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The Kalman autonomous planetary rover

The project presented in the article is proof of the usefulness of student organizations and its effectiveness in the popularization of advanced technologies as well as future solutions in industry. A student-developed planetary rover, using a Kalman filter and other algorithms responsible for dynamic terrain mapping and pathfinding, is capable of non-collision movement in the most challenging environments. Moreover, the rover uses a 6DOF arm developed by students to undertake manual actions, such as soil sampling or maintenance tasks with ease. The invention is provided with a drill to be capable of extracting a sample from a depth of 30 cm, which is expected to greatly enhance the research of the geological history of the surveyed region. The robot has been tested numerous times at planetary rover competitions with success, proving the potential of such platforms as one of starting points in space exploration and opportunities in industrial use, especially in hard-to-reach mining areas. The featured project represents an inspiration for future young engineers and scientists by opening perspectives for implementing similar technologies for more efficient and safer operations in industry.

Key words: *rover, robot, autonomy, mechanization, mining*

1. INTELLIGENT PROCESSES

In the context of robotics, an intelligent process refers to the capabilities of a robot or a robotic system in terms of autonomous decision-making, information processing, learning from the experience and adapting to changing conditions. Intelligent processes in robotics cover a variety of advanced features, which enables robots to fulfil complex tasks, interact with the environment and humans, as well as improving their abilities. Below are a few examples of intelligent processes in a context of robotics:

- Movement planning: Robots use movement planning algorithms to plan optimal routes and avoid collisions when moving in an environment.
- Computer vision: Robotic systems use machine vision techniques, such as image recognition and scene analysis, in order to identify objects, humans as well as read road signs.
- Adaptive control: Robots can adjust own actions to changing conditions, e.g. respond to unexpected obstacles or new tasks.
- Machine learning: Robots learn from experience, gathering data from their surroundings and using it to perfect their own abilities to make more intelligent decisions.
- Human-robot interaction: Robots utilize speech and emotion recognition technology to better communicate and cooperate with humans.
- Autonomy: Autonomous robots are capable of independent actions without constant human supervision, making decisions in real-time based on data gathered from sensors.

The aim of intelligent processes in robotics is to increase the efficiency, safety, and utility of robots, by enabling more advanced tasks for them which would be impossible to achieve by standard, programmed machines. However, at the same time, they need advanced technology, algorithms, and proper safety guarantees to prevent any potential unpredictable behaviour of the robots.

1.1. Macrocam and visual analysis

There are a variety of cameras on board the rover, including ones that are dedicated to autonomous driving, analogue and digital cameras which are used at the time of remote manual control over the rover driving, as well as cameras that allow close-up images to be obtained [1]. The observation of a rock under magnification is sometimes a key element to its identification. The ability to specify rock characteristics has significance in estimating regional mining potential. For this purpose, on board the Arducam IMX298 MIPI 16MP macrocam is used, which enables the observation of rocks at substantial zoom levels and saving results in the form of pictures. The macrocam works the best at a distance of 6–10 cm, giving significant magnification while preserving sufficient material quality.

MS Learns platform offers a free course using data from NASA to learn how to develop an artificial intelligence network to recognize rock samples [2]. The course allows participants to acquire geological data analysis skills, imaging processing, and machine learning techniques, which can find a use in supporting operations conducted on Earth and in space. It brought new opportunities for the Kalman rover project, since such a network would allow the real-time detection of objects of higher interest. This would allow the rover to notify operators as to whether it had found anything interesting in surveyed location, as well as record timestamps in the footage itself for later human analysis of the recording fragments. This would be especially useful during various competitions when it is necessary to analyse the collected research material in a limited time. That is why the Science team, independently of the Software team, took the course for the acquisition of new skills and the implementation of its own neural network.

1.2. Trajectory and inversed kinematics

The automatization of sample collection is a critical element in branches such as geological surveys or space exploration. One advanced approach in that area is the use of programmed trajectories. This depends on a pre-defined movement path for the device collecting samples, for example, a planetary rover manipulator. Thanks to programmed trajectories, precise movement control, and sample collection, location determination is possible, which minimizes risks of damaging or losing samples.

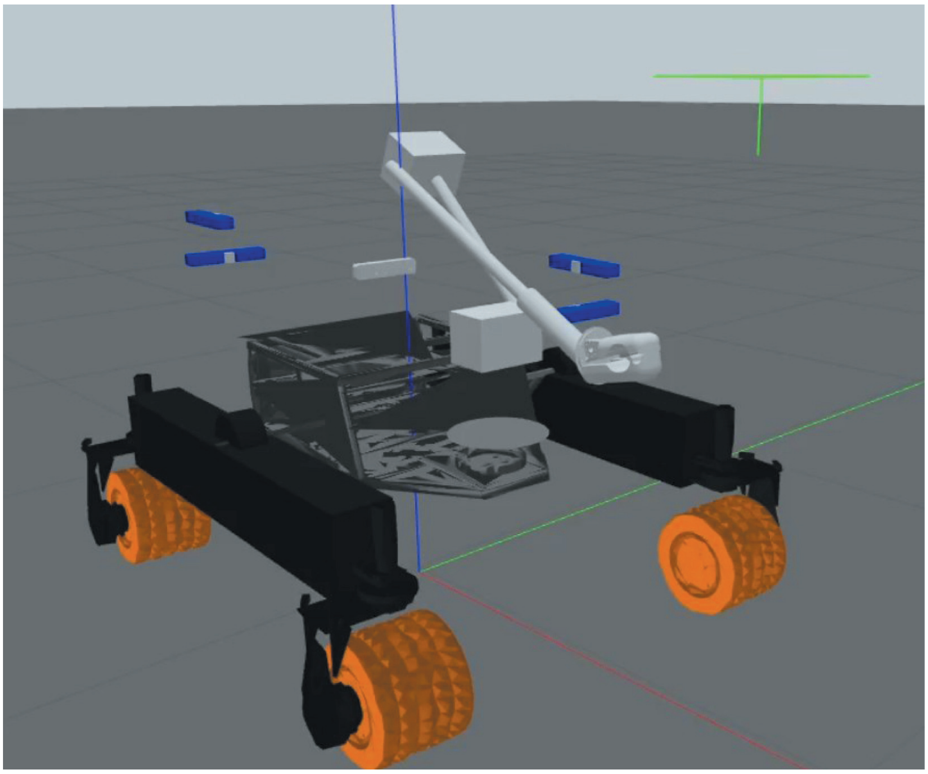

Fig 1. Model of a rover in the app of ground station, visualizing status of individual elements in the space

Inversed kinematics is an indispensable element of programmed trajectories implementation. It is a mathematical mechanism allowing the determination of an appropriate location and the orientation of various elements of the manipulator with the aim of reaching final position. In the case of sample collection, inversed kinematics provides a determination of the adequate gripper or tool settings to aptly place it where sample will be collected.

By using programmed trajectories and inversed kinematics, the automatization of sample collection is becoming more efficient, precise, and effective. It not only accelerates sample collection process, but also allows for safe and accurate acquisition of information, which are essential for scientific research and space exploration, in a way which is more effective and advanced technologically. A screenshot from the app to control the robot remotely, on which simplified model of the rover undertaking operation with trajectories of the arm, is visible on Figure 1.

1.3. Distributed intelligence

Distributed intelligence is often applied in the context of complex systems such as communities of organisms, groups of people, and also in the field of technology, in robotics and artificial intelligence. In such systems, intelligence arises from the interaction and collaboration of multiple elements that together create an organized and intelligent system. In the field of technology, distributed intelligence can refer to the cooperation of multiple robots to accomplish complex tasks. Each robot may have its own limited capabilities, but as a group, they can effectively complete a task that would be unattainable individually. The Kalman planetary rover is a robot with advanced construction that allows it to navigate challenging terrain. The rover can move between different waypoints, including geological objects such as rocks or obstacles like poles and stakes. During the traverse, data is collected in the form of GPS coordinates. If Kalman were actually being used as a planetary rover, there would be an opportunity to gather data obtained from the rover's onboard sensors along with data from orbiters. Combining data from orbiters and Kalman's onboard data using artificial intelligence algorithms would enable the better processing of the information, leading to more detailed geological interpretations of the region, especially concerning the precise mapping of its surface. The Kalman rover utilizes tools such as GPS, encoders, and depth cameras. During actual missions, it would be valuable to expand this toolset by adding elements that would make signal triangulation and detection of the sun's position possible. Sun position monitoring could serve as a safety feature for the rover. For instance, if there ever were any communication issues, the rover could use the sun's position to determine its current location and relay that information to the ground station. This would aid in locating the rover in the case of any malfunction or loss of communication. If the unit would leverage photovoltaic panels for charging, sun position detection could allow for optimal positioning of the panels to efficiently capture solar energy and extend the operational capabilities of the vehicle. Additionally, if the rover has to travel at a significant distance from the ground station or other communication endpoint, radio signal triangulation would help to precisely determine the direction from which the transmission originates. This would allow for better connectivity and improve communication quality.

2. EXCAVATING ABILITIES

2.1. Gripper

The main concept in the Kalman planetary rover project is application of modularity. For the purpose of the realization of various tasks, the rover is equipped with several types of jaws, which are mounted on a manipulator and the choice of them is adjusted to the specific tasks the rover is expected to perform. For precise operations, the special gripper is used, featuring shaped tabs which prove to be useful for carrying objects or performing easy maintenance tasks, such as unscrewing or screwing valves. Models of overlays in use with the ready gripper module are presented in Figure 2 [3].

The set of jaws used for excavating purposes has also been designed in a unique way. The design of those jaws makes it possible to obtain soil samples and after that, thanks to the tight connection of the upper and bottom jaws, the transfer of the sample to a mobile lab or special container intended for storage is feasible. Such flexibility and functionality of the modular jaws greatly enhances the universality of the Kalman rover, enabling the successful completion of various missions on a planet surface.

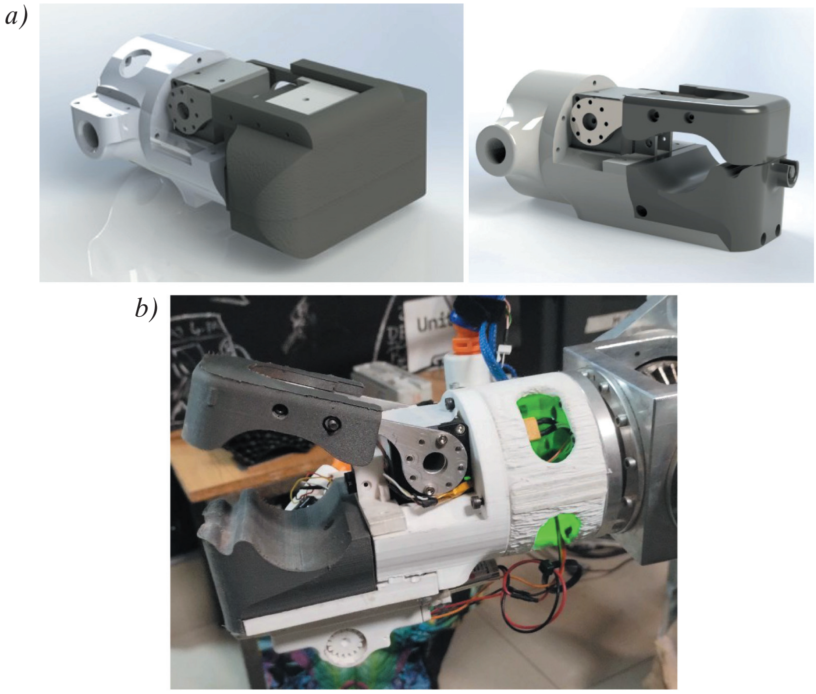

Fig. 2. Models (a) and assembled gripper (b)

2.2. Arm

Since it implemented a new mechanical 6DOF arm, the Kalman planetary rover gained the ability to work in two modes: autonomously and via remote control. The new arm offers significantly higher precision in task performance thanks to 6 degrees of freedom of movement. Equipped with cameras, it enables the rover to undertake the efficient observation of objects in its vicinity. A special advantage of the 6DOF arm is its large scale of operations and reach, which makes observation and sampling from less accessible places easier for the rover. The robot arm is becoming an invaluable tool to support repair operations, thereby increasing the functional value and the efficiency of the operations of the Kalman rover [3]. In Figure 3 a model of the arm currently in use is presented.

Fig. 3. Arm 6DOF currently in use

2.3. Drill

The drive system used in this project was inspired and adjusted directly from solutions available on the market, and its design includes several key components. The core of the drive is a DC brush motor with 18 V voltage. Besides that, planetary gear combined with a safety (ball) coupling is installed and the combination of those two elements ensures reliable functioning of the system. A mechanism of rack and pinion was used to achieve vertical movement. Such mechanism is propelled by the DC drive, which was mounted with the planetary gear and ensures smooth and efficient functioning. Additionally, special rails have been used to stabilize mechanism movement, which allows smooth and controlled lowering. The whole drive system was carefully adapted and optimized to not only provide high performance, but also the safety and stability of operations. Due to the functioning of the components from previously used devices, as well as precise mechanical solutions, this drive unit is not only an efficient tool but also an excellent example of the adaptation of existing technology to new uses.

The current drill model has been developed to meet the requirements of new European Rover Challenge rules, during which the rover should have the capability of obtaining a sample from a depth of more than 30 cm. The Mars regolith analogue expected during the competition makes it vital that subsequent prototypes will not only be tested for the ability to drill, but also for durability of the materials and elements used, in order to securely store the retrieved core at the end of the operation. The mechanism of the drill as well as core auger is shown in Figure 4.

The implementation of 3D printing allows fast prototyping of further iterations of an auger for applications of new forms improving the functioning. When a specific model meets expectations in terms of overall performance, the manufacture of components from more durable materials, such as steel, follows.

Fig. 4. Models of current versions of the mechanisms of the drill and core tube

3. AUTONOMY

3.1. Robot localization

The Kalman rover was named to honour Rudolf Kalman, inventor of the Kalman filter, an algorithm which has been in use in robotics extensively since the 1960's. The Kalman filter helps with robot's sensor readings denoising and predicting its status at any moment in time. The Kalman rover utilizes that algorithm to multiply the efficiency of odometry, which is a subsystem measuring changes in repositioning and determining its position in space. Kalman odometry is based on a GPS module and IMU containing gyroscope and accelerometer. These instrument readings are compared with the results of visual odometry, which measures the robot's movement based on imagery from cameras placed around its hull. All of the gathered data is combined, which, with the help of the Kalman filter, gives highly accurate information about the rover's position with millimetre-level accuracy.

3.2. Terrain mapping

Martian landscapes are full of boulders, steep cliffs, and craters. Such difficult environments pose a challenge for planetary rovers like Kalman. Rovers would not be able to traverse autonomously without the use of any cameras and environmental sensors. Therefore, Kalman is equipped with a set of electronic "eyes" in the form of Intel RealSense depth cameras that operate simultaneously as standard cameras and also in a manner akin to a LIDAR scanner. RealSense cameras use stereoscopic vision, which means that they feature two infrared sensors located on both ends of them. Through them, cameras extract the depth of the image viewed in a way that is similar to human vision [4].

Information about depth sent by the cameras are represented as a point cloud, where every "pixel" in the image frame corresponds to one vertex in the cloud. Unfortunately, such a data format contains a lot of redundant information and does not allow us to determine with ease in which directions Kalman is able to drive. For this reason, autonomic Kalman algorithms convert the data stream from the cameras to extract only those features our rover is concerned with from the detailed point cloud, namely whether or not an obstacle is present in a particular location. Kalman, along with the course of the traverse, repeats the point cloud analysis multiple times and saves inaccessible areas in a so-called cost-map, a two-dimensional matrix that stores the structure of the surroundings visible from an aerial perspective around the rover. A visualized point cloud is included in Figure 5.

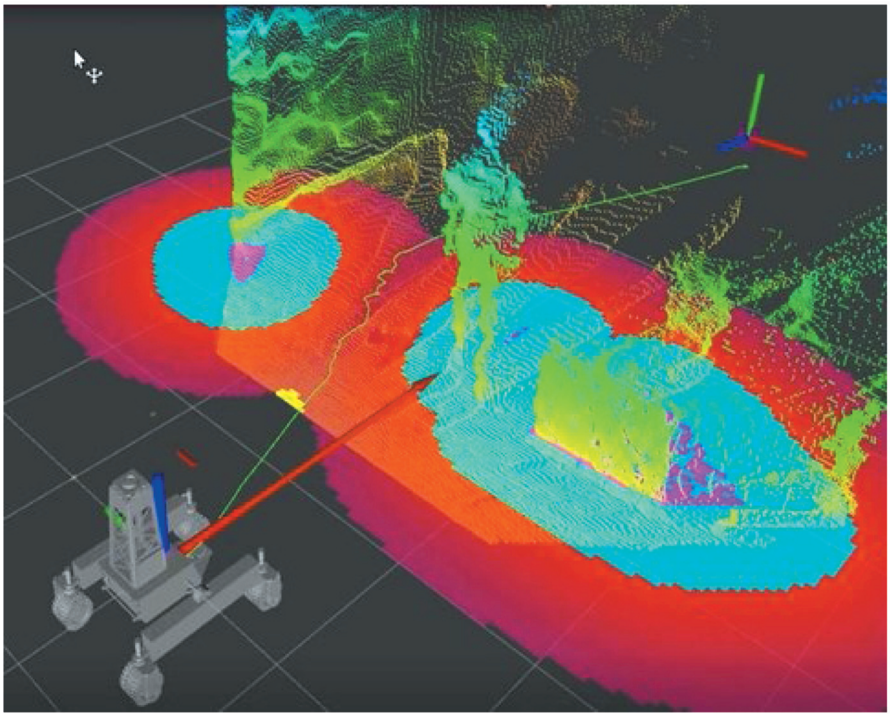

Fig. 5. Point cloud recorded by the rover during trials

3.3. Determining and tracking the pathway

Kalman uses cost-map via an A-star (A*) algorithm to plan non-collision pathways of movements at the time of the travel to assigned coordinates. Finally, another autonomy module, the so-called "path follower", changes the planned traverse and information about the position of the robot into the commands for his wheels. The concept is presented on Figure 6.

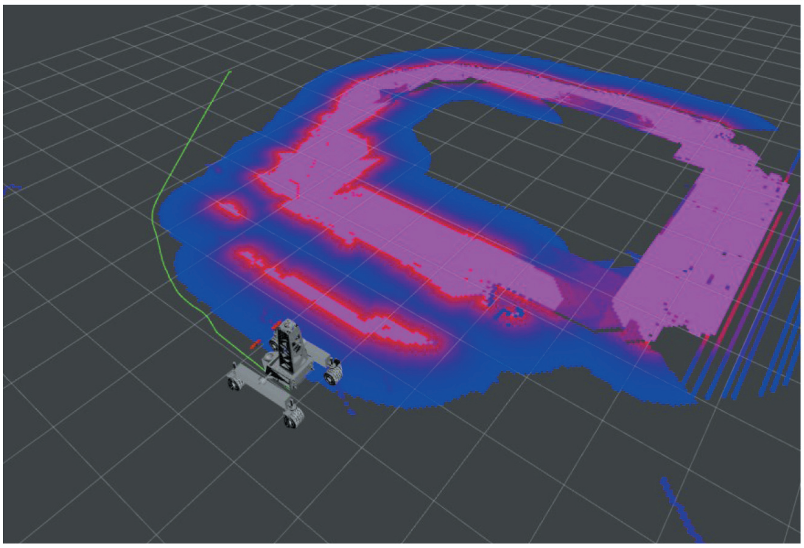

Fig. 6. Remembered obstacle locations in a coordinate system and designated path

3.4. Object detection

Kalman is able to detect all kinds of objects used during the competition as points of interests for the rover. Such functionality is implemented with AI (Artificial Intelligence) used in combination with conventional methods of computer vision. For instance, the black arrows used in the competition in India are identified by simple edge detection and contrast adjustments of camera images, while cones, which are more difficult to detect, are traced by a neural network trained especially for this purpose. Its imaging is shown in Figure 7.

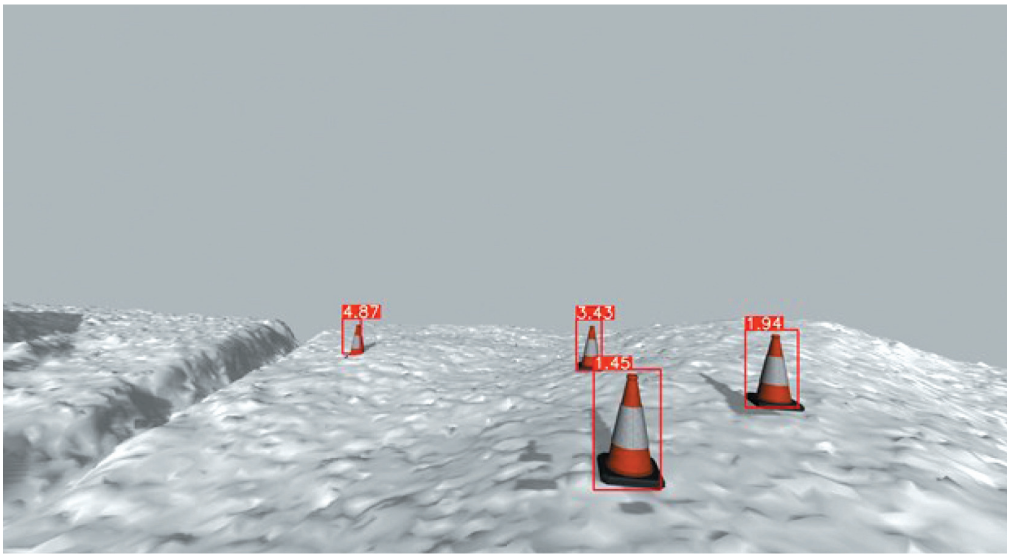

Fig. 7. Cones detected by the rover

3.5. Supervisor: Kalman's brain

Despite the fact that the Kalman rover can easily move on a planet surface and detect objects it finds interesting, this alone is not enough to perform a successful autonomous exploratory mission. Kalman also has a so-called "supervisor" that serves as the brain of the robot during a mission. This supervisor controls all of the activities which the robot is expected to perform during the traverse and plots next target points for the rover. Before the start of every contest, the rules of the autonomous competition are published and, based on this instruction, the supervisor is designed by us to maximize the capabilities of Kalman. In summary, Kalman's autonomous driving system combines sophisticated algorithms, including Kalma filter, visual odometry, pathway planning, object detection and supervision module. A complex structure like this enables autonomous navigation, terrain mapping, object detection, and performing complex tasks in difficult Martian environments. The combined functionality of those subsystems ensures the success of Kalman's autonomous exploration missions.

4. CONCLUSION

Kalman is a robot which can perform tasks autonomously and its mechanical design makes it capable of handling demanding terrain well. Such a planetary rover could participate in space voyages as a companion during space walks as it is able to carry cargo and tools, and is able to provide aid in emergency situations. It can also take part in exploration and mining missions, which can be helpful during the field reconnaissance that may be crucial while expanding territory for colony development. Kalman, via modules such as the gripper, mobile research laboratory, or core drill, can provide assistance in the assessment of resources on a designated area. Kalman has the capability to detect places of interest and record their location in addition to its ability to make contact with the base. Part of the tasks that would accompany the colonization of an alien planet could be performed by Kalman.

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