A Technology Review of Idler Condition based Monitoring Systems for Critical Overland Conveyors in Open-pit Mining Applications

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***Abstract*—Large-scale overland belt conveyor systems have been installed in mining to meet the increasing demand for higher capacity and longer distance continuous transport of bulk material. Currently, the Overall Equipment Effectiveness of belt conveyors (availability, utilization & load-factor) is a major concern for mining operators. The downtime of overland conveyors leads to the stoppage of bulk material handling, disrupting ore extraction and material processing. Root Cause Analysis shown that failures of rotating components such as idlers are the main responsible for unplanned shutdowns. Idler rollers are relatively simple and low reasonable running cost. However, their reliability has a large impact on the performance of long overland conveyors due to their large amount in service along the system (up to 26,500 idler rollers for a 10 km conveyor). The idler roller failures are stochastic. There is uncertainty in predicting its location, severity and time of occurrence. Since bearings have a limited lifespan, and a very large amount of idlers are operating under different conditions in a harsh environment, it is possible to estimate that a significant number of idler rollers are close to the fault condition, anytime. To meet cost per ton targets and zero harm goals, while reduce unplanned downtime, operators are installing different on-line condition based monitoring systems to continuously check on the health and provide early warning on problems with idler rollers. But, the deployment of idler monitoring systems presents several challenges in mining environments that must be addressed. This paper presents a technology review of idler condition monitoring systems for critical overland conveyors based on the operational key drivers claimed by personnel to upgrade their processes to predictive maintenance using a wireless-, smart-, and self-powered condition monitoring system. This includes initial investment, O&M costs, safety standards, instrumentation wiring issues, inexistence of power supply connections, and interference in wireless communications among other key design factors for mining.**

***Index Terms*—overland conveyor, idlers, condition monitoring, technology-based-applications, mining.**

I. Introduction

Overland belt conveyors are used in various applications, including transportation of bulk materials such as ore in mining operations, from one location to another. Typically, an overland belt conveyor comprises an endless belt movable around end rollers or pulleys, and supported by intervening idler rollers. Each idler roller typically comprises a roller shell mounted on an axle by bearings accommodated in bearing housings at the ends of the roller shell (see Figure 1) [1-4]. Preventive maintenance of large-scale overland belt conveyors in mining is costly because the intensive use of labor in regular inspections of idlers for cleaning, replacement of parts, as well as the shutdown time required to correct the progressive damage suffered by conveyor components to prevent major faults. Additionally, the long distances (kilometers) covered by overland belt conveyor systems (see Figure 2) often difficult the accomplishment of scheduled inspection and maintenance. This increases equipment operational cost per ton, unplanned shutdowns and corrective maintenance (see Figure 3) [2-4].

Idler roller failure may result in wear or damage to the conveyor belt, along with significant loss of production. Bearing failure is a common cause of idler roller failure. With the aim to avoiding damage to the conveyor belt, it is desirable to conduct regular inspections of idler rollers to detect any detrimental change in their operating condition, so that they can be repaired or replaced as necessary. However, such inspections can be difficult, particularly for conveyors which are extensive in length, and operate in harsh environment conditions [2-10].

Overheating of faulted bearings of idler rollers can cause damage of the rubber conveyor belt, and potentially can ignite fire in the overland conveyor system if the fault is not detected properly. These problems can result in unplanned shutdowns to repair the conveyor belt damage and production losses. In cases of extreme damage, it may be necessary to replace entire sections of conveyor belt. Although the probability of failure with major damage of the conveyor belt is relatively low, the severity of potential incidents can be very high. The risk of disruption of material handling and mine safety issues can be significant. Since bearings of idler rollers have a limited lifespan, and a very large amount of idler rollers are in service along the overland belt conveyor system, it is possible to estimate that a significant number idler rollers always operate under fault conditions, or operate very close to the fault condition, anytime [1-10].

One common inspection routine in preventive maintenance programs of overland conveyors require that two qualified technicians walk alongside the entire length of the belt conveyor system, inspecting each idler roller for noise signatures or thermal images that indicate a failure condition of roller bearings. These preventive maintenance inspections have not proved to be altogether satisfactory for various reasons, one being that it can be difficult to reliably identify which particular roller might be generating the indicative noise of failure. Further, such inspection routines can be particularly time-consuming and often involve significant occupational safety implications. Manual inspection takes approximately 2 weeks per conveyor. It requires walking 20 km or more, and means that if idler rollers fail a few hours after a manual condition monitoring inspection, the time to detect these failures could be 168 hours or more [2,5-10].

Fig.1 Mining industry conveyor idler = frame + rollers [1].

Fig.2 View of a large-scale overland belt conveyor system in service at a large copper mine site.

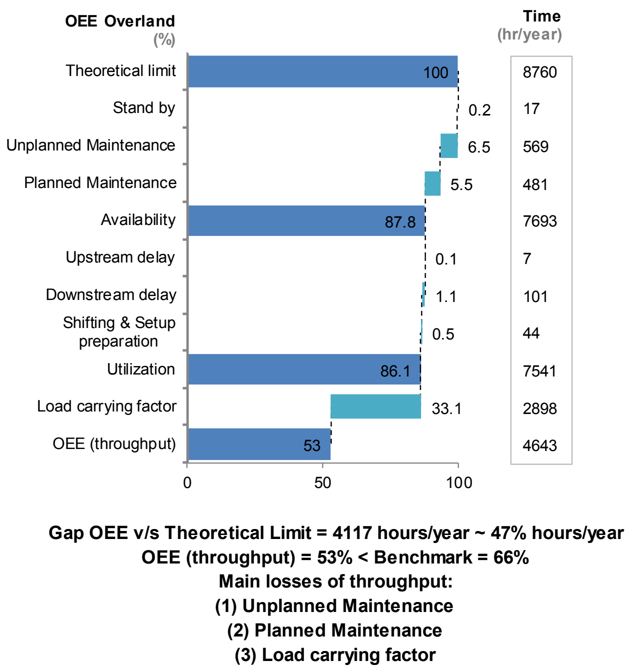

Fig.3 Overall Equipment Efficiency (OEE) of a large-scale overland belt conveyor system in copper mining.

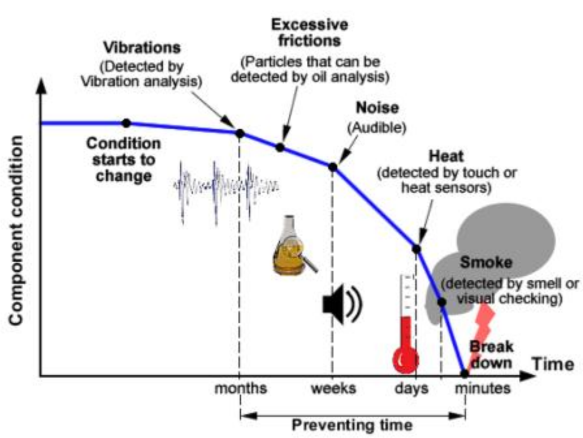

Fig.4 Evolution of failure signals in industrial equipment.

Main disadvantages of manual methods for idler condition monitoring are [2-10]: (a) time-consuming and low frequency of inspections, (b) inaccurate measurement and inconsistent inspections, (c) risk of injury during the process; (d) work in high pollution environments for long periods, (e) accessibility problems due to conveyor safety guards, (f) inspection can only be performed while belt is moving, and (g) inspection can only be carried out in day shift, as many sections of conveyor belts are without lighting.

To mitigate the risk of single points of failure in material handling, operators are installing different on-line condition based monitoring systems to continuously check on the health and provide early warning on problems with idler rollers. For this purpose, it is possible to integrate appropriate smart-sensors into the overland conveyor belt system infrastructure; scheduling condition monitoring inspections through manned or unmanned robotic systems; and use other innovative condition monitoring technologies to reduce the time involved in regular inspections and idler maintenance programs from 10 days or more to hours/minutes. With real-time information about the state of health of idlers in overland belt conveyors, maintainers involved in condition monitoring inspections could be reassigned to others maintenance tasks and the frequency of inspections could increase, improving mine operation management.

By using condition monitoring solutions, operators expected to meet cost per ton targets and zero harm goals, while reduce unplanned downtime and increase Overall Equipment Efficiency (OEE). However, the deployment of systems for on-line monitoring presents several challenges in mining environments that must be addressed. This paper presents a technology review of idler condition monitoring systems for critical overland conveyors. Proposed assessment considers the technology readiness level, initial investment, O&M costs, safety standards, instrumentation wiring issues, inexistence of power supply connections, interference in wireless communications and other operational key drivers claimed by maintenance personnel to upgrade their processes to predictive maintenance using wireless-, smart-, and self-powered condition based monitoring systems.

II. CONDITION MONITORING

The performance of overland conveyor belt systems in mining is strongly related to the operating conditions and the maintenance accomplished to the equipment during its life cycle. Factors such as harsh environment conditions, occupational safety and health standards, O&M costs and effective early failure warning define the comparative advantages of the different options for idler condition monitoring and fault location.

Condition monitoring is an important maintenance activity in mining industry that provides key information about the health status of critical equipment components. Information obtained through condition monitoring can be used to detect early failure warning signals to avoid unplanned downtimes, improving the equipment performance and the expected lifetime.

Figure 4 shows how different failure warning signals appear over time on industrial equipment. Normally, the first early fault signals appear in the form of vibrations out of range for normal operating conditions. These vibrations can be detected months before the occurrence of a fault requiring unplanned shutdown. Weeks before the occurrence of a fault appear audible noise out of range due to deterioration of rotating parts and bearings. From weeks to days before the occurrence of a fault, it is already possible to detect temperature increase of mechanical parts through temperature sensors and thermography. From this point forward, it is highly probable and imminent the occurrence of a major fault. As shown, through a proper selection of the condition monitoring system, it is possible to detect signs of potential failures months before a repair is necessary, allowing adequate planning of the maintenance. Consequently, best practices for maintenance of critical equipment encourage the implementation of idler condition monitoring systems based on non-destructive testing solutions with the following priority order: (*i*) vibration monitoring, (*ii*) noise monitoring, and (*iii*) temperature monitoring, (*iv*) visual inspection.

III. Trends in Material Handling in Mining: In-Pit Crushing and Conveying Systems

Truck/shovel systems are batch systems in which the mining system is a sequence of unit operations each having stochastic cycle times. Cycle time variance causes inherent inefficiencies at the boundaries of the unit operations. For example, shovels waiting on the arrival of trucks or trucks queueing to dump to the ROM crusher. Continuous (or semi-continuous) mining systems promise to eliminate many of these delays, improve labor productivity and reduce the energy requirements and emissions [1,11].

Currently, a number of mining companies are evaluating the use of In-Pit Crushing and Conveying systems, or IPCC systems. IPCC systems transport material by conveyor belts, inherently more energy efficient than trucks due to the large empty vehicle mass required to power truck movement. However, conveyor belts will only accept material within a fine particle size distribution. This is the function of the crushing component of the IPCC. For hard rock applications this will often be a gyratory crusher, but for soft rock it will be a lower profile sizer or roll crusher. Crusher feed is via trucks in the case of semi-mobile IPCC system, or directly via a rope shovel or hydraulic excavator, as is the case with fully mobile IPCC systems. At the discharge end of the conveyor a stacker for ore or spreader for waste is employed [11].

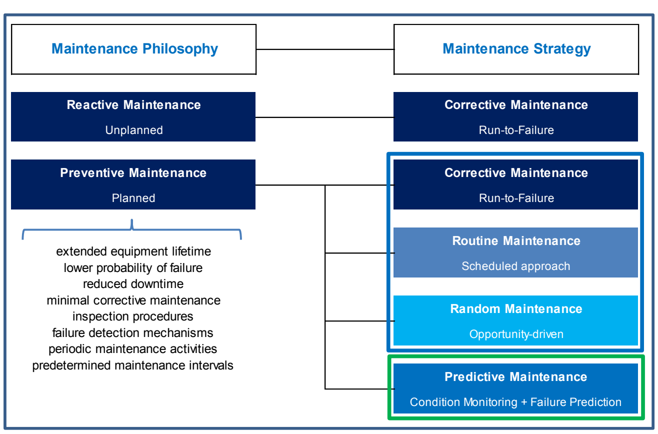

Fig.5 Summary of strategies for preventive maintenance [1-4].

To date, several IPCC systems with complex systems of conveyor belts have been installed in Australia, and other places are currently evaluating to use IPCC systems. Given that IPCC systems can potentially halve the workforce necessary to operate surface mines, there are more systems under evaluation for many operations worldwide, increasing the potential to use of overland conveyor systems in mining operations in the near future [11].

IV. Requirements for Idler Condition Monitoring

Figure 5 shows a summary of the maintenance strategies used for preventive maintenance. A complete preventive maintenance in modern mining operations includes activities of corrective maintenance (run-to-failure), routine maintenance (scheduled approach), random maintenance (opportunity-driven), and predictive maintenance based on condition monitoring and failure prediction.

Preventive maintenance measures may still result in some unplanned failures. Corrective maintenance is executed at the point where equipment failure has already occurred. Routine maintenance is related to fixed intervals, which can be time-driven (every month/year) or cycle-driven (end of life of critical components). It can be specified by the OEM. Random maintenance activities do not necessarily have to be trigged by the condition of components. It is executed when maintenance opportunity arises. Finally, in Predictive maintenance, condition monitoring, probability theory and statistics are used to predict failures. In case the conditions reach critical values according to predetermined criteria, action will be undertaken to prevent nearly failure [1-4].

Each mining operation has its own specific solution requirements for idler condition based monitoring systems. Solution requirements include: (*i*) specific system features/functionalities, (*ii*) condition monitoring capabilities, (*iii*) time and labor implementation targets, (*iv*) occupational safety and health expected goals, (*v*) system investments, and (*vi*) O&M costs constraints, among others.

The main preferred system functionalities for equipment monitoring include user-friendly interface, multi-user role-based access, multi-platform reportability, capacity of integration to the existent management system, and ability to calculate key performance indicators according to customer standards. The condition monitoring must provide real time information about the health state of the equipment, early warnings for idler roller failures (as early as possible), fault location identification (indicate the idler number as a minimum, roller position is desired), and automated system operation (no personnel intervention required for trend analysis and fault diagnosis). Sensors must comply with IP67 or NEMA 4X standards for harsh environment conditions; withstand continuous mechanical shock/vibration, operation under temperatures between -20°C and 120°C, and present capacity to operate at high-altitude (> 3,000 m.a.s.l.).

System implementation targets include reduced installation time and minimum wiring deployment for power, instrumentation and communications over infrastructure of conveyor belts. The system also must exhibit a high reliability and robustness for mining operating conditions. The technology should not require special permits for installation or operation (for example the system should not use ionizing radiation sources). The condition monitoring system should not require the implementation of a dedicated electrical power system. Self-powering capability is desired as far as possible.

The system must be able to operate in on-line and stand-alone modes to cope with possible interference in communications. Most importantly, it is desired that the system must be specifically designed for condition monitoring of overland conveyor belts using a dedicated, low-power consumption, ad-hoc wireless communication network with self-forming and self-healing capabilities. This wireless communication network must be fully compatible with other IEEE Std. 802.xx existing networks.

In terms of Occupational Safety and Health (OS&H), the condition monitoring system must be able to operate without the supervision or intervention of maintainers for the identification of conditions. The condition monitoring system should assist remote fault location, reducing the exposure time of maintainers to harsh environment conditions to perform maintenance activities.

Finally, the system must be non-invasive, low-cost in terms of investment and O&M during the project life cycle (8 years). The required solution need to be cost-effective. The condition monitoring system must not disrupt the processes during its operation or maintenance. A failure of the condition monitoring system shall not cause a failure of idler rollers or interfere with the belt. A summary of the operational key drivers claimed to implement an automated idler condition monitoring in overland belt conveyors is shown in Figure 6.

V. Evaluation of Idler Condition Monitoring Systems

A brief description of each of the six commercial systems for idler condition monitoring studied in this paper is presented in Table I. The monitoring systems covered in this paper are: (*i*) Roller Condition Monitoring system (RCM), (*ii*) Smart-Idler, (*iii*) Distributed Temperature Sensing system (DTS); (*iv*) Spidler, (*v*) Robotic Idler Predict, and (*vi*) Unmanned Aerial Vehicle Monitoring (UAV). The first three technologies are based on distributed stand-alone monitoring sensors along the overland conveyors that employ vibrations/noise/temperature measurements and wireless communication methods for condition monitoring. The last three technologies are based on robotic systems and unmanned vehicles that travel along the overland conveyors for condition monitoring [2-10].

Table II presents a comparison of monitoring and early fault detection capabilities of the idler condition monitoring systems under study. Figure 7 presents a summary of an integrated criteria-based assessment of the idler condition monitoring systems. The scores for each system are presented against to the solution profile defined by mining operators for each evaluated dimension. Figure 8 presents the weighted score of each idler condition monitoring system for critical overland conveyor belt application estimated using the integrated criteria-based assessment proposed by this work. Figure 9 presents the implementation time estimated for each idler condition monitoring system for a 10 km long overland conveyor belt in a large open-pit mining operation in Chile.

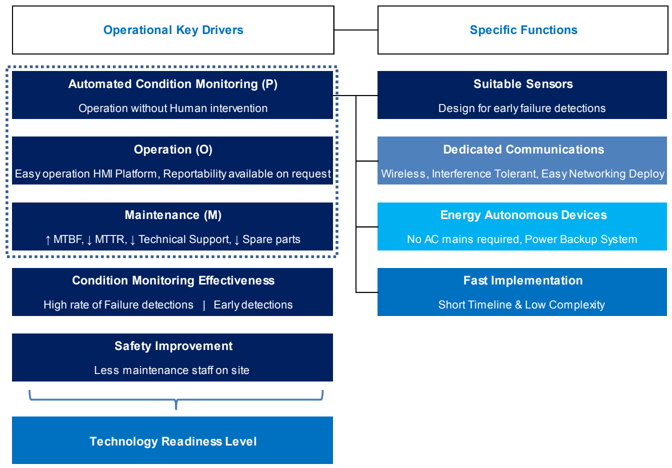

Fig.6 Summary of operational key drivers of automated idler condition monitoring systems.

Figure 10 presents a comparison of system investment and O&M costs during 8 years (project life cycle defined for evaluation) for each idler condition monitoring system in the same reference mining operation. Finally, Figure 11 shows the strong link between capital/operational expenditures and evaluation scores derived for idler condition monitoring systems in critical overland belt conveyors using the integrated criteria-based assessment methodology.

The evaluation of investment and costs for operation, maintenance and technical support of the systems considers information disclosed by different vendors, expert opinions, data from research articles, independent engineering evaluations and projections prepared for the operating conditions of a large mining company. The degree of fulfillment with the operational key drivers for automation of idler condition monitoring of the different technology solutions shown in Figure 8, considers surveys and valuations from the Engineering, Operations and Maintenance staffs of a large mining company with more than 45 km of critical overland belt conveyors between crushers and stockpiles.

The integrated criteria-based assessment of *Implementation Project*, *Operation* & *Maintenance* (P+O&M) accounts for the complexity of installation and deployment of the monitoring system along the conveyor infrastructure; labor and full-time equivalent employees required for operation, maintenance and support; training requirements; permits; the robustness of design of sensors/devices; power requirements, source and self-powering capabilities; instrumentation/power wiring; compatibility with 3G/4G/LTE and IEEE Std. 802.xx wireless communication networks; advantageous features like self-forming and self-healing, ad-hoc wireless communication networks integrated to the system; and O&M performance against to the operational key drives and specific functions defined in Figure 6.

System Effectiveness assessment is directly related to measurements of functionality and condition monitoring effectiveness required to get high rate of failure detection and early fault detection time. This evaluation includes: (*i*) condition monitoring and fault detection capabilities, (*ii*) minimum detection unit (idler frame, idler roller or bearing),

TABLE I
DESCRIPTION OF IDLER CONDITION MONITORING SYSTEMS

#	Technology	Vendor	Readiness Level	Description
(1)	Roller Condition Monitoring (RCM) [2,5] Vibrations	Intium Solutions Australia, 2012	Commercial Product Industrial test reported power source: AA Batteries	The RCM system allows conveyor operators to monitor idler roll's condition based on the exerted vibrations via a web-based dashboard. The system warns operators when rolls are exhibiting faulty behavior, and provides a priority list of alerted idler frames. A collector hub unit is first installed and connected to a general power outlet. If no power is available, a solar panel can be used to provide the necessary power. Staff needs to walk along the conveyor to mount a sensor to every frame, both carry and the return side. The sensors will form a mesh network to communicate with the collector hub. Vibrations measurements will be reported to the collector hub every two minutes. The collector hub that manages up to 500 sensors compiles all data and sends it to the vendor headquarters for reporting every hour. The system has a proprietary reportability platform [2,5].
(2)	Smart-Idler [2,6] Vibrations + Noise +Temperature	Vayeron Australia, 2015	Commercial Product Industrial test reported power source: Kinetic energy harvesting	Smart-Idler directly monitors the key characteristics of roller bearings and actively measure shell wear in order to holistically predict roller failure in advance. The Smart-Idler provides an accurate, safe and real-time view of the state of conveyor rollers from control room and instantly alerts to any problem areas. Condition monitoring variables are reported 1 to 4 times per day. Smart-Idler is completely wireless. It harvests power directly from the rotation of rollers and relays data via a mesh network. Simply requires to drop-in a roller embedded with the Smart-Idler instead of conventional rollers and add a gateway to run the system. The solution has been designed to be rugged, low-cost and easy to install. It seamlessly integrates with any roller in use. The system has a proprietary reportability platform [2,6].
(3)	Distributed Temperature Sensing (DTS) [3] Temperature	Yokogawa Japan, 2013 Micomo Chile, 2014	Commercial Product Industrial test reported power source: AC mains	Fiber optic Distributed Temperature Sensing (DTS) method uses the Raman-effect. Fiber optic-based DTS measures temperature using optical fiber instead of thermocouples or thermistors. The optical fiber is the intrinsic sensor. DTS system represents a cost-effective method for obtaining thousands of accurate, high-resolution temperature measurements. One temperature measurement per meter along the length of the optical fiber sensor cable, once per day. DTS technology offers a safe and non-intrusive measurement. It has the capability to identify the location of any temperature change accurately. Method uses a laser pulse to measure thousands of temperature samples in fiber optic sections at 1m intervals. Round trip time is used to calculate the location of temperature excursions in idler rolls along the length of the conveyor belts. The system requires the development of a reportability platform [3].
(4)	Spidler [2,7] Temperature	SandPit Innovation Australia, 2013	Commercial Product Industrial test reported power source: On board diesel genset (15kVA)	Spidler is a semi-automated robotic machine custom designed to replace faulty conveyor idler rolls. This solution is a response system rather than a detection system. With such a machine a mine would be able to respond to failures without affecting production. Sandpit Innovation believes that the machine does not need a very advanced detection tool with a long prediction horizon, because the change-out system can respond very quickly. Spidler consists of a carriage running on light gauge rails mounted to either side of an existing conveyor system. Combined with a servo-driven wheel system, these rails enable to travel along the length of the conveyor at a maximum speed of six km per hour. Due to the rail system, Spidler can gain access to a wide range of conveyor idlers, irrespective of weather conditions, rough terrain or conveyor angles up to 15 degrees. A rotary table-mounted robot with a gripper is fitted with various scanners for positional determination, four to six thermografic cameras for condition monitoring purposes (system can scan 3 load idler rollers every 2 minutes), and two hydraulic pins for idler removal if necessary. An on-board generator ensures electrical power for at least 24 hours run-time. The system requires the development of a reportability platform [2,7].
(5)	Robotic Idler Predict [2,8] Temperature	Scott Automation & Robotics Australia, 2014	Commercial Product Industrial test reported power source: On board PTO generator (30kVA)	The Robotic Idler Predict is capable of inspecting idlers on loaded, operational conveyors, providing mine sites with the ability to conduct predictive maintenance on conveyors without downtime. The system consists of a 6-axis robot manipulator mounted on a moving track. Equipped with sensors the robot manipulator is capable of automatically positioning the sensing arm at the required locations of a conveyor. Travelling alongside a conveyor mounted over a loader or dedicated truck, the system will continually monitor conveyor idler rollers to identify signs of failure. Utilizing thermal imaging data, the analysis of each idler is collected and presented directly to an on-board system for analysis (monitoring of 3 load idlers and1 return idler every 4 minutes). On detection of signs of roller failure, the system will trigger an alarm to warn operators. The system requires the development of reportability platform [2,8].
(6)	Unmanned Aerial Vehicle Monitoring (UAV) [2,9] Temperature	Multiple vendors	Solution under R&D power source: Li-ion rechargeable battery packs	UAVs represent an attractive technology for condition monitoring and fault detection on conveyor belts. UAVs can cover long overland conveyors in relatively short time, regardless of terrain characteristics (1 complete survey per day). They can maintain a static position in the air without moving, allowing the collection of process data in a non-invasive way. UAVs can be equipped with sound sensors, temperature sensors and video camera systems, giving an integrated view of the health status of idlers. Important challenges to implementing efficient monitoring solutions must be solved to meet their high energy requirements, provide flight control and navigation solutions in high pollution and wind environments, as well as to determine which process variable sensors are most appropriate to integrate into the equipment in terms of energy consumption, weight and measurement resolution to effectively identify potential failures in the conveyor belt system. This solution is under development. The system requires the development of a reportability platform [2,9].

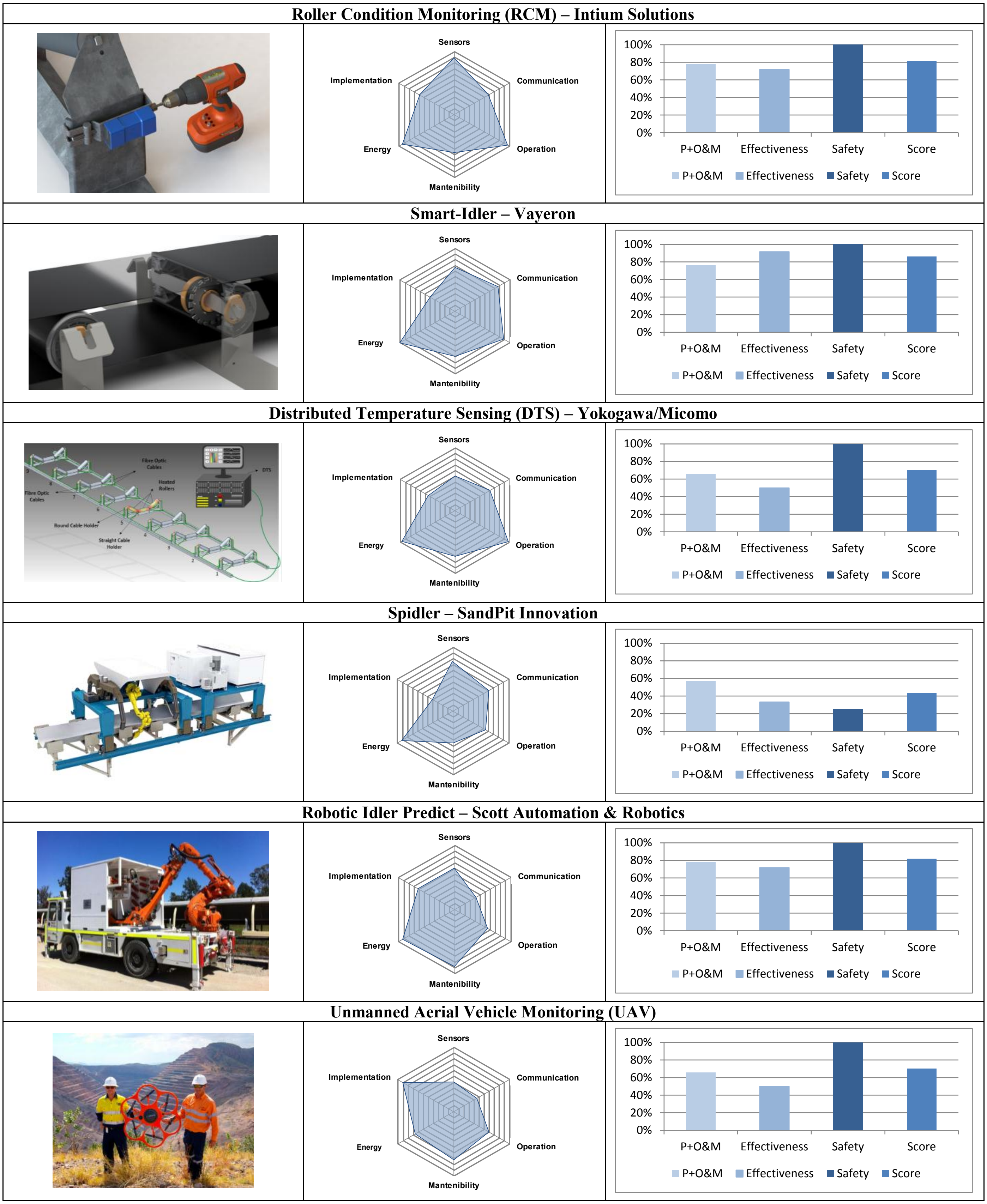

Fig.7 Integrated criteria-based assessment *Implementation Project*, *Operation & Maintenance* (P+O&M), *System Effectiveness* and *Safety Improvement* of idler condition monitoring systems for critical overland belt conveyor systems in mining. The score of each system is presented against to the solution profile defined by mining operators for each evaluated dimension.

TABLE II
COMPARISON OF MONITORING AND EARLY FAULT DETECTION CAPABILITIES OF IDLER CONDITION MONITORING SYSTEMS

System	RCM	Smart-Idler	DTS	Idler Predict	Spidler	UAV
Condition Monitoring Variable(s)	Vibrations (accelerometers) 1 device per idler frame	Vibrations (accelerometers) Noise (transducers) Temperature (thermistors) 1 device per idler roller	Temperature (fiber optic) 1 system per conveyor	Temperature (thermography) 1 robotic system per conveyor		
Condition Monitoring Capability	Idler Normal status Idler Maintenance status Idler Critical failure	Idler Normal status Idler Critical failure Idler roller temperature Idler roller vibrations FFT noise per roller	Idler roller and/or bearing temperature			
Fault Detection Capability	Idler failure | maintenance Idler failure | replacement	Predicts/detects idler failures Bearing failure Roller shell wear Missing idler roller Idler roller locked up	Idler over temperature Missing idler roller Idler roller locked up Bearing failure Roller shell wear			
Problems not detected	Missing idler roller Missing return idler roller Idler roller locked up	-	-		Return idler condition	
Minimum Detection Unit	Idler frame fault	Idler roller/bearing fault			Load idler roller fault	
Fault Detection Effectiveness	80%	100%	High (< 100%)			
Early Fault Detection Time	280 h v/s manual detection	Not reported information estimated value: >168 h v/s manual detection	Systems do not have early fault detection capability			

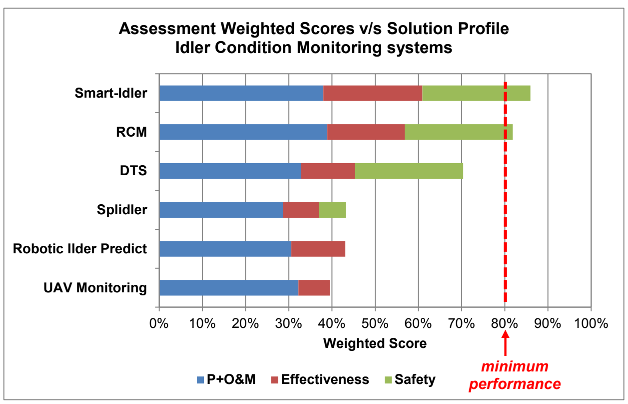

Fig.8 Weighted score estimated for idler condition monitoring systems using the integrated criteria-based assessment method.

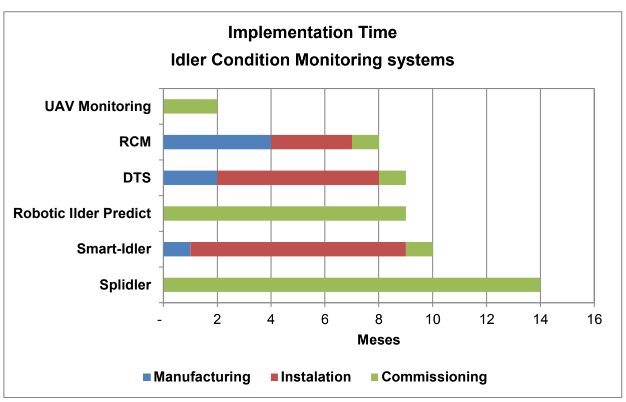

Fig.9 Implementation time estimated for each monitoring technology.

(*iii*) fault detection effectiveness, and (*iv*) early fault detection time (hours or weeks). *Safety Improvement* assessment represents a comparative measurement of health and safety risk inventory projected during the implementation for each system, in addition to the safety risk reductions due to the automated operation of the monitoring system without human intervention in the field; and less maintenance staff exposed to the harsh environment conditions of mining sites for failure location, surveying and perform maintenance tasks.

VI. DISCUSSION

The technologies for idler condition monitoring in critical overland conveyor applications can be classified into (*i*) systems using distributed stand-alone sensors and (*ii*) systems using mobile robotic systems. The condition monitoring systems using stand-alone distributed sensors exhibit high effectiveness in early fault detection (>72%). See Figure 7. Also, these monitoring systems present high accomplishment of solution profile demanded by the application in terms of implementation, O&M, effectiveness and safety (>82%). See Figure 8. Only the idler condition monitoring systems based on distributed vibration sensors enable early fault detection according to the information of industrial tests reported by vendors and mine operators. These systems allow idler condition monitoring along a complete overland belt conveyor in real time (every 2 minutes), providing early fault detection (up to 280 hours earlier than manual method) and location of faulted idlers. See Figure 7 and Table II.

In contrast, the idler condition monitoring systems based on mobile robotic systems and UAVs show low monitoring effectiveness (<50%) and limited accomplishment of solution profile (<70%). These monitoring systems mainly conduct temperature inspections of idler rollers and bearings while moving from one idler to another along the conveyor. Mobile robotic systems have been designed as fault-response technologies to support idler roller replacement while the belt running, rather than inspection and condition monitoring systems. Thus, they do not allow premature fault detection.

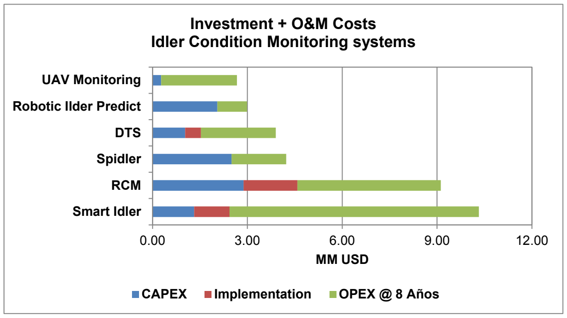

Fig.10 Comparison of investment and O&M costs estimated for the idler condition monitoring systems studied (8-year life cycle project).

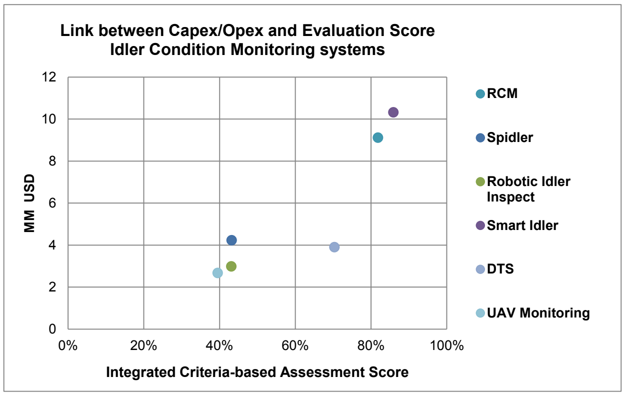

Fig.11 Link between capital/operational expenditures and evaluation scores derived for idler condition monitoring systems using the integrated criteria-based assessment methodology.

UAV is an attractive technology for condition monitoring and fault detection on conveyor belts. UAVs can cover long overland conveyors in relatively short time, regardless of terrain characteristics. However, important challenges to implementing efficient monitoring solutions need to be faced: (*i*) high energy requirements, (*ii*) weight constraints, (*iii*) measurement resolution issues to effectively identify idler failures on flight, (*iv*) training of personnel for flight control in high pollution environments, and (*v*) wireless communications in remote locations, among others. Unfortunately, even if all these challenges are solved, the solution still demands a trained drone pilot exposed to harsh environment. See Figure 8.

When implementation time is evaluated (see Figure 9), the idler condition monitoring systems based on mobile robotic systems present the most extensive implementation times. This is a consequence of the time and interventions required in system engineering, implementing rails mounted to either side of an existing conveyor system, integrating device carriers, solution assembly, commissioning and site acceptance testing (SAT) according to mine site operating conditions, among others. In contrast, idler condition monitoring systems using distributed stand-alone sensors, fiber optic distributed temperature sensor devices or UVAs allow time savings in implementation up to 35% against their counterparts. Smart-Idler represents a special case of technology solution that requires replacing all idler rollers of the overland conveyor for installation (up to 26,500 idler rollers for a 10 km conveyor).

Moreover, the study shows that exists a strong link between accomplishment of solution profile and capex/opex when evaluate automated idler condition monitoring technologies for critical overland conveyor belt systems. As a rule of thumb, distributed sensor-based systems require higher initial investment and present higher operating costs over the project life cycle. However, these monitoring systems exhibit higher monitoring effectiveness, reducing potential unplanned shutdowns while increasing OEE. See Figures 8, 10 and 11.

VII. Conclusion

The technologies commercially available for the automation of idler condition monitoring in overland belt conveyors are still under development to improve the technology readiness level demanded by the application. When considering the requirements of functionality; condition monitoring effectiveness; on-site implementation project tasks; occupational safety and health improvements; lowest initial investment and reduced O&M costs over the life cycle of brownfield project; just a few existing solutions accomplished the minimum performance expected by mine operators.

Currently, only idler condition monitoring systems based on distributed vibration sensors are able to provide higher effectiveness in early fault detection and higher accomplishment of the solution profile according to the integrated criteria-based assessment methodology proposed in terms of implementation, effectiveness, and safety (>80% assessment weighted score). The study shown that exists a strong link between accomplishment of solution profile and capital/operational expenditures.

When considering O&M, self-powering (no AC mains, on board genset and/or battery-powered solutions that require replacement over short-periods) and wireless communication integrated interface for remote analysis and maintenance planning, arise like key features to ensure the effectiveness of automated idler condition monitoring systems in the long-term.

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