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Increased safety in deep mining with IoT and autonomous robots

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ABSTRACT: 'Safety first' – all miners know the importance of this slogan. Personal protective equipment, automated or remote-controlled machinery and safety instructions all help to avoid accidents underground. However, there are still many dangerous mining situations where the risk to human life is too high. Modern technologies can help to overcome this obstacle. Researchers at the TU Bergakademie Freiberg are working with autonomous robots and the Internet of Things in underground mining. A mobile autonomous robot, in combination with a wireless sensor network, can help to explore unknown or inaccessible areas. These could be in abandoned or active mines, where hazardous situations occur with unpredictable risks too severe for human activity. This paper will focus on development and application possibilities of this technology, especially regarding mine safety. The first test results from the prototypes will be presented from the viewpoint of a mining engineer, with respect to benefits and limitations for mine operators.

1 INTRODUCTION

The feasibility of a mining project is determined not only by its profitability, but also by the fact that work must be carried out safely. In contrast to other branches of industry, mines seem to be a particularly unsafe workplace due to the special environmental conditions. Lack of light, confinement, danger of falling rocks, and the occurrence of dangerous gases are just some of the factors. Today, almost all accidents can be avoided through targeted actions. If we consider only the accident statistics of the BGRCI (German Social Accident Insurance Institution) for the raw materials and chemical industry as an example, we can see that both in 2010 (13.9) and in 2017 (10.4) the lowest number of accidents per 1,000 full-time workers were reported in the mining sector compared to the other branches of industry represented in the BGRCI (Ø 2010: 19.2 and 2017: 18.1) (Berufsgenossenschaft Rohstoffe und chemische Industrie 2010, 2017). These figures show a positive downward trend. Nevertheless, the Saxon Mining Office recorded a total of 70 reportable accidents at work in 2017. Of these, 21 were caused by falling rocks or other objects (Sächsisches Oberbergamt 2017).

The goal for research and development in mining should therefore always be to increase occupational safety, so that even more accidents can be avoided. Increasing the automation level and the use of autonomous robots within the mining process is just one way to achieve this goal. Another approach is a significant increase in sensory data acquisition and the use of intelligent evaluation algorithms. Large mining companies, for example, are already using autonomous trucks for underground mining (Mining Magazine 2016). However, technologies that can be used in unknown and non-instrumented underground mining environments are not yet fully developed or commercialised. Forgotten, abandoned or historic mines can all be found in the Saxony Ore Mountains. When damage occurs to the surface, such mines must be remediated and supported by specialised mining companies. Unawareness of the exact locations, extent and conditions of such mines can be a great danger to workers.

Scientists of the TU Bergakademie Freiberg investigate technologies in a number of projects and implement prototypes to support those activities. In the following, the project ARIDuA, its possible use-cases, requirements and challenges are shown in two examples. The researchers focus on the practical aspects during the implementation and deployment phase. In specific one may see that besides the increasing safety underground, robots and sensors themselves can become a source of danger.

2 PROJECT OVERVIEW

Robotics and IoT technologies are research targets of the ARIDuA-Group (Autonomous Robots and Internet of Things in underground mining) at TU Bergakademie Freiberg (Germany). These junior research group, founded in 2017, has an interdisciplinary structure in order to benefit from synergies through the combination of technology concepts. Six PhD students from the disciplines of computer science, materials science, mine surveying and mining, develop interdisciplinary concepts and prototypes with the aim of progressive digitization and automation in underground mines.

The ESF-funded project (European Social Fund), which runs until mid-2020, aims to develop an autonomous moving robot for the installation and maintenance of underground IoT infrastructure (Lösch et al. 2018b). The mining robot "Julius" from the previous project "Mining-RoX" (Grehl et al. 2017) id used as a platform and will be developed further. Among other things, a wireless sensor network (WSN) is installed. To further benefit from this structure, mobile sensor box integrate a communication layer and act as nodes within this network, instrumenting the mine itself. These sensor boxes should be able to record relevant ventilation data using sensors and connect wirelessly both to the Internet and other devices. In addition, evaluation algorithms for predicting dangerous events using neural networks based on the acquired sensor data will be developed. In parallel, a classification algorithm for the detection of ore veins based on optical characteristics will be created (Varga and Grehl 2018), so that all technologies together are a first step to a unmanned mine. The universities own research and teaching mine "Reiche Zeche" in Freiberg is available as a unique test environment (Mischo 2015). Sections of the mine (depth: 150 m) are used for underground tests in a real-world environment.

3 POSSIBLE APPLICATION SCENARIOS AND TASKS

Before developing and installing underground wireless networks, neuronal networks, autonomous mining robots or mobile sensor boxes, the question of the purpose for which these technologies are to be used must be answered. As a boundary condition for the ARIDuA project, the sites should be limited to underground mines. Within the framework of the project, the focus will be on mines in Saxony, Germany. Both the research and training mine "Reiche Zeche" and the abandoned mines in the Ore Mountains (Erzgebirge) are former ore mines, where mainly silver, non-ferrous metals and uranium were mined. In these mines, active mining was stopped at the latest in the second half of the 20th century. Today, they are mostly used for tourism. In total, there are 52 mines open to visitors in Saxony (Sächsisches Oberbergamt 2016). Other historic mines have been partly abandoned since the Middle Ages and their existence or condition is poorly known. The only three active underground mines in Saxony are located in Niederschlag (fluorspar), Seilitz (kaolin) and Hammerunterwiesenthal (marble) and are managed by small companies (Sächsisches Oberbergamt 2014). While there is a large number of remediation work underground in old and abondened former mines.

The resulting technologies can be also used in regular operation, for scheduled monitoring or maintenance of the mine. Possible tasks include the automated sensoric measurement of environmental conditions. In addition to ventilation data such as gas concentrations or

Table 1. Environmental parameters of particular interest in "Reiche Zeche".

Gases	Air	Mine water	Flora & Fauna
Rn	Temperature	pH-value	Fungi
CO	Humidity	Sulphate content	Bacteria
CO_2	Air pressure	Electrical conductivity	
NOx	Air velocity	Flow volume	
O_2		Content Cr, Cu, Ni, Cd, Co, Pb, Zn, Cl, Fe, C, As	
H_2S		Water level	
CH_4		Redox potential	

temperature, this also includes information about mine water. Table 1 provides an overview of the environmental conditions of particular interest in the "Reiche Zeche". It is possible to integrate systems for personnel or machine tracking via a wireless data network. The precise location of workers and visitors underground is of considerable interest, especially in hazardous situations. This IoT instrumentalisation of a mine, comparable with the functionalities of "Smart Home" solutions for private houses, can be installed and maintained by workers or a robot. Further robotic tasks can be mapping, providing 3D scans for calculations and virtual mine models, as well as colour images and video recordings of the drifts. This can be done both in addition to human inspection and data recording, but also especially in those areas of the mine that are unknown or inaccessible. At the same time as the environmental conditions are recorded, robots and WSN can also be used to explore abandoned mining areas.

In the case of incidents such as a major gas blowout, an explosion or an unexpected roof collapse, information about the current condition of the mine and the ventilation conditions underground is rarely available. Under these dangerous conditions, people must explore the situation on site slowly and with measuring instruments, without endangering their own health. Especially in such situations, the first ascent after the event and collection of relevant data without endangering human life is of high interest. A robot could remotely or autonomously access and explore all hazardous areas accessible even only through small openings. Either the data is transmitted directly to the surface or to a safe area, or the robot first returns and the data can be evaluated. In addition to being used after an event or incident, it is also conceivable that IoT and robotics could be used together with the mine rescue team to prevent hazards and for rescue operations. As well as for preliminary exploration in front of the team, a robot could also be used to transport material and establish a communication link to the incident command. In addition to voice transmission, video transmission to the surface can also be beneficial for more detailed mission planning. Further task scenarios are of course imaginable for the individual mines. It should also be considered that not all tasks can be performed simultaneously by one robot, thus a number of robots can be deployed simultaneously.

4 ADVANTAGES

The advantages of using this type of modern equipment are a massive improvement in work safety for the miners. If machines can be sent to unknown or potentially dangerous areas instead of people, numerous dangers to human health can be avoided. In addition to risks of rock fall or water entry, these include the dangers of toxic or non-respirable air and natural radioactivity. Moreover, descent into the mine can be avoided in areas with inadequate ventilation or high temperatures.

Robotic map creation of previously unmapped areas benefits work planning, the deployment of mine workers and is basis for ventilation planning. In an emergency, a tracking system shows the position of people underground and, if necessary, their direction of movement. This allows rescue operations to be coordinated more efficiently. The installation of (wireless) communication networks by the robots, mobile or fixed, is an advantage for the entire mine operation. Today, communication during an incident or rescue operation is often only possible via a few permanently installed telephones. Once an overall network exists, devices can be integrated to transmit voice or text messages. This enables workers to get help faster, be informed about events or receive instructions quickly.

A massive increase in sensor data collection, in addition to, or even in combination with, an intelligent evaluation algorithm, can detect increased gas concentrations or other deviations from the normal value at an early stage. Occupational safety actions can be initiated more quickly to prevent accidents. Besides the higher frequency of automatic data acquisition in contrast to manual measurements, it is also easier to store relevant digital data for documentation. These can be used for later assessment or as a data basis for improvements in operation.

In addition to numerical sensor data, image data also reflect the state of the environment. By recording point clouds and various camera and video images, mine workings which are difficult to access can also be seen without human on site-inspection. The data can be used for pure visualization, inspection, documentation or to create models. 3D mine models are an excellent basis for training, e.g. for learning machine handling or for simulators. At the TU Bergakademie Freiberg, for example, a mine rescue simulator was developed from the data recorded in the "Mining-RoX" project from a section of "Reiche Zeche" mine (Schmieder 2017). In this simulator the students train to handle rescue operations in a team, while sitting in front of laptops. They are using software, which is designed like a computer game and they control virtual mine rescuers in a simulation of the 'Reiche Zeche'. This is the preparation for trainings in the real section in the mine. Additionally such simulations can be extended to virtual reality environments, with the expectation of a much more higher learning effect.

Therefore, not only the health protection of the workers but also the higher efficiency and accuracy are valuable factors for the application of these new technologies. Machines can also work in cooperation with employees but at a constant quality, independent of break times.

5 CHALLENGES FOR REALIZATION

Despite the significant advantages the progressive automation and digitization with the long-term target of an unmanned mine are confronted with numerous difficulties. In particular, these difficulties result from the special nature of the mine environment in contrast to surface industrial facilities, legal issues, the handling of large amounts of data and the individual requirements of prospective users. Furthermore, each mine must be considered separately for each application. The following sections give an overview of possible problems and challenges, although it is not an exhaustive list.

5.1 *Underground environmental conditions*

Underground mines are artificial cavities created for the purpose of extracting raw materials. The environmental conditions in a mine highly depend on the depth of the mine; the mineral extracted, the surrounding rock and geology, the mining technology or current use of the mine and several other factors, and are unique to each mine. Temperatures range from cool to very high (typically from 8°C to 50°C). This defines high requirements on material durability. Materials behaviour during temperature changes should also be considered, e.g. when entering or leaving the mine. Ore mines in particular are characterised by a very high relative humidity, up to 100%. Often there is dripping or stagnant water on the floor, and the mine water often has very low pH values, causing corrosion or short circuits. In general, no natural light is available underground, hence without artificial light absolute darkness exists. Specifically, for the use of detection algorithms based on optical features, the very different lighting conditions represent a problem. The outgassing of CH_4 in some pits can create explosive environments, so potential ignition sources must be avoided. Depending on the extraction method and raw material, a lot of dust is generated during driving, which can contaminate sensors and equipment and make them unusable.

5.2 *Difficulties for construction*

In contrast to above-ground facilities, mines are defined in their maximal spatial extent. They are bound to the place of the deposit and active operations continue to develop dynamically. There are at least two entrances to the mine, sometimes more. However, these shafts or ramps have a limited cross-section. This limits the maximum dimensions of the equipment that can be transported underground. The same applies to the mine workings in which they are used. The transport possibilities in a mine are restricted by the dimensions of the relevant machines. The equipment must be transportable with the available machinery and be loadable or even drivable. Vibrations or bumps may occur during transport which may cause damage to the construction or electronics. For the construction of mobile robots, the necessary ground clearance of the device and a suitable mode of transport must also be selected. Obstacles can be rails, uneven floors, installations and support, standing or flowing water and rock masses. Mobile devices must have independent power supply, i.e. sufficient battery capacity. When rechargeable batteries are used, safety during charging must be ensured. The main hazards here are explosion or ignition of the battery in the event of defects. None of the devices must block escape routes in the event of a defect. Furthermore, protection of workers from mechanical hazards such as jamming or falling over of the device must be ensured by the constructive design in advance.

5.3 *Challenges for autonomous navigation*

Autonomous driving for street vehicles is already well advanced above ground. However, the findings can only be applied to a limited extent in autonomous underground navigation. The biggest difference is the lack of GPS or a similar localization system on an industrial level. As a minimal requirement any autonomous robot needs information about its surrounding area, i.e. by the method of laser scans. Its geo-reference inside the mine however is more a nice-to-have feature, from which especially the robots mapping algorithms will benefit. Particularly in unknown or non-instrumented mine environments, it is a challenge to link the local map of the robot with the real-world coordinates. A similar problem arises for determining the exact depth at which the robot is located. Other factors such as the uneven floor, reflections on water surfaces or changing cross sections, challenge the autonomous navigation. Besides this independent operation mode, the robots activities may always be overwritten by a human operator at any given time, ideally remotely either from underground or outside of the mine.

5.4 *Data transmission and further processing*

The establishment of data networks in mines is much more difficult than in other closed environments. It is possible to transmit wired data; however, this is only practicable for permanently installed sensors. Due to the continuous dynamic development of the mine and the mining process, installation and extension work of the corresponding infrastructure is continuously necessary. The use of wireless networks is also advantageous with regard to the integration of numerous mobile sensors and devices. However, the expansion of radio waves underground is massively restricted due to the small cross-sections, massive walls of rock, unevenness of the walls, supports and installations in the route, layout of the drifts and others. In some cases, data can only be transmitted over a few meters or, in most cases, only with a visual connection (line of sight, LOS). The selection of a suitable radio network is crucial for its performance underground. The use of electromagnetic waves underground must be checked in advance with regard to explosion protection and blasting work. Through automation, digitization and monitoring, the number of sensors and therefore the acquired data increases immensely. The collection and further processing of data must comply with legal regulations. The extent to which personal data may and must be collected has to be considered in the same way as the anonymization of data in individual cases. The large amounts of data still pose a problem. In order to manage this, they have to be selected, evaluated, processed and stored using suitable algorithms. Questions like these have to be solved before the data acquisition starts.

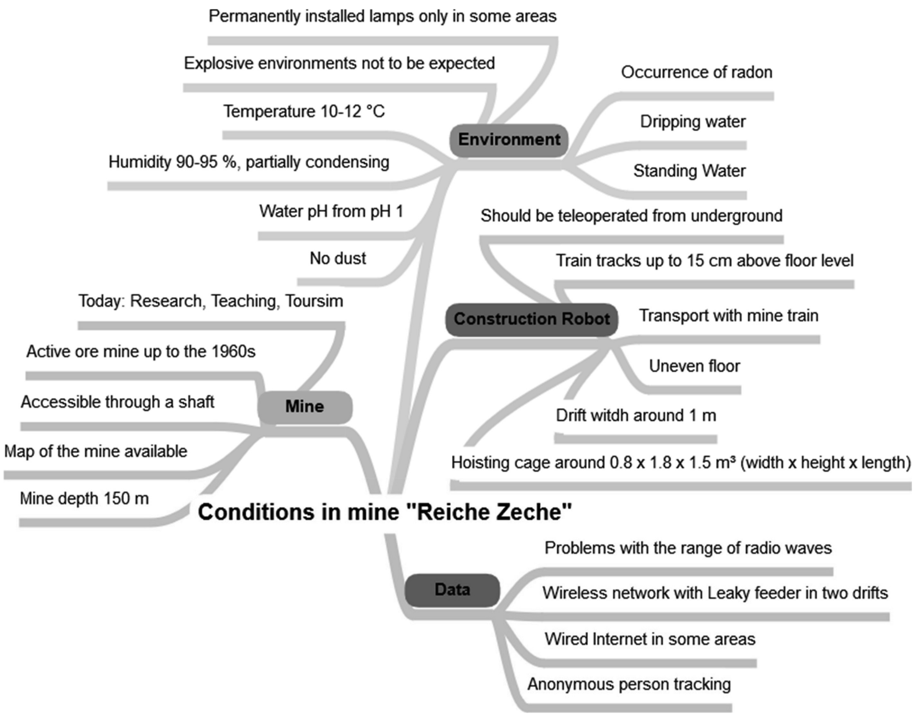

Figure 1. Conditions in the research and teaching mine “Reiche Zeche”.

5.5 *Integration into mine operations*

The scepticism of mine operators and especially miners regarding IoT technologies and robotics is usually very high. The operability of the equipment must be adapted to the training level and capabilities of the workers. This also includes ergonomic design. Currently there are still difficulties in answering legal questions regarding the use of autonomous machines together with humans. This concerns health protection but also liability issues in the event of accidents involving autonomous technology. In spite of the benefits for employees in terms of increased safety, smaller companies in particular have to ask themselves whether investments in these new technologies are economically viable. The applications presented are not primarily aimed at increasing productivity or output. Furthermore, qualified specialists must also be available for installation and maintenance.

5.6 *Conditions in the research and teaching mine “Reiche Zeche”*

A review of some of the challenges addressed in the previous sections was carried out for the Research and Training Mine “Reiche Zeche”. The technologies researched in the ARIDuA project will initially be adapted for the test cases in this particular mine. Knowledge of the conditions there became necessary for the prototypes presented as examples in Chapter 6. The representation of some aspects can be seen in Figure 1.

6 RESULTING PROTOTYPES

So far, a large number of devices and algorithms have been developed in the ARIDuA project. Two focal points of the project work, the robot and the WSN, are described in detail in the following chapters as excellent examples of the research work. It is also shown how the challenges described in chapter 5 were solved, in particular how they were adapted to the special challenges of the “Reiche Zeche” (see 5.6). In addition, excellent work has been done in the field of data evaluation, automated geological mapping, robotic manipulation and navigation, which is here not further discussed.

6.1 *Wireless Sensor Network (WSN)*

The developments within the project regarding the WSN have focussed so far on two aspects: the identification of a wireless data transmission technology suitable for the layout of the Research and Teaching Mine and the implementation of sensors for relevant variables as listed in Table 1. Suitable equipment for both tasks were selected from commercially available components with special emphasis on low energy consumption, small form factor and freely accessible data interfaces. This approach enables the assembly of tailor-made and battery powered sensor nodes from parts by various manufacturers for specific measuring tasks. All sensor nodes consist of at least four functional units: a power supply, a microcontroller, a wireless transceiver and the sensors. One example of a sensor box for gas concentration measurements is shown in Figure 2. The microcontroller has a LoRa (Long Range) modem for wireless data transmission at a frequency of 868 MHz offering very high receiver-sensitivity and hence long range at low power consumption (Centenaro et al. 2016). In an experiment a range of 240 m in a straight drift and 85 m in an angled drift was achieved which is far superior to tests with WLAN and Bluetooth. A second design using a 6LoWPAN (IPv6 over Low power Wireless Personal Area Network) based mesh-network-topology operating at 868 MHz has been described in (Güth 2018). While the achievable range in this case is smaller than with LoRa, the mesh approach allows data to be forwarded by each unit of the network, which increases the maximum distances. These sensor boxes (see Figure 3) use sensors for the measurement of environmental variables such as temperature, humidity and air pressure. The hardware is made by Texas Instruments (Texas Instruments) and the software by Thingsquare (Thingsquare). Two weeks of continuous measurements in a selected part of the mine resulted in no measurable degradation of the sensors and electronics, i.e. over that time span, their functionality was not impaired by the environmental conditions. In a lab trial, the nodes wirelessly transmitted data every five minutes for 162 days, powered by two AA batteries with a total capacity of 3000 mAh at 3 V. Future work will focus on the combination of the LoRa standard and the mesh network topology while including more relevant sensors into the WSN.

6.2 *Robot “Julius” and autonomous navigation*

The aforementioned robot is based on a platform by Innok Robotics and is depicted in Figure 4. Due to the environmental conditions and the research objectives, the chassis was upgraded to protection standard IP67 and optical sensors as well as a robotic hand and arm, whose protection is increased by a rubber sleeve and glove, were added. The robot’s

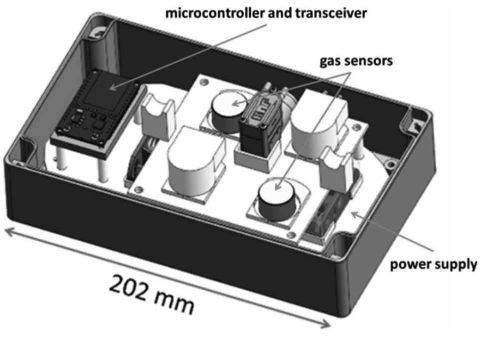

Figure 2. CAD model of the gas sensor box without lid.

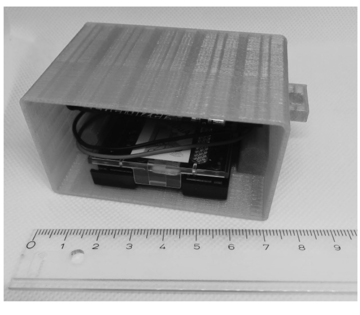

Figure 3. Photograph of one 6LoWPAN sensor box without lid. The electronics including microcontroller and sensors are in the black housing.

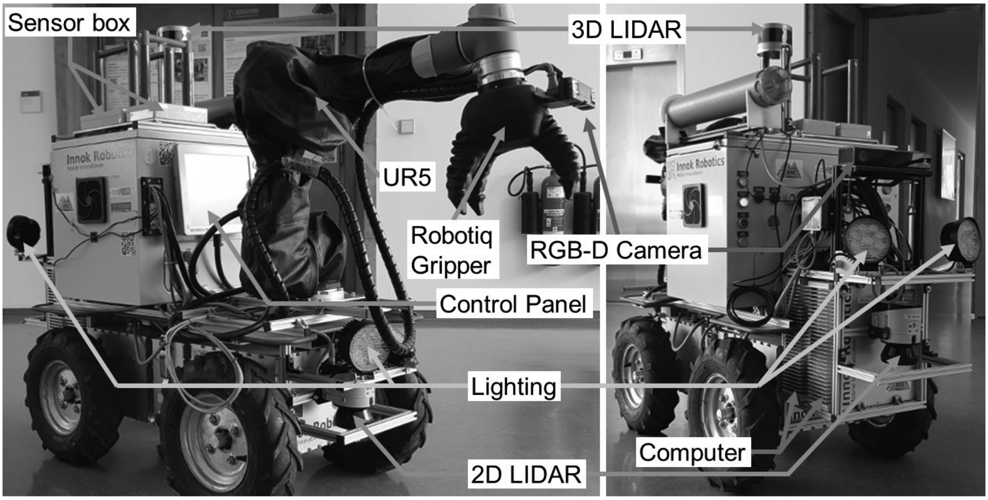

Figure 4. The research robot "Julius", which was retrofitted to withstand the mine's environment and suffice ARIDuA's objectives. In particular, its robotic arm and hand are protected by a rubber covering. Furthermore, it comprises LED spotlights, optical sensors e.g. 2D laser scanners, a 3D laser scanner and colour and depth cameras. Several sensor boxes are carried on top. Adapted from (Lösch et al. 2018a).

footprint is about 0.65 times 1.42 metres and it measures 1.3 metres in height (without arm). It is powered by a four-wheel-drive and the whole robot weights roughly 160 kilogrammes. More details about the platform, its sensor setup and navigation capabilities can be found in (Lösch et al. 2018a).

With its sensors and computational power, the robot is able to drive autonomously, i.e. it is able to steer and accelerate automatically and detect obstacles. Members of ARIDuA tested two types of navigation strategies: absolute and relative navigation. The former requires mapping an area beforehand and placing points on the map. With these preconditions, the robot is able to localise itself in the map and drive autonomously from one point to another. The mapping algorithm uses the front camera and therefore depends on light. The latter navigation strategy does not require a map and uses the robot's environment for orientation and navigation. The implemented algorithm uses the 3D laser scanner and thus does not depend on light.

7 SUMMARY AND OUTLOOK

For the underground use of autonomous machine, data networks and various sensors there is a wide range of applications in underground mining, especially for unknown and non-instrumented areas. In particular, the avoidance of accidents in the future by pre-exploration or by the autonomous work of a robot in potentially dangerous environments is very important. The loss of a machine compared to the health of life of a human being is negligible. However, the special environmental conditions underground also place challenging demands on the developers of the technology, and successful solutions from aboveground applications cannot simply be duplicated. In the ARIDuA project, however, both a robot and a first WSN were developed and successfully tested. The findings from the first experiments, which were not all error-free, offer interesting hints for the further development of the technologies. The goal is to be able to offer concrete solution ideas for the development of products at some point in the future.

The next steps will be to improve existing developments, in particular robust autonomous navigation and a mobile wireless sensor network with increased ranges. As soon as this has been achieved, the individual technologies will be connected. In the future, the robot should be able to set up the sensor network with its arm autonomously and the data should be evaluated automatically. After stable test operation, the final step will be to test the technologies in other mines as well.

REFERENCES

Berufsgenossenschaft Rohstoffe und chemische Industrie (Ed.) (2010): Auf einen Blick 2010. Aktuelle Zahlen der BG RCI. Available online at https://www.bgrci.de/fileadmin/BGRCI/Downloads/Publikationen/Auf_einen_Blick_2010.pdf, checked on 1/30/2019.

Berufsgenossenschaft Rohstoffe und chemische Industrie (Ed.) (2017): Auf einen Blick 2017. Aktuelle Zahlen der BG RCI. Available online at https://www.bgrci.de/fileadmin/BGRCI/Banner_und_Artikelbilder/Presse_und_Medien/Publikationen/AufEinenBlick2017_finalDeutsch.pdf, checked on 1/30/2019.

Centenaro, Marco; Vangelista, Lorenzo; Zanella, Andrea; Zorzi, Michele (2016): Long-range communications in unlicensed bands: the rising stars in the IoT and smart city scenarios. In *IEEE Wireless Commun.* 23 (5), pp. 60–67. DOI: 10.1109/MWC.2016.7721743.

Grehl, S.; Mischo, H.; Jung, B. (2017): Research perspective–mobile robots in underground mining. Using robots to accelerate mine mapping, create virtual models, assist workers and increase safety. In *BULLETIN MAGAZINE* (02), pp. 44–47.

Güth, Frederic (2018): Autonomous Robots and the Internet of Things in Underground Mining. With assistance of Steve Grehl, Robert Lösch, Bernhard Jung, Sebastian Varga, Nasrin Rezaei-Abadchi, Franziska Günther et al. In Otto (Ed.): Proceedings of the 12th Smart Systems Integration Conference 2018: International Conference and Exhibition on Integration Issues of Miniaturized Systems. Smart Systems Integration. Dresden, 11.04.-12.04.2018: Mesago Messe Frankfurt GmbH, pp. 215–222.

Lösch, Robert; Grehl, S.; Donner, M.; Jung, Bernhard; Buhl, Claudia (2018a): Design of an Autonomous Robot for Mapping, Navigation, and Manipulation in Underground Mines. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Madrid, Spain*.

Lösch, Robert; Grehl, Steve; Güth, Frederic; Günther, Franziska; Rezaei-Abadchi, Nasrin; Jung, Bernhard (2018b): Roboter und Internet der Dinge zur Umgebungsdatenerfassung unter Tage. In *Acamonta–Zeitschrift der Freunde und Förderer der Technischen Universität Bergakademie Freiberg* 25, pp. 41–45.

Mining Magazine (Ed.) (2016): Volvo tests driverless trucks at Kristineberg. Available online at https://www.miningmagazine.com/fleet/news/1263537/volvo-tests-driverless-trucks-kristineberg, updated on 9/8/2016, checked on 8/27/2018.

Sächsisches Oberbergamt (2014): Der Bergbau in Sachsen. Bericht des Sächsischen Oberbergamtes und des Landesamtes für Umwelt, Landwirtschaft und Geologie (Referat Rohstoffgeologie) für das Jahr 2013. Available online at http://www.oba.sachsen.de/download/2014_09_24_JB2013_web.pdf, checked on 1/23/2019.

Sächsisches Oberbergamt (2016): Der Bergbau in Sachsen. Bericht des Sächsischen Oberbergamtes und des Landesamtes für Umwelt, Landwirtschaft und Geologie für das Jahr 2015. Available online at http://www.oba.sachsen.de/download/2016_11_09_JB2015_Druckfassung.pdf, checked on 1/23/2019.

Sächsisches Oberbergamt (2017): Zahlen und Fakten. Available online at http://www.oba.sachsen.de/278.htm, updated on 12/13/2018, checked on 1/23/2019.

Schmieder, T. (2017): Research project Mining-RoX—From 3D mine scans to a mine rescue simulator. In *GeoResources Journal* (1), pp. 41–42.

Texas Instruments: Information on SensorTags by Texas Instruments. Available online at http://www.ti.com/ww/en/wireless_connectivity/sensortag/tearDown.html, checked on 4/23/2018.

Thingsquare: Website. Available online at http://www.thingsquare.com, checked on 4/23/2018.

Varga, Sebastian; Grehl, Steve (2018): ARIDuA—Autonome Roboter und Inernet der Dinge n untertägigen Anlagen. In Jörg Benndorf (Ed.): 19. Geokinematischer Tag. Freiberg, 17.-18.05.2018. Nossen: Wagner Digitaldruck und Medien GmbH (Schriftenreihe des Institutes für Markscheidewesen und Geodäsie an der Technischen Universität Bergakademie Freiberg, 2018-1), pp. 147–158.