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Remotely Operated Robots for Underground Applications

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Abstract: The use of autonomous systems for exploring underground structures is a promising technological step forward. These systems can be used for technical exploration, regular inspection, and also as first responders in emergencies as they offer the possibility of entering potentially hazardous areas with relatively little risk. Flying systems (drones, UAVs), land-based robots, and mobile systems are all suitable technology platforms for this purpose. An essential aspect of the use of such autonomous systems is the interaction between humans and machines. Humans may be present in the immediate working environment underground, for example as victims of an accident, or they may be operating the robotic systems. To this end, Graz University of Technology, Montanuniversität Leoben, and Imerys Talc Austria have formed a consortium that addresses precisely these aspects for land-based "robot dogs." We focus on telepresence and teleoperation, whereby the robot acts as an avatar for humans and enables remote interaction with the environment. The robot does not serve to embody the person, but to enable them to perceive and act through it.
The aim of this article is to demonstrate this interaction between humans and machines using practical examples. Particular attention is paid to operating the robot remotely and without direct visual contact. In addition to the technical and operational aspects, the use of robot sensors for correct visual representation and the requirements for smooth movement and remote perception are also discussed.

Keywords: Remote operations, Robots, Virtual reality, Augmented reality, Human-machine interaction

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Aus der Ferne gesteuerte Roboter im Einsatz unter Tage

Zusammenfassung: Der Einsatz autonomer Systeme für die Erkundung von untertägigen Strukturen ist ein vielversprechender technologischer Schritt. Diese Systeme können für die technische Erkundung, regelmäßige Inspektion und auch als „first responder" in Notfällen eingesetzt werden, bieten sie doch die Möglichkeit, mit relativ geringem Risiko in potenzielle Gefahrenbereiche vorzustoßen. Als Technologieplattformen bieten sich dabei sowohl fliegende Systeme (Drohnen, UAV) als auch landgestützte Roboter und fahrende Systeme an.
Ein wesentlicher Aspekt des Einsatzes solcher autonomen Systeme ist das Zusammenspiel zwischen Menschen und Maschinen, wobei die Menschen sowohl im direkten Arbeitsumfeld unter Tage sein können, wie zum Beispiel als Opfer eines Unfalles, oder auch als Bediener der robotischen Systeme auftreten können. Dazu haben sich Know Center, TU Graz, Montanuniversität Leoben und Imerys Talc Austria in einem Konsortium zusammengeschlossen, das eben diese Aspekte für landgestützte „Roboterhunde" behandelt. Wir konzentrieren uns auf Telepräsenz und Teleoperation, wobei der Roboter als Avatar für den Menschen fungiert und eine Interaktion mit der Umgebung aus der Ferne ermöglicht. Der Roboter dient nicht dazu, die Person zu verkörpern, sondern sie zu befähigen, durch ihn wahrzunehmen und zu handeln.
Ziel dieses Artikels ist es, diese Interaktion zwischen Mensch und Maschine anhand praktischer Beispiele zu demonstrieren. Besonderes Augenmerk wird dabei auf die Bedienung des Roboters aus der Ferne und ohne direkten Sichtkontakt gelegt. Neben den technischen und bedienungstechnischen Aspekten werden auch der Einsatz der Robotersensoren für eine korrekte visuelle Darstellung sowie die Anforderungen an eine reibungslose Fortbewegung und Fernwahrnehmung behandelt.

Schlüsselwörter: Fernsteuerung, Roboter, Virtual reality, Augmented reality, Mensch-Maschine Interaktion

1. Introduction

Throughout the centuries, mining has been a fundamental pillar of human progress, supplying the essential materials that have set in motion technological, infrastructural, and economic advancements (currently the extraction of mineral raw materials significantly enhances regional economic value in Austria, with the raw materials industry underpinning approximately 25% of the nation's GDP). To increase productivity and optimize mine operations the digital transformation in the mining industry is essential. Various consultants and researchers have identified that the mining industry has generally been lacking behind the global trend leaving plenty of room for a more pronounced uptake of digital technologies at large [1–3]. More recently, the Austrian "Masterplan Rohstoffe 2030" [4] has identified the benefits of digital technologies for all aspects of the mining industry, i.e. both management and administration.

A survey among industry leaders has revealed the most important keywords and technologies in relation to the digital mine. These include robotics, Internet of Things (IoT), Machine learning (ML), Artificial Intelligence (AI), 3D-printing, and automation (listed by increasing importance) [5]. Mines and equipment suppliers have recently successfully taken up huge efforts in digitalisation and automatization. Well-known and well-established examples are the increasing fleet of autonomous haul trucks in open pit operations worldwide, which is in the range of a total of 3600 in June 2025 [6]. The same accounts for remotely operated and semi-autonomous equipment (mainly LHDs) in underground operations (e.g. [7–9]).

In this context, autonomous inspection units aka robots and drones (UAVs) are becoming ever more widespread in all engineering fields. Mining has traditionally been at the forefront of deploying these exciting technologies, due to the unique opportunities it provides. Additionally, mining imposes one of the harshest environments for deploying these technologies (keywords: dust, moisture, vibrations, confined spaces) making the utilization of robotic units a challenge. This article tackles the grand challenges identified for deploying robots, i.e. with regards to human-robotic interaction, and highlights some potential use cases that could be of interest for domestic and international mining operations.

2. Grand Challenges

Autonomous mobile platforms (robots) promise suitable support in scenarios that require sensing and processing physical properties of a possibly remote environment. However, the variety of possible scenarios or use-cases where autonomous mobile systems are to be used introduces challenges at multiple levels. In a nutshell, the robot is assumed to be able to (autonomously) move in the target environment and use its sensors to collate spatially organized data from it. Based on the data collected, humans would like to make various analyses and make decisions. It is important to consider i) what the level of autonomy the robot should exhibit is, ii) at what time a response is expected, iii) what quality and accuracy is expected from the data collected.

These aspects adopt different answers depending on the scenario and the use-case, and often with varying requirements of the use-case. We focus on underground scenarios. These scenarios are characterized by the absence of GNSS signal, poor lighting, featureless environments, and large-scale unknown terrains. Added to this is the potential lack of communication and power infrastructure, which, depending on the scenario, might be more or less critical. The latter constraints have to be actively considered when designing the robot autonomy/decision making.

The great **challenge** is the provision of digitalization capabilities that enable humans to explore and utilize remote environments with sufficient spatial and general sensory detail so that they are indistinguishable from physical presence. The challenge outlines a **goal**: Real-time digitization, exploration of, and interaction with remote environments, supported by robotics and mixed reality technologies.

2.1 Robot Mapping and Autonomy

A crucial enabler for robots to navigate and operate autonomously is Simultaneous Localization and Mapping (SLAM), a technology that takes sensor data as an input to build a map of the (unknown) environment while keeping track of its own position within it [10] To improve robustness and accuracy, multiple sensor modalities are used in conjunction through sensor fusion, for example relying on LiDAR-Vision [11] and/or Inertial/Visual Odometry [12].

A SLAM system has to continuously collect and correctly match sensor measurements (visual features, Lidar points) with acquired knowledge (landmarks, map elements, features, [13]). Incorrect associations lead to significant errors in the map and affect the robot's localization. Hence, a critical challenge lies in achieving *robust data association* in challenging conditions [14] such as perceptual aliasing, dynamic environments, or sensor noise. Incorrect associations challenge loop-closure, the process by which a robot recognizes a previously visited location in its environment, correcting accumulated drift in its pose estimation and map [15]. With missing input features, errors in association of locations lead the robot to drift and lead to missing connection with points that have been visited. In order to train, fine-tune, and validate the SLAM system, specialized datasets and benchmarks are required, and acquiring them is already a challenge. The SubT-Tunnel dataset [16] is a benchmark for SLAM in underground mining tunnels but it lacks ground-truth trajectories. The SubT virtual testbed [17] uses the Gazebo simulator [18] to provide flexibility in adjusting robot dynamics and environments, but it is a purely synthetic environment with little resemblance to real underground operations. One challenge lies in developing complete benchmark environments including real-datasets to quantify efficiency of SLAM systems.

The robot autonomy referring to its navigation capabilities consider two types of tasks, i) surveying the process where the robot traverses a novel environment to system-

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atically map its surroundings and ii) searching, has a goal that may be determined at runtime and aims to maximize the likelihood of finding a target. During surveying, for instance, the robot uses a frontier based approach designating the adjacent space between explored space and unknown space as potential goals [19]. Besides, the robot should consider information about its energy storage and communication capacity as decision points during decision making.

The robot uses the map to know its pose in the environment and for decision making. Nevertheless, the environments and scenarios where robot autonomy would be necessary happen to pose major complications starting with sensing limitations that affect the mapping as described above. Erroneous or inaccurate mapping affects navigation decisions, which indeed further feeds mapping errors. Despite these difficulties, sensor data can be post-processed and corrected in most cases, and with sufficient illumination and access to outside-in positioning, faithful mapping is achievable. When robot decision making may be compromised, e.g. by unreliable mapping, or when complex decisions are in play, the role shifts to direct human operation.

Humans also require spatially correct information for their decisions, but there are options on how to provide this information. Humans can work with raw or less processed data and selectively ignore processing errors. Still, a major challenge lies in the digitalization of 3D spatial information. Besides, use-cases are rarely just about localizing the robot. Indeed, we would like to use the mapping capacity of the robot to spatially anchor other measurable physical properties of the environment. For example, localizing gas sources [20] or spatializing CO2 concentration [21]. Indeed, the spatialization of sensed data will also be dependent on the spatial mapping.

2.2 Human Interaction through Virtual Reality

When involving humans, it is important to consider what kind of perspective they require on the environment and what information is important for their decisions. Environment spatial information captured during surveying exercises may be sufficient when attention to dynamic objects is less important. Data from robot sensors are processed through SLAM, often obtaining point-clouds that need to be triangulated and colorized. The resulting 3D models may contain artefacts such as holes and weird shapes that need to be cleaned with a manual modeler, e.g. Blender. The 3D model can be rendered and further augmented with visualizations created from other spatialized sensor data.

Immersive technology offers diverse methods to experience 3D data and take advantage of the human's learned abilities to move in space. Virtual Reality is a technology intended to offer an all encompassing experience, perceptually isolating the user from the environment they are in and providing a complete computer generated 3D multisensory experience and the ability to interact in it. Augmented Reality (AR) is another form of immersive technology that uses the real physical environment as a platform and aligns virtual objects with physical ones in a real environment, interactively and in real-time [22]. AR and VR are often considered to be extremes in a spectrum gauging the amount of virtuality or digital content added to reality and termed together as mixed reality. These technologies are called immersive technologies, and the term immersion refers to the extent to which the system delivers a convincing sensory input, replacing normal perceptual sensations [23]. Immersion is a powerful concept for data visualization because of its ability to display any spatial scale (from atomic to cosmic), any temporal scale (still, slow down, accelerate), and any location [24]. With immersive technology the natural locomotion of users serves as an interaction device [25]. When integrating 3D data obtained from a robot sensing system into an immersive application, the major challenge is providing a sufficiently rich sensory experience, since the captured models may be too sparse and breach the immersion. Another challenge lies in the feedback or commands the user may want to give to the robot, and its real-time response.

With the 3D models, different perspectives offer diverse possibilities for interaction and feedback, which are convenient for visualization. An exocentric (bird's eye) view on the environment may provide sufficient information, for example when monitoring multiple actors, different robots, or for an overview of visualized sensor data. An egocentric view through a camera at head height is coupled with the perception of space and scale.

Video trails and video clouds are commonly used, e.g. to represent the path followed by a robot in 3D reconstruction [26]. Besides, the SLAM [27] system estimates a full 3D pose in 6DOF and delivers a geometric 3D map in real-time. These maps may include noise or even be sparse, and yet they may also provide sufficient geometry components for image-based rendering [28]. Indeed, robots can be used as cameras for remote visual perception. Avery and Sandor used a robot controlled remotely with a joystick [29] to offer a ghosted-view X-ray vision through walls [30]. Erat et al. provided exocentric and egocentric control of a drone to explore hidden areas with augmented reality [28].

In a different setup, Kasahara et al. propose using camera based remote visualizations [31]. They continuously register the camera viewpoint in a system that provides omnidirectional remote visualization on the remote user's application. Instead, we will incorporate techniques to support direct exploration of the environment through the robots [32]. We will explore novel multimodal interaction techniques to control robots while exploring the environment. Hereby we build upon previous work [28, 33–35], offering hybrid methods that more closely combine overview with direct interaction or inspection in first-person view.

3. Use Case: Remote Exploration and Safety Operations in Underground Mining Tunnels

Underground mining tunnels present significant operational risks, including low visibility, unstable terrain, re-

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stricted ventilation, and the potential for structural collapse. Safety requirements often necessitate halting operations for manual inspections, which can negatively impact productivity. The objective of a remote exploration system is to enable real-time, remote digitisation and interactive exploration of tunnel sections so that experts can assess conditions and guide interventions without physically entering hazardous environments.

The solution involves a mining robot platform, equipped with LiDAR, RGB-D cameras, thermal imaging, and gas detection sensors, with the option to integrate a manipulator arm for collecting samples or performing physical interventions (Fig. 1). An onboard edge computing module processes simultaneous localisation and mapping (SLAM), hazard detection, and map compression for efficient transmission. Outside the mining area, a control centre receives the processed data, fuses maps, stores historical records, and hosts multi-user mixed reality sessions. The mixed reality operator, typically a geologist, safety inspector, or engineer, wears a mixed reality headset that captures head, hand, and body movements for intuitive robot control.

The operational workflow begins with the robot entering the tunnel and performing real-time digitization. Using SLAM with LiDAR, depth sensors, and inertial measurement units, it generates a detailed three-dimensional map, even in low-light, dusty, and GPS-denied conditions. Gas and thermal sensors detect hazards such as methane build-up, oxygen depletion, or heat signatures from malfunctioning equipment. The collected sensor data is transmitted to the control centre, where it is processed into a persistent three-dimensional digital twin of the tunnel. Semantic processing automatically labels structural supports, geological features, installed equipment, and hazardous areas.

The mixed reality operator can then explore the digital twin as though physically present, viewing it at full scale (Fig. 2). Live overlays display sensor readings for gas concentration, temperature, and geotechnical stress, while historical maps can be layered to reveal changes in structure or geology over time. The operator's tracked movements and gestures are mapped directly to robot controls. For example, pointing at a rock fissure prompts the robot to reposition for a closer scan. The manipulator arm can be directed to collect rock samples, place monitoring devices, or mark areas that require reinforcement.

In addition to inspection, the robot is capable of executing safety and intervention tasks such as placing supports, marking surfaces for drilling, or installing environmental monitoring devices. All operations are recorded with time-stamped three-dimensional maps and associated sensor datasets. These records are used for predictive maintenance modelling, incident investigation, and regulatory compliance documentation.

The benefits of this approach include the elimination of the need for personnel to enter hazardous areas, thereby significantly reducing exposure to toxic gases, unstable ground, and collapse risks. It enables a rapid hazard response by allowing the assessment of a tunnel section within minutes of an alert. It maintains an operational continuity by permitting inspections without stopping nearby mining activities (Fig. 3). It also provides an ongoing geological monitoring by detecting progressive rock deformation through historical comparisons. Furthermore, it improves resource efficiency by allowing a single remote specialist to monitor and assess multiple sites within one shift and enhances training by providing replayable mixed reality inspection records for staff development.

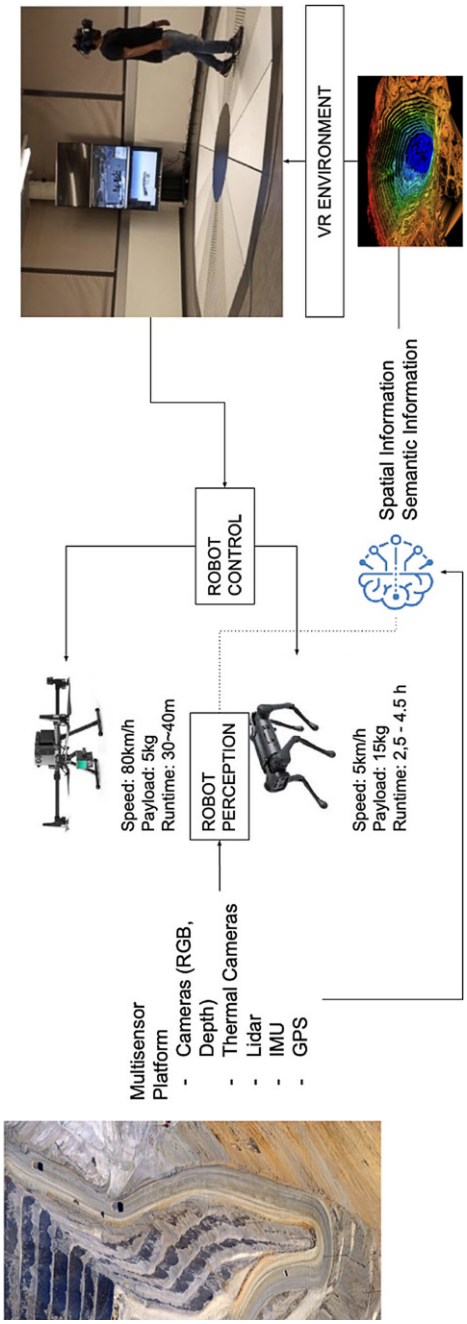


Fig. 1: Remote exploration and safety operations in underground mining tunnels

This approach incorporates advanced SLAM technology for environments without GPS, the reuse of maps for building and maintaining accurate digital twins, and mixed reality interfaces for intuitive remote exploration and control. The system maps operator motion to robot motion for natural telepresence and supports multi-platform sensor in-

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Fig. 2: Mining digitial twins in Mixed Reality



Fig. 3: Potential use case in mining area: Robot walking over uneven rocky ground for remote exploration (left). Robot walking through a mining tunnel for remote inspection. (right)

tegration, including unmanned ground and aerial vehicles for comprehensive inspection coverage.

4. Conclusions

Robots, drones, and other autonomous platforms offer a huge potential in the mining industry. One of their strengths is the collaboration with a human acting e.g. as the "remote eye and hands" of the operator. The use case example shows how the human can walk the robots in a remote operation benefiting from the real time perception of the situation. This will enable teams to act faster on the basis of a more reliable basis for decision making, i.e. in situations where it is risky to send humans to the actual working site, e.g. in case of emergencies.

The setup and mission design require a strong collaboration between domain experts from all areas involved. In the use case example, this would be mining engineers, robotics as well as visualisation experts.

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