Road-quality classification and motion tracking with inertial sensors in the deep underground mine

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Abstract. For many years now the mining industry has seen boost in exploring and developing the systems for monitoring operational parameters of mining machines, in particular of load-haul-dumping machines. Therefore, further researches on algorithmics have also advanced dynamically regarding effective performance management as well as predictive maintenance. Nonetheless, the issue of road conditions is still being neglected. That issue has substantial impact on both the overall operator's convenience, their performance and machinery reliability, especially its construction node and tyres damages. Moreover, such negligence pertains also to the maintenance of mine infrastructure, including the network of passages. The paper explains the use of the portable inertial measurement unit (IMU) in evaluating road conditions in the deep underground mine. The detailed descriptions of the road quality classification procedure and bump detection have been included. The paper outlines the basic method of tracking motion trajectory of vehicles and suggests the method of visualisation the results of the road conditions evaluation. This paper covers the sample results collected by the measurements unit in the deep underground mine.

Keywords: Inertial Sensors, Road-Quality Classification, Bump Detection, Motion Tracking, Load-Haul-Dumping Machines.

1 Introduction

In copper ore mines, where mining is performed in room and pillar method, passages constitute the main transportation infrastructure for both crew and autonomous mining machines operating in mining areas. The quality of passages is subject to the number of machines exploited in a mining department and harsh environmental and exploitation conditions. Damaged, bumpy passages often cause increased dynamic overloads of machines, resulting in hindering the parts' durability and their damaging. Construction node damages in the machine prove to be the severe problem. Neglecting the issue of deteriorating road conditions may completely thwart the possibility to rebuild a passage. The awareness of the transportation surface conditions facilitates pre-planning of the optimal haulage routes for self-propelled machines, repairing activities and increasing pro-active motivation of road maintenance staff. It has been proved that using monitoring system to reward operators for their high-quality work contributes to considerable reduction of maintenance issues and improves the key performance indicators. Hence, ongoing tracking of road surface parameters (bumps and other abnormalities) may avail convenience and secure working conditions of the crew and of the machines' reliability. Road quality analysis shows dynamic overloads impacting the working machine, what may constitute the valuable information for the constructors to redesign respective machine units and adjust them to unique exploitation conditions. Currently, measuring departments of mines use common cartographic and laser scanning methods.

There have been new road-quality tracking methods acknowledged in luxurious passenger cars. Besides, the more common smartphones, the more popular the method of surface condition detection with the use of integrated inertial sensors. Suggested procedures are perfect solutions for collecting data, their validation, statistical evaluation and road condition classification [6,10,15,23].

The literature elaborates on automated road condition classification methods, such as machine learning, heuristic approach, Euclidean distance, processing videos and photos or laser scanning [1,8,21].

Apart from evaluating road conditions, inertial measurements can be successfully applied to estimate road grade with measurements collected by the machine during driving that road. The issue of estimating road grade has been already widely discussed in the literature. Most of publications concern four-wheel vehicles: [3,11] especially heavy duty vehicles varying in weight [7,17,18].

Next practical use of IMU is mapping the motion trajectory of a vehicle. This subject has been constantly advancing in robotics, sports, rehabilitation and film industry [2, 5,14, 16, 22].

The paper outlines the basic method of obtaining the road surface analysis by the read-out of Z-axis accelerations on accelerometer. Prior to the presentation of results, the motion trajectory of self-propelled machine had been specified outlining the parameters of velocity and angle velocity in Z axis. The route had been further covered with road surfaces of different, 3-scale quality levels. The variations in operating the machine with empty and filled cargo box had to be taken into consideration.

2 Construction of the machine and anticipated results of the project

2.1 Investigated machine - haul truck

Haul truck is used to haul material, including hauling from mining faces to department preloading points secured with grids. There are a few types of haul trucks operating in mines. They vary mainly in the capacity of cargo boxes. Haul trucks are designed and constructed to operate under harsh mining conditions. Both maintaining the proper stability of the machine and choosing the matching parameters of the drive unit contribute to satisfactory haulage performance of the machine even in passages with longitudinal grades up to 8°. In case of transversal grades, the upper grade limit equals 5°. The best manoeuvrability of the truck depends on a joint of two basic units of the machine: a drive unit (tractor) and a transportation unit (trailer/cargo box). There are two degrees of freedom in the joint of the haul truck. Two hydraulic actuators assembled between the above-mentioned units control the turning mechanism. This mechanism eases passing over perpendicular drifts (90° angle). Cargo box - trailer is the part of the machine operation unit. Operator uses the hydraulic unit to control the trailer operation unit. The cargo box is designed so that it allows free load and dump of material. The most common type of haul trucks are trucks with fixed cargo box and lid. Material is dumped through the sliding hydraulic partitions.

Fig. 1. Investigated machine - haul truck.

2.2 Characteristics of load-haul procedure

As already mentioned, haul trucks are designed to haul material from mining faces to department preloading points in which there are grids and hydraulic hammers to break oversized rocks. Single haulage cycle encompasses four basic procedures: (a) loading of the cargo box of the machine at the mining face, (b) hauling material to the dumping point, (c) dumping material, (d) returning to the loading zone at the mining face.

While loading, ore is directly preloaded from the bucket to the cargo box of the haul truck. Cargo box capacity is decisive for the selection of optimal loader type. It has been assumed that fully loaded cargo box of the machine requires 3 full haulage cycles. The haulage route of the haul truck does not exceed 1500 m. The speed of the truck passing through the sectioned passages should not exceed 12 km/h. Haulage process is usually short and lasts less than a minute.

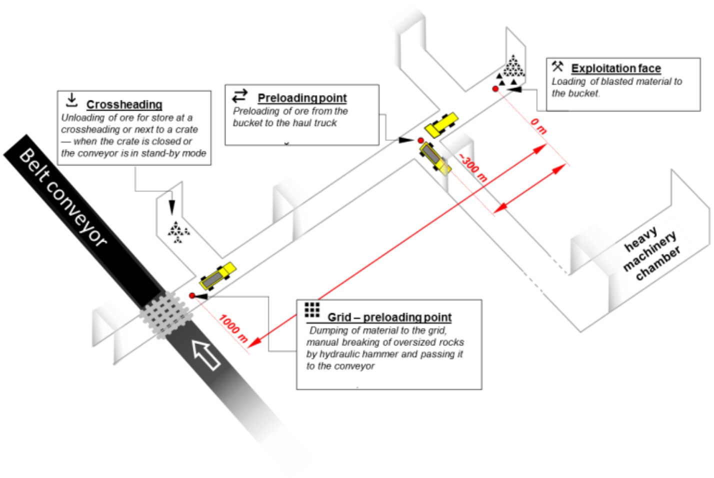

Fig. 2. Operation of LHD machines in mining area.

2.3 Identifying operation cycles - key variables

Typically, haul trucks perform basic operations - they drive from point A to point B, where their boxes are respectively loaded and dumped. In order to identify their operation cycles and individual procedures: loading, hauling, dumping and returning, the data were collected from the on-board monitoring system mounted on the machine. The key data crucial for identifying procedural components of the haulage operation regimes are:

- Torque of engine (ENGRPM),
- Speed (SPEED),
- Instantaneous fuel consumption (FUELUS),
- Current gear and movement direction (SELGEAR), (Fig. 3).

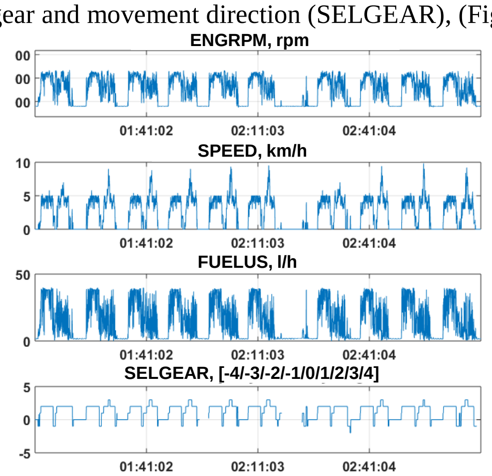

Fig. 3. Key data crucial for identifying procedural components of the haulage operation regimes.

The detailed description of the system has been included in [24]. Sampling frequency of signals equals 1Hz. Recorded signal features cyclical variations, namely variables act alike in the consecutive cycles. The variability of signals is highly dependable on the haulage route, road conditions, number of machines in the mining department and operator’s driving style.

2.4 Inertial sensors

The project used the portable Inertial Measurement Unit described in [4]. The measurement unit is equipped with 3-axis accelerometer, gyroscope and magnetometer - the device for measuring magnetic field strength. Thus, 9 axes of freedom can be measured, and the location can be specified with the known starting point. Besides, the unit measures barometric pressure, temperature and humidity. The source data used in this project are:

- Z-axis gyroscope (range: ±2000°/s; resolution (min Δ):0.06°/s; sampling frequency: 50 Hz)
- Vibration acceleration sensor on Z axis (range: ±16 g; resolution (min Δ):490 μ; sampling frequency: 50 Hz)

Suggested mounting location of IMU is depicted in Fig. 4a. Fig 4b illustrates the 3-dimensonal orientation of IMU sensors.

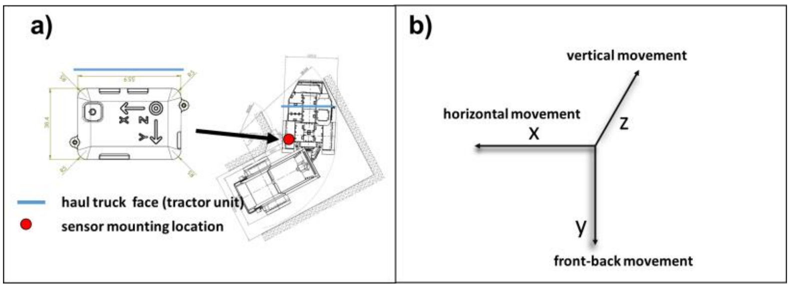

Fig. 4. a) sensor mounting location, b) 3-dimensonal orientation of IMU sensors.

2.5 Underground experiment and measurement data

The experiment was conducted during the regular haulage operation in G-63 mining unit in one of the copper ore mines. During one shift, the machine operated along two routes.

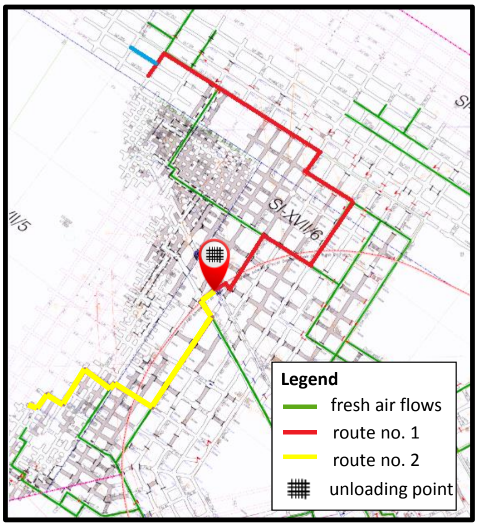

Fig. 5. Map of mining passages with highlighted routes of the haul truck during the experiment.

Fig. 6. a) loading of the haul truck with the use of the wheel loader, b) a part of the road surface - dip covered with mud, c) driving with empty cargo box.

3 Methodology

3.1 Synchronizing inertial data and data from on-board monitoring system

The analysed data have been obtained from two sources: the on-board monitoring system and the inertial measurement unit. The first steps are data validation, outliers' removal and completing missing data. Next, the data from different sources need to be rescaled. The IMU data are densely sampled whereas the data from the on-board monitoring system are sampled with 1-Hz frequency. Therefore, the data interpolation is necessary to calibrate the data to 50-Hz frequency.

3.2 Defining work cycles with signal segmentation

In order to define the work cycles of the machine, the patterns of operational data in specific operation regimes are to be acknowledged. The next step is to segment signals based on the recommended statistical parameters and condition classification principles. Algorithm with blind source separation approach described in [20] has been recommended herein. The issue of signal segmentation is omitted in this paper. For further information, please refer to [9, 12,13].

3.3 Road-quality classification

The key variable considered in classifying the road condition was the signal from Z-axis accelerometer. First, 1-value was deducted from the data obtained from accelerometer to level out the speed of gravity. Afterwards, the data were overlapped with modulus. Python library, including cut function from pandas module, was used to section the road condition. Thus, the signal was segmented into 3 different sections matching the following road quality classes: good, fair and poor. Analyses are suggested to be performed individually for filled and empty cargo boxes. To correctly identify dynamic overloads, it is recommended to analyse the data of empty cargo box rides. The data may be supplemented with the statistical description of each cycle.

3.4 Calculating the motion trajectory

The method suggested herein has been developed with the use of the common inertial navigation system and AHRS (Attitude and Heading Reference System). Using trapezoidal rules for approximating integrals from Z-axis gyroscope, it has been possible to calculate the tilt angle of the machine. The x, y positions of the machine in time are determined by its speed and movement direction. Therefore, the route may be depicted as a graph, and thereafter - as 3-dimensional visualisation of the route driven and of the surface quality in various configurations (such as animation).

<u>Procedure description:</u>
STEP 1: Cycle segmentation,
STEP 2: Using trapezoidal rules for approximating integrals from Z-axis gyroscope, individually from each cycle to calculate the tilt angle of the machine,
STEP 3: Change of mathematical symbol of SPEED variable (driving speed), when SELGEAR (current gear and driving direction) is negative,
STEP 4: Defining x, y in t time by trapezoidal rules for approximating integrals of SPEED and the given angle, Fig. 7.

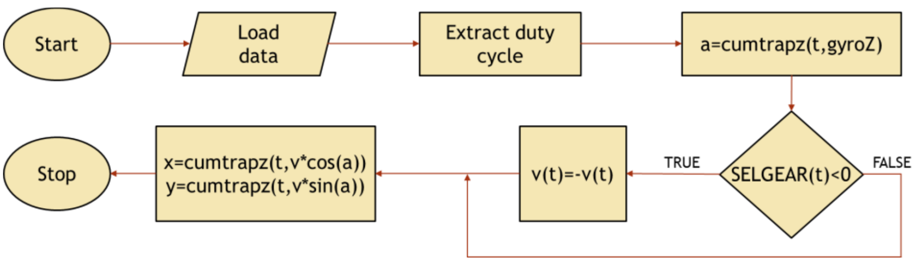

Fig. 7. Block schema of the algorithm for calculating the motion trajectory.

Trajectories calculated for individual haulage cycles have indicated the same route shape but some angular shifts (Fig. 8a). Such shifts resulted from gyroscope drift and signal noise, while the signal integration procedure has resulted in summing up the mistakes. The authors had endeavoured to improve the results merging the data with Kalman filter [19] and quaternion. That method failed due to a steel cover of the sensor used in the underground experiment - magnetometer was not able to properly read the data. Hence, future developments of alternative algorithmics in that issue are presumed. The developed algorithm allows also to depict animated route (Fig. 8b).

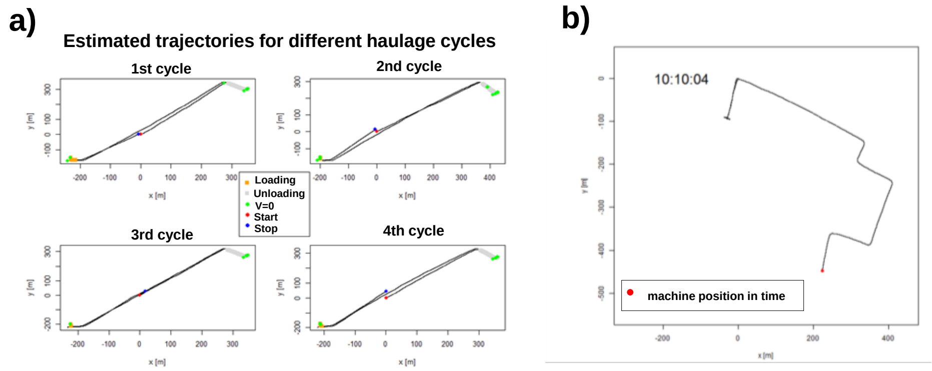

Fig. 8. A) Estimated trajectories for a few haulage cycles, b) Exemplary animation.

3.5 Filled and empty cargo box drives

Trajectories of driving with filled and empty cargo box should be presented concerning the quality of the road specified in line with the methodology described in 3.3 of this paper (Road-quality classification). The proper colour coding of the route with the use of 3 colours facilitates 3-dimensional presentation of the road and indicates the damaged spots which need repairing.

4 Results

The experiment lasted one working shift. Six hours of operational parameters from on-board monitoring system of the haul truck and mobile IMU sensor were registered. Additionally, the whole procedure was recorded with a camera. The data were then merged analytically and validated, including time synchronization in line with the method outlined in 3.1. Next, the signal segmentation with algorithm was performed [20] and the main procedure of evaluating the road condition and calculating the 2-dimensional route commenced. The analysis considered the following variables: SPEED, SELGEAR, ACC Z, GYRO Z. A sample section of signals from two haulage cycles is shown in Fig 9.

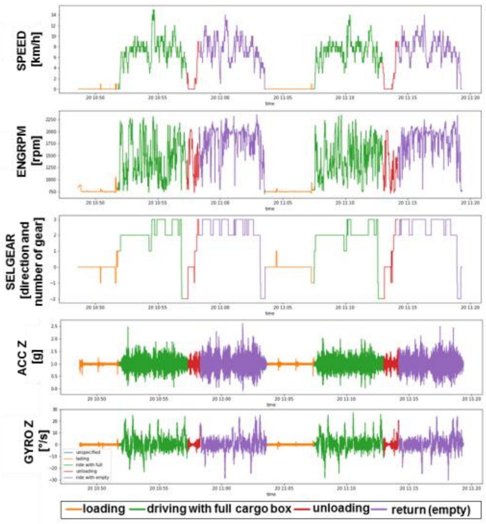

Fig. 9. Key timelines analysed after segmentation: driving speed (SPEED), current gear and movement direction (SELGEAR), Z-axis accelerometer (ACC Z), Z-axis gyroscope (GYRO Z). Operational regime is colour coded. Changeable torque (ENGRPM) is added to facilitate the interpretation of the data.

All variables have demonstrated patterns characteristic for individual operation regimes. Indeed, while driving with empty cargo box the increase of signal power from Z-axis accelerometer has been observed. The signal is unstable and depends on many factors (for example self-vibration of the machine, road condition and grade, driving speed, motor capacity, tyres traction, load carried by the machine, noise or human factors). It is advised to check the accelerometer read-outs while idling the machine (ENGRPM ≈750 rpm) for reference value. Another good practice is to note ACCZ and GYROZ variables for the consecutive 3 dumps of material from the bucket of the wheel machine at the loading points.

In the next step, in order to apply the road surface classification: good, fair or poor, we analysed the data from Z-axis accelerometer.

Route trajectories for individual cycles of driving with filled or empty cargo box have been mapped. The results are shown in Fig. 10. Fig. 7b illustrates high-frequency vibrations in the exploitation area resulting from the stand-by and loading of the machine, not from road conditions. Because of the low thill, the loader hit the roof and pushed down the machine during loading.

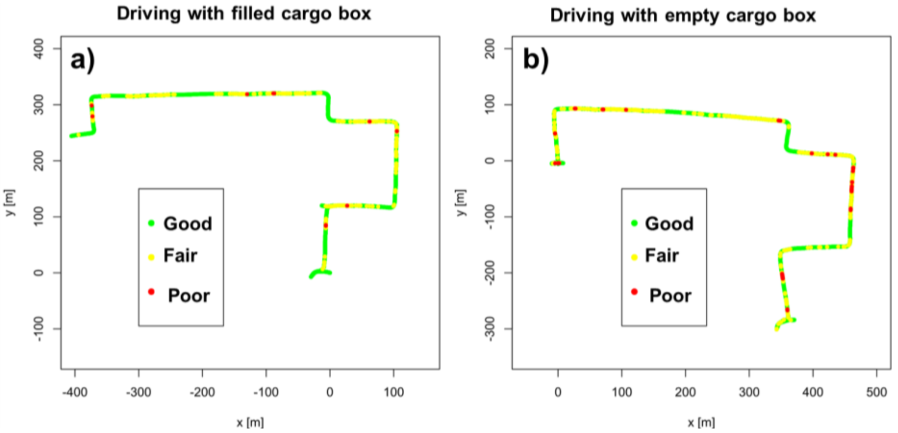

Fig. 10. Results of classifying the road conditions: a) driving with filled cargo box, b) driving with empty cargo box.

5 Summary

The paper outlines the basic method of using the inertial sensors for evaluating the road condition and mapping the trajectory of the machine's movement calculated by the IMU signals registered in the underground mine. The suggested algorithm operates on data from the on-board monitoring system - variables: speed, direction and the data from Z-axis accelerometer and Z-axis gyroscope. The experiment was conducted in the deep underground mine, on the haul truck and lasted one working shift. Next, the collected data were analysed. The route has been mapped on 2-dimensional map with the respective symbols indicating the road surface condition. The experiment showed the increased vibration of the machine during the rides with empty cargo box.

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