# A Hand-Held Teleoperation Device for the Control of the Mars Rover Analogue Manipulator

Adam Przemysław Buczyłowski, Maciej Rećko, Adam Wolniakowski, and Karol Haraburda
Faculty of Mechanical Engineering, Białystok University of Technology, Białystok, Poland
Email: adam.buczylowski@gmail.com, m.recko@outlook.com, a.wolniakowski@pb.edu.pl, karol.haraburda@gmail.com

***Abstract*— Presented paper deals with remote robotic arm teleoperation problem. The discussed solution is our design device in the form of a glove that is equipped with sensors allowing the operator to quickly and most important accurately control movements of a robotic manipulator without the need for any additional controllers. The first section of the paper identifies the problem and discusses solutions developed in various use cases. Here we also describe our own specific planned use of the device- control of an arm attached to a Mars rover analogue. Following part describes the test robotic arm's kinematics and the design our device followed by an explanation of movements used by the operator during operation. The third part consists of the evaluation experiment's description, along with the results of the carried out test. Our observations allow us to believe that usage of the proposed device helps the operator to swiftly perform tasks, faster than with the manufacturer's dedicated control panel. This assumption is based on the steeper learning curve, compared to the default solution, that our device was compared to.**

***Index Terms*—teleoperation, robot control, mars rover analogue, manipulator, robotic arm**

## I. Introduction

The use of robots in industry, research and space exploration offers many possibilities and interesting challenges to be addressed.

Control of such machines challenges designers and engineers in pursue of the most powerful yet convenient and intuitive method. Their efforts mostly revolve around four basic means of robot control: strict programming, programming by teaching, Human- Machine Interface (HMI), or giving the controlled object some level of autonomy. The rise of collaborative robotics stresses the importance of the development of the HMI that allow for seamless and precise integration of the capabilities provided by the robots and the skills uniquely possessed by the human operators [1]. A variety of applications and methods of achieving such interface is currently under research and development around the world [2]-[5]. Some approach this problem by means of computer vision and 3D sensors that track operator's arm (Fig. 1) movement in space and interpret them into control commands [6]-[8]. Others aim to use biosignals [9], [10], while others use phantom devices [11] sometimes in exoskeletal form [12], [13]. All of those solutions have significant disadvantage by depending on additional equipment. Vision based solutions also require a large amount of space for movement recognition and high processing power. This is why a goal was set on creating small and convenient device enabling its usage even in confined space. Space exploration is an especially challenging context, in which massive effort is exerted to develop robust and dependable solutions through the use of simulation and testing of analogues, by the way of robotic Mars rover analogue competitions.

Figure 1. Device mounted on operator's arm.

During University Rover Challenge (URC) - one of the most prestigious space robot's competition - the team and their rover have to ace four field tasks: 1. Scientific reconnaissance of selected area in search of life indications; 2. Traversal of a very difficult terrain and delivering cargo [14]; 3. Autonomous travel mission; 4. Equipment servicing task. A typical task during the competition involves performing a teleoperation, based on the main assumption of the competition: Rovers assist manned mission to Mars. As so, it is possible to remotely control them, without tremendous delay in communication unavoidable if controlled from the Earth. Some tests of orbital control of ground rovers were carried out by NASA in 2013 [15] and successfully repeated in 2019 [16], proving that such a scenario is not only possible but useful for exploration missions. A

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successful execution of the task depends both on the skills of the operator, as well as the design of the rover, rover manipulator, the software system and the interface. The requirements that must be met are in particular: sole dependence of the camera and sensory feed from the mobile platform - each task must be performed from remote and isolated location, rover cannot break during task, there is a limited time allotted to each team for each task.

These requirements are difficult to meet due to numerous constraints. A space-faring robot is limited by mass, each gram that is sent to space is costly, so in case of URC rover the mass is limited to 50 kg. Furthermore, a limiting factor in the Mars analogue competitions is a fixed cost limit for the final design of the robot. This usually does not allow for the use of the cutting edge technologies and instead calls for the exploration of the tried and tested alternatives, with the implicit goal of exploiting them to the limits.

Typically, the control of a Mars rover analogue is achieved by means of a joystick [17]. The problem of a robotic arm's control was identified and addressed before [18], [19]. The possible solution presented was use of a phantom device. Though it simplified control, was impractical due to its size and thus lack of mobility.

In this paper, we propose a hand-held IMU based teleoperation system - Glove (see Fig. 2.) for the control of the Mars rover analogue robot manipulator.

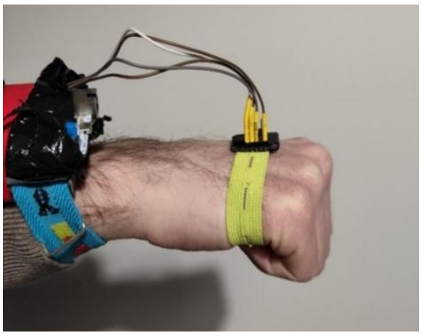

Figure 2. The Glove teleoperation device in a neutral position.

In Section II we describe the design and the principle of the operation of the device. We further perform an experiment to establish the usability of the device and provide the results in Section III. In Section IV we discuss the obtained results and arrive at the directions of the future work.

## II. Methods

### A. Robot Arm

The robot arm used for the experiments was an Universal Robot UR5 [ur5]. The manipulator has 6 degrees of freedom and reflects the kinematic structure of the rover manipulator, which was not available due to the construction still in progress. The kinematic structure of the robot is shown in Fig. 3. The UR5 kinematic parameters are presented in Table I. Table II contains the technical specifications of the robot arm.

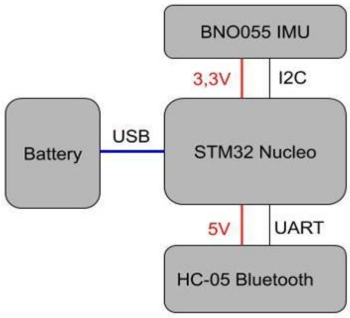


Figure 3. Components of the Glove.

TABLE I. Kinematic Parameters of UR5 (Fig. 4) [20]

| Kinematics | theta [rad] | a [m] | d [m] | alpha [rad] |
|---|---|---|---|---|
| Joint 1 | 0 | 0 | 0.089159 | π/2 |
| Joint 2 | 0 | -0.425 | 0 | 0 |
| Joint 3 | 0 | -0.39225 | 0 | 0 |
| Joint 4 | 0 | 0 | 0.10915 | π/2 |
| Joint 5 | 0 | 0 | 0.09465 | -π/2 |
| Joint 6 | 0 | 0 | 0.0823 | 0 |

TABLE II. UR5 Technical Specifications [21]

| Weight | 18.4 kg / 40.6 lbs |
|---|---|
| Payload | 5 kg / 11 lbs |
| Reach | 850 mm / 33.5 in |
| Joint ranges | +/- 360 ° |
| Speed: | All joints: 180 °/s.Tool: Typical 1 m/s. / 39.4 in/s |
| Repeatability | +/- 0.1 mm / +/- 0.0039 in (4 mils) |
| Footprint | Ø149 mm / 5.9 in |
| Degrees of freedom | 6 rotating joints |

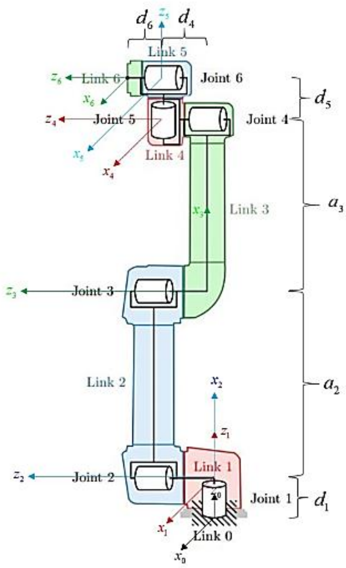


Figure 4. Kinematic structure of the UR5 manipulator [22].

The manipulator can be controlled through a touch-enabled panel (see Fig. 5). Furthermore, an URScript programming language [23] can be used to either create a program running on the control unit, or to send as individual commands through the network interface.

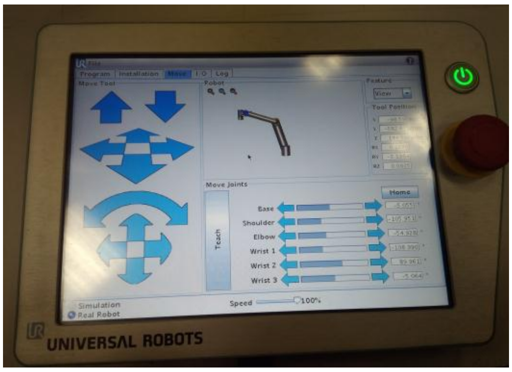


Figure 5. Polyscope operator panel for the UR5.

In this experiment, we have used the former approach, with the control of the robot achieved with a program running on the control box and communicating with a ROS node running on a PC used as the working station (Fig. 6). The ROS node used for the purpose of controlling the robot is a part of a package developed for the robotics laboratory at BUT [24].

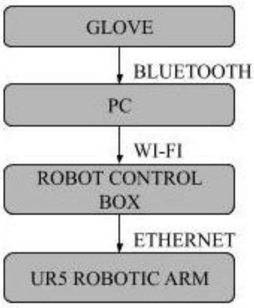


Figure 6. Block diagram of the teleoperation system.

The UR operator panel (Polyscope) allows for the control of the individual axes of the robot and for the movement of the TCP linearly in the cartesian coordinates.

The ROS node allows for the velocity and position control of the robot both in the configuration space and in the cartesian coordinates. The latter possibility was used for translation of the Glove movements to the movement of the TCP.

## B. The Glove

The teleoperation device introduced in this paper consists of Adafruit 9-DOF Absolute Orientation IMU Fusion Breakout - BNO055- (Fig. 7) [25] the data generating sensor, STM32 Nucleo-144 development board with STM32F767ZI MCU that is responsible for acquiring the sensor data via the I2C bus and sending it to the computer over the HC-05 bluetooth module, and a power bank as the power supply.

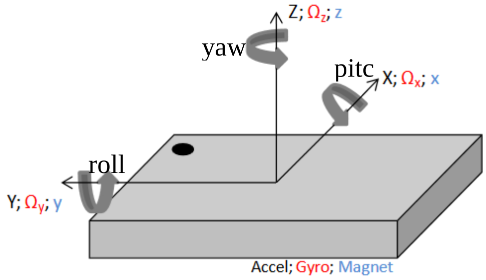


Figure 7. The BNO055 module frame of reference [26].

To make the device fully mobile it is necessary to send the data wirelessly. Therefore, the data-frame is passed over the Bluetooth with the frequency of 125 Hz, such that the delay in motion compared between the devices is not noticeable.

## C. Robot Control Scheme

As the robot moves in three axis we needed to provide three signed velocity vectors. These vectors are calculated from the orientation angles provided by the BNO055 gyroscope module.

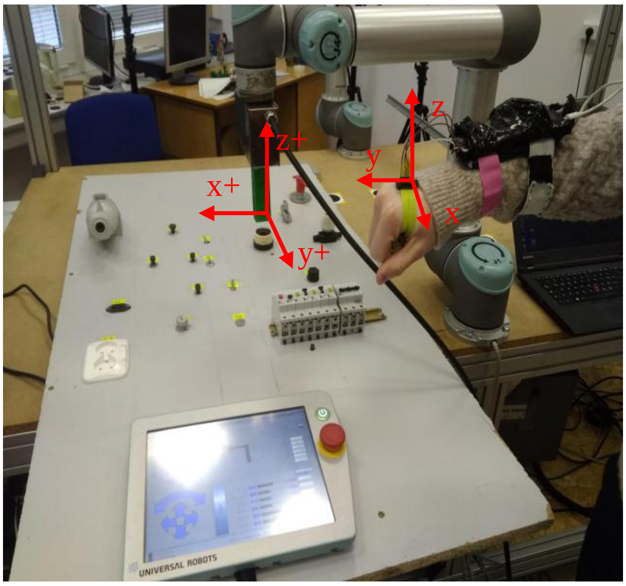


Figure 8. Experimental setting. Alignment of the TCP and the Glove frames of reference is shown.

The IMU allows for the measurement of the roll θ, pitch φ and yaw ψ angles, as well as accelerations $a_x$, $a_y$, $a_z$.

With the initial device frame of reference coincident with the base frame of the robot (see Fig. 8), we have introduced the following control law for the robot:

$$\dot{x}\begin{cases} 0 & if\ |\theta| < t_\theta \\ k_\theta(\theta - t_\theta) & if\ \theta > t_\theta \\ k_\theta(\theta + t_\theta) & if\ \theta < -t_\theta \end{cases}$$

$$\dot{y}\begin{cases} 0 & if\ |\varphi| < t_\varphi \\ k_\varphi(\varphi - t_\varphi) & if\ \varphi > t_\varphi \\ k_\varphi(\varphi + t_\varphi) & if\ \varphi < -t_\varphi \end{cases}$$

$$\dot{z}\begin{cases} 0 & if\ |\psi| < t_\psi \\ k_\psi(\psi - t_\psi) & if\ \psi > t_\psi \\ k_\psi(\theta + t_\psi) & if\ \psi < -t_\psi \end{cases}$$

The equations presented above were used to calculate the velocities applied for the movement of the robot's TCP. We added thresholds $t_\theta$, $t_\varphi$ and $t_\psi$ ($t_\theta$ = t=$t_\psi$ = 5°) in order to eliminate unconfident movements induced by unsteady hand movement. The factors $k_\theta$, $k_\varphi$ and $k_\psi$ ($k_\theta$ = $k_\varphi$ = $k_\psi$ = 0,35) were used to scale the desired velocities.

The Glove orientation expressed in Euler angles is scaled to find the desired velocities. For each axis the velocity is in clamped to a range from -0.3 to 0.3 m/s. The key feature of the implemented system is that the velocity can be controlled in this range as opposed to operator's panel where the velocity is constant and only the direction can be set. In order to give the operator some comfort and let him change the position of the hand there is a zero-button which sets all the velocities to 0.

To move UR5 forward and backward (in *y* axis) the user needs to flex and extend the wrist down and up accordingly (Fig. 9a, 9b). By adduction and abduction of the wrist the left-right motion (*x* axis) is enabled (Fig. 9c, 9d). Finally the TCP position in z axis is regulated by pronation and supination of the wrist (see Fig. 9e, 9f).

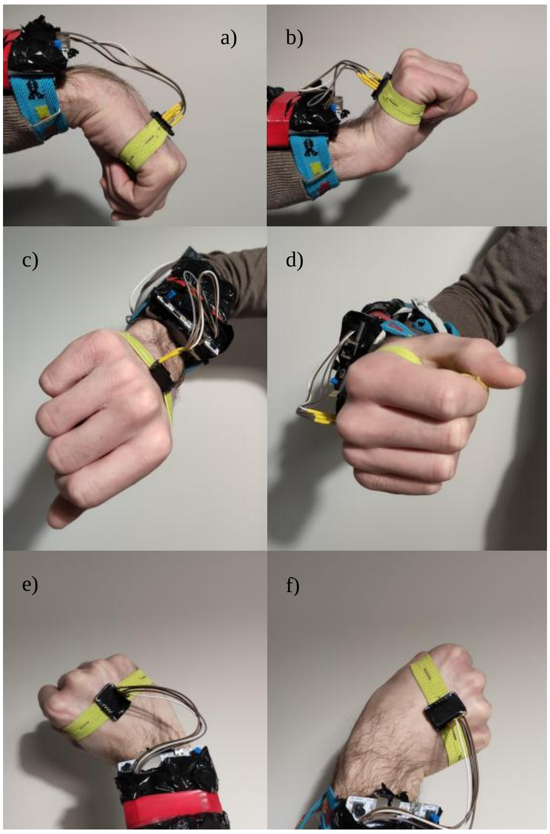


Figure 9. The orientations for the velocities desired: a) forward ($-v_x$), b) backward ($+v_x$), c) left ($-v_y$), d) right ($+v_y$), e) up ($+v_z$), f) down ($-v_z$).

## III. Experiments

To perform our experiment we engaged 5 people of ages 20-50 and of different experience level of robot control. Their task was to toggle four switches from their initial positions (Fig. 10) to the desired positions (Fig. 11). Task sequence was fixed (P1→P2→P3→P4). Every subject has been instructed on how to use the device and had an opportunity to test executing the task before the experiment commenced. Each experiment was repeated three times. Times recorded during test are listed in Table III.

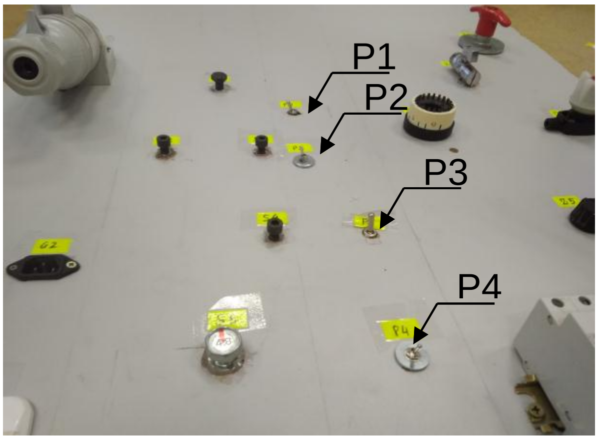


Figure 10. Initial setting of switches P1-P4.

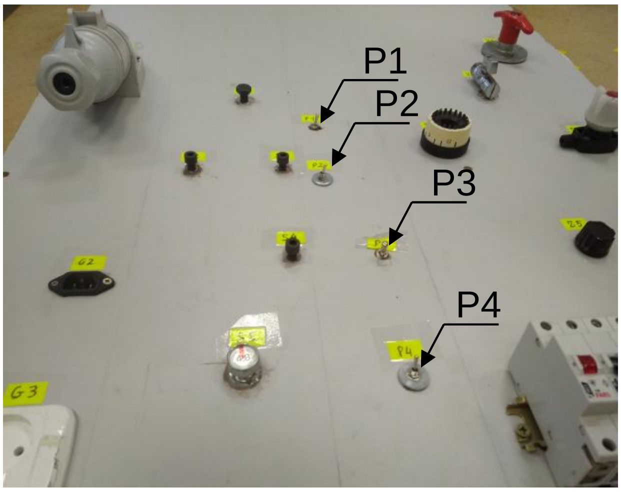


Figure 11. Desired positions of switches P1-P4.

TABLE III. Test Execution Times [s].

| | | Glove | | | Operator panel | | |
|---|---|---|---|---|---|---|---|
| | | test 1 | test 2 | test 3 | test 1 | test 2 | test 3 |
| Person 1 | p1 | 39.85 | 32.87 | 23.51 | 28.97 | 27.09 | 20.97 |
| | p2 | 71.4 | 53.85 | 36.87 | 50.81 | 38.81 | 35.5 |
| | p3 | 79.21 | 64.93 | 46.05 | 57.09 | 45.79 | 40.1 |
| | p4 | 105.01 | 80.17 | 59.74 | 67.55 | 55.45 | 48.34 |
| Person 2 | p1 | 18.73 | 17.5 | 15.29 | 19.93 | 20.1 | 18.7 |
| | p2 | 27.21 | 26.08 | 26.84 | 48.87 | 32.34 | 33.17 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | p3 | 35.69 | 31.22 | 31.7 | 61.57 | 38.08 | 38.02 |
| | p4 | 45.28 | 49.18 | 39.94 | 77.26 | 47.96 | 50.83 |
| Person 3 | p1 | 26.57 | 24.03 | 19 | 35.2 | 15.64 | 16.46 |
| | p2 | 42.79 | 43.28 | 30 | 53.08 | 31.43 | 32.03 |
| | p3 | 70.79 | 56.68 | 38.79 | 65.67 | 46.12 | 43.88 |
| | p4 | 90.81 | 69.22 | 53.61 | 80.86 | 58.01 | 59.25 |
| Person 4 | p1 | 38.47 | 31.38 | 42.1 | 24.06 | 19.21 | 23.06 |
| | p2 | 58.27 | 48.78 | 54.09 | 38.08 | 27.9 | 45.62 |
| | p3 | 87.26 | 65.27 | 74.11 | 47.55 | 36.29 | 52.28 |
| | p4 | 122.56 | 106.18 | 95.06 | 57.58 | 45.41 | 59.62 |
| Person 5 | p1 | 18.64 | 19.79 | 15.25 | 30.6 | 22.16 | 33.14 |
| | p2 | 39.79 | 37.36 | 25.72 | 61.14 | 43.03 | 50.96 |
| | p3 | 55.82 | 46.97 | 32.84 | 77.03 | 51.01 | 58.73 |
| | p4 | 100.7 | 56.9 | 45.12 | 88.98 | 63.97 | 71.3 |

Despite the fact the average time was mostly better using the operator panel 3 of the 5 achieved the best time achieved using the Glove (Fig. 12).

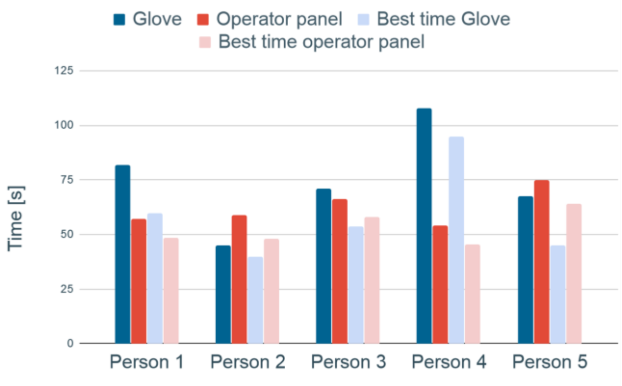


Figure 12. Comparison of average time of completing the task using the Glove and the Operator panel and the best time scored in a single test.

The observation during the experiment showed us that our design enables the operator to focus directly on the robotic arm while moving it, without necessity to look back and forth between the manipulator and the panel during the robot operation. It is very interesting that the execution time of operator panel test 2 was mostly better than of test 3 (Fig. 13). It could be explained by too high confidence using the Polyscope and not looking at the panel while trying to click an array to steer the robot.

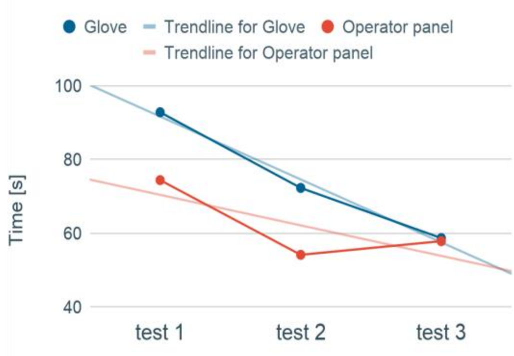


Figure 13. Improvement of the average task time over the course of the experiment. Thick blue line indicates the Glove average time. The thick red line shows the improvement of the panel performance. The thin lines show the corresponding trends.

The results overall indicate a higher rate of proficiency improvement for the Glove as compared to the use of the operator panel.

## IV. Conclusion

In this paper we have proposed an implementation of a IMU-based hand-held device for teleoperation of a robotic arm mounted on a Mars rover analogue. The device was designed to provide a simple and intuitive hand-free alternative for other devices commonly used in the scenario, such as operator panels and joysticks. The device was implemented based on IMU controlled by a STM microcontroller. The data transmission is realized wirelessly over Bluetooth with a PC controlling the robotic arm.

We have tested the device experimentally to compare the success ratio and times achieved in a simple switch operation task. The experiments were carried out using a UR5 universal arm with 6 degrees of freedom. The achieved results are promising, suggesting a comparable performance of our proposed device to a standard manufacturer-supplied teach pendant. The qualitative advantage of the new is its wearability and intuitive real-time operation of the robot as contrasted with the use of a panel, which requires two hands to operate and only allows for a single joint actuation at a time.

The experiments have provided us with valuable feedback on how the design and the control scheme could be improved. These prospects will be explored in our future work.

## Conflict of Interest

The authors declare no conflict of interest.

## Author Contributions

A. P. Buczyłowski has developed the Glove device and conducted the experiments. All of the authors have participated in writing the paper and all have approved the final version.

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**Adam P. Buczyłowski** student of automatic control and robotics at Bialystok University of Technology (BUT) (Poland). Currently participates in a creation of the Mars rover analogue at BUT to participate in Rover Challenge Series. His interests include automatics, robotics, robot control, wearables and engineering.

**Maciej Rećko MSc. Eng.** doctorate candidate at Bialystok University of Technology (Poland) in the field of mechanical engineering. He accured both engineering and masers degree in the field of automatic control and robotics at BUT. Has successfully participated in creation of Mars rover analogue that won University Rover Challenge in 2014.

His scientific interests involve mechanical engineering as well as automatic control and robotics. He prepares a dissertation about remote control of the robotic arms using phantom device with haptic feedback

**Adam Wolniakowski PhD Eng**. is an assistant professor at Białystok University of Technology and a Post-Doc at University of Southern Denmark. His scientific interests include robotic control, learning by demonstration, and optimization of workcell configuration with a focus on the automated design of gripper fingers.

**Karol Haraburda** student of automatic control and robotics at Bialystok University of Technology (BUT) (Poland). Currently participates in a creation of the Mars rover analogue at BUT to participate in Rover Challenge Series. His interests include designing embedded systems, robotics, automatics and engineering.