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Keynote Paper

Recent developments towards Autonomous Tunneling and Mining Machinery

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ABSTRACT

Today's trend in tunneling business is clearly moving towards automation and autonomous machineries. This trend entered into mechanical excavation machineries as well and Sandvik developed a semi-autonomous excavation mode for their Roadheaders. Together with a geodetic guidance system it is possible to tele-operate the Roadheader from surface with a maximum on safety by removing operators from potentially hazardous environments. This semi-autonomous operation of the equipment requests certain requirements like a higher level of safety integration, stable tunnel network connections, reliable technologies and clear interfaces to other tunneling processes. Overcoming these challenges, a machine equipped with the automated excavation mode will provide tremendous benefits like increased excavation productivity, safety, serviceability, reduces human error, decrease costs and overcomes the lack of skilled machine operators. Further developments in Roadheader automation will continue to expand within tunneling industry to increase the productivity of tunneling sites– particularly as the infrastructure development moves underground.

1. INTRODUCTION

Automation in mining and civil tunneling have been increasingly utilized in recent decades to enhance health and safety, to improve economic profitability and to ensure sustainable surface and underground operations (Torlach 1998). These technologies can provide more energy-efficient methods, which obviously can facilitate successful mining and tunneling projects. Moreover, mining and tunneling operations require less number of higher-skilled labor forces in tough and dangerous conditions. Therefore, risks of accidents can be reduced significantly by reduced exposure of miners to potential hazards. Although automation could be a threat to the continued employment, considering the aging and retirement of experienced mining practitioners and lack of mentorship for younger miners, automation and potentially robotics will be a unique opportunity to get training and experience.

Regardless of their sizes and types, due to technical and economic reasons, mines should be equipped with smart mining systems such as automated machines, satellite communications, and smart sensors for accomplishing sustainable mining objectives.

The use of advanced technologies provides more competitive working environments in a safe and environmentally sound manner through efficient and reliable operations (Arvind et al. 2002)

As technology advances in many industries around the world, autonomous machinery has started to replace human labor force. For the last two decades, automation and robotics have been on the agenda of the mining and tunneling industry as well. Although automation has entirely and successfully been implemented in other industries, the mining and tunneling industry does not fully benefit from a complete automation solution so far. Therefore, advancements of mining and tunneling automation are emerging, especially for under-ground operations where increased efficiency and productivity and reduced risk of accidents are of an utmost concern. (Entezari 2014)

The more widespread use of the mechanical excavation systems is a trend set by increasing pressure on the mining and civil construction industries to move away from the conventional drill and blast methods to im-prove productivity and reduce costs. The additional benefits of mechanical cutting include significantly im-proved safety, reduced ground support requirements and fewer personnel. These advantages linked with re-cent enhancements in machine performance and reliability have resulted in mechanical cutting Roadheaders taking a larger share of the rock excavation market.

2. PROPOSED FAILURE SURFACE

Roadheaders are the most widely used underground partial-face excavation machines for soft to medium hard rocks. They are used for both development and production in soft rock mining industry (i.e. main haul-age drifts, roadways, crosscuts, etc.) particularly in coal, industrial minerals and in various other rock types. In civil construction, they find extensive use for excavation of tunnels (railway, roadway, sewer, diversion tunnels, etc.) in a wide range of different ground conditions, as well as for enlargement and rehabilitation of various underground structures. Their ability to excavate almost any profile and cross-section makes them very attractive to those mining and civil construction projects where various opening sizes and profiles need to be constructed.

In addition to their high mobility and versatility, Roadheaders are generally low capital cost systems com-pared to the most other mechanical excavators. Because of higher cutting power density due to a smaller cutting unit, they offer the capability to excavate rocks harder and more abrasive than their counterparts, such as the continuous miners and the borers. (Copur et al. 2000). Roadheaders excavate the rock by means of a cutter head mounted on a cutter boom. The cutter boom can be independently moved in horizontal and vertical direction. In addition, many Roadheaders have the ability to extend the cutter boom by a telescope unit.

A Roadheader in standard design covers the following functions:

- Cutting the rock face
- Loading the cut material on the loading table with loading arms or spinners
- Muck transfer onto consecutive haulage systems (vehicles or belt conveyor), this is done by a chain conveyor located in the center of the machine

3. SCOPE FOR AUTOMATION

3.1 Motivation for Automation

Development and utilization of automation in industries is motivated due to following potential improvements (Nof 2009):

- Feasibility

Implementation of some micro-scale operation requires high speed and accuracy, which humans cannot handle.

- Productivity

Automatic devices can continuously operate with high speed and large capacity, rising over-all efficiency and productivity.

- Safety

Automated machines can work in environments that are not safe for humans,

- Quality and Economy

Automation allows the organized operations to be handled with high quality and it reduces economic losses due to labor salaries and insurance, safety and maintenance expenses. Besides the advantages, automation holds some limitations such as, high initial investment, labor resistance, and requirement of skilled labor. (Rajput 2008) Suitability of automated devices for operations and payback period of the expenses for automation should be analyzed carefully. Technology without suitable integration with production can result in loss of money and time. In addition, although utilization of skilled machines raises productivity, presence of these machines in a work environment can cause jobs that are more competitive and leads to decrease in labor intensity. It can induce unemployment inside the sector. Therefore, all factors with negative and positive sides should be analyzed both socially and economically before adapting automation to production cycle.

Productivity is one of the most motivating items for automation in a cyclic production system. Companies in every sector are under pressure to achieve high quantity of production at low-level costs to raise profitability (Humbert 2007). In general, this pressure eventuates in increasing numbers of workplaces with new improved technologies. Profitability is critical since economical implementation of sectors depends on production that can be traded above limit profits where total cash outflow for capital, operation expenses as well as environmental, and social cost is lower than cash inflow. Therefore, companies must monitor their expenses to ensure their long-term profitability. In this sense, personnel expenses such as, salary, insurance, transportation, and food, one of the largest variable cost items, can be reduced due to the implementation of automation. Automation allows the control and operation of more machines by less number of operators. In addition, unmanned machines controlled at safe distances from the face area allow operation with high accuracy in risky and tough working environments. Furthermore, manually controlled machines work with lower availability compared with automated ones since responsible personnel for manual systems cause system downtimes due to the elimination of human needs. Automated systems can operate continuously without any break except for compulsory and planned maintenance, breakdowns or other machine failures.

Another motivation for automation is clean working environment with less health and safety problems. The introduction of remotely managed systems provides direct benefits concerning occupational health and safe-ty since automation allows the same task management of processes physically away from potentially dangerous working places. In addition to health and safety benefits, compensations paid to labors due to accidents and workforce loss are eliminated with minimizing human factor in excavation areas with unmanned autonomous systems.

Reduction in human errors and growth in production quality is another item in automation motivation. Task complexity and stress on personnel for increased performance may cause human errors in production. Sensors and diagnostic tools with programmable monitoring services mounted on automated systems support production with high accuracy as well as minimized maintenance cost and downtime periods. (Entezari 2014)

3.2 Areas for Automation

As Roadheader provide many different functions, it is necessary to automate any single functionality. The challenges lies in the fact that the mining system has to fulfil a lot of different features, like cutting, loading, roof supporting, following a defined alignment or profile and keeping communication to many other under-ground components. A lot of information and many degrees of freedom have to be managed at the same time. The aim for the performance of the new automated system is to reach the operational cutting performance of an average machine operator, but to deliver stable performance without significant overloading of the system. This results in smoother machine loading and consequently in higher system reliability, less downtime and reduced operational costs as well as more comfort for the underground team.

Therefore, the technical improvement and automation of such machines is mainly focusing on the integration of features, which support the operator to make the mining and excavation process safer, more reliable and easier to be handled in order to ensure good and constant operating performance.

Some examples to improve the excavation on Roadheaders are:

- Positioning support

Positioning support to keep the desired orientation of the advance and to follow the predefined tunnel alignment or to keep the angle of inclination or declination for opening up the access tunnel. All these positioning activities are currently done by manual measurements of the mining and surveyor team. The ma-chine operator currently defines the size, position and individual shape of the profile to be cut by means of manual methods. An integrated guidance system that takes care about tunnel direction and shape of profile to be cut is beneficial.

- Automation of the cutting sequence

Currently, when the machine operator is cutting the face, he is controlling all the individual movements of the boom and the complete machine inclusive tracks, stabilizing cylinder, conveying system etc. This gives a lot of flexibility but it requests well skilled and experienced operator. The automation at least of some parts of the complete cutting cycle would provide a more reliable and more user-friendly system.

- Maintenance planner and diagnosis system

Automated and integrated planning and controlling of maintenance activities as well as an automatic check of the conditions of wearing components at such machines would result in an increase of the reliability and reduction of the downtime of the mining system. A diagnosis system would combine existing fault messages in order to find their original roots and causes and would give the machine operator some useful hints and information how to manage and prevent faults. (Kargl et al. 2010)

Most of the automation trends are coming out of the mining industry. However, some of the new technologies could be transferred to tunneling applications as well.

3.3 State-of-the-art Automation

3.3.1 Machine positioning and seam recognition

Before the machine operator is going to cut a face, he needs to define the position and shape of the area to be excavated in relation to the machine's position in order to perform suitable navigation. Therefore, one needs to know the expected layout of the tunnel and the position and orientation of the mining machine in-side the tunnel. The tunnel layout is usually defined by design of the underground construction and, especially in mining, influenced by the level of the mineral seam. To evaluate the exact position and orientation of a mining machine inside the tunnel separate equipment is needed, for instance theodolite-based navigation systems, which are quite commonly used at construction sites. In typical coal mining, such systems are not used for continuous position measurement and so there is much less online information available: typically, a single laser beam, which is positioned by the underground surveyor along the desired tunnel direction, provides information on heading orientation only. Normally there is no online information about the ma-chine position along the tunnel chainage available. Vertical navigation is usually defined by the actual level of the mineral seam in front of the miner rather than predetermined in detail by a planning process. (Kargl et al. 2010)

3.3.2 Roadheader Guidance System

Today's standard technology on Roadheaders include guidance systems, data logging and remote monitoring capabilities for networked machines.
The system is designed to periodically track the actual 3D position and orientation of a road header's cutter head during operation and to visualize this data together with the actual centerline and profile geometry on the on-board monitor of the operator cabin. The core component is a robotic total station serviced by the on-site surveying personnel communicating with the machine's control system.

The main features of the system are:

- Continuous determination of the absolute 3D machine position and orientation in the project coordinate system by automatic geodetic observations from the robotic total station
- Continuous determination of the absolute 3D cutter head position and orientation by means of above data and data of additional on-board sensors (2 inclinometers, 2 angular sensors, boom sensor for boom telescope position)
- 3D visualization of the actual cutter head position and orientation within the designed pro-file geometry and numerical display of all relevant guidance

parameters (station of tunnel face, horizontal and vertical distance from cutter head to profile line, etc.)

- Due to the integration of machine data with geodetic machine position information georeferenced machine data reporting becomes available. This in turn enables the following advanced features:
  - Accurate cut volume reporting
  - Calculation of specific energy requirements
  - Specific pick consumption monitoring (manual input of pick changed necessary)

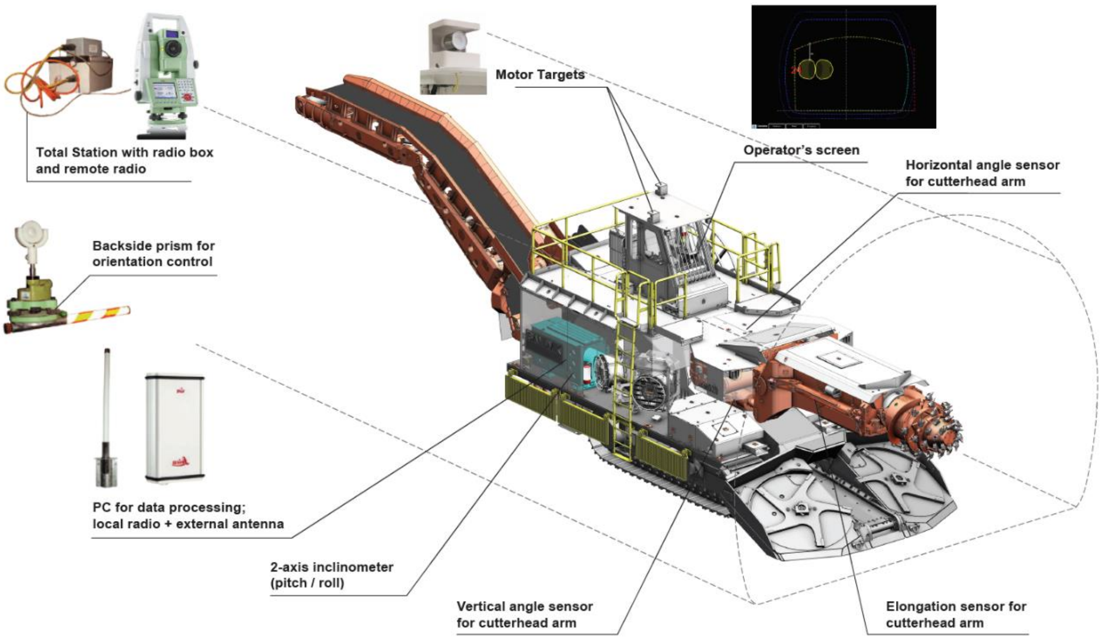

Fig. 1 Layout of Sandvik Geodata Roadheader guidance system

3.3.3 Automatic Cutting Cycle

The development of the automated cutting cycle is a complete new approach aiming to improving the central task of the machine. Similar to the machine concept itself a balance has to be found between several key requirements on the system. On the one hand, a high amount of flexibility is necessary in order to cope with various and often changing boundary conditions such as excavation geometries, rock hardness and support requirements. On the other hand, the ultimate demand of the customer obviously is production and every automated system that targets the core process has to perform at least as well as an averagely skilled ma-chine operator solely on his own hand. Here it has to be pointed out that the aim of such a system has never been to replace the operator. In a similar way that a cruise control of a car is not designed to replace its driver, this system aims at relieving the operator of the normally rather dull task of controlling the individual back and forth movements of the arm but still keep him in control of the governing parameters. Therefore, the machine operator still has the full control and responsibility over the entire machine operation.

One challenge of the design was to minimize this number of governing cutting parameters the operator has to keep track of.

For cutting automation of a Roadheader in principle, three degrees of freedom have to be taken into account: one horizontal, one vertical swing axis and the telescoping boom.

One further aspect has been to introduce a certain kind of learning behavior into the system, by keeping track of and analyzing key feedback parameters, such as the resulting cutter motor current, and thereby optimizing cutting performance for instance by calculating the optimum cutting height for every single cut.

The automatic cutting cycle is handled in the way that the machine operator plans the path by the online visualization component, whereby minimal configuration is necessary and the machine operator can define the cutting parameters if necessary. The planned cutting paths are visually checked by the operator and it is finally transmitted to the PLC system before executed by the equipment.

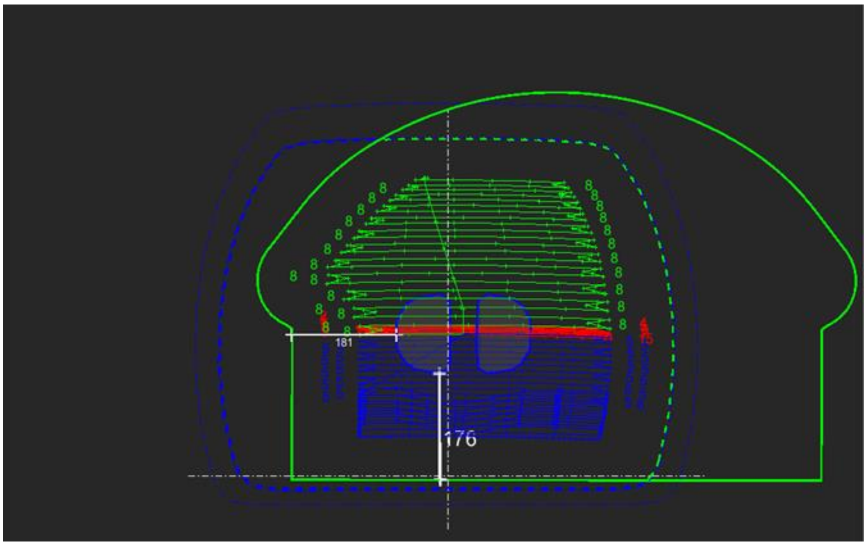

Fig. 2 Automated cutting cycle in large profile

4. TELE-REMOTE TECHNOLOGY

Tele-remote operation is a new way to explore the full potential of automated mechanical cutting equipment while achieving the benefits of increased productivity, safety, and cost-efficiency in mining and tunneling operations. Tele-Remote is the entry-level solution from Sandvik to its industry-leading AutoMine™ offering.

Currently, machines are operated from a cabin or via radio remote control from a nearby position. Operators are exposed to hazards such as dust, noise and to moving equipment in confined space. Furthermore, immediate working area close to unsupported ground. The target of the tele-remote operation is to operate machines from a secured area in a remote position, e.g. from surface. The ultimate aim at the end of the day is, to operate machines completely autonomous

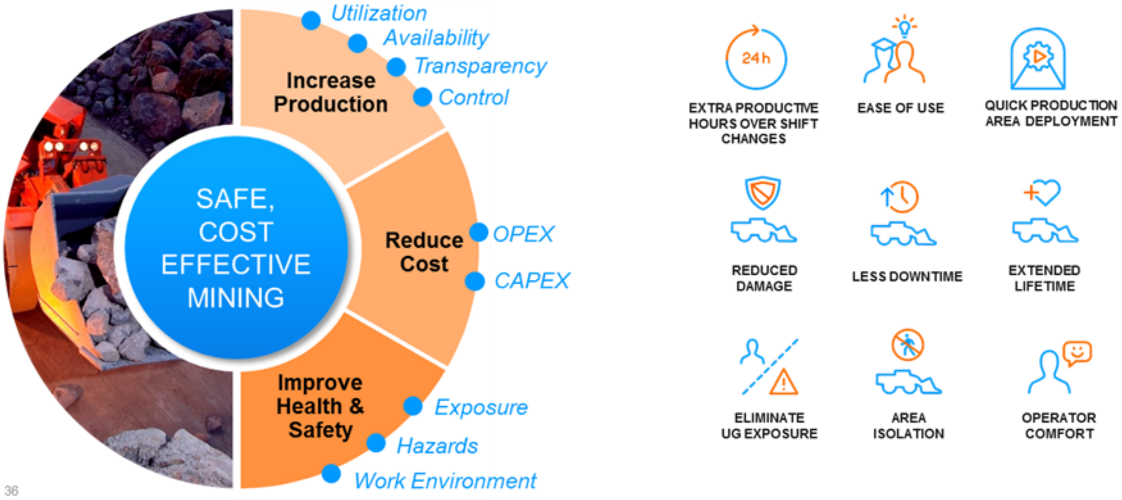

Fig. 3 Value proposition of tele-remote operation

4.1 Guidelines and standards

However, it is necessary to consider certain prerequisites for a tele-remote operation of a Roadheader via a distributed control system (DCS). Standards and guidelines to consider in Europe are the “Machine guideline 2006/42/EG (control system and actuators)” and “Standard for Safety for Machines DIN EN ISO 13849 (ma-chine safety)”. One part or the machine guideline EN13849 is the risk assessment to evaluate the safety risks ensuing from a machine. If a risk is evaluated as too high, design actions need to reduce the risk to an acceptable residual risk.

After the execution of a risk assessment, safety system with according performance levels need to be implemented. In total, five performance levels a, b, c, d and e for safety systems describing the failure probability of a safety component related to the operating hours. (Haubmann 2013)

4.2 Communication and transmission technology

The communication between the operator’s location with the automated and tele-remote controlled machine is an aspect of utmost importance. The communication system layout is structured into a remote operator station with supervisory system functionality, a machine-onboard automation package including an integrated navigation system and control and monitoring capabilities. The installation of access control system barriers at the application area is used for safety isolation. Finally, the communication between remote operator station and machine is essential.

Safety is an important topic in terms of the process data communication, which means, it needs to be determined if the communication line is interrupted. It is clearly defined that any dangerous operating condition must be avoided due to communication related situations.

Thus, it is clear that there are certain functional requirement demands to the field control system. Those requirements are, for example, real-time abilities, reliability, flexibility, high bit rate and finally yet importantly cost efficiency. Such control systems are process field bus (Profibus) or CAN bus (control area network).

A typical communication system is Ethernet or WLAN communication with fast bit rates of 10 to 100 Mbit/s. Also to the Ethernet network, certain requirements like reliability under industrial or even mining or tunneling environment or real-time ability are demanded.

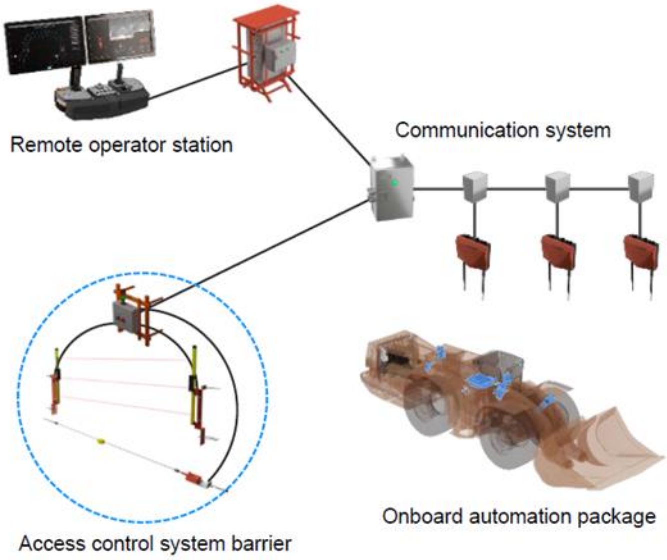

Fig. 4 Communication layout with machine safety concept

4.3 Machine concept

A potential machine concept for a tele-remote controlled Roadheader in a tunneling application requires certain prerequisites, especially safety relevant installations and protective functions defined by any applicable guideline or standard. Additionally, it is necessary to establish a reliable communication network between control station and machine. The most important aspect is to have a safe operation of the mine mitigating any kind of risk for humans and machines.

To have a distinct operation mode it is necessary to implement an “operation-mode-selector-switch” to re-lease the tele-operation modus. On the one hand, maintenance and repairs works can be conducted at the machine; on the other hand, a tele-remote modus can only be achieved with the right position of the mode selector switch.
In the so-called maintenance mode, the machine can be operated by a line-by-sight radio remote control, if necessary. This is already a passive safety mechanism for a safe operation. The operation mode selection is an additional feature to clear danger zone.

Especially, for dangerous equipment like tele-remotely controlled machines, it is appropriate to install additional safety barriers in the danger zones. If a person or another equipment approximates the danger zone, a dangerous movement of the machine must stop. A big challenge is to detect a movement as harmless or potentially dangerous for the operational action. The system needs to decide automatically, if the machine operation must stop or proceed. However, it necessary to have other equipment or machines entering the danger zone for haulage, rock support and other necessary operational activities. This is already an evidence how difficult it is to have an operation automated.

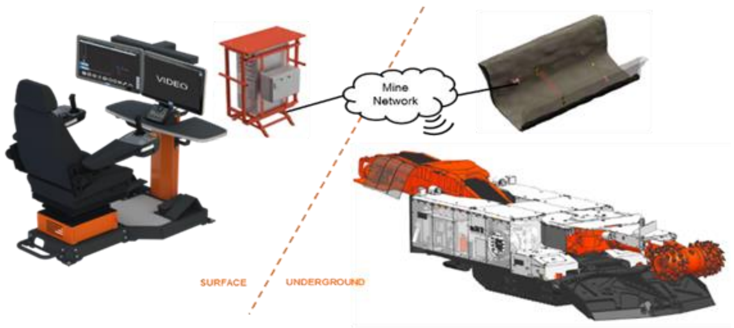

Fig. 5 Machine concept for a tele-remote operation

It is necessary to implement a safety barrier in dangerous operating areas. There are few different technologies for safety barriers like contactless safety concepts. It is necessary to not exceed the required distances between the sensors defining a working area. The concept design with minimum distances of contactless sensors is to protect humans against risky approximation to a danger zone. Potential threats like, crushing, cutting, shearing, collision, puncture hazard etc. are considered according to international standards. (Gräf 2003)

The protection of danger zones can be established also with emergency stops. However, an emergency stop is not a substitute to safety design requirements of the machine and an emergency stop is not allowed to cause another unsafe condition during activation. When activated a machine must stop and an independent restart must be avoided. Those emergency stops must be marked with right colors on a Roadheader. (Gräf 2003)

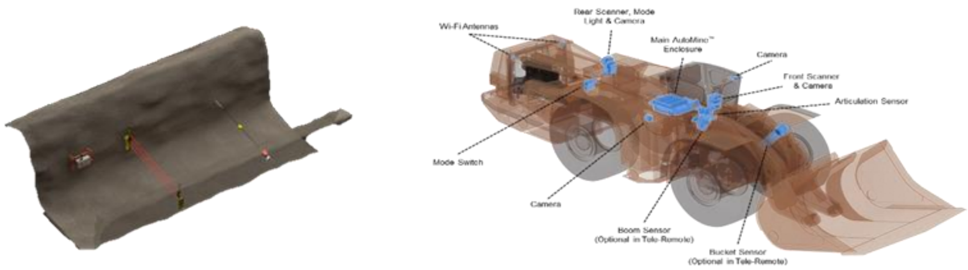

Fig. 6 Safety barriers and machine sensor for tele-remote operation of a loader

Laser scanner are some other contactless safety barriers applied in tunneling and mining applications. This optical control system is scanning relevant danger zones. If an external individual or a machine not allocated to the operating area enters, the tele-remotely controlled machine must stop. A big advantage of the scanner is the potential to define three different ranges – measurement field, warning field and safety field. This gives the opportunity of a pre-warning before a deactivation takes place. (Gräf 2003)

Light barrier and light grids are the next level of safety barriers. Those safety systems must be installed neither in the way that it is not possible to bypass them laterally nor underneath. Those systems must avoid the stay between safety field and danger zone. (Haubmann 2013)

5. CONCLUSIONS

Considering today's developments in automation, it can be stated that a tele-remote and semi-automated operation of a tunneling machinery is possible. Automated equipment is already state-of-the art technology and applied in many applications. The safety concept, which needs to be implemented into the machine control system, is essential for securing the operational areas and to protect miners from hazards arising from machine operations. At any time, no harm to humans and to machines are acceptable. Corresponding monitoring and emergency stop mechanisms must be implemented in the conceptual design. A reliable data connection together with a safe data protocol between machine and control station is very important.

Such a tele-remote operation protect miners as they control equipment from remote and safe places without hazardous and tough working conditions like dust, heat, noise, vibration humidity, etc. The ergonomic situation of the operator is another advantage of the tele-remote operation.

As personal is present only during maintenance and repair works at the dangerous underground location, the risk for geological and machine related hazards is minimized. The huge advantage of an autonomous machine application is in achieving much higher performances by eliminating the human influence on the operation. Furthermore, a new level of accuracy in tunneling with nearly no overprofile can be achieve which helps to save costs for, e.g. shotcrete. The lifetime of components will be increased due to the optimized utilization of the Roadheader.

Due to the technical implementation of tele-remote controlled Roadheaders, future mining and tunneling applications will be further optimized. A big advantage will be that from one control station several ma-chines can be controlled and operated. This will increase productivity, decrease the risk for injuries and counterbalance the lack of well-trained miners in mining and tunneling industry. However, today's technology is heading towards autonomous equipment working in underground applications with the ultimate goal to fully automate the complete mining process.

REFERENCES

Arvind, A., Bandopadhyay, L. K., & Kumar, H. (2002). Mining Automation - Requirements and worldwide Implementations. Indian Mining & Engineering Journal, 29-33.

Copur, H., Ozdemir, H., & Rostami, J. (2000). Roadheader applications in mining and tunneling industries. Golden, Colorado, United States.

Entezari, R. (2014, September). Deevelopment of a remotely-controlled Roadheader robot. Middle East Technical University, Mining Engineering Department.

Fuentes-Cantillana, J. L., Catalina, J., & Rodriguez, A. (2014). Use of Computer Vision for Automation of a Roadheader in Selective Cutting Operation. https://hal-ineris.archives-ouvertes.fr/ineris-00971823.

Gräf, W. (2003). Maschinensicherheit: Auf der Grundlage der eurpäischen Sicherheitsnorm. Heidelberg: Hüthig Verlag.

Haubmann, H. (2013, March 13). Teleoperation einer Bergbaumachine. Graz, Austria.

Humbert, M. (2007). Technology and Workforce: Comparison between the Information Revolution and the Industrial Revolution. Berkley: university of California.

Kargl, H., Gimpel, M., & Preimesberger, T. (2010). Development of an automatic cutting cycle for part face mining machines. Glückauf Mining Reporter, International Journal for Mining, Equipment and Technolo-gy – Made in Germany.

Nof, Y. S. (2009). Handbook of Automation. Berlin: Springer Verlag.

Rajput, R. K. (2008). Robotics and Industrial Automation. S.Chand Publishing.

Torlach, J. (1998). Regulating the Mining Industry in the 2st Century. Mine Safe International.