PAN/TILT-UNIT AS A PERCEPTION MODULE FOR EXTRA-TERRESTRIAL VEHICLE AND LANDING SYSTEMS

A. Wedler(1), A. Maier(1), J. Reill(1), C. Brand(1), H. Hirschmüller(1), M. Schuster(1), M. Suppa(1),
A. Beyer(1), Neal Y. Lii(1), M. Maier(1), H.J. Sedlmayr(1), R. Haarmann(2)

(1) German Aerospace Center, Robotics and Mechatronics Center DLR-RMC, Germany
(2) Kayser-Threde GmbH, Wolfratshauser Strasse 48, 81379 Munich, Germany
Contact: armin.wedler@dlr.de

ABSTRACT

In this paper the development of a space qualifiable pan-tilt unit (PTU) is presented. This modular hardware is based on several sub modules, such as the motor modules from DEXHAND and the electronic components from DEXHAND and MASCOT. This strategy of reusing hardware modules is in line with the overall space module development strategies of German Aerospace Center - Robotics and Mechatronics Center (DLR-RMC).

The main purpose of the PTU development is to provide light weight mechanics to enable the use of different camera heads with different sensors suitable to the target application scenarios. In addition, this development is aimed for space applications with special requirements for radiation shielding, temperature and shock and vibration resistance.

The pan-tilt (PT) prototype is particularly developed for autonomous driving and navigation of small rover vehicles for extra-terrestrial exploration, such as the Autonomy Payload Experiment (APE) on the Mobile Payload Element (MPE) rover [24].

This paper describes the overall concept and development of the mechanism, and thepossible relevant project implementations.

1. INTRODUCTION

Sufficient view of the remote environment is essential for telerobotic control as well as partly autonomous and fully autonomous navigation. This is necessary to ensure safe and fast driving of a planetary robot.

The field of view for navigation cameras is typically chosen between 40° to 60° [20]. Without a PTU, the view would be limited to the frontal area. For looking around, either many cameras would be required, or the whole rover must rotate to the desired direction. The latter is not only the most costly in terms of energy consumption, but also the most high-risk maneuver, as the rover could be hindered by obstacles that it does not see.

In contrast, a PT mechanism with a camera beam would significantly increase the viewing area of the scene, and allow the operator to focus on crucial regions. Obstacle avoidance and analyzing of distant scientifically relevant regions would no longer depend on the orientation of the rover. Furthermore, the robot could observe itself during operations with a scientific payload such as a robotic mole, or arm.

The mechanical design of the PTU is based on the knowledge gained from DLR's DEXHAND and MASCOT flight system projects. The modular actuation system and control electronics can be chosen and used for different environments. E.g. the MASCOT drives may be considered for a long term mission on the Moon, such as ELL (European Lunar Lander) and MPE with a to nine-month target mission time. For shorter missions, such as one Moon day (i.e. 14 Earth days), the DEXHAND electronics could be considered, as discussed in Section 5.

Figure 1: PT Mechanism Breadboard

The PTU is an important functional block for a rover controlled through a mixture of telerobotic and semi-autonomous navigation. To address these concerns, DLR-RMC has developed and studied the key elements for a perception system based on a pan-tilt mechanism, a stereo camera system, an inertial measurement unit, space grade FPGA hardware, and software modules for navigation in unknown, rough terrains. The software performs high resolution stereo matching, visual odometry and data fusion with an inertial measurement unit, which can be computed with a frame rate of up to 15 fps by a mixed CPU / FPGA implementation. A 2.5 dimensional map is created and evaluated for traversability, which the basis for autonomous path planning. Due to short computation times and active control of the PTU, the rover can navigate at speeds of more than 10 km/h. The combination of the PTU with the perception and navigation software leads to a robust and fast semi-autonomous navigation system, which helps improve mission safety and reducing critical mission time.

Figure 1 shows the first prototype PTU. The prototype camera head system is designed with three cameras. A black and white stereo camera pair is used for autonomous navigation, and a grayscale camera at the center can be used for teleoperated driving or for scientific exploration.

2. REQUIRMENTS OF THE PT MECHANISM

The requirements for a PT can be drawn from space application related literature and projects, as well as previous work carried out at DLR. The design of the head of a PT depends on the requirements of navigation to ensure safe driving. It should be able to accommodate a variety of scientific instruments such as cameras, filter wheels, and focusing mechanisms. For example, the Curiosity rover is equipped with the ChemCam (laser-induced remote sensor for chemistry with its own remote micro-imager), Mastcams (mast cameras) and Navcams [22]. The ELL carries a close up and a pair of wide angle cameras. This camera system can remotely sense the geological terrain of the landing site and provide detailed 3D terrain models [23]. The imager for the Mars Pathfinder is a stereo imaging system with color filtering capability provided by a set of selectable filters for each of the two camera channels [21]. All the above mentioned PT camera heads consist of a wide angle stereo pair of cameras to enable triangulation, which in turn places a minimum requirement for the width of the camera head.

The hardware requirements for the PT mechanism are determined by the mission environment specifications such as lifecycle, functionality, temperature, and atmosphere. One critical requirement for planetary exploration missions is the sealing of components, which can be influenced by numerous criteria such as seal strength, life span, and friction, etc. The mass of the head also plays an important role on the design. It must be sufficiently light to be maneuvered and held in position by the mechanism. In addition, scientists require a precision pointing mechanism with highly repeatable and accurate positioning to match images to map terrains with a low mechanism failure rate. For example the EXOMARS requires an angular position accuracy of 0.5° [2]. Furthermore, it is necessary to rotate the pan axis the full 360° to ensure panoramic view of the total horizon without moving the vehicle. The tilt mechanism should be able to see the terrain directly beneath with the cameras placed in front of the vehicle. This is achieved by tilting the camera 90° below the horizon [2]. Furthermore, the tilt mechanism must be able to look up toward the sky to map stars, and look up out of craters e.g. the MER (Mars exploration Rover) can tilt its head 180 degrees, such that it can see behind the vehicle and itself [21].

To summarize all the above requirements for a general, multi-purpose, light weight pan-tilt mechanism, the following upcoming requirement can be assumed.

Table 1: Requirements for a modular multiuse pan tilt mechanism

Minimal tilt opening angle	-90° up to 90°
Minimal pan opening angle	360°
Minimal repeatable pointing accuracy	0.5°

3. HARDWARE AND SYSTEM DESIGN

The target application of the first PT prototype is focused on small mobile robots. Therefore the baseline width of the stereo cameras has been defined to 90 mm. The hardware and system design in this development process fully complies with the requirements for a terrestrial functional prototype with the capability for space flight mission. The exchange of required materials and components are defined and documented as part of a space-qualifiable development process.

The mechanical design of this PTU is based on the requirements as discussed in Section 2.

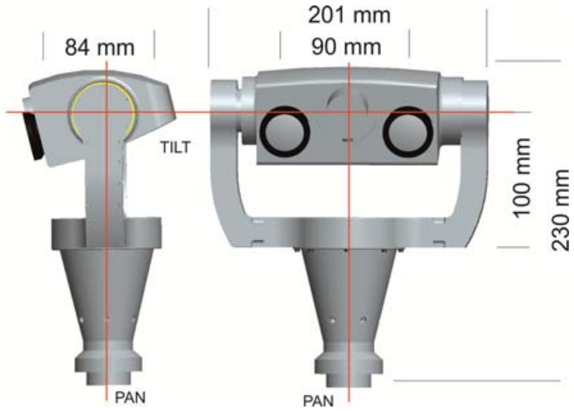

Figure 2: General dimensions of the pan tilt unit focused on small rovers

In order to provide proper shielding, the PTU houses all cables for the electronics, actuators, cameras and additional scientific instruments. Therefore a cable shaft has been implemented. Furthermore, the exact cable routing is known and planned to avoid clamping and unexpected positioning of the cable. The bending friction can be more easily estimated and calculated due to the repeatable positioning of the cable. Guiding the cable inside the PTU also covers it from any exterior

mechanical treatments, which could influence the cable and function.
During terrestrial tests, experiments, transports or other field acceptance tests, the PTU appears to be more capable than with cables routed on externally.

With respect to the environmental requirements the unit is implemented with a full sealing and shielding concept. All contacts and attachments consist of a labyrinth design to avoid unintended leakage to the outside and ensure elimination of all gaps. With a fully conductive housing of the PTU, radiation shielding and EMC resistance can be achieved. Furthermore, all rotating axes are sealed with PTFE (Polytetrafluorethylen) based sealing with additional labyrinth design.

Typical PTUs consist of serial actuator units. To reduce complexity, the units are installed in the neck configuration. The neck configuration in the PTU, particulary the tilt actuator unit, is arranged directly behind the pan motor unit. The camera head moves on a radial rail. This means that at the full tilt angle, e.g. 90° in the front, (for surveying in front of the wheels of a vehicle) the tilt motor must support the full weight exerted on the camera head. This leads to a design with the tilt axis near the center of mass of the camera head, while maintaining all viewing requirements. Thee reduced inertias also allow smaller actuators for this joint unit.

Additional absolute positioning sensors are implemented inside the PTU to provide absolute angular information. The sensors in this terrestrial prototype are based on high precision conductive potentiometers. The sensors' AD channels have a resolution of 10 repeatable bits, resulting in an angular resolution of <0.1°.
Commutation of the motor unit is measured through digital hall sensors, where the motor has seven pole pairs, three phases and a gear reduction ratio of 1:100. This leads to an incremental redundant sensor, at the motor side, which can be calculated as the following, ignoring the elasticity in the system:

$$RES = 7 * 3 * 2 * 100 = 4200 \tag{1}$$

$$Ang_{RES} = \frac{360°}{RES} = 0.08571° \tag{2}$$

The motor modules are single-failure tolerant, redundant driver electronics with redundant computational sensor available (see Section 3.1).

One of the main design challenges has been the guiding of the cables through the curvature in the hollow shaft to ensure full camera head rotation within low friction. The eventual solution depends on several criteria, in particular the space hardening of the casing material and cables. In this prototype the development is focused on achieving minimal weight and maximal cable diameter.

360° range of rotation without a mechanical stop (e.g. free continuous rotation of the camera head) would result in tangling and damage to the cabling. It would also call for complex multi-track rotational encoder for angular position measurement. As a result, mechanical stop is introduced to limit the maximum rotation to less than 360°. Overlapping of the images must be ensured to allow the visual algorithms processing continues DEM (Digital elevation model) models. The proposed PTU prototype system is designed with a rotation angle of 355° in the pan joint, which enables a continuous panoramic view and image processing with overlapping field of vision of the camera.

In order to utilize the PTU as a general design solution for space application, the camera head is interchangeable to fit different scientific and perception requirements of the mission. Redesigns to the PTU camera head and cable assembly are under investigation.

The current PTU incorporates an adjustable-size U-Beam to accommodate different camera head sizes. This is necessary for space qualification of the unit. The PTU is able to provide a nominal torque of 2.4 Nm in the tilt and pan axes, which allows a wide variety of camera heads. Thick gauge cables are currently implemented. Thinner gauge cables are also being investigated for space saving and improved maneuverability. The current implementation includes three Firewire camera cables, one Ethercat, and two 10-pin actuator cables (motor phases and hall sensor signals). The hollow shaft diameter is 20 mm. The allowable bending radius calculation and estimation are performed individually for each cable/application itself.

The final design of the PTU depends on the application and is influenced by the lunar environment: extreme temperature ranges, lunar dust, and radiation. High-performance lubricants are required which are able to maintain their tribology properties over the extreme temperature range on the lunar surface. Thus a robust space sealing against harsh regolith is necessary to prevent blocking or contamination of the mechanisms.

Table 2: Operational temperature design of the space flight unit

Component	Temperature range	testprocedure
Actuators	-20...80	LN2 tested
Electronic	-55...125	tbd

The operational temperatures margins of the subcomponents for the space PTU is estimated and shown in Table 2.

3.1. Motor modules

The broad range of applications and the intended interaction with the environment requires motor characteristics that differ from standard industrial actuation scenarios. For example, the robot may have to deliver high torques at low speed for one application, and provide high dynamics in another. Since robotic actuators are usually attached to the moving structure, they also need to be small and lightweight. In order to reduce positioning errors, and to avoid disturbances during reverse motions, all gears should be backlash-free. The most important ones are summarized in the following list:

- High torques at low speed and stall torque
- Low weight
- Small size
- High dynamics
- High efficiency / low losses
- Backlash free gearing
- Sensor feedback (position and force-torque)
- Optimized power dissipation

In order to meet these requirements, permanent magnet synchronous motors were developed at DLR-RMC. These high performance robotic actuation units are designed in combination with low backlash Harmonic Drive (HD) gears. They provide high dynamics and high link side torques due to low inertia components and high reduction ratios. Furthermore, their low number of components reduces the probability of failure.

The DLR brushless Motors

The key components of the DLR drive train concept are the mentioned permanent magnet synchronous motors. The Innen-Läufer-Motor (ILM, German for “motor that rotates inside”) is well suited for highly dynamic tasks involving frequent reversing motions with smooth torque output characteristics. To utilize existing components, all motors are specified to fit available HD gear dimensions.

Brushless Direct Current (BLDC) motors have several advantages over brushed motors to cope with the lack of an atmosphere on the Moon. First, they offer higher power density leading to lower motor weight in comparison to brushed motors of similar torque output. BLDC also offer higher peak torque for the comparable size, which is necessary to overcome the initial breakaway torque after the long travel to the Moon, long idle time due to periodic darkness on the lunar surface, which can result in cold welding in the mechanics. Finally, BLDCs do not suffer from mechanical friction and abrasion apart from the bearings, which increases the reliability and maintenance-free lifecycle. As an performance example, the torque/current constant of the ILM 25 (stator diameter of 25 mm) is 0.008 Nm/A. The motor requires approximately 12.5 A (without saturation effect) to provide a torque of 100 mNm.

The corresponding HD gears with 1:100 reduction ratio (HFUC8) has a nominal torque of 2.4 Nm, a repeatable torque of 4.8 Nm and a peak torque of 9 Nm. The limiting factors for the motor torques are thermal constraints related to the passive cooling. In case of active cooling the torque output of the motors could be further increased. At the time of development the motors achieved a 50% reduction in weight and losses compared to commercially available units with similar torque ratings. These high performance robotic drives are available in commercialized form as the RoboDrive actuators [5].

The DLR Actuator Units

Aside from high performance, low weight and low losses, two properties of the actuation units are relevant to space applications. First, the high torque capacity of the motors allows applying short bursts of high torque to free the unit in case of cold welding within the bearings or the HD stage. The power electronics istypically designed to supply those large currents for a short period of operation.

The second aspect is the low number of mechanical components, which reduces the probability of failure. In the following, the mechanical components of one joint unit are listed:

- Stator
- Rotor with magnets
- Rotor bearing
- HD wave generator (WG)
- HD flex spline (FS)
- HD circular spline (CS)
- Output bearing.

The rotor bearing and the WG bearing are the most crucial elements as the associated friction must be overcome by the motor torque directly.

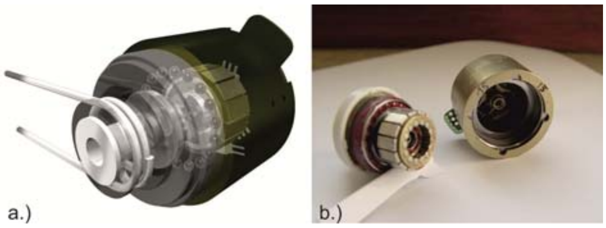

Figure 3: DLR-RM RoboDrive 25 Space Unit - a.) design rendering, and b.) the realized unit

The two motor modules inside of the PTU are taken from this actuation module concept. In Figure 3 the ILM25 space unit is shown.

Table 3: ILM25 space unit key parameters

Parameter	
Nominal torque [Nm]	2.4
Repeated peak torque [Nm]	4.6
Momentary peak torque [Nm]	9
Max speed [rpm]	85
Angular resolution @ gearbox output [counts]	4200
Gear ratio	1:100

The resulting design of the actuation units allows highly dynamic and powerful operation as well as precise control in fine manipulation tasks.

The proposed drive unit technology is based on the ROKVISS (Robotics Component Verification on the International Space Station) actuation unit [4,6,7,8,9,10], which has been returned to Earth after six years operation in space in early 2011. It was further developed and adapted for the DEXHAND [3] and MASCOT [17].

3.2. Motor electronics selection

The motor units described in section 3.1 require motor drivers, control electronic and sensors. These sensors include position sensors for commutation, temperature, and relative position measurements on the motor side, as well as absolute position sensors on the link side.

The motor side position sensors of the Space Units are based on space qualified Hall sensors. Several concepts have been developed to realize the driver electronics and signal processing units.

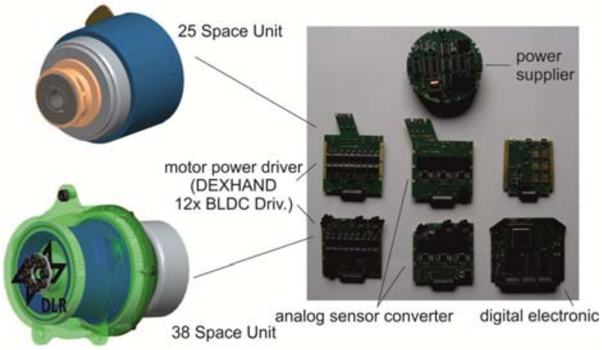

Figure 4: DEXHAND electronic for up to 12 BLDC space units without redundancy

Due to the need of powerful components with small size DLR is conducting radiation tests for several off-the-shelf components (COTS) [16].

DEXHAND electronics implementation concept

The electronics include motor drivers, sensors with measurement, controllers, communication bus (CAN), supply and filter for the control of 12motors. On a TI DSP all tasks of the DEXHAND are computed, an FPGA is used to interface the six-step motor controllers. The interface is a 28V power line and a CAN bus. [3].

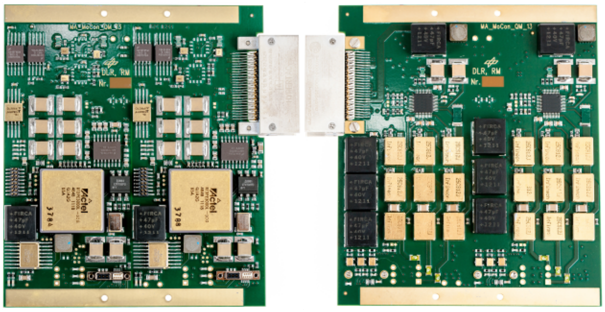

Figure 5: MASCOT Electronics, redundancy for one BLDC motor

MASCOTelectronics implementation concept

The electronics include one motor driver with low level control. The MASCOT electronics is designed to be fully cold-redundant [16]. Due to space and weight limitations the motor is not redundant in that project. The motor controller is based on a Microsemi (former ACTEL) FPGA combined with a space qualification tested COTS motor driver (two lanes). The communication interface to the unit is RS422 [16].

ROKVISS electronics implementation concept

The electronics are based on COTS with an additional latch up protection. Power converter, filter, SERCOS communication bus, motor driver with control units, drive units and the joint control DSP are included. The actuation units of ROKVISS comprise of a large set of sensors enabling sophisticated impedance and admittance controllers with underlying high performance torque and/or position control loops [1].

The combination of different actuator and science hardware may significantly influence the size, weight and power consumption. Table 4 describes the power consumption of the PTU with electronics based on the DEXHAND design:

Table 4: Estimated power consumption of the PTU electronics

Item	Power (W)	Power (W) + 20% margin
PTU electronics	3	3.6
PTU motor average	5	6
PTU motor peak	7	8.4
Electronics + motor peak	10	12

3.3. Mass estimations of different PTU versions

Table 5 gives the mass specifications of the components in the prototype version of the PTU.

Table 5: Mass of the terrestrial prototype for small mobile vehicles (camera separation of 90 mm)

Item	Number of units	Mass
PTU terrestrial industry ETHERCAT motor driver	2	110 g
PTU structure with the two motors and gears (90mm Baseline)	1	650 g
Internal harness (PTU)	1	70 g
Actual Camera Head with three Firewire terrestrial cameras	1	734 g
Harness of the camera Head	1	95 g
Total		1769 g

Two space qualifiable camera head designs are explored for space application in this work. The first variant is designed with a narrow camera separation of 90mm, whereas the second variant incorporates wide separation camera placement.

Table 6 and Table 7 give the mass specifications for the PTU with narrow and wide camera separations, respectively. The items addressed in these two tables aim to help underline the influence of component weight on the design.

Table 6: Mass estimation of the light weight space unit for small mobile vehicles (camera separation of 90 mm)

Item	Number of units	Mass
PTU motor/gear	2	110 g
PTU electronics (one failed redundancy)	2	120 g
PTU structure (90mm Baseline)	1	650 g
Internal harness (PTU)	1	195g
Subtotal		1075 g
Margin 20%		215g
Total		1290 g

Table 7: Mass estimation of the light weight space unit for Lander application (camera separation of 900 mm)

Item	Number of units	Mass
PTU motor/gear	2	110 g
PTU electronics (two failed redundancy)	2	200 g
PTU structure (90mm Baseline)	1	1400 g
Internal harness (PTU)	1	245 g
Subtotal		1955 g
Margin 20%		390 g
Total		2345 g

The motor modules are used in different projects with different TRLs (technical readiness level). In order to facilitate fault tolerance, The DEXHAND project employs single-failure tolerant electronics, whereas MASCOT incorporates double-failure tolerant redundant electronics. DEXHAND COTS elements were tested for total ionizing dose (TID), proton, heavy ion and thermal qualifications. MASCOT's final flight tests are currently underway. This includes TV (thermal vacuum) environmental testing for C-type asteroid 1999 JU3.

All implemented electronic components are either RadHard (radiation hardening) or COTS tested for EMC, and heavy ion qualifications

3.4. Over all TRL estimation and definition of sub components

In this section, a first estimation of the main subcomponents of the PTU unit is described. Further development would be necessary to achieve a flight version development. The subcomponents and its estimated TRL Level are shown in Table 8:

Table 8: Level (TRL) of the concept

Item	TRL	Comments
PTU motor/gear (Mascot Tests finish 2013)	6	DEXHAND/ MASCOT
PTU electronics (two failure redundancy – Mascot test finish 2013)	6	MASCOT – Radiation and TV Tests
PTU electronics (one failure redundancy)	5	DEXHAND Radiation and thermal Tests
PTU structure (90mm Baseline)	4	Terrestrial Prototype Functional Tests
PTU structure Lander version (900mm Baseline)	2	Equal design concept

The development of the PTU utilizes a combination of existing and previously developed hardware.

4. THE PTU PROTOTYPE ON A SMALL ROVER BREADBOARD

Autonomous navigation is necessary to cope with communication latencies, and limited bandwidth, which are inevitable in space robotics. The PTU is an essential component for realizing such an autonomous navigation system. With autonomous waypoint navigation, the operator on Earth can select a target, e.g. by clicking on a position on the image, from which the rover would identify and navigate to the target fully autonomously [15]. This is accomplished by using the PTU with the stereo camera for capturing the local environment three dimensionally. The stereo images are used for computing depth as well as a visual odometry for precisely determining the egomotion of the system. Since radiation hardened, space qualified CPUs are typically very slow, image processing and navigation performances are limited, with top speed below 0.01

m/s. As a result, a radiation hardened FPGA is selected for depth image computation, as well as optical flow for supporting visual odometry. Both are well suited for parallel implementation.

Our solution is based on an FPGA implementation of the Semi-Global Matching (SGM) method [12], [13]. In comparison to correlation based stereo methods, SGM offers higher spatial resolution, and performs well with low textured scenes as well, which results in a denser depth image. The current terrestrial Xilinx Spartan 6 implementation processes images with a resolution of 0.5 million pixels and 128 pixels disparity range at almost 15 frames per second [14]. The space version is designed for matching images with 512 x 512 pixels and 64 pixels disparity range of 5 frames per second. In the proposed configuration, the stereo camera covers an area up to 2 m in front of the rover with depth accuracy between 0.75-5 cm.

In addition, the FPGA also performs stereo rectification and image compression. The image data is sent to Earth for further processing. All less time consuming operations such as fusion of visual odometry with IMU data, map projection and path planning, are performed on a space qualified CPU.

The space version of the autonomous waypoint navigation would be capable of supporting a top speed of 1.6 m/s (5.8 km/h). However, in field deployment, the rover would be limited to avoid dynamic effects and dust turbulences. However, the high speed of visual navigation improves robustness, accuracy and shorten the mission time.

5. PROJECT INTEGRATION OF THE PTU

The PTU is constructed to be applicable to different projects with different variations. The small vehicle camera head application with narrow separation sensors and small scientific sensors can be adapted for wide separation stereo cameras, as well as heavy and large scientific equipment, as in the case for a lander camera unit. Thanks to the light weight mechanical design and powerful actuation, the PTU is able to lift and pan/tilt heavy camera systems.

The concept of an Autonomous Payload Experiment (APE) is planned as part of the Mobile Payload Element (MPE), which is intended as a German member nation contribution to the ESA Lunar Lander Mission [20]. The APE enables fully autonomous operation of the MPE. It demonstrates fast autonomous driving and ability to support the rover's operation with additional safety features. It is designed as a self-contained payload that can be completely switched on and off.

The APE is a significant technological improvement for the MPE mission. The technology has been implemented on the Asimov Rover by a German team participating the Part Time Scientists (PTS) program, which entered the Google Lunar XPrize (GLXP) competition [18], [19]. The drive train of the Asimov prototype rover is based on the DLR actuator concept. The autonomous drive package is planned to be implemented as a technology demonstrator, similar to the APE for the MPE project.

6. CONCLUSION

In this paper the hardware design of a PTU for mobile systems has been presented. The PTU is implemented with different electronics and design variations for various applications. The applications may differ in their reliability requirements (e.g. different planetary surfaces, scientific of technologically driven missions), as well as functional requirements for the pan and tilt mechanism (mobile robots, lander cameras and scientific payloads). DLR's endeavor into autonomous driving and navigation of mobile robots with the PTU has also been presented. Finally, the paper discussed space mission implementation possibilities based on the ELL/MPE project as well as the GLXP cooperation project.

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