Why Should Inspection Robots be used in Deep Underground Mines?

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1 Introduction

Mining has very long history, in some sense (mechanical processing of minerals) could be dated even in around thousands B.C. Acquiring raw materials has been usually risky and dangerous. Unfortunately, due to a rapid development of modern technologies, as well as globalization, easy-to-mine resources have been already exploited. Socio-environmental awareness also should be considered as serious problem for the mining industry that is frequently presented as "dirty" one. However, space, automotive, IT, etc., technologies require specific raw materials (for example, rare earth). So, deep underground mines impose new challenges for mining industry when searching for new hardly accessible deposits. These challenges are related to

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locations of deposits, their geometry (thin layers), and harsh environment (dust, temperature, and humidity) including natural hazards (gas emission, water, and seismic events). Even nowadays, miners are allowed to work during shorter (6 h only) shifts. It is expected that this period will be shortened in incoming years. More demanding conditions in the mine focus activities of companies and research institutions toward introducing robots to the mines. There are many successful examples of autonomous machines operated in the mine, robotized processes, and some support from UAVs in open-cast mines. Unfortunately, applications of robotics in an underground mine are still limited [3, 6, 9]. In this paper, we will introduce recently launched project THING, supported by H2020 EU programme that is devoted to the usage of the autonomous four-legged robot ANYmal for inspection of infrastructure in deep copper ore mine. To be more precise, we will discuss how to support daily maintenance procedures for belt conveyors.

In the paper, we will discuss in general development of robotics in mining, analyze inspection robots used in mining industry, and related areas that could be at least in theory easily adapted to the mining industry, and finally briefly present ANYmal, highlight main research tasks from a robotic perspective, and discuss possible inspection missions for belt conveyor maintenance.

1.1 Robotics in Mining—A Review

Robotics has been recognized as future for mining decades ago [1, 2, 4, 22]. Similarly, to other branches of industry a serious resistance from employee unions has been noticed. However, due to mentioned safety demands, more and more harsh conditions and increasing production and effectiveness of mining companies' automation, recent robotics applications are growing in the mining industry.

Robotic solutions could be divided into several groups as follows:

- Inspection robots (tunnels, infrastructure, pipe systems, and slopes) [6, 9, 10, 12, 14, 15, 20, 21, 31],
- Rescue robots (roof collapse accidents) [7, 8, 18, 29],
- Robotics for main technological processes (drilling, autonomous transport, defragmentation of oversized lumps, etc.) [4, 5, 26, 27],
- Robotics for auxiliary technological processes (mapping, exploration) [11, 16, 17, 19, 24, 30], and
- Others [6, 9].

1.2 Robots for Inspection: Mining and Close-to-Mining Applications

Mines are usually located on a large area. In case of underground mine (considered mostly in this paper), our object should be visualized as a complex system with varying in time geometry and environment. According to mining regulations, there is a need to monitor processes, a condition of mining cavities (chambers, tunnels, etc.), geotechnical, electric, and mechanical infrastructure. Unfortunately, this classification is very simplified. Miners should take care of everything during their work underground. Due to a scale of the problem and dynamic development of mine, most of the inspection tasks are performed by miners. For critical stationary elements, there are specialized monitoring systems. Unfortunately, due to cost and technical constraints, it is probably impossible to cover by monitoring systems the whole mine area (3000 km of underground roads). An idea of supporting miners using robots seems to be very promising. In this paper, we propose an inspection robotic system for maintenance of belt conveyors. The advanced legged robotic system developed by ETH will be the basis in the project.

2 Maintenance of Belt Conveyors

Belt conveyor (BC) is an element of a transportation system in the mine. BC is used for transport of copper ore from dumping points to shafts responsible for vertical transport. From mining faces to mentioned dumping points, ore is provided by mobile LHD machines (loaders or trucks).

There is a variety of conveyor design in sense of length (short could have dozens of meters while long might have more than several kilometers), power, and configuration of driving system (one up to four engines for driving station, drives could be installed in different locations to “distribute” stress in belts), structure of belt support, etc. (Fig. 1). In any case, there is a need to monitor and/or inspect the condition of conveyor components and its proper operation [25]. For some components of conveyor, online monitoring (measurement system) is available (current consumption for each electric motor, the temperature of bearings in motor, gearbox, and pulley, etc.) [23]. However, due to spatial nature of conveyor network structure, number of components, number of external factors that could influence process and machine, and finally specific philosophy is applied in machine maintenance in which a human-assisted inspection plays a crucial role. According to general and internal regulations, each conveyor should be inspected every day; sometimes it should be done several times [23, 28].

Introduction of inspection robots can be beneficial on several levels of abstraction. Firstly, elimination of human error can allow to significantly reduce the number of accidents occurring during the inspection. Since robot will not do anything beyond what it is told to do, it is expected to eliminate all situations induced by irresponsible human behavior. Secondly, assessment of environmental conditions (concentration

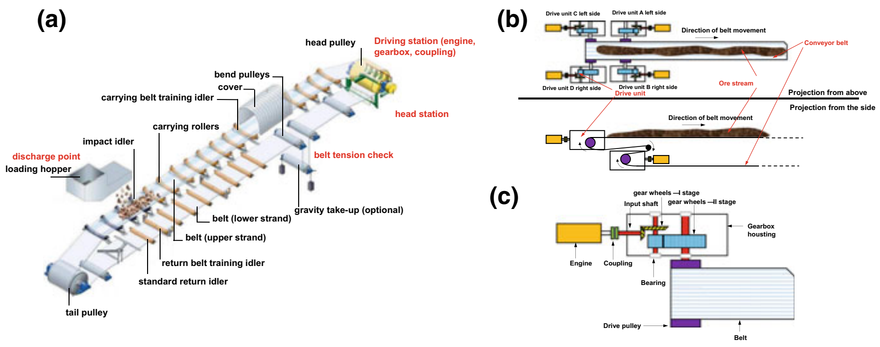

Fig. 1 **a** General structure of belt conveyor, **b** head station with drive units, **c** key elements of a single drive unit

of dangerous gases, air temperature pressure, etc.) can prevent introducing workers to mine areas harmful from the environmental point of view. Thirdly, some inspection tasks (e.g., thermography of the conveyor infrastructure) can improve safety by providing alarming information in a reliable way, which can reduce the impact of hypothetical fire by creating a possibility of sending firefighting crew soon enough. Besides that a worker responsible for such inspection can instead be occupied with other tasks, so the overall effectiveness of this worker would be increased, or at least better focused.

3 ANYmal for Belt Conveyor Inspections

A consortium of University of Edinburgh, ETH Zurich, University of Pisa, University of Oxford, University of Poznan, KGHM Cuprum R&D Center, and two spin-off companies QBROBOTICS SRL and ANYbotics AG has been successfully applied for H2020 research project focused on "THING subTerranean Haptic INvestiGator." It was agreed that basis for the project will be the legged robotic system ANYmal developed by ETH Zurich and ANYbotics AG. Our ambitions are related to support maintenance staff using ANYmal for inspection of belt conveyor system. There are also several key research challenges related to the purely robotic field (perception, control, path planning, adaptive feet, etc.); however, they will be discussed in appropriate journals devoted to robotics. In this paper, we want to discuss an application part of the project, focused on the definition of needs, mission planning, and inspection data processing (online for quick evaluation of situation and critical events detection and offline for long-term analysis out of robotic platform) [12].

Fig. 2 ANYmal legged robot used in the project (ANYbotics) [12]

3.1 ANYmal—Advanced Legged Robotic System

ANYmal is a quadrupedal robot designed for autonomous operation in challenging environments (Fig. 2). Driven by special compliant and precisely torque controllable actuators, the system is capable of dynamic running and high-mobile climbing. Thanks to incorporated laser sensors and cameras, the robot can perceive its environment to continuously create maps and accurately localize. Based on this information, it can autonomously plan its navigation path and carefully select footholds while walking. Driven by its first real-world application, namely, industrial inspection of oil and gas sites, ANYmal carries batteries for more than 2 h autonomy and different sensory equipment such as optical and thermal cameras, microphones, gas-detection sensors, and active lighting. With this payload, the machine weighs less than 35 kg, and hence can be easily transported and deployed by a single operator [12].

3.2 Belt Conveyor Drive Unit Maintenance Problem

Vibration-based gearbox diagnostics is a well-established technique for gearbox condition assessment. In considered mine, it bases on vibration and input shaft rotational speed measurements using portable "Diag Manager" system developed by Wroclaw University of Technology [28]. The preliminary result could be received after 60 s of measurement, for long-term maintenance management purposes measurement and diagnostic features are stored in the GIS-based database system and they are used for reporting. DAQ system is a four-channel measurement system developed using LabVIEW and National Instrument DAQ components. To measure acceleration, three sensors are mounted on gearbox housing using magnets (Fig. 3). Speed measurement is used to evaluate load condition of the conveyor drive. Diag Manager system

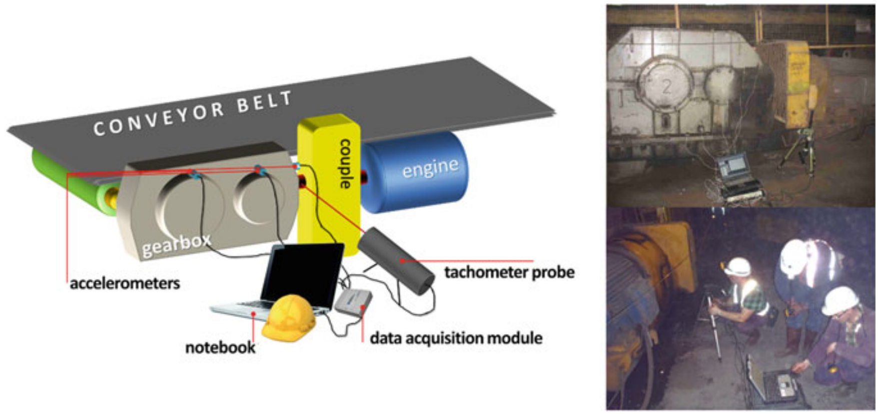

Fig. 3 Maintenance inspection for conveyor gearbox—vibration measurement using Diag Manager system

detects local damages as well as using simple energy-based spectral features it could evaluate operational wear of gearbox. Due to reach history (already it operates several years) and a number of objects covered by the system, we were able to specify warning and alarm thresholds (validated by visual inspection of gear inside).

3.3 Diagnostic Missions

To provide holistic view regarding conveyor condition and operation there are several internal requests announced by higher management responsible for transport. Although they are formalized; however, for robotic inspection they could be redefined. Figure 4 presents graphically what should be done by maintenance staff. Among others, it might cover the following:

1. Vibro-diagnostics of conveyor gearbox.
2. Infrared thermography of conveyor gearbox.
3. General inspection for belt conveyor—image analysis.
4. General inspection for fire protection system for belt conveyor—image/noise analysis.
5. General inspection for belt conveyor—smoke detection.
6. General inspection for belt conveyor—infrared thermography.
7. General inspection for mining corridor—image analysis.
8. General inspection for mining corridor—atmospheric quality assessment.

"Algorithmization" of inspection tasks might be challenging as well. In general, the person responsible for inspection of conveyor should make a decision whether a machine could continue operation, and such decision is based on experience and

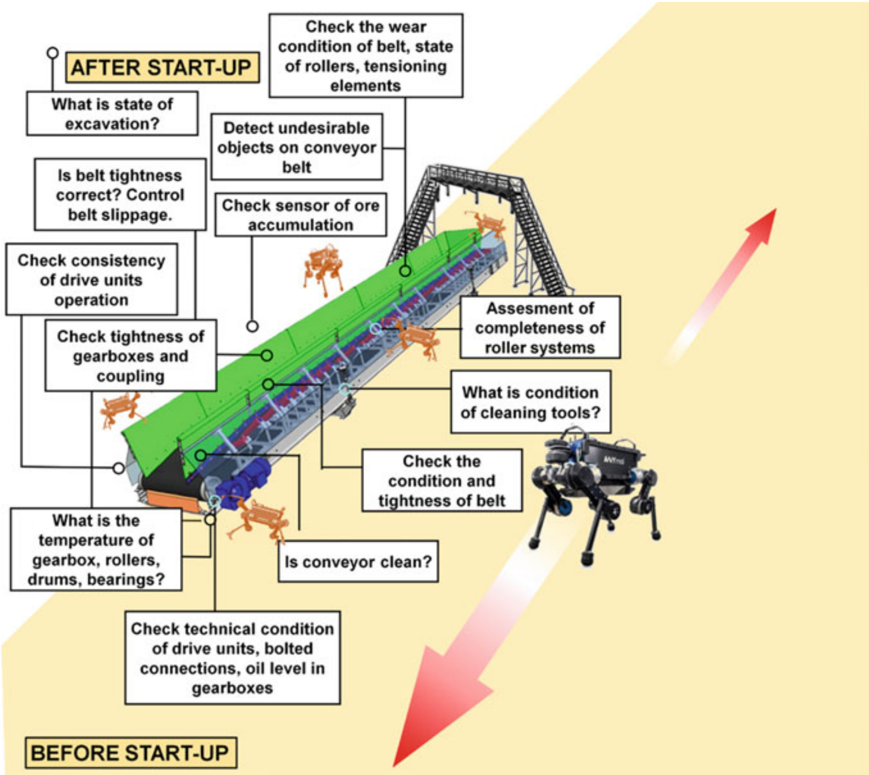

Fig. 4 Inspection missions with ANYmal robot for belt conveyor

deep understanding of the physical object. Using pattern recognition language, they search for the anomaly. However, "normal" case would be very difficult to define formally.

3.4 Diagnostic Mission Example: Haptic Vibration-Based Diagnostics of Gearbox

An idea of this exemplary mission is simply based on repeating the same procedure as defined in the section above. The robot should arrive to drive station, identify the object to diagnose, identify the appropriate place on the gearbox housing, and "touch" it to acquire vibration. In fact, this is what intuitively miners are doing on regular basis—they "touch" housing to "feel" vibration level, temperature, etc. After measurement, robot should perform preliminary analysis (simply check amplitudes of vibration) and store data for offline advanced processing (as Diag Manager system

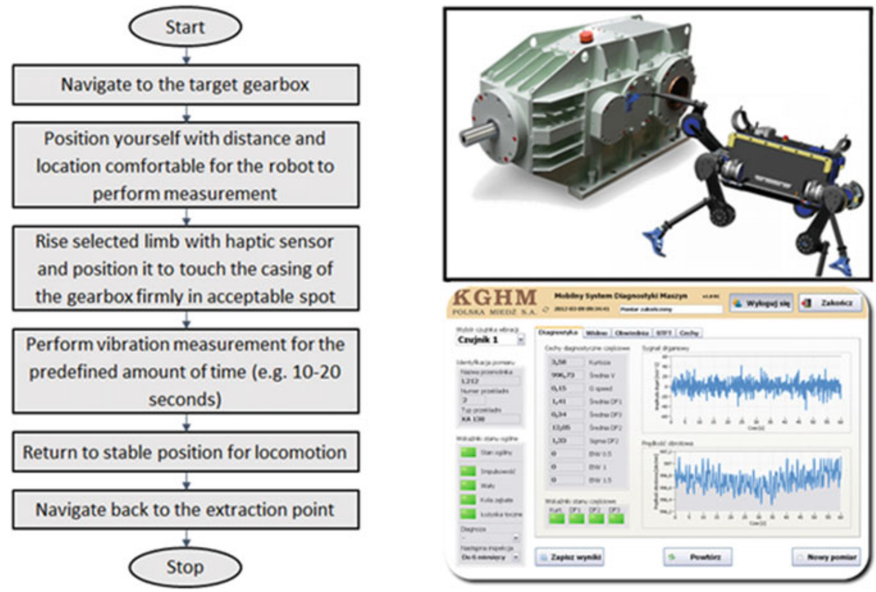

Fig. 5 The general algorithm for gearbox inspection missions with ANYmal robot

is doing). Figure 5 presents general algorithm for this mission, rough visualization of measurement, and example of the user interface from Diag Manager—the data processing part could be the same for robot-based mission.

3.5 Challenges for Inspection Robot

Although ANYmal robot is a great example of a very advanced robotic system developed for oil and gas industry [12], there are still many challenges when considering its use for belt conveyor inspection. (Note that THING is ICT, robotic-oriented research project; however, we minimize these aspects in this paper as they will be considered in other publications.)

Several keys already identified issues that need to be solved during the project from diagnostic/maintenance perspective which are as follows (Fig. 6):

– Harsh conditions in the mine: There is a lot of dust and low visibility.
– Floor surface in the mine: Water, rock lumps, etc.
– Harsh environment: Dust, humidity, uneven ground surface, and standing water.
– Navigation accessibility: Tight spaces.
– Hardware design and placement: Gearbox type, location, and accessibility.
– Contact accessibility: Safety structures, hardware casings, and rotary elements casings.

Fig. 6 Graphical examples of harsh environment and other constraints

– Tachometric sensor—rotational speed measurement—may not be possible using a robot, speed should be recovered from the vibration signal.
– The access to some parts of the machine is difficult or impossible.
– Correct sensor placement is crucial.

4 Conclusions

This paper discusses several important issues under the umbrella of the question asked in the title: what could be done by inspection robot, how to transform our wishes into algorithms and robotic system, what to measure and how to exploit data acquired by the inspection robot, and finally how robot applications would modify safety, efficiency, etc. of mining processes in deep underground mine. This discussion is introductory material, the project "THING: subTerranean Haptic INvestiGator" technically started in January 2018. Our ambitions are to have an inspection robot to support maintenance of belt conveyor system in deep (>1200 m) mine. Nowadays, such inspections are done by maintenance staff, unfortunately, according to Central Mining Authority [13] reports, accidents happen every year during operation of conveyors. We have presented an idea of an adaptation of ANYmal platform developed by ETH Zurich and ANYbotics AG to form an inspection robot for belt conveyor inspection and maintenance. We have defined examples of inspection/diagnostic missions and some constraints and critical issues have been identified. Illustrations of harsh environment in considered mine have been presented too.

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