, and visualization of the subsurface in a 3D environment following the Rover path was possible. This allowed to identify a potential interesting rock interface at 60 cm buried beneath the surface in an area, the presence of which was confirmed by a drilling simulation performed afterwards. For some of the WISDOM sites also PanCam surface 3D vision products could be obtained. After localization by means of the Rover GNC data, a fusion in PRo3D was possible (Figure 9).

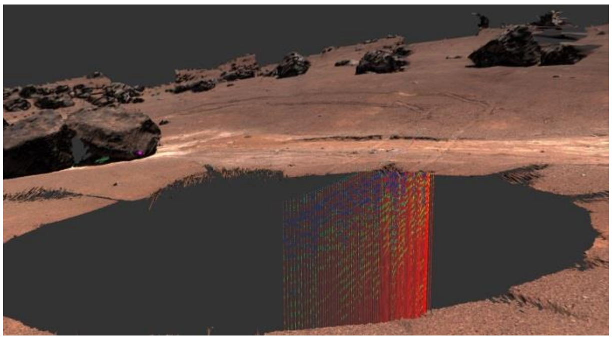

Figure 9: PRo3D Visualization of PanCam OPC and WISDOM VTK data set captured during SAFER trials

5. CONCLUSIONS AND OUTLOOK

Data fusion and visualization of PanCam and WISDOM 3D data products has been successfully tested during the ESA SAFER Campaign having taken place in Chile in 2013.

The possibility to embed WISDOM data in PanCam terrain visualizations enables the analysis and interpretation of subsurface data in its surface context yielding a better understanding of the geologic structures at hand. A high resolution digital elevation model (DEM) derived from PanCam images taken from surface areas selected for WISDOM measurements may improve the accuracy of surface permittivity values derived from WISDOM data. The projection of the WISDOM antenna footprint on a precise DEM will significantly support de-embedding of subsurface features detected by WISDOM measurements.

The current version of the presented PRo3D viewer already enables the virtual exploration and analysis of reconstructed Martian terrain. It provides a valuable tool for scientific investigations and operations planning. A future version of the PRo3D viewer will provide simulated PanCam views to see the reconstructed Martian environment from the Rover's perspective. Furthermore it will be possible to render still images from chosen viewpoints in photorealistic quality and produce videos sequences from navigation paths.

Further work will be conducted to enhance the possibilities to adapt visual appearance of WISDOM data, for data manipulation, and embedding further sensors' data such as the Infrared Spectrometer ISEM.

WISDOM data processing will be extended to provide the certainty margins of the measured data for visualization in the 3D context. The clear target is a better understanding of the underground and surface situation in geological context.

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