A REMOTELY OPERATED ROBOTIC ROCK BREAKER WITH COLLISION AVOIDANCE FOR THE MINING INDUSTRY

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ABSTRACT

Rock-breaker automation and remote operation improves the safety and efficiency of mining operations. This article presents an overview of the Rocklogic rock-breaker automation system architecture that provides collision avoidance, automated parking, and remote operation functionality. The system consists of a distributed computer control system that interfaces with sensors attached to the rock-breaker, the rock-breaker hydraulics, and the site infrastructure. We present results of an automated Transmin rock-breaker installed in a production environment at an underground Australian mine site. The system has been in production use for over 900 days during which there have been no reported collisions, and 100% adoption of the remote operation technology. As a result, Rocklogic has significantly improved the safety of rock-breaking operations and reduced the rock-breaking cycle time, thereby improving the sites overall throughput.

KEYWORDS

Rock-breaker, Mining, Robot, Tele-operation, Collision Avoidance, Automation, Remote Operation, Manipulator, Boom

INTRODUCTION

Recently the mining industry has embraced automation and mining robots as a solution to: increasingly complex and hazardous mine sites; increasing operation costs; and shortages of skilled employees (Lever, 2011). The mining environment poses a number of challenges to machine automation, including hazardous environments, remote locations, uncertain and variable workloads with high performance and high uptime requirements. This makes the development of safe, efficient and reliable mining machinery a challenging task.

A typical operational hard rock mine site process begins with drilling and blasting of the ore, which is then loaded onto a vehicle and dumped at a crushing plant's Run-Of-Mine (ROM) bin. A crusher will reduce the size of the ore for further processing in the plant. The crushing often takes place in multiple stages (e.g., primary, secondary, and tertiary) to successively reduce the ore to the required size. If a rock is too hard or too large to pass through the crusher then a rock-breaker is deployed to reduce the oversize material into smaller pieces. The plant then processes the ore in a series of stages (e.g., milling, floatation) and the final product is then stockpiled and transported to the customer.

Rock-breakers are critical to eliminating delays caused to the crushing process by oversize material. A comprehensive study of Codelco's underground Teniente 4 SUR mine site analysed the operation to determine how the mine could be fully automated and identified major disruptions to production (Cordova et. al., 2008). Equipment found to have the greatest impact on production when they had suboptimal performance were the secondary crusher, the rock-breakers and load-haul-dump (LHD) vehicles, in order of importance. For high throughput operations any delay to crushing can cause supply issues downstream, corresponding to a significant revenue loss. A typical iron-ore site in Western Australia processes millions of tonnes per annum, resulting in thousands of tonnes of lost ore for any hour of downtime at the site (Howard & Everett, 2008). Therefore there is a strong incentive to minimise downtime and interruptions to production.

PREVIOUS ROCK-BREAKER AUTOMATION PROJECTS

A rock-breaker is a large hydraulic machine, which consists of a boom assembly and an impact hammer (Figure 1). The hammer uses a repetitive linear percussive force to break the rock. Alternatively, the hammer can be used to manipulate the rocks, to rotate oversize material or remove loose material. The boom assembly consists of a number of joints (typically 4DOF) that are actuated by hydraulic cylinders. Fixed rock-breakers are machines dedicated to the rock-breaking task and are either responsible for primary crushing or mounted next to a primary (e.g., jaw) crusher, often mounted on a pedestal.

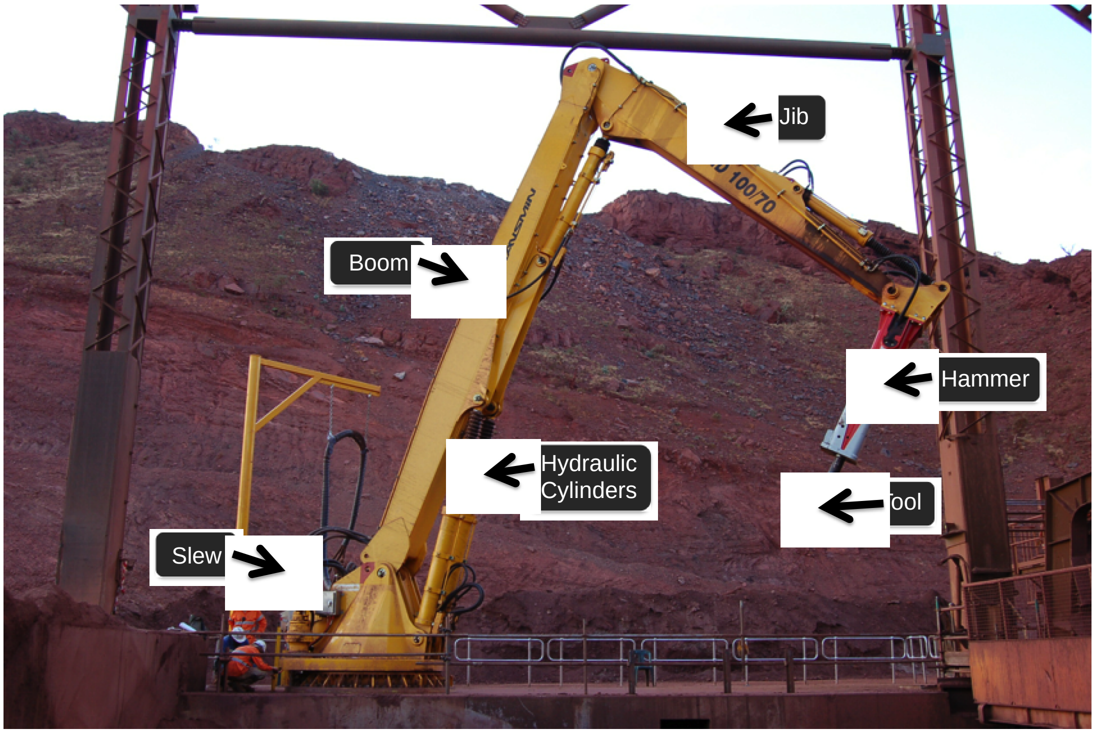


Figure 1 – Transmin XXHD 100/70 rock-breaker at an open-pit site

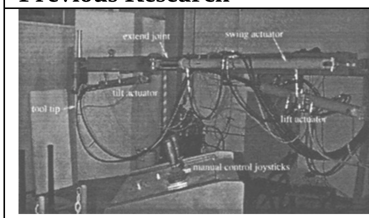
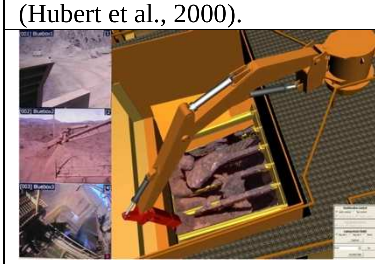
An early project investigating rock-breaker automation was undertaken by the CSIRO in 1998 (Corke, et. al., 1998.) where a prototype hydraulic control system was constructed for testing in a laboratory environment. In addition, a 3D sensing system was developed to detect oversize material on a grizzly using a custom-built actuated laser range finder. Field tests for the 3D sensing system were completed at an underground site, and the authors proposed a set of requirements for a semi-automated rock-breaker.

Corke, Roberts and Winstanley identified several key challenges to controlling Rock-breakers, including highly compliant booms, significant joint flex, high payload to self-mass ratios, and flow-limited hydraulics, in addition to sensor and computing limitations. Overall, it was found that it was not feasible to automate a rock-breaker at the time (Corke et al., 1998).

Hubert et al implemented a rock-breaker remote control system at the Freeport IOZ underground mine. Initial trials used line-of-site remote control, however this was not found to significantly reduce the risk to operators from wet muck spills (Hubert et al., 2000). A reliable surface to underground communications system was implemented and control of four Rock-breakers from an above ground control room was achieved in a production environment.

Further work in rock-breaker automation was undertaken in 2009 by Rio Tinto, Transmin, and CSIRO, which investigated rock-breaker tele-operation (Duff et al., 2009). Duff et al investigated 3D rock sensing via stereo-vision as well as a user interface for tele-operated rock-breaking. A field trial connecting Rio Tinto's open-pit West Angeles mine site to an operator based in Perth, a distance of over 1000 km. The trial demonstrated that remote rock-breaker operation was possible over vast distances, and that it is desirable to have an integrated interface providing full situational awareness to an operator, and that automated motion control is beneficial to the operator. During the trial the rock-breaker hit a wall, highlighting the need for collision avoidance during remote operation.

Table 1 – Previous research in rock-breaker automation

Previous Research	Key accomplishments/Findings
 1998 - CSIRO prototype (Corke, et. al., 1998).	• Identified rock-breaker control challenges – compliance, slop, mass ratio • Hydraulic actuation challenges • Closed loop control – single cylinder • Ruggedized sensors and control valve required • Identified automated rock-breaker requirements • Investigated 3D sensing
 2000 – Freeport remote control (Hubert et al., 2000).	• Production quality remote control • Open loop control • Reliable surface to underground communications system • Surface control room improves safety • Rock-breaker remote operation improved integration with remotely operated LHD vehicles
 2009 – Tele-operation prototype (Duff et al., 2009).	• Tele-operation over 1000km • Closed loop control • Motion control / path planning • Integrated interface • Demonstrated 3D sensing • Identified need for collision avoidance system and operator situational awareness

Transmin trialled a direct remote control system for an underground rock-breaker from a surface control room located 3 km away (Boeing & Kings-Lynne, 2012). It was found that remote operators had difficulties controlling the machine due to limited visibility, poor depth perception, latency, and crude machine control. This trial identified a strong need for a computer supervised rock-breaker control system, CCTV vision, automatic parking, and collision avoidance technology. In addition, independent studies have demonstrated the importance of collision avoidance systems in the successful tele-operation of robotic arms (Lumelsky, 1991).

Thus, the requirements for a tele-operated rock-breaker for the mining industry include:

- electronic control system for the machine, to overcome the mechanical and hydraulic control challenges and improve machine control;
- robust and reliable sensing and computing hardware designed to survive the harsh mining environment, with a fault-tolerant design to ensure stringent uptime requirements are met;
- a collision avoidance system to reduce the risk of machine damage during remote operation;
- an automated path planning and motion control system to simplify and optimise rock-breaker control, reduce the impact of remote operation latency, and reduce the impact of operators poor depth perception;
- an integrated Human Machine Interface (HMI) to provide full situational awareness to the operator.

TRANSMIN ROCKLOGIC SYSTEM OVERVIEW

Rocklogic is a rock-breaker automation system that provides remote operation, automatic parking and collision avoidance functionality. It is designed to increase the safety and efficiency of operations and integrate tightly to existing control and automation infrastructure on-site.

Rocklogic has a number of operational modes. A remote operator can initiate an automated movement with the press of a button to automatically park or deploy the rock-breaker. Alternatively, Rocklogic can operate in a "drive-by-wire" mode where all inputs by the user are modified by the system into safe and smooth control commands to the machine. If there is a failure with the site communications network then the system can be operated from a local portable radio control console by selecting one of several fall-back operation modes.

Rocklogic consists of four major components:

1. a remote operator workstation, consisting of a remote joystick control console and a PC equipped with the rock-breaker user interface, plant control software, and audio/visual feedback (e.g., CCTV). This is typically located in a control room many kilometres away from the rock-breaker.
2. The Rocklogic panel, which contains a high-performance ruggedized computer, a programmable safety system and plant control devices (Figure 2). This panel is located on-site, usually in an equipment room close to the rock-breaker.
3. A rock-breaker Input/Output (I/O) panel, located directly on the base of the rock-breaker. This houses a specialised I/O controller responsible for interfacing with all instruments, sensors and actuators on the rock-breaker.
4. Rock-breaker position sensors. This includes specialised in-cylinder linear sensors for accurately determining the extension of the hydraulic cylinders.

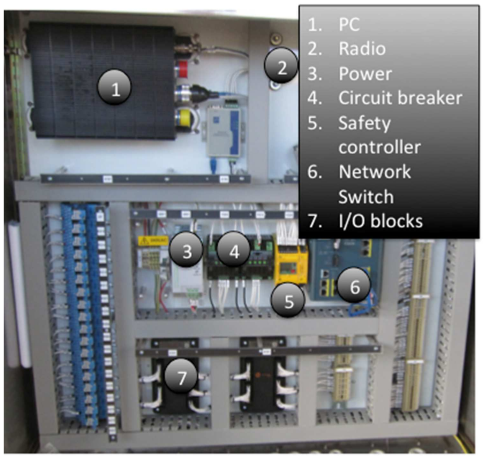


Figure 2 – Rocklogic rock-breaker control panel

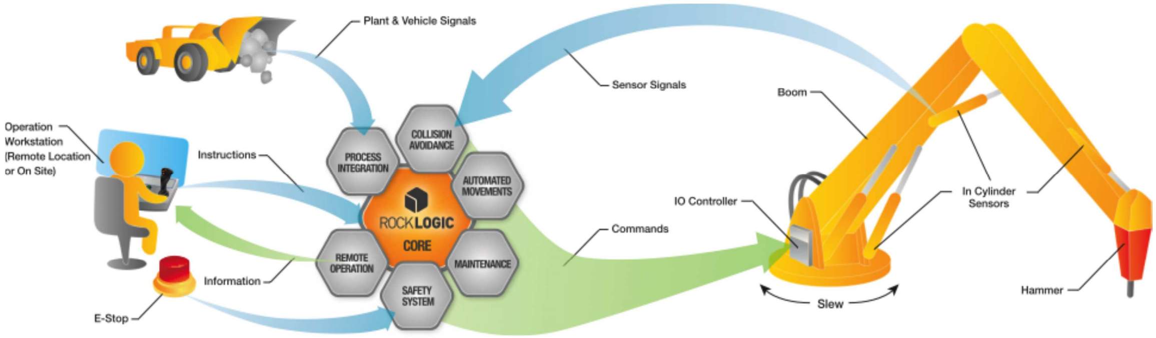


Figure 3 – The Rocklogic system

An overview of the systems operational information flow is illustrated in Figure 3. A remote operator can issue instructions to the Rocklogic system via the site's communications backbone (e.g., Fiber). These instructions can be high-level instructions (e.g., automatically park the machine), drive-by-wire instructions (e.g., slew left), or system functions, such as resetting alarms or turning on the hydraulic power unit.

The Rocklogic computer then executes the higher-level control algorithms and issues lower-level motion commands and receives sensor signals from the I/O controller. The system also receives information from the plant control system and fleet management systems, and presents the information on the integrated systems state back to the operator. Figure 4 illustrates a typical remote operator's workstation.

Figure 4 – A typical remote rock-breaker operator's workstation

There are seven major functions the Rocklogic rock-breaker control system provides:

1. tele-operation from a remote control room, which may be located off-site;
2. a Human Machine Interface (HMI) that provides visual information on the system state, and drive-by-wire control of the rock-breaker to ensure operator commands result in smooth and efficient motion;
3. collision avoidance that provides active breaking, ensuring an operator can not collide with the surrounding site structure;
4. automated movement that enables the rock-breaker to deploy to a pre-programmed location (e.g., automatic parking);

5. condition monitoring and data logging of the machine to provide metrics on its performance and information on alarms and warnings;
6. safe machine shutdown functions, implemented according to the relevant safety standards;
7. integration with the plant control system and fleet management systems to provide plant control, alarm reporting, and scheduling interactions between LHD vehicles and the rock-breaker.

ROCKLOGIC SOFTWARE ARCHITECTURE

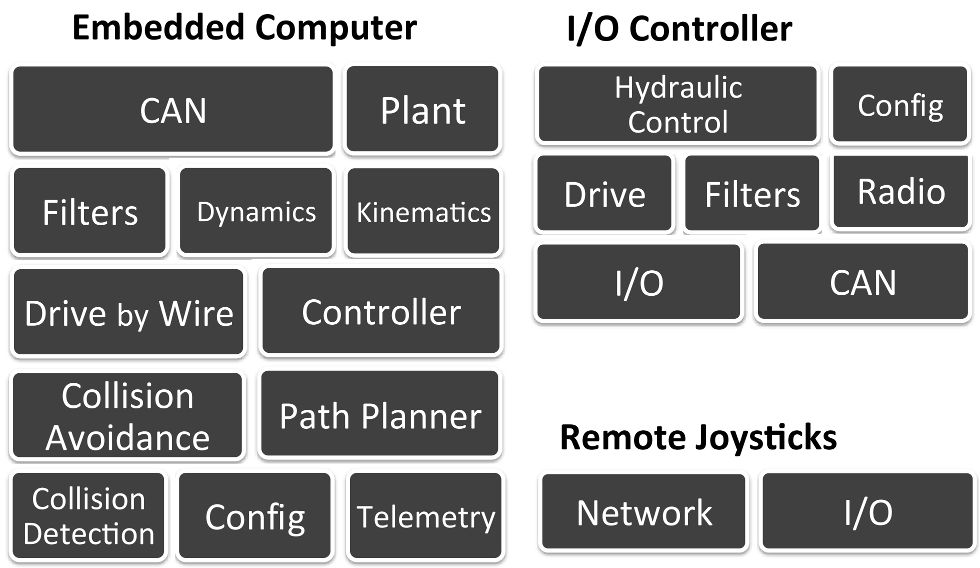


Figure 5 – Rocklogic Rock-breaker Control System software architecture diagram

An overview of the Rocklogic software architecture is depicted in Figure 5. The information flow through the system starts with the I/O controller, which reads data from the sensors, instruments and other input devices (e.g., plant signals). The sensor values then pass through a set of high-speed filters to minimize noise and reduce transient effects from mechanical shock and vibration. The processed data is passed via CANbus to the Embedded Computer that updates another set of filters, and calculates the kinematic and dynamic state for the machine.

Rocklogic's automated movement system uses a global path planner to generate safe and efficient paths to any desired location using a pre-programmed graph of waypoints. The kinematic sub-system is then used to calculate the required rock-breaker configuration for the motion control system. A hydraulic control algorithm balances the load across the hydraulic cylinders using information from the machines dynamic and kinematic state to ensure multiple joints can be moved synchronously without overloading the available flow from the hydraulic power unit.

The collision detection system uses the machines current state to determine the distance to obstacles and is queried for velocity obstacles by the collision avoidance system. The site structure is pre-programmed into the Rocklogic system using either existing 3D CAD data, surveyor data, or laser-scanned information. This data is converted to an internal representation in convex polytopes or one-sided triangles for fast signed distance calculations, and the rock-breaker itself is represented as line segments.

The collision avoidance system continuously monitors all actions taken by the automated movement system and will disable the automated movement controller if it deviates from the desired path or is likely to result in a contact. If an operator is manually controlling the system then the collision avoidance system pre-emptively reduces the speed of the machine as it approaches any obstacles using an active breaking system.

The final output commands are issued to the I/O controller that updates a high-speed control algorithm that fine-tunes the flow to each cylinder to ensure optimal adherence to the desired trajectory. Finally, the drive signals are then sent to the actuating valves.

A watchdog and alarm system continuously monitors all activity in the Embedded Computer and I/O controller and reports any warnings and alarms to the plant. A separate dedicated safe machine shutdown system is triggered by the RCS in the case of an alarm condition.

REMOTE ROCK-BREAKER MANUAL AND AUTOMATED OPERATION COMPARISON

The manual (non-automated) use-case for a rock-breaker begins with an operator that identifies oversize rocks at the crusher. The operator will then travel to the rock-breaker, request that the control room stops the vehicles from dumping and starts the machine. Using local controls, the rock-breaker will be manually maneuvered from its parked position to the location of an oversize rock. The operator will then manipulate and break the oversize material, eventually completing the task and then parking the rock-breaker. The operator will then notify the control room that the task is complete and permit vehicles to resume dumping.

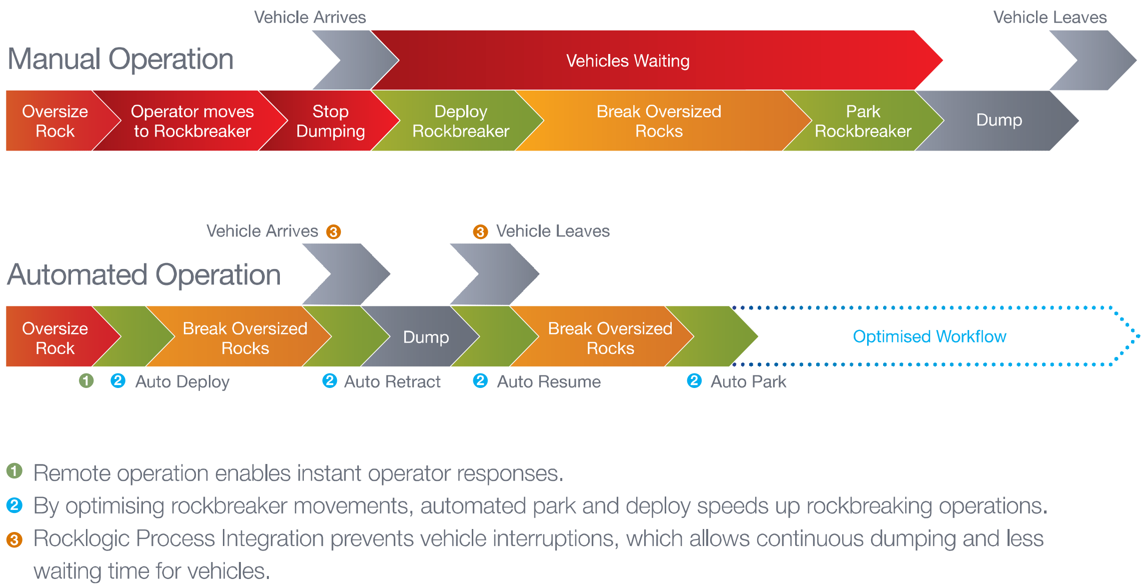


Figure 6 – Rock-breaker manual vs. automated operation cycle

The speed at which this task is completed is highly dependent on the skill of the operator, when the operator notices the oversize rock, travel time, and the communications between the rock-breaker operator, the control room and vehicle operators. Often vehicles are interrupted from dumping due to rock-breaking operations, and the rock-breaking process takes much longer than necessary due to novice or badly trained operators.

With an automation system, the operator has an integrated interface that provides information on the vehicle status, as well as the ability to remotely start and deploy the rock-breaker. The operator automatically deploys the machine by selecting a destination from the user interface. The automation system drives the rock-breaker to the desired location with no further operator input, and automatically notifies approaching vehicles that the rock-breaker is deployed. Once the rock-breaker reaches its destination, the operator can begin breaking rocks. During this process the collision avoidance system ensures the machine is operated safely.

If a vehicle approaches during rock-breaking, the system will automatically retract and permit the vehicle to dump, before returning to its previous location. When the operator has completed breaking the rock they can request the rock-breaker to automatically park.

The manual and automated operation work cycles are contrasted in Figure 6. Automation provides a number of improvements to the overall cycle time:

1. remote operation eliminates the travel time required to operate the rock-breaker, in addition to removing the operator from on-site hazards;
2. automatic deploy and parking operations are faster and less variable than manual operations, and reduce operator training requirements;
3. Automated and formalized communications processes between the rock-breaker, site control room, and vehicles eliminate communications delays and mistakes. This enables tighter scheduling of rock-breaker and vehicle interactions, and reduces vehicle-waiting times.

UNDERGROUND SITE PRODUCTION USE

Following a series of trials starting in 2010, the Rocklogic system has been in production use on two rock-breakers at an underground site since June 2011 for the first system, and April 2012 for the second. The system has been used on-site for over 27,000 rock-breaking cycles and 3,500 hours of fully automated operation with a total up time of over 23,000 hours.

The key findings from the production use include:

- the system design is robust, and reliable to provide continuous operation in a production environment;
- remote operation has seen 100% adoption. The confidence in the remote operation system is so high that the local operator area is no longer available on site.
- Collisions between the rock-breaker and the surrounding cave have not occurred since the system has been adopted. Prevented near-collisions are reported for 2% of operations.
- After initial training, the operators have adopted the use of automated movements, and automated deploy movements are used for 99% of rock-breaker cycles.

BENEFITS OF ROCK-BREAKER AUTOMATION

Rock-breaker automation provides significant benefits, primarily increased safety, improved efficiency, and reduced costs. Key benefits of rock-breaker automation include:

- improved working conditions for operators who can now be located in safe and comfortable control rooms. This results in reduced occupational injuries and improves staff retention.
- Less downtime from collisions and reduced delays to vehicles dumping, resulting in higher overall throughput.
- Faster cycle times through the use of automated movements, improving rock-breaking efficiency.
- Improved planning and collaboration between the rock-breaker operators and other operators (e.g., LHD operators) that lead to significant improvements in cycle times and throughput.
- Lower maintenance costs due to smoother operation and the elimination of collision damage to equipment. In addition, remote condition monitoring enables accurate preventative maintenance further cutting maintenance expenses.
- Ease of use is greatly improved, reducing training time and the requirement for skilled employees.
- Lower labour costs and on-costs as the rock-breaking role can be shared between control room operators, or a single operator can control multiple machines. Remote operation further reduces costs for remote sites by eliminating on-site accommodation and flight costs.

CONCLUSION

Rock-breaker technology has seen major advancements in the last decade. The Rocklogic is the first automated rock-breaking system used in a permanent production environment. Rock-breaker control challenges have been addressed with an intelligent load-balancing hydraulic control system, in addition to an active breaking collision avoidance system. This enables safe and efficient long range remote-operation that optimize the Rock-breakers work cycle and provides cost and maintenance benefits. The production system has in been in place for over 900 days, no collisions have occurred since the system was installed and automated movements are used in over 99% of rock-breaker operation cycles.

The major remaining challenge is to achieve fully autonomous rock-breaking. To reach this goal, further work is required in reliably sensing and classifying oversize material, as well as scheduling and planning rock-breaking activities. In addition, automated rock-breaking poses new challenges to the design of future mine sites to support improved methods of rock-breaking.

ACKNOWLEDGMENTS

The authors would like to acknowledge the efforts of the Transmin team that have devoted their efforts to rock-breaker automation, in particular Daniel Adams, John Heard, Angie Kings-Lynne, Michael Kradolfer and Tane Pendragon.

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