EXOMY: A LOW COST 3D PRINTED ROVER

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ABSTRACT

In this paper, we describe the educational robot ExoMy inspired by the mars rover Rosalind Franklin of the European Space Agency. ExoMy features a triple-bogie locomotion subsystem with six steerable wheels. All mechanical parts are 3D printed. The electronics consist of a battery, power distribution, on board computer and camera, which are widely available and cost-efficient

The software allows teleoperation of ExoMy using a gamepad or a custom web interface, which further features a camera view. It is programmed in Python, within the ROS framework to make future expansion easy and is deployed with Docker.

The project is published under an open source licence and comprehensive assembly and installation instructions are provided. ExoMy has successfully been built, using only the provided documentation and can be a feasible introduction to space robotics for students and enthusiasts.

1 INTRODUCTION

There is a large incentive in introducing children and students early on to technology, the fascination of space and robotics. While a vast amount of robotic kits and open source projects, as an entry into robotics exist, few of them are related to space.

The SPHERES project [1] from the National Aeronautics and Space Administration (NASA) as well as the Astro Pi project [2] from the European Space Agency (ESA) aim to bring robotics and software development for space closer to students, by running experiments of students on the International Space Station.

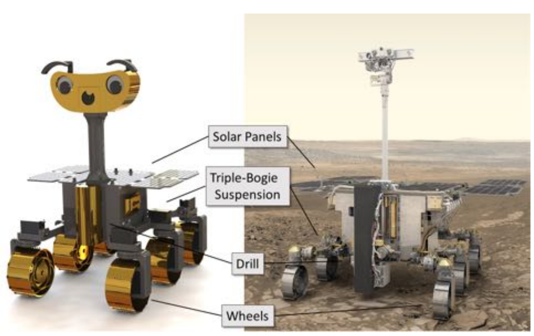

Figure 1. ExoMy features the most important characteristics of the ESA rover Rosalind Franklin.

As an introduction to planetary robotics in classrooms, the NASA Jet Propulsion Laboratory (JPL) released the JPL Open Source Rover [3]. The remote controlled rover features a rocker-bogie suspension system, which has been the go-to suspension design for all NASA martian rovers since the Sojourner mission [4]. However, the barrier of entry for enthusiasts to build the JPL Open Source Rover is high, due to hardware costs of around ~2100 €. Further, a significant amount of tools is necessary to complete the project.

The derivative project Sawppy [5] reduced the material costs down to ~420 € , by replacing the sheet metal construction of the JPL Open Source Rover with aluminium extrusions, connected by 3D printed brackets and by using hobby servo motors instead of individual motors, gear boxes, encoders and controllers. While Sawppy introduced a low cost rover, it still uses a significant amount of metal parts such as shafts, extrusions and bearings, some of which have to be modified using powertools, which is not ideal for a class room activity.

In this work we present ExoMy, a 3D printed rover inspired by ExoMars as shown in in Fig. 1. It features six dual actuated wheels, a passive triple-bogie suspension, a Raspberry Pi as its on-board computer and a camera. It can be teleoperated using a web interface or a gamepad.

The full design and source code of ExoMy are open source [6], allowing people to easily customize and expand the platform. An extensive documentation describes the assembly and programming process, enabling anyone with a 3D printer to build ExoMy.

2 HARDWARE DESIGN

The design of ExoMy was developed with printability, simplicity and durability in mind, while using only widely available, cost-efficient, off-the shelves components, as shown in Tab. 1 and Fig. 2. Characteristic features of the European mars rover Rosalind Franklin were visually adapted in parts such as the solar panels, the drill and the wheels, as well as functionally represented in the triple-bogie suspension, as seen in Fig. 1.

2.1 Mechanical Design

The passive triple-bogie suspension ensures that all six wheels make contact with the ground at all times and offers the same performance as the rocker-bogie system, as well as reduced complexity by eliminating the need for differential linkages, as shown in [7]. All six wheels are

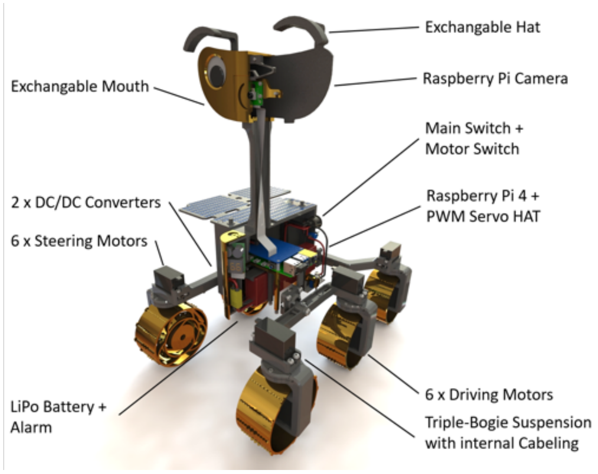

Figure 2. ExoMy is open source and can be built from 3D printed parts and off-the-shelve components.

Table 1. ExoMy uses off-the-shelve components, that are available from a wide range of suppliers.

Component	**Quantity**	**Supplier**	**Total Cost**
Motors	12	RS	180 €
Microcomputer	1	Conrad	50 €
Camera	1	Conrad	20 €
PWM Board	1	Adafruit	15 €
Power Electronics	1	Conrad	25 €
Filament	1.5 kg	RS	50 €
Screws	143	RS	20 €
Total Cost			**360 €**

actuated with a low cost Parallax continuous servo motor each. They can be individually steered with a Parallax servo motor with a range of 180 °.

ExoMy weighs 2.5 kg and measures $392\,mm \times 300\,mm \times 420\,mm$ in length, width and height. All parts except the flexible wheel sleeves were printed with polylactic acid (PLA) filament, since it is environmentally friendly, easily printable and sufficiently strong. Screws were used as the axles of the bogies and to reliably connect the 3D printed parts. In most cases, the bolts were screwed directly into the plastic, cutting a thread in the process.

All motor cables are hidden within the bogie to increase the aesthetics, protect them from dust and prevent them from making contact with moving parts. The ports of the Raspberry Pi are easily accessible by removing the port cover on the side and the drill-mock-up in the front. This allows for rapid connection of USB devices, HDMI displays and an external power source.

Removal of the drill mock-up further grants access to the battery, which is secured in the chassis by a 3D printed flexible latch. The head of ExoMy is mounted to a mast and features an interchangeable mouth and hat, which allow easy customization, as shown in Fig. 3. The mouth is fixed by a 3D printed latch and covers a Raspberry Pi Camera v2. The pupils of ExoMy's eyes can be moved, so it can "look" in any direction.

Figure 3. The hat and mouth can be exchanged to customize the look of ExoMy.

The grousers on the wheels help with traversing loose soils, rocks and other obstacles. On flat ground however, they cause unwanted vibrations and disturbances. Flexible wheel sleeves, printed out of Thermoplastic Co-Polyester (TCP), can be slid over the wheels, as shown in Fig. 4, to better drive on smooth surfaces.

2.2 Electronics Design

The Raspberry Pi on board computer provides sufficient computing power, interfaces for the addition of sensors, a large community surrounding the platform and a Linux based operating system, which offers a wide range of open source software.

The twelve motors of ExoMy are controlled using pulse width modulation (PWM) signals, which are provided by the Adafruit 16-Channel PWM/Servo HAT addon board, connected via I^2C. PWM servo extension cables create a reliable connection between the servo motors and the PWM/Servo HAT. A Raspberry Pi camera module

Figure 4. The wheel sleeves increase the contact area to the ground and allow driving on smooth surfaces

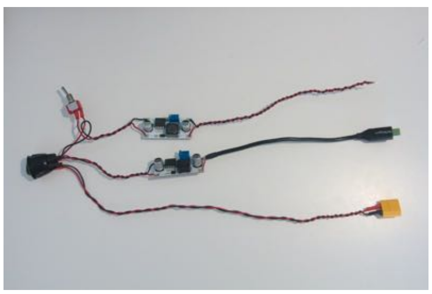

Figure 5. The wire harness for the power supply can be easily assembled outside of the rover.

v2.1 connected via the dedicated camera socket, opens the possibility for image processing applications and remote teleoperation.

The rover is powered with a 3S lithium polymer (LiPo) battery and two adjustable DC/DC converters step the battery voltage from 11.1 V, down to 5 V for the Raspberry Pi and to 6 V for the motors. We use a dedicated voltage converter for the Raspberry Pi, as spikes in current draw from the motors can lead to a temporary shut off of the DC/DC converter. This in turn would shut down the Raspberry Pi.

The wire harness can be soldered and assembled outside of the rover, as seen in Fig. 5 and later be installed as one piece. As shown in Fig. 6, Switch 1 controls the power to the whole system, while Switch 2 additionally controls the power to the PWM Board, which in turn powers the servo motors.

3 SOFTWARE DESIGN

3.1 Software Architecture

The functionality of ExoMy was implemented using Python and the robotic operating system (ROS) [8].The

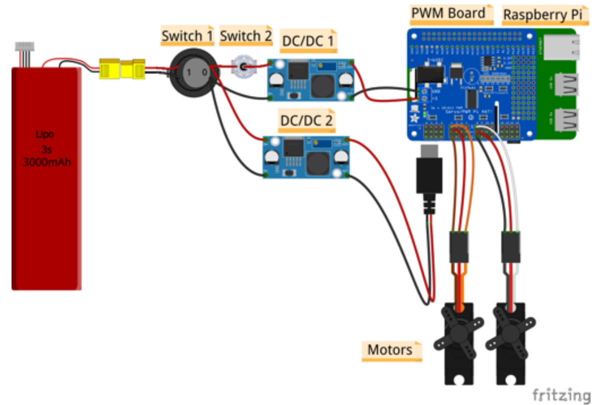

Figure 6. A LiPo battery powers the electronics. Two DC/DC converters ensure the required voltage levels for the motors and the Raspberry Pi.

extensive documentation and tutorials of ROS, help to keep the system accessible for inexperienced users and the flexibility of the framework allows more advanced users to expand the functionality with their own code.

Each ROS distribution is officially supported under a specific Ubuntu version. The installation of a specific Ubuntu version on a Raspberry Pi can be difficult though, given the variety of Raspberry Pi versions, that people might use with ExoMy. To solve this, Raspberry Pi OS is installed natively and therein a Docker image, containing Ubuntu. ROS is run within said Ubuntu Docker image as shown in Fig. 7. This allows the use of the full functionality of ROS and the Raspberry Pi, simplifies the installation and makes the software independent of the Raspberry Pi version used.

Figure 7. The use of Docker allows reliable deployment, independent of the OS and Raspberry Pi version used.

The functionalities are divided into several nodes, as shown in Fig. 8, allowing seamless expansion and reusability of the software.

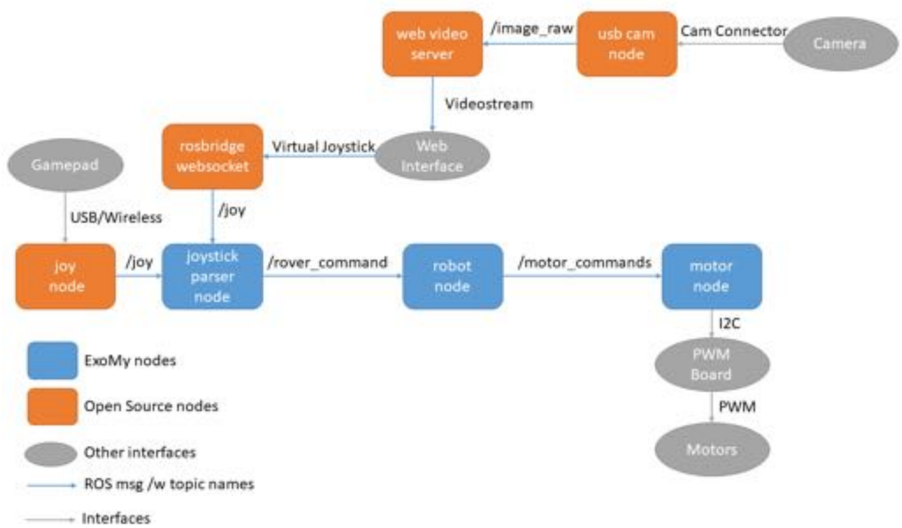

Figure 8. The software of ExoMy can easily be extended, due to the usage of ROS.

3.2 Software Features

The rover can be teleoperated using a gamepad, or a custom web GUI, featuring a live video stream, as shown in Fig. 9. The web interface can be accessed by a wide range of devices (laptop, tablet, smartphone) via a Wi-Fi hotspot, that is hosted by the Raspberry Pi.

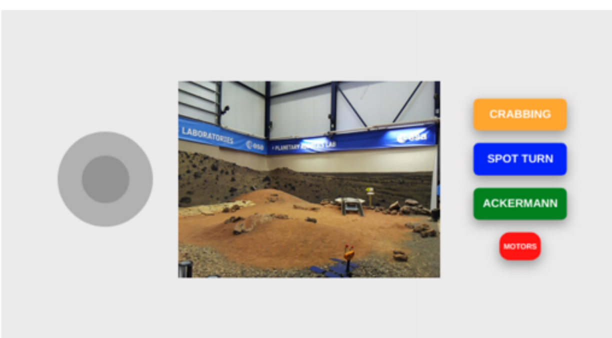

Figure 9. The web GUI provides a joystick control, a video live stream of the on board camera and buttons to switch the locomotion mode.

ExoMy is able to drive in three locomotion modes. With Ackermann steering ExoMy can be commanded a linear velocity in forward direction, as well as an angular velocity and thus creating a driving behaviour similar to a car. The Spot turn mode enables ExoMy to rotate on its current location. In the Crabbing mode ExoMy can traverse in both forward and sideways direction without changing it's orientation, by steering all six wheels in the same direction.

4 RESULTS

Iterative testing in the mars yard of the Planetary Robotics Laboratory at ESA was essential to the development of ExoMy, as it allowed a quick way to validate and improve mechanical parts.

The maximum speed of ExoMy was measured at 23 cm/s, which is sufficiently high for entertainment, education and research use. Furthermore it can be seen in Fig. 10, that ExoMy is able to traverse stones up to the size of its wheels.

The continuous current consumption of ExoMy was measured, to evaluate the potential operation time. An average of 700 mA was measured while driving at full speed in loose gravel and 600 mA when driving in firm sand. With a battery capacity of 3000 mAh, this leads to a theoretical battery life of 4h 16 min and 5 h respectively.

The teleoperation software stack showed to be reliable enough to operate continuously on the ESTEC Open Day 2019 as well as the VSV Symposium at the Technical University of Delft and showed to be intuitive for users of different experience levels.

The project was shared on various social media platforms. Three months after the release, the first person built his own ExoMy. With little 3D printing experience, he independently completed the build on an entry level printer (Ender 3 Pro) and confirmed the expected two weeks print time and two days build time. Software installation went without a problem, following the given tutorials. We know of two more people that began the build.

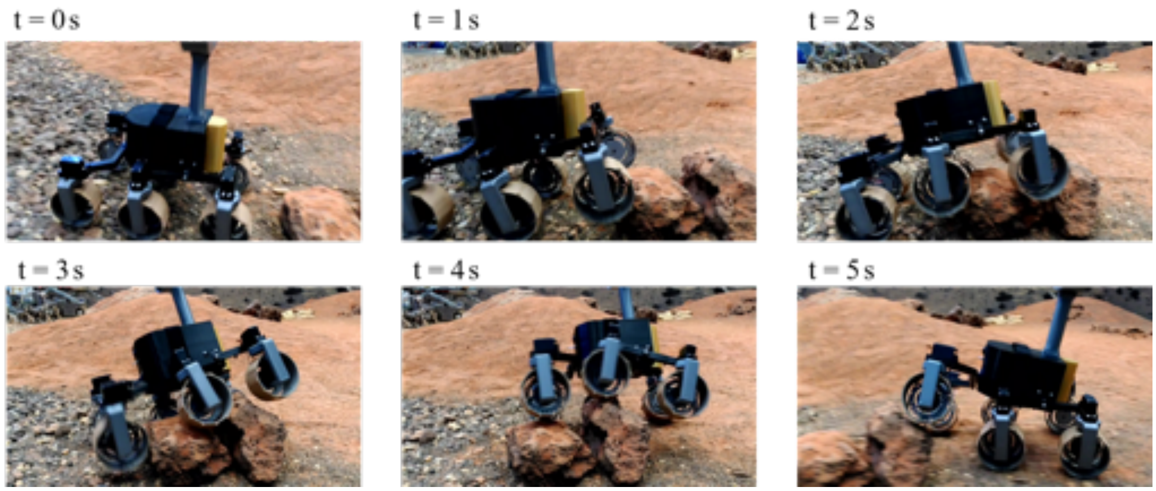

Figure 10. The triple-bogie suspension system allows a stable traverse of obstacles.

5 CONCLUSION

We present a fully 3D printed rover with six steerable wheels capable of traversing rough terrain. The robot can be teleoperated using a web GUI, as well as a gamepad. A built in camera allows for remote teleoperation and provides the capabilities for the implementation of computer vision algorithms.

The rover performed reliably during multiple events and various tests in the Planetary Robotics Laboratory at ESA. It was controlled by more than 50 people and generated interest and public awareness for space robotics.

Six months after release, more than three people started the build of ExoMy, with one person having it completed. The open source nature of the project gives anyone with a 3D printer access to an advanced rover platform, at the very low cost starting from 360 €, which can serve as educational platform in the three main fields of robotics: mechanics, electronics and software.

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References

[1] Sreeja Nag, Jacob G. Katz, and Alvar Saenz-Otero. Collaborative gaming and competition for cs-stem education using spheres zero robotics. *Acta Astronautica*, 83:145 – 174, 2013.

[2] N. Navarathinam, D. Liddle, D. Honess, J. Bell, L. Howarth, P. Colligan, L. Jackson, J. Curtis, J. Chinner, S. Eves, T. Lyons, D. Gibbs, P. Norris, A. Hansom, R. Elliot, T. Tinsley, C. Holmes, and A. Powell. Astro pi: Launch your code into space. volume 13, pages 9992–10003, 2015.

[3] Jpl's open source rover, online: accessed (09.2020), opensourcerover.jpl.nasa.gov, 2018.

[4] Donald Bickler. Roving over mars. *Mechanical Engineering*, 120:74–77, 04 1998.

[5] Sawppy the rover, online: accessed (09.2020), hackaday.io/project/158208-sawppy-the-rover, 2018.

[6] Exomy - the 3d printed rover, online: accessed (09.2020), esa-prl.github.io/exomy, 2020.

[7] Nildeep Patel, Richard Slade, and Jim Clemmet. The exomars rover locomotion subsystem. *Journal of Terramechanics*, 47(4):227 – 242, 2010.

[8] Morgan Quigley, Ken Conley, Brian Gerkey, Josh Faust, Tully Foote, Jeremy Leibs, Rob Wheeler, and Andrew Ng. Ros: an open-source robot operating system. volume 3, 01 2009.