Developing a Planetary Rover with Students: Space Education at TU Berlin

Submitted: 5th May 2013; accepted: 1st July 2013

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DOI: 10.14313/JAMRIS_1-2014/3

Abstract:
Practical engineering education in space technology is a major challenge. TU Berlin has collected many years of experience in educating prospective space system engineers. With its history of developing and operating real space missions and its many ongoing research activities in the field, students are provided the opportunity to experience space technology. The Chair of Space Technology adresses the issue of innovative education constantly. Novel methods in hands-on education that arise through new technologies and trends are embedded into the curricula. A current project envisages the development of the autonomous planetary rover SEAR (Small Exploration Assistant Rover) with students. With SEAR, TU Berlin will participate in the SpaceBot Cup, a planetary exploration competition aimed to push forward key technologies in space robotics. To comply with the strict development timeline of nine months, educational methods for efficient utilization of student's ressources and provision of high-level education are applied.

Keywords: *education, object identifiacation*

1. Introduction

Globalization, rapidly evolving technologies and shifts in demographics are changing the nature of engineering practice. Broader skills and a priority for application–driven engineering is demanded by students nowadays [1]. This creates new requirements for curricula at universities. With its origins in the 1980's, educational change in engineering is a relatively new field of research and many innovative changes are stand-alone and do not impact departmental and national practice [2]. Project-based courses have proven to be a suitable approach for engineering training and further help students in improving their teamwork and communication skills [3].

Since spacecraft design is a mature endeavor and the academic world is almost devoid with experience in the space industry, engineering in space technology is a major challenge for universities [4]. However, with miniaturization of technology and new trends in space engineering education, new opportunities arise for students and universities to become involved with practical space education.

The TU Berlin, Chair of Space Technology is experienced in spacecraft missions and devoted itself to offer high-class hands-on education for its students. By involving undergraduate students in real practical research activities during their curriculum, they are offered the best possible methods to graduate as aerospace engineers. An example of such a project is SEAR (Small Exploration Assistant Rover). It is the attempt to develop an autonomous planetary rover with mostly undergraduate students. Planetary exploration is an inherent part of astronautics and there are many parallels to terrestrial applications in robotics [5]. The SpaceBot Cup is an initiative launched by the German Aerospace Center (DLR) to push forward key technologies in space robotics. TU Berlin, as participant, uses the opportunity to utilize the experiences in methodological education in yet another lecture course.

2. Space Technology at TU Berlin

The TU Berlin, Chair of Space Technology is affiliated to the Department of Aeronautics and Astronautics. The focal point of the facility is on educating space system engineers to meet the demands of the future space market. By housing all facilities that are characteristic for a space technology site, reaching from laboratories, ground station and mission control center to testing facilities, students can work and learn in a professional environment.

The research focus of the Chair is set on miniaturization of technologies for small satellites. The research activities are spread over all segments of a spacecraft mission. TU Berlin has a long heritage in development and operation of satellites. Its complete satellite fleet with specification of masses and main payloads is displayed in Figure 1. In a study of the statistical history of university–class small satellites, conducted by Swartwout [6] in 2011, TU Berlin was leading the list with seven launches into orbit.

The launch and therefore the mass of a spacecraft is one of the major cost drivers of a satellite mission [7]. More frequent launches of low priced satellites allow a faster return of science [8]. Small satellites open up potentials for universities and small businesses to conduct formation and constellation missions. TU Berlin is highly involved in developing miniaturized components for small satellites based on commercial off-the-shelf hardware. Further research activities encompass the development of launch vehicles, conduction of high-level technological studies and robotics for planetary exploration.

3. Space Education Practices at TU Berlin

The Chair of Space Technology offers a variety of space related lectures for Bachelor's and Master's stu-

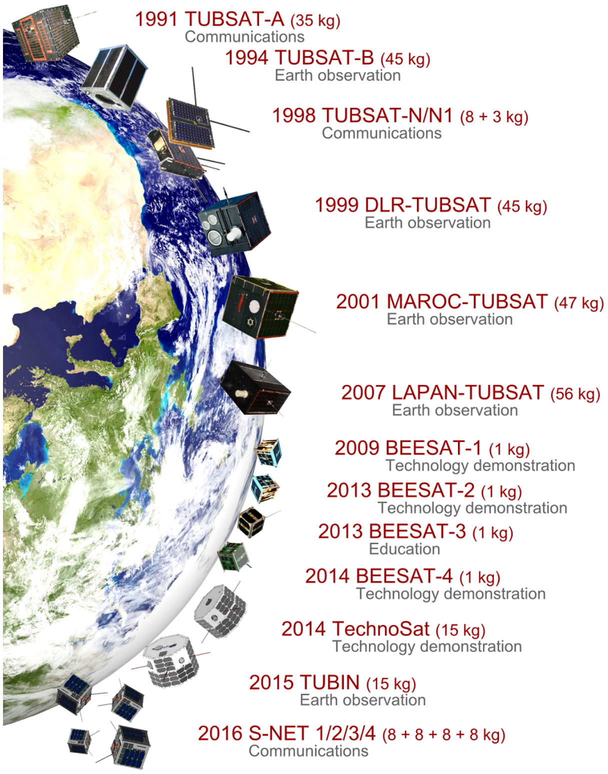


Fig. 1. TU Berlin's satellite fleet (Including past and future missions).

dents. The curriculum covers basic and advanced topics of spacecraft technology, mission design, operations and further topics in several lecture courses. The philosophy of the Chair is to bring space technology close to students by collecting practical experience. With small satellites emerging, it has become feasible to conduct a complete satellite mission with students. Practical lecture courses at TU Berlin are composed of several approaches for project based education. These emphasized to be mission design courses, space-related experiments and hands-on courses. In following, the education approaches shall be explained in detail with highlighting selected practical projects in context.

3.1. Mission design courses

Mission design courses have been widely conducted for many years at TU Berlin. The topic of a project is mostly a high-level technology spacecraft mission. The variety reaches from complex satellites and planetary rovers to Mars sample return missions.

The mission design courses are organized in a way that an almost real economy-like environment is created. This includes work processes according to ECSS (European Cooperation for Space Standardization) standards. The main mission goals and the high-level mission requirements for a project are given due to specific circumstances or by the course supervisor. The mission is broken down into several work packages that cover all aspects of the mission. These include e.g. the design of a satellite attitude control system, conduction of thermal analysis for a spacecraft or preparation of a mission operations schedule. Each work package is worked on by one or multiple students, depending on the estimated work load of the work packages.

The precise defintion of interfaces is of great importance. Therefore, the assignment of a systems engineering authority is indispensable. The main parameters are updated and discussed during several group meetings to initiate the next design iteration. Interim reports and presentations help to push the design process forward. All results are documented properly until end of semester. The documentation is distributed to several reviewers composed of researchers and experts of the facility. As closing of the course, a review according to ECSS standards is conducted, during which the students shortly present their results and have to respond to critical questions from the review board. The project is evaluated for each student by the performance in midterm and end presentation, as well as by the documentation.

With this course concept, a large group of students can be reached who, in the end of the course, will have a good understanding of the mission design process, a broad understanding of all mission aspects and a deepened knowledge in a specific discipline. Over 20 such mission design courses have been conducted at the Chair of Space Technology so far. Most of them showed promising results. It was found that students are more motivated when the course topic is conducted in context of a real mission. The students are stimulated by the huge responsibilities assigned to them.

3.2. Space-related experiments

Many components in TU Berlin's satellite fleet are developed in-house with the help of students. Space components development involves extensive functional and environmental verification processes. In the TUPEX (TU Berlin Picosatellite Experiments) series, students have the chance to participate in a sounding rocket campaign to test novel miniaturized components. The REXUS/BEXUS program allows students from Europe to fly an experimental payload on a high altitude balloon or a sounding rocket. It is sponsored by the German Aerospace Center (DLR) and the Swedish National Space Board (SNB) in collaboration with the European Space Agency (ESA). TU Berlin participated three times in a sounding rocket campaign with diverse experiments. Other space-related experiments involve flights in reduced gravity aircraft.

These kinds of activities address fewer students than mission design courses, but the intense education provided to a handful of students in conducting a real experiment, reflects in a very deep practical knowledge and experience at the end. In most cases, the students write their theses about the related project, since a sounding rocket campaign runs over a period of approximately one and a half years.

3.3. Hands-on courses

A high challenge lies in conducting an aerospace lecture, in which the goal is to develop real hardware in short time. The Chair of Space Technology is largely involved in this area and has collected a broad experience over the years. The lectures often desire a minimum set of requirements, e.g. basic knowledge of electronics, mechanics and satellite subsystems, which are all covered by previous courses at the Chair. Following, some examples for hands-on courses shall be given.

CanSats and sounding rockets For space education, some particularly new concepts arose, for example with the CanSat programs. A CanSat is a satellite in shape of a standard soda can. An international class CanSat has to follow certain specifications. It shall have a maximum mass of 350 g and a cylinder shaped body with 66 mm in diameter and 115 mm height [9]. With this body, it fits into a rocket that usually carries a CanSat to an altitude of a few kilometers. It is then ejected in apogee and drops to ground safely with a parachute. A CanSat is not a real satellite, but it contains many downscaled subsystems that are pretty similar to those of an ordinay satellite. With costs of a few hundred dollars, a CanSat project provides an affordable opportunity for educators and students to acquire basic knowledge of space engineering and to experience engineering challenges in building a satellite [10]. Students can develop interesting missions like atmospheric measurement experiments with telemetry downlink or conduct more advanced missions like a GPS-based flyback.

Also, sounding rockets are developed at TU Berlin with strong involvement of students. Some examples are the hot water driven AQUARIUS and the rocket DECAN [11] that is designed to launch up to 15 km altitude and can carry one CanSat. Impressions of CanSat and sounding rocket projects at TU Berlin are shown in Figure 2.

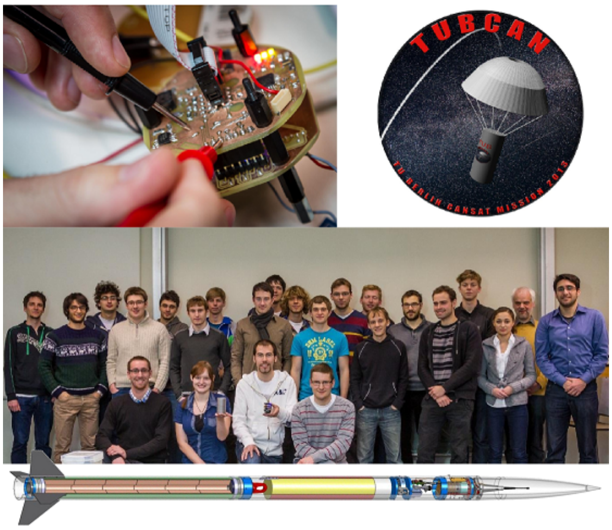


Fig. 2. Impressions of TU Berlin CanSat and sounding rocket projects

CubeSats Another, more sophisticated, approach lies in designing real satellite missions. With the CubeSat specifications, it has become feasible to build a satellite for comparably low costs. The specification states that the satellite shall be a cube with the size of 10 cm × 10 cm × 10 cm and a maximum mass of 1,33 kg [12]. There are small components, ejection mechanisms and launch providers available on the market for this standard. More and more universities worldwide are building CubeSats. Since TU Berlin was very successfull with the Berlin Experimental and Educational Satellite (BEESAT-1), which was launched in 2009 and is still operating, it had launched the initiative to build a completely new CubeSat, BEESAT-3, in lecture courses. The payload of BEESAT-3 is a new S-band transmitter for picosatellites, with downlink rates of 1 Mbit/s [13]. The phases of development were spread over four semesters and the students designed the subsystems and all other mission aspects. The works were supplemented by a group of researchers, volunteers, and students writing their theses.

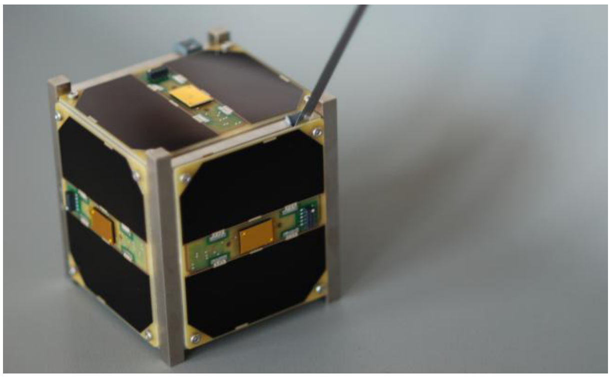


Fig. 3. BEESAT-3: CubeSat developed by students

Rovers Robots are part of space technology and thus moving in the focus of the Chair of Space Technology. They offer a great platform for developing hardware, electronics and software with results that can be observed almost immidiately. With the TU Berlin Robot (TUBROB) program, a small rover was built by students during several semester theses. TUBROB-2, a less complex rover was built during a lecture course on aerospace electronics. SEAR is a high-technology rover that will take part in the DLR SpaceBot Cup. Major parts of the rover are developed in a lecture course titled "Planetary Exploration and Space Robotics".

With these kinds of projects, the students get a very deep knowledge in a specific subsystem. Due to the high motivation enforced by taking part in a real mission, students are very commited to the project. Nonetheless, it was found that a test on general subjects related to the project is a good way to maintain that students pay high attention when all topics are discussed in the group.

4. The DLR SpaceBot Cup

Space robotics has gained more and more attention in Germany since 2009 [14]. It is now in the focus of the national programme for space and innovation. It combines technologies from different disciplines and

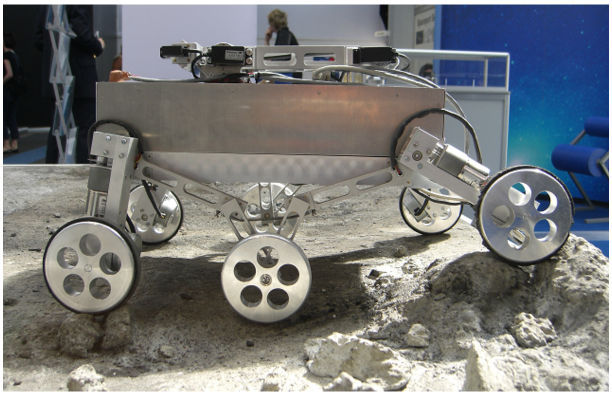


Fig. 4. TUBROB: TU Berlin educational rover

is a driver for cutting edge technologies that can be utilized in space and on Earth.

The DLR SpaceBot Cup is a space robotics contest organized by the German Aerospace Center (DLR) and funded by the Federal Ministry of Economics and Technology (BMWi). With this contest, the advancement of key technologies in space robotics shall be pushed forward. The setting for the contest is a planetary exploration scenario. Competitors from universities and small companies in Germany have been called to take part in the contest. Out of all applicants, ten candidates have been selected to build one or more robots that shall achieve all predefined tasks. On an area of 36 m × 28 m that represents a planetary surface including rocks, sand and acclivities, the robots have to fulfill several tasks that are typical for a future planetary exploration scenario. There are several constraints for the contestants and the overall design time of nine months is very short. A special focus in this contest is set on aspects of autonomy. The robots have to perform all tasks autonomously. Therefore, e.g. no crew member in the control room can have visual contact to the robot(s) during the contest course.

Constraints

- The time on the planetary surface is limited to 1 h per contestant.
- The number of robots per contestant is not limited.
- The total mass that can be dropped onto the planetary surface cannot exceed 100 kg.
- The use of GPS is prohibited.
- A rough map of the environment with elevation profile will be supplied four weeks prior to the contest.
- Each team can have three contacts for five minutes with the rover, for telemetry download and software update. Steering of the rover is prohibited.
- Contact with the rover can only be established from inside of a control room from which the planetary surface is not visible.
- There will be latencies of a couple of seconds when communicating with the robot(s).
- Inclinations of 15 degrees have to be overcome.

Tasks

In general, there are three categories of tasks to be absolved. The main success criteria for winning the contest is time. For any more contacts needed, interventions and not achieving tasks, this will result in addition of penalty minutes.

4.1. Locating and identifying objects

The robot has to allocate itself in an unknown area. Three predefined objects that will be distributed randomly over the area have to be found, identifyied and mapped. The objects, as seen in Figure 5, consist of a battery pack, a glass filled with water and a base station. All objects will have a distinctive color. The battery pack has a size of 10 cm × 20 cm × 4 cm and a mass of 1 kg. The glass has a diameter of 8 cm, a height of 12 cm and a mass of 1 kg. The base station has a size of 20 cm × 40 cm × 20 cm.

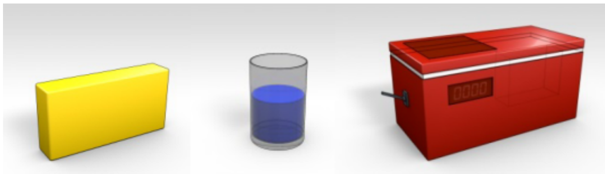


Fig. 5. Objects to be located and identified (Source: DLR)

4.2. Planning and Transport

Two objects, the battery pack and the glass filled with water, have to be grasped and transported to the base station. Therfore, an optimized route through the terrain has to be calculated.

4.3. Obstacle avoidance and assembly

On the drive back to the base station with the objects, an additional obstacle has to avoided that will be put in the way of the robot(s) nominal path. With arrival at the base station, the battery pack has to be mounted to it. A contact will verify successfull mounting. The glass filled with water has to be placed on top of the base station. The mass of water will be measured automatically to figure out how much was spilled on the way. To complete the course, a switch on the base station has to be triggered.

5. Design of SEAR

The requirements for SEAR are derived from the tasks it has to achieve. SEAR is a conventional rover. The concept was prefered over crawlers and other types of robots, due to its simplicity and stability in basic state. Figure 6 shows a drawing of SEAR with its body, undercarriage and manipulator.

SEAR is still under development. Following are some current design parameters. SEAR has a width of 860 mm. When the manipulator is driven to its full extent, SEAR can reach a length of 1950 mm with a height of 670 mm. The overall mass is estimated with 60 kg. With a battery capacity of 20 Ah SEAR is powered for at least two hours in full operational mode.

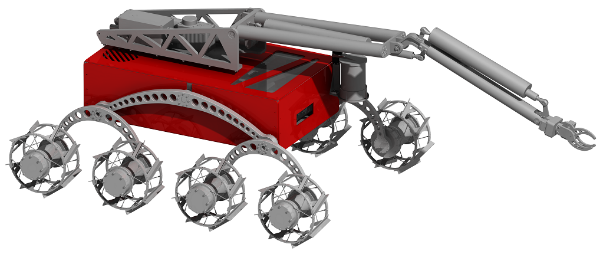


Fig. 6. SEAR assembly

5.1. Core components

The core of SEAR consists of on-board electronics for power distribution and computer processing. The power system makes use of a 24 V 20 Ah $LiFePO_4$ battery block and DC/DC-converters for generating the 12 V and 5 V bus voltages. A set of eight motors for locomotion are connected to the battery. A manipulator on top of the rover is used to grab, store and mount objects. Due to the short development timeline, the hardware concept is kept relatively simple. Most of the components are plugged and merged to a central processing unit. The main sensors are three Kinect cameras for 3D vision. One is mounted onto the manipulator, one at the front of the chassis and one at the back. An intertial measurement unit (IMU) is used supplementary for several purposes in location, navigation and manipulation tasks. Data from the wheel motion controllers is additionally used for odometry. For connecting small devices like infrared range sensors for measuring distance to closely located objects or servos for storing mechanisms, a supplementary microcontroller board is being used. Simple commands can be sent to the board by the main central processing unit. Several electronics components can easily be attached to the board if necessary during late phases of development.

5.2. Locomotion

SEAR belongs to the class of wheeled robots for planetary exploration. The drivetrain consists of eight wheels passively suspended on a Rocker-bogie system as shown in Figure 7. Both rockers are connected to each other and to the chassis through an averaging mechanism.

By adding bogies to each end of the rocker arm, two wheels on one end of the rocker can be suspended from two on the other end. The Rocker-bogie suspension system shown in Figure 7 produces no asymmetrical loads on the wheels. The Rocker-bogie's big advantage is that it can negotiate obstacles that are twice the wheel height [15]. Each wheel is passively loaded by the Rocker-bogie suspension increasing traction greatly compared to a layout with eight wheels simply attached to the chassis.

The Rocker-bogie suspension is skid steered, which reduces the average system complexity. Compared to the most common six-wheeled concept with four steering motors for the front and the rear wheels and six wheel motors (as used in four Mars rovers

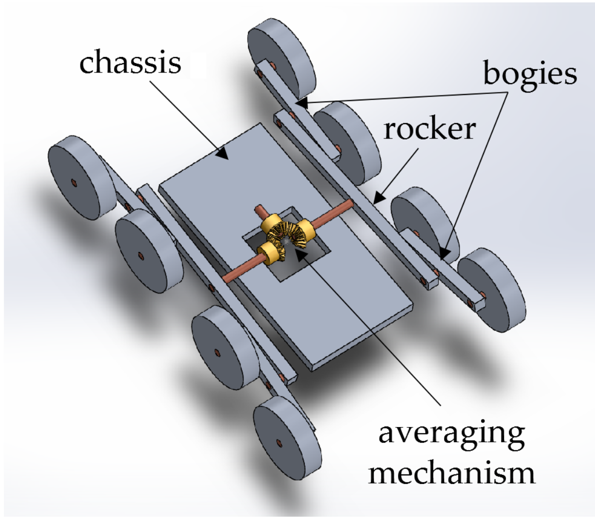
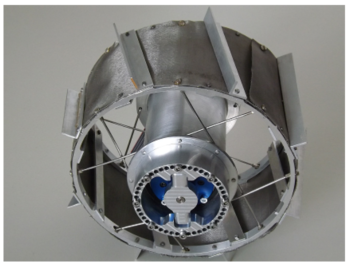
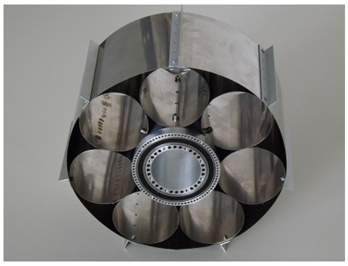


Fig. 7. SEAR's eight-wheeled Rocker-bogie locomotion system concept

since Sojourner developed by NASA), which is proposed to be the system with the highest mobility, the SEAR concept needs eight motors only. The rockers and the bogies are designed to withstand the side moments produced during skid steering.



(a) Rigid wheel.

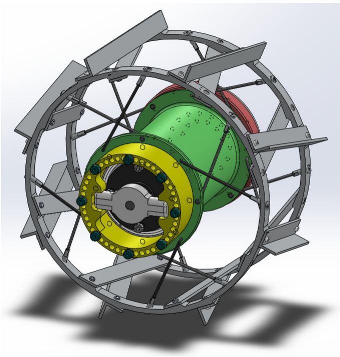


(b) Flexible wheel (concept rejected).

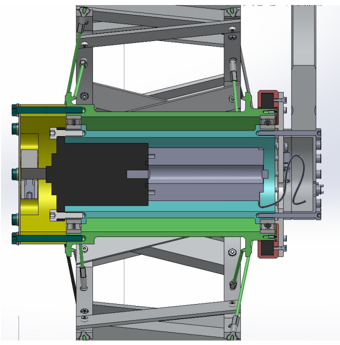
Fig. 8. Two wheel prototypes for SEAR manufactured at the TU Berlin, Aerospace Department's workshop

As mentioned above, a wheel based chassis was selected and constructed according to the formula 8×8. Two different types of wheels had been investigated, each with an outer diameter of approx. 20 cm and the width of the total supporting surface of 100 mm (see Figure 8). A metal-elastic wheel showed a very good soil traction performance in a theoretical investigation. In the end, the flexible wheel design was rejected due to several difficulties in manufacturing it at the department's workshop. After a redesign, a rigid wheel with spikes was chosen as shown in Figure 8(a).

The supporting surface is formed by a steel mesh. The mesh is spanned between two rings machined from an aluminum alloy using outer and inner hoops. For the case of the rover driving across soft soil, the supporting surface was designed larger. Each of the aluminum rings is connected via eight steel spokes to a hub made from aluminum alloy. Inside the hub a commercial-off-the-shelf brushless motor with a gear box is used. The wave of the gear box is decoupled from axial and radial forces via a coupling shaft (see Figure 9(b)). The main axial and radial forces between the rotor and the stator are contained by two dedicated ball bearings and not only by the ball bearings of the gear box. Each of the motor-wheels is controlled individually by a wheel drive electronics implementing amongst others wheel velocity and momentum-of-rotation control loops. The dissipated heat is transferred from the motor to the bogie via a thermal interface composed of several heat conductors made of copper.



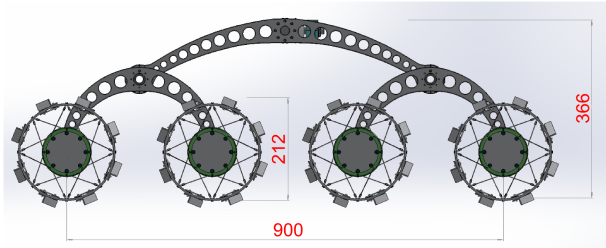
(a) Isometric view.



(b) Cut through the motor-wheel.

Fig. 9. CAD design of SEAR's spiked wheel

The rockers and the bogies are machined from an aluminum alloy. Each of the bogies with the length of approx. 30 cm carries two wheels and is connected to the rocker (approx. 70 cm) via ball bearings exactly in its middle as shown in Figure 10. An averaging mechanism consisting of three ball-beared gear-wheels is attached to the chassis of the rover. The rocker and the bogies are curved in order to achieve a certain relation of the center of gravity and the point where the forces from the rocker are coupled into the main body of the rover. The suspension mechanism, the motor-wheels and the averaging mechanism together achieve a total mass of approx. 17 kg wich can be reduced by decreasing safety factors using advanced analysis methods and by utilising materials with better mechanical properties.



(a) Side view.

Fig. 10. Side view on SEAR's drivetrain (Dimensions in mm)

5.3. Software architecture

Selecting a robotics software framework is a mandatory task, if one wants to use as much preexisting knowledge and technology as possible. Among several options [16–19] the Robot Operating System (ROS) [20] as main framework was selected, because of its built-in publish-subscribe mechanism, a thriving community [21] and a detailed documentation together with an open source license. ROS' use in several well-known research projects [22, 23] is just a small hint to the leading-edge software paradigms and application programmin interface (API) of the framework. This also makes it an ideal choice for education purposes as students get a deeper insight on the inner workings of a robot. The publish-subscribe nature of ROS on the other hand enables it to easily distribute key development tasks among the students. For this purpose at first key tasks have been identified which could easily be put into separate so-called ROS packages. For many of these tasks there are already standard packages existing in the ROS framework which are adapted to work with SEAR.

5.4. Task planner

Task planning is organized into a hierarchy which resembles the corresponding high-level and low-level routines of the rover. While low-level routines are beeing carried out by individual ROS packages, a finite state automata is used to generate the high-level commands and propagate them down the hierarchy.

5.5. Simultanous Location And Mapping (SLAM) and path planning

Mapping of the rover's environment and simultanous location is beeing provided by the navigation stack of ROS which is well integrated with a commercial Kinect sensor. This sensor is a widely used sensor among robotics projects and generates point cloud data from the environment. The navigation nodes then use this data to calculate the position of the sensor within the surroundings by correlating geometric features from the map data with those in the point cloud. While the original map generated from the point cloud is a 3D map, the path planning algorithm provided by ROS requires a 2D pixelmap (Figure 11). The 3D data is used and converted into the required format by representing regions with slopes too steep to be handled by SEAR as obstacles. The path planning algorithm first tries to find a way through obstacles without taking details into account. This is called the global path. In a next step the local planner takes care of the details like steering and turning radius. For this purpose a detailed model of the rover provides the necessary parameters.

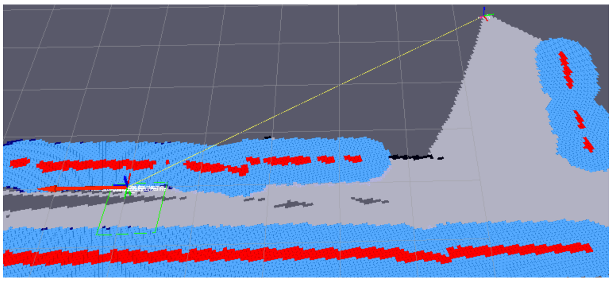


Fig. 11. 2D pixelmap of the global cost map calculated from the point cloud data of the Kinect sensor

5.6. Object recognition

Searching for the required objects, identifying them and subsequently measuring range and orientation is beeing done with the widely used OpenCV library [24] coupled with the Kinect sensor. The algorithm primarily uses color information from a video image, as the target objects have a specified color in contrast to a rather monotonous environment.

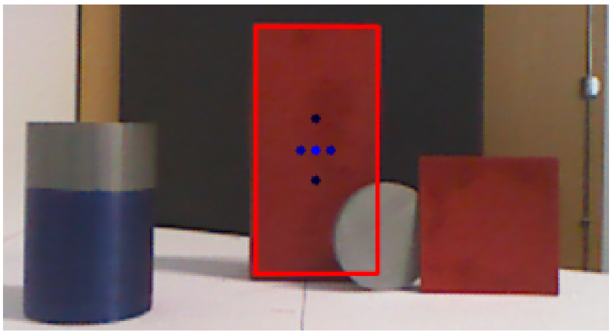


Fig. 12. Recognition of the battery pack prototype by using Kinect sensor data

5.7. Manipulation

In total, the manipulator has six degrees of freedom. It is able to reach for objects around the rover. A stereoscopic camera on the manipulator allows a 360 degrees observation without having to rotate the rover itself. A special grasping mechanism has to be developed to grab the specified objects. An additional challenge is the transportation of the glass of water. Control algorithms are also provided by the ROS manipulation planning stack. It relies on a generic gradient-based numeric algorithm for inverse kinematics. Trajectory planning for collision avoidance works by taking the point cloud into account, which is provided by one of the Kinect sensors (Figure 13).

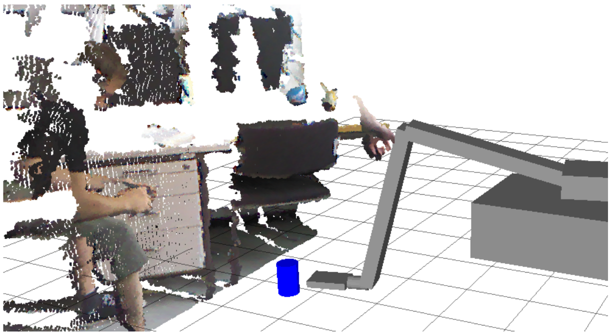
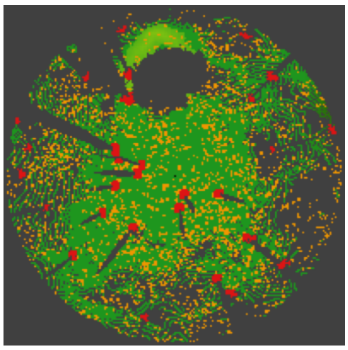


Fig. 13. Simulation of manipulator trajectories utilizing the point cloud for collision avoidance

5.8. Navigation

The navigation is based on input from a COTS stereoscopic camera. The Kinect camera has proven to be a good solution in many robotics projects around the globe. A colored scatter-plot allows visual navigation like shown in Figure 14. It is made use of the open-source framework ROS in combination with image processing libraries like OpenCV and for SLAM algorithms. Besides visual odometry with the stereoscopic camera, data from wheels and an inertial measurement unit in fusion shall allow a more accurate position determination.

(a) Terrain view.



(b) Local environment view.

Fig. 14. Principles of SEAR's exploration strategy. (a) Position of rover within terrain. (b) Local environment based on simulated sensor data

6. SEAR in education

SEAR is a project that is mainly conducted with undergraduate students under supervision of staff members. SEAR is put together of a core team consisting of three permanent staff members who are mainly involved in other projects and three undergraduate student assistants solely dedicated to the project. The staff members are each responsible for supervising aspects of project management, mechatronics and software. The student assistants are provided with a work environment and facilities. Having a core team has proven to be a critical success factor for the good advancement of the project. Much groundwork had to be layed by the core team in terms of setting up a programming environment and defining interfaces in order to make it possible for over 20 students to write software in parallel. For example, an Ubuntu image was created that encovered the ROS environment and all important packages for a kick-start in a uniform working environment. A two-layered hierarchical structure was also found out to be helpful for increasing decision makings inside the project.

During summer term 2013, aspects of the rover development are covered by students in project work in the lecture "Planetary Exploration and Space Robotics". Students receive 6 ECTS credits for the course which consists of a weekly theoretical lecture and project work. With a total number of 20 students there is huge manpower that can efficiently be utilized within three months. The members of the student group have a different background. Most are Master's and Bachelor's students from the aerospace engineering study course between the ages of 20 to 25. One fourth are computer engineering students. The rest is coming from related engineering study courses. Most of the students have a basic knowledge in programming. The interdisciplinary group emerged to be a great basis for distributing tasks in the areas of mechanics, electronics and software. By using the programming language Python, even students with little understanding of programming managed to write sophisticated code. A strong support by group members, good introductary tutorials and the well-documented robotics framework made a fast and efficient software development possible.

High attention was payed in designing the course structure. During the first week, the students were introduced to the contest and the rough rover concept. Like in industry, a job catalogue provided an overview of available positions within the project. The job description file was developed in brainstorming and mind mapping sessions with the SEAR core team. In general, it is a challenge to find self-containted work packages with an appropriate and equally spreaded work load. Around 15 jobs for up to two persons each were to be found in the document. Following, a typical job description for each a mechanical, electrical and software engineer is listed.

For a rapid start of the project, in each work package a specific initial task was presented. The task had to be done withing four weeks after the students had been allocated to their work packages. The allocation process was done as follows. After students received the jobs description document, they had to fill out a one page application form within one week. Desired position, application writing, curriculum vitae and three alternative positions were necessary information to be delivered by the students. By carefully evaluating the application forms, the jobs were assigned fairly.

JOB DESCRIPTIONS

Mechanical engineer for conception of a grasping mechanism

In the contest, two specific objects shall be grasped by the rover. Therefore, a concept for the grasping procedure has to be developed. A gripper, sensors for touch feedback and prototypes of the objects shall be developed. Tests shall be conducted.

Tasks until course date 4:
- *Evaluation of available grippers for specific objects.*

Electrical engineer for design of on-board electronics

All components on the rover including on-board computer, motors, sensors, actuators etc. have to be supplied with electrical energy. An appropriate energy storage has to be alloted that can provide all systems with energy for at least one hour. For all components, appropriate voltages have to be conditioned. For some electronics, adapter circuits have to be designed.

Tasks until course date 4:
- *Presentation of a block diagram that shows all electrical components, their properties and interfaces.*

Software engineer for image-based object identification

During the contest, three objects on the terrain have to be located and identified. Therefore, image-processing algorithms have to be assembled and adapted. With test settings and object prototypes, the algorithms shall be proven.

Tasks until course date 4:
- *Learning basics of robot operating system by doing the tutorial.*

The course structure is very promising for the students to make a good engineering education experience. The course is evaluated by project work and a test on general knowledge about planetary exploration and space robotics. Withing 10 weeks the students finished the mechanical design of the rover and had written functioning software parts covering all aspects of the mission. They won deep practical insight in at least one specific part of developing mechanics and software for a robot. Through the strong collaboration, weekly meetings and laboratory work hours they also gained an insight into all other aspects of a robot. During a period of approx. two months for manufacturing, the software parts will be extended and tested seperately. After assembly, complete system tests will be conducted on a 5 m $\times$ 7 m planetary surface testbed.

7. Conclusion

Although, practical space engineering education is a major challenge, several approaches for a successfull implementation of a practical curriculum have been presented. TU Berlin successfully excercised several approaches like mission design courses, space-related experiments and hands-on courses. Over the years, it has been found that students are highly motivated when they are assigned responsibilities within a project with real impact. Not only students can benefit from a real project experience in education, but also the Chair can benefit from a well-organized manpower in lecture courses to push forward important projects.

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ACKNOWLEDGEMENTS

The SEAR project is funded by the German Aerospace Center (DLR) with funds from the Federal Ministry of Economics and Technology (BMWi) on the basis of a decision of the German Bundestag (Grant No.: 50RA1314).

Special thanks go to all students that allowed the implementation and successfull completion of practical lecture courses at TU Berlin.

REFERENCES

[1] J. J. Duderstadt, "Engineering for a chaning world," The University of Michigan, Ann Arbor, MI 48109-2094, Tech. Rep., 2008.

[2] R. Graham, "Achieving excellence in engineering education: the ingredients of succesful change," The Royal Academy of Engineering, 3 Carlton House Terrace, London SW1Y 5DG, Tech. Rep., March 2012.

[3] C. L. D. et al., "Engineering design thinking, teaching, and learning," *Journal of Engineering Education*, vol. 94, pp. 103–120, 2005.

[4] M. Gruntman, "The time for academic departments in astronautical engineering," in *Proceedings of the AIAA SPACE 2007 Conference & Exposition*, Long Beach, California, USA, September 2007.

[5] T. Ltd., "Space exploration and innovation," Brighton, United Kingdom, Tech. Rep., October 2010.

[6] M. Swartwout, "Attack of the cubesat: A statistical look," in *Proceedings of the 25th Annual AIAA/USU Conference on Small Satellites*, Logan, UT, USA, August 2011.

[7] J. V. B. et al., "Affordable launcher for small spacecraft missions," in *Proceedings of the 19th AIAA International Communications Satellites Systems Conference*, Toulouse, France, April 2001.

[8] M. B. et al., "A survey of small satellites domain: Challenges, applications and communications key issues," *ICST'S Global Community Magazine*, 2010.

[9] *French CanSat Competition Rules, 5th edition*, CNES, 2011.

[10] H. S. et al., "Cansat leader training pogram (cltp) report," Tokyo Metropolitan University, Tokyo, Japan, Tech. Rep., July 2010.

[11] K. L. et al., "Stern - raketenprogramm für studenten," in *Deutscher Luft- und Raumfahrtkongress 2012*, Berlin, Germany, September 2012.

[12] *CubeSat Design Specification Rev. 12*, California Polytech State University, 2009.

[13] M. F. Barschke, "Beesat-3: A picosatellite developed by students," in *Proceedings of the 61st Annual Deutscher Luft- und Raumfahrtkongress*, Berlin, Germany, September 2012.

[14] B. für Wirtschaft und Technologie, "Schlaglichter der wirtschaftspolitik, monatsbericht mai 2012," Tech. Rep., May 2012.

[15] P. E. Sandin, *Robot Mechanisms and Mechanical Devices Illustrated*. The McGraw-Hill Companies, Inc., 2003.

[16] J. Jackson, "Microsoft robotics studio: A technical introduction," *Robotics & Automation Magazine, IEEE*, vol. 14, pp. 82–87, December 2007.

[17] A. Makarenko, "Orca: Components for robotics," in *Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Beijing, China, October 2006.

[18] H. Bruyninckx, "Open robot control software: the orocos project," in *Proceedings of the 2001 ICRA. IEEE International Conference on Robotics and Automation*, Seoul, Korea, May 2001.

[19] R. D. et al., "Openrave: A planning architecture for autonomous robotics," no. CMU-RI-TR-08-34, July 2008.

[20] M. Q. et al., "Ros: an open-source robot operating system," in *Proceedings of the 2009 IEEE International Conference on Robotics and Automation*, Kobe, Japan, May 2009.

[21] S. Cousins, "Exponential growth of ros," *Robotics & Automation Magazine, IEEE*, vol. 18, pp. 19–20, March 2011.

[22] T. Krüger, "Exoskeleton control of the robonaut through rapid and ros," in *Proceedings of the 12th Symposium on Advanced Space Technologies in Robotics and Automation*, Noordwijik, Netherlands, May 2013.

[23] S. Cousins, "Ros on the pr2," *Robotics & Automation Magazine, IEEE*, vol. 17, pp. 23–25, September 2010.

[24] G. Bradski, "The opencv library," *Doctor Dobbs Journal*, 2000. [Online]. Available: http://elibrary.ru/item.asp?id=4934581