HDPR: A MOBILE TESTBED FOR CURRENT AND FUTURE ROVER TECHNOLOGIES

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ABSTRACT

The paper in hand presents a mobile testbed –namely the Heavy Duty Planetary Rover (HDPR)– that was designed and constructed at the Automation and Robotics Laboratories (ARL) of the European Space Agency to fulfill the lab's internal needs in the context of long range rover exploration as well as in order to provide the means to perform *in situ* testing of novel algorithms. We designed a rover that: a) is able to reliably perform long range routes, and b) carries an abundant of sensors (both current rover technology and futuristic ones). The testbed includes all the additional hardware and software (i.e. ground control station, UAV, networking, mobile power) to allow the prompt deployment on the field. The reader can find in the paper the description of the system as well as a report on our experiences during our first experiments with the testbed.

1 INTRODUCTION

In the research context of planetary exploration rovers, it is crucial to benchmark our algorithms in representative scenarios. As the rovers become ever more advanced in power and mobility, such test scenarios should be long range (i.e., 1+ km). Moreover, these tests should be useful for assessing future technologies such as global localization [1] and for evaluating new sensors such as Time-of-Flight cameras (ToF) [2]. Unfortunately, most of the available space-oriented datasets, with the exception of ESA's Seeker activity [3] and the work in [4], are not ideal for such tests. Furthermore, the Automation and Robotics Lab (ARL/TEC-MMA) of the European Space Agency (ESA) did not possess (internally) a long-range mobile testbed rover which was capable of performing such missions. Therefore, the authors decided to build a rover —along with special infrastructure such as a ground control station, accurate RTK GNSS positioning for ground truth, etc.— which is able to fulfill these mission objectives. The rover, depicted in *Figure 1*, is named Heavy Duty Planetary Rover (HDPR) and is capable of traversing different types of terrain with a speed of up to 1 m/s.

Figure 1. The Heavy Duty Planetary Rover (HDPR).

The decisions concerning the rover setup were based on two main aspects:

1. The close resemblance to the ExoMars mission (cameras setup) and,
2. The representation of future technologies (ToF).

The camera system of the rover is based on the ExoMars one, placing the cameras in the same configuration (height and tilt) and creating an analog for the "Wide Angle Camera" WAC on the ExoMars Pancam. The ToF sensors which we have integrated are now under development (space/radiation hardening) for future integration in space missions.

The rest of the paper is organized as follows:

- Section 2, presents the general system overview.
- Section 3, describes the rover, including the mechanical design, sensor integration and capabilities.

- Section 4, presents the rover software and operation interface.
- Section 5, describes the dry-runs and first experiments with the testbed, as well as highlights some lessons learned that we think can be of interest to the community.

2 SYSTEM OVERVIEW

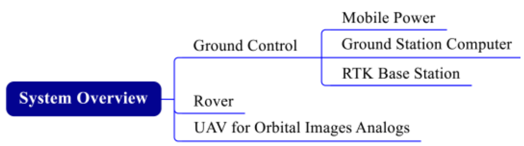

Figure 2. The mobile testbed and its sub-modules.

The testbed includes all the required components for prompt deployment on the field. Figure 2 depicts an abstract representation of the components in our system. The three main components of our system are: a) the "ground control" station, b) the rover, and c) the UAV. The rover is presented in detail in section 3.

The ground control station (GCS) is equipped with all the tools necessary for the connection, tele-command, telemetry and general monitoring of the system. The power requirements of the GCS are kept low enough so that it can be supported by a single 1000W internal combustion generator.

The networking is achieved employing a long range directional antenna that can reach up to a range of 2.5km –assuming line-of-sight. On the rover side another long range omnidirectional network interface is employed. The network is deployed onboard the rover, for safety reasons. In case of a network shutdown, the rover can be found and tele-commanded using its onboard access point. The main operations in the GCS are performed in the "Robot Construction Toolkit" framework, which lays on a computer operating on Ubuntu 14.04. More details about the rover software and operation interface are presented in section 4.

In order to provide accurate ground truth on the system a highly accurate Real Time Kinematics (RTK) Global Navigation Satellite System (GNSS) solution was employed. The base station of this solution relies on the Trimble "BX980" GNSS receiver that is connected to a Trimble "Zephyr 2 Geodetic" antenna. The error of the GNSS system, in a range of 0-1.5km, is less than 1.5cm in most cases, while outliers (with a rate of less than 5%) do not surpass 0.5m in any case.

Another important feature of our testbed is the ability to acquire analogs of orbital images of the test area. Such images can be used for planning as well as for the evaluation of novel algorithms as in [1]. The UAV we employ is the Sensefly EBee. It is a fixed wing drone capable of autonomously collecting the required images of a test area which are then processed in order to produce georeferenced Digital Elevation Maps (DEM) and orthorectified images.

3 ROVER SETUP

As previously mentioned the HDPR was built in order to provide high resemblance with the ExoMars rover, in terms of vision sensors, and also in order to bear novel instruments that will allow the evaluation of novel algorithms. The rover is based on a chassis that was delivered to the ARL by the Autonomous Systems Laboratory (ASL) of the ETH University, Zurich – namely the "Heavy Duty Planetary Chassis" (HDPC). Notwithstanding, either the advanced capabilities of this rocker-bogie chassis (Figure 3,Figure 4) or its novel out-of-the-body differential, we must mention that it did not bear any sensors or untethered autonomy. Firstly, we integrated a power system which: a) provides a max power of 1000W, and b) includes a UPS capable of powering the critical parts of the system (computer, networking, cameras), in the case of a power shutdown, in order to avoid data loss and to protect the rover integrity in general. A powerful –yet compact– computer was installed in order to fulfill the onboard computational requirements. The specifications of this computer are:

- CPU: Intel® Core™ i7 @ 3.9GHz,
- RAM: 16GB,
- Storage: 250GB SSD (Ubuntu O.S.) + 2TB SSD,
- Networking: Gigabit Ethernet,
- Graphics Processor: Intel® Iris™ Pro graphics 5200,
- Camera Bus: IEEE-1394 Firewire,
- General Serial Port: RS232.

The networking of the rover is handled by a Gigabit switch and a high power long range WIFI access point. A custom aluminum frame was added to the HDPC to support the various new components (Figure 5).

Furthermore, we equipped the rover with an abundant of sensors. It is important to mention the resemblance of HDPR LocCam and PanCam to the LocCam and Wide Angle Camera (WAC) of ExoMars. In the case of the PanCam we specifically designed a custom made stereo rig, with cots cameras following a thorough analysis of the WAC. The goal of the aforementioned analysis was to be on par with the Wide Angle Cameras (WAC) stereo of the PanCam of Exomars. Due to, reasonable cost restrictions, we cannot have the same sensor (detector) nor the same filter bank. Nevertheless, we adjusted our optics in a way that were able to achieve the same radial resolution, also known as the Instantaneous Field of View (IFOV). The ExoMars PanCam will be equipped with a sensor of 1024x1024 pixels, where the pixel size is 15υm [5]. The baseline of the ExoMars PanCam is 500mm. The authors in [6] report a FOV of 52º, a focal length of 23 mm, a pixel size of 15υm and an IFOV of 580υrad/pixel. Following a thorough search of the available cots options we ended up with the PointGrey Grasshopper2 1.4 MP, which bears a sensor with 6.4υm, and a Fujinon HF9HA-1B lens (9mm) which results in a FOV of 40.3º and an IFOV of 716.6 υrad/pixel. The baseline of the HDPR PanCam is 500mm. An indicative example of the PanCam Image, the disparity and the respective 3D reconstruction is depicted in Figure 6.

The sensor suite of the HDPR rover comprises the following main components:

- Exteroceptive:
  - LocCam Stereo Camera (PointGrey Bumblebee 2)
  - PanCamm Stereo Camera (PointGrey Grasshopper 2)
  - Kinect Time of Flight
  - MESA SR4500 Time of Flight
  - Velodyne LiDAR (VLP-16)
- Proprioceptive:
  - Trimble GNSS receiver (BD970)
  - Inertial Measurement Unit (Sensonor STIM300)
  - Shaft Encoders and Potentiometers.

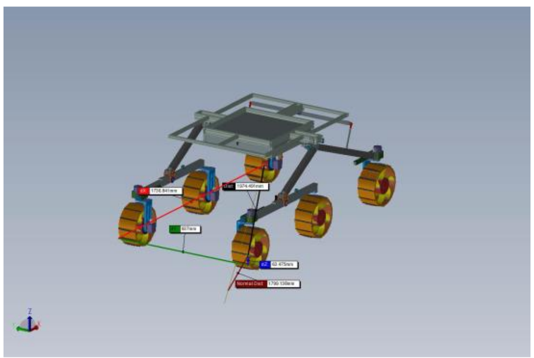

Figure 3 HDPC original CAD design (produced by ETH)

Figure 4 HDPC Original Setup (Produced by ETH)

The main rover characteristics are summarized in the following table:

Characteristic	**Value**
Max width	937mm
Max length	1750mm
Max height	1907.85mm
Wheel diameter	250mm
Wheel width	120mm
Wheel base	817mm
Side wheel separation	750mm
Ground clearance	536mm
LocCam Baseline	120mm
LocCam Height	1117.68mm
LocCam Tilt	18º
Pancam Baseline	500mm
PanCam Height (nominally tilted @ 19.17º)	1897.7mm

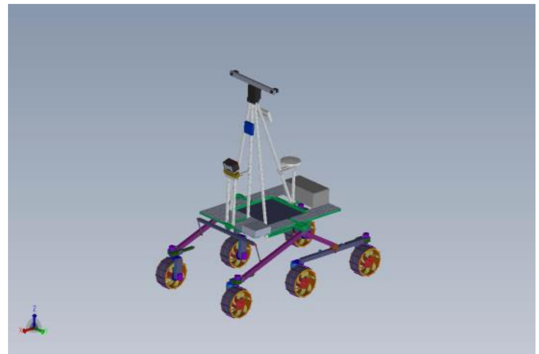

Figure 5 Heavy Duty Planetary Rover (HDPR) CAD.

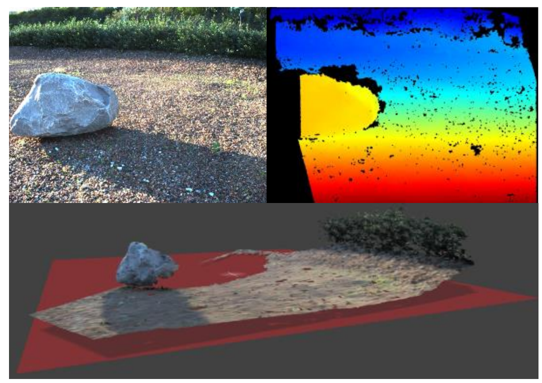

Figure 6 PanCam Stereo of HDPR, Disparity Map and 3D Reconstruction.

4 ROVER SOFTWARE AND OPERATION

The software of the HDPR lays on the Robot Construction Toolkit (ROCK) which is based on the Orocos Real-Time Toolkit (Orocos RTT). Our ROCK setup includes a generic c++ base of drivers and algorithms, with c++ orogen components in a task based architecture. The framework supports the Ruby scripting language for the interconnection of the several components. The reader can find a detailed analysis of the ROCK framework in [7]. We have made the source code freely available on github [8]. Figure 7 depicts the interface for accessing previously recorder data.

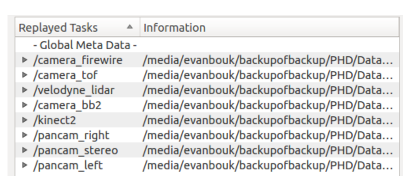

Figure 7 Replay of sensor and rover-state data.

5 DRY-RUNS AND ISSUES

In the process of preparing the HDPR for long range campaigns we organized several dry runs on the parking area of the Decos Technology Group which is located in Noordwijk, near ESA European Space Research and Technology Centre (ESTEC). The goal of these tests was to assess the readiness of the system and robustify it through an iterative "test and fix" approach. An overview of the test area, along with the rover route is depicted in Figure 8 and Figure 9.

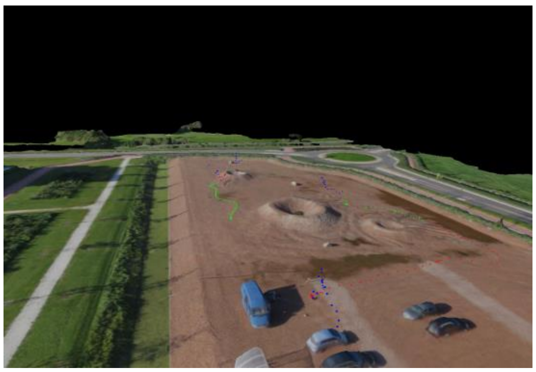

Figure 8 3D reconstruction of the DECOS test area. The trajectory of the rover –as measured by the RTK GNSS– is annotated.

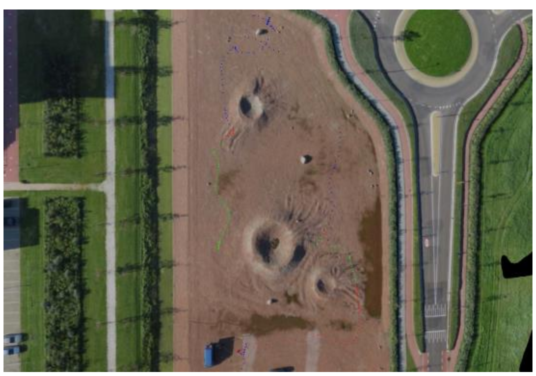

Figure 9 Orthorectified and georeferenced image of the DECOS test area. The trajectory of the rover –as measured by the RTK GNSS– is annotated.

The data products of these tests were recorded for further analysis. The LocCam data ensured us that the camera was able to capture adequate images apart from the case of pointing towards the sun. The LocCam is equipped with a charge-coupled device (CCD) sensor. A known problem of the CCDs is the so-called "blooming effect". This led us to the decision to avoid pointing towards the sun in most of the next field tests. Nextly, a sample instance of the PanCam data is presented, along with the corresponding disparity and 3d reconstruction (Figure 6). The results of both the image and the disparity has proven that the PanCam stereo setup is rigid and the calibration procedure is adequate.

In order to verify our algorithm as accurately as possible, we benchmarked the capability of our rover to acquire precise groundtruth information. The output of our GNSS setup on the DECOS area is presented in Figure 10. The following table summarizes the different types of GNSS position solutions in an RTK system [9,10]:

Solution Type	Details	Accuracy
Autonomous	Independent position derived from pseudorange observations.	20m
Differential	Pseudorange differentially derived position.	1-2m
RTK Floating	Pseudorange and carrier phase differentially derived position. Integer ambiguities have not been resolved.	0.2-1m
RTK Fixed	Pseudorange and carrier phase differentially derived position. Integer ambiguities have been resolved.	0.03m

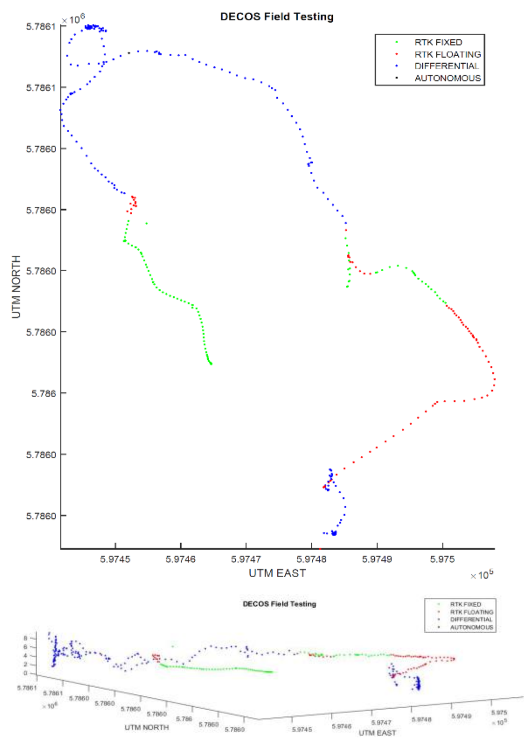

Figure 10 The results of our RTK GNSS solution in our first dry-run at DECOS

The goal of a "perfect" setup is to have "fixed" RTK all of the time. There are two factors that cause the system not to have “fixed” RTK; i) the network connectivity between the rover and the base station and, ii) the ability of the rover to track satellites. As it is clearly shown in Figure 10, the rover did not have RTK “fixed” in all cases. Following a thorough investigation, we concluded that the rover did not have line of sight with the base station WIFI antenna and that there was interference on the rover's GNSS antenna from the rest of the rover's wireless devices. The solution to the problem was to place the antenna higher on the rover and make sure that the base station WIFI antenna is always in line of sight to the rover.

Other issues that were revealed during the dry-runs – and we would like to provide as feedback– include general hardware failure points. Among them, the firewire card and a motor controller (ELMO whistle) failed once. Our analysis proved that due to inertia the motors were acting as power generators driving excessive current to the motor controller. In order to solve the problem, an electrical circuit that restricted the back-current from running through the controller was installed and its acceleration/deceleration ramps were re-calibrated. As a general advice the authors propose to always have duplicate –easy to replace– parts in case of a hardware failure.

HDPR was employed in the acquisition of a long range dataset suitable for the evaluation of global localization algorithms as well as ToF based SLAM. The experiment was performed at the coast of Noordwijk, where an actual Mars area was emulated by placing boulders of various sizes on the beach. A 3D reconstruction of this area is presented in Figure 11. The testbed was able to fulfill all the requirements of the mission including the robust acquisition from all the sensors of rover, the accurate RTK GNSS positioning and the orbital image analogs. The dataset of the aforementioned field test will be released in a following publication.

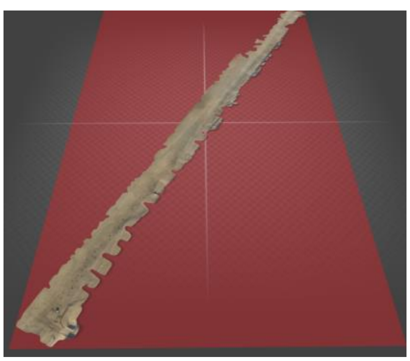

Figure 11 The HDPR long range dataset for global localization.

6 CONCLUSION

In this paper we presented the Heavy Duty Planetary Rover (HDPR) which was designed and constructed for the internal needs of the ESA ARL. This rover will be used for the evaluation of several algorithms that are suitable for long range navigation. The first tests of the rover, as well as a list of problems that arose were presented as feedback. The rover has already been used to produce a dataset for global localization and time-of-flight (ToF) based SLAM, which will be released in an upcoming publication.

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