

OPTIMIZATION OF AN AUTONOMOUS VEHICLE DESPATCH SYSTEM IN AN UNDERGROUND MINE

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Abstract: The mining industry can potentially benefit from automation. A great deal of work has been done on this subject and is still ongoing. With automation comes the possibility for optimization because more information is available and actions can be repeated with more accuracy. This paper looks at possible solutions to the problem of optimizing the autonomous vehicle despatch system in an underground mine. Possible optimization strategies are evaluated using a simulated environment. The results indicate improvements on the current methods used in mines.

Keywords: autonomous, simulation, hybrid, vehicles, optimization.

1. INTRODUCTION

Automation in the mining environment is a field that enjoys considerable attention. Because of the hazardous environment, a strong drive exists to have as little human presence underground as possible. Many factors make automation underground a challenging prospect. These factors include difficulty in collecting and distributing data. Mining automation in general and the challenges accompanying it are described in Pukkila et al. (2000). This paper focuses on a mining setup where vehicles such as LHDs (Load Haul Dump) and trucks are used to collect and transport ore underground. A considerable amount of progress has been made in automating underground vehicles, and full scale, fully automated (and semi-automated with remote operator) vehicles have been successfully tested underground. More information on the automation of LHDs can be found in Steele et al. (1993) and Scheduling et al. (1999). As a result of the automation process the availability of data (from local sensors on vehicles and global sensors) increases and a central point of control and monitoring can be established. The next step must be to find ways of using this data to optimize the control algorithms to ensure higher productivity. The increase in productivity must be high enough to justify the cost of automation.

In this paper it is assumed that the vehicles are fully automated and a central point of control and data collection exists. The aim of this paper is to outline work done on the optimization of the vehicle despatch system in an underground mine.

Therefore there will be no further discussion concerning automation, but it must be kept in mind that it is needed as a foundation for optimization of the despatch system.

Scheduling and optimization in a vehicle despatch system is not new. A lot of work has been done on this topic in the field of manufacturing, and also in the field of automated road traffic. Examples of this can be found in Evers et al. (1996), Smith et al. (1992). The application of these techniques to the underground mining environment is however very limited and relatively new. Most research is still done on the automation of vehicles, and the dispatching currently relies mostly on human discretion and experience. In the near future mines will become increasingly automated as technology develops. This will lead to an increase in the need for optimal use of the available information and control possibilities. With the existing automation infrastructure it will then be very cost effective to implement some strategy to make optimal decisions possible. The work described in this paper will therefore become more applicable as automation in mines develop, but it can also provide benefits (in terms of decision making) in any mine where some sensing capabilities are available even if the vehicles are manually operated.

2. SYSTEM MODELLING

A system of vehicles in an underground mine can be described as a hybrid system. A hybrid system is a dynamical system composed of discrete and continuous states. A more complete and generic definition of hybrid systems can be

found in Tomlin et al. (2000). In the context of autonomous vehicles, the vehicles can be in one of a number of discrete modes (states). In each of these modes the behaviour of the autonomous vehicle is governed by continuous dynamics. Examples of states that are typically found in a mining environment are: loading, off-loading, refuelling, etc. Another state is when the vehicle is in transit. In this state it is obvious that the movement is governed by continuous dynamics. In a state like loading there is no movement of the vehicle as a whole, but the continuous dynamics can be found in the movements associated with the scooping up of ore (by LHD) or the tilting of a bucket (by truck).

In Bemporad et al. (2000) a simple temperature control system is used as an example of a hybrid system. The graphical representation of the temperature control system is called a hybrid automaton. The hybrid automaton representing the dispatch system of the vehicles in an underground mine, can be seen in figure 1. The figure shows a simple representation of the different states of each LHD in the underground mine environment as well as the transitions between states, and the requirements for each transition is given beside the arrow. The representation of the truck despatching is the same with only the top left state substituted with 'at transfer point' and the top right state with 'at crusher'.

The modelling of the system serves only to give a better understanding of the operation of the system. The simulations that will be discussed later are not based on a specific mathematical model, therefore no further attention will be given to the modelling of the system in mathematical terms.

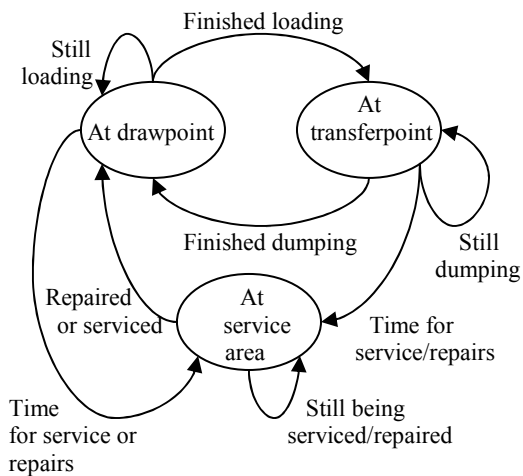


Fig. 1. Automaton for vehicle despatching.

3. SIMULATIONS

The simulations discussed in this paper are done in Matlab¹.

3.1 Description of environment

The simulated environment is based on the layout of a diamond mine implementing a blockcave mining technique. The specific details of the type of mine and the mining technique are not important for the scope of this research. The principles used in the despatching of vehicles will be similar for many different types of mines and mining techniques. The results discussed in this paper are therefore not limited to this specific mining setup.

A graphical representation of the simulation environment is shown in figure 2. It can be seen that the movement of the vehicles is confined to tunnels. The possible routes between different points are therefore limited. The environment in the simulation has 7 tunnels that are in production with 15 drawpoints between each pair of tunnels. These numbers closely reflects real-life mining environments.

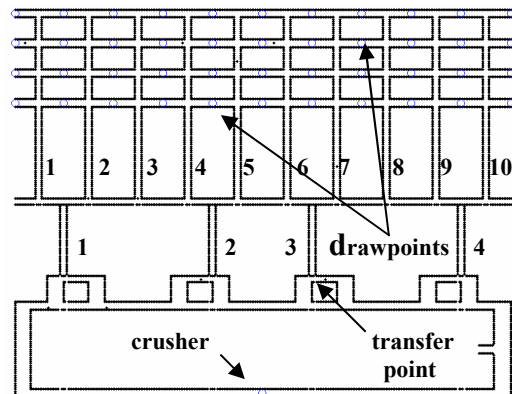


Fig. 2. Simulation environment.

The circles in figure 2 represent drawpoints. The circle at the bottom represents the crusher, and the loop at the bottom is the tunnel connecting the transfer points with the crusher (this is not drawn according to scale).

The basic operation of the mine is as follows: Ore collects at the drawpoints because of blasting and caving. The ore are loaded by LHDs and transported to the transfer points. At the transfer points an LHD dumps its load into a truck. After the truck has received enough ore to

¹ Matlab: A technical computing language. The MathWorks, Inc.

fill its bucket, it transports the ore to the crusher. The load is dumped into the crusher, from where the ore is crushed and processed further. The simulation is only concerned with everything from where the ore are available at the drawpoint until it is dumped into the crusher. The main objective is to test different despatching strategies to determine if the movements of the vehicles can be optimized.

3.2 Generating initial conditions

To obtain relevant results the simulation conditions must be as realistic as possible. Included in the simulation is the random occurrence of hang-ups. A hang-up occurs when a rock is too big and gets stuck in a drawpoint. This requires additional drilling and blasting before a drawpoint is active again. Random hang-ups are generated according to a probability distribution based on historical data from a physical mine.

The servicing and repairs of the vehicles are not included in the simulation. This is not that unrealistic because the simulation is run for only one week of production. Vehicles can easily run for a week without a breakdown or being serviced. The fuel consumption and refuelling of the vehicles are however included in the simulation.

Realistic initial conditions for further simulations were obtained by running the simulation for a week of production. A week of production stretches over 5 days, 24 hours a day. This was done from a zero state, i.e. the crusher level was at its minimum and the total loaded from each drawpoint was zero. Random hang-ups were generated. The rules for despatching of the vehicles, was obtained from an industrial partner, and closely followed that which is currently found in physical mines. The LHDs are each assigned to a specific tunnel, and visits the active drawpoints, in that tunnel, sequentially. The trucks only move in one direction around the loop (seen in figure 2). A truck stays at a transfer point until it has received enough loads to fill it up, and then moves to the crusher. If all transfer points are occupied then the trucks that have finished dumping into the crusher must wait. The values of all the relevant variables were saved to be used as initial conditions for further simulations.

3.3 Despatching strategies

The generated initial conditions were used for the simulation of each of the strategies discussed below. All the drawpoints were made

active i.e. all hang-ups were assumed to be cleared. All the simulations were run for the equivalent of one week of production.

Strategy 1: This strategy is the same as the one used to generate the initial conditions. The results obtained with this strategy are used as the base case against which the rest of the results can be evaluated.

Strategy 2: This strategy is exactly the same as the first one, but the order in which the LHDs visit the drawpoints is reversed for every other tunnel. In other words an LHD will start from the nearest drawpoint and the LHD in the next tunnel will start from the furthest drawpoint.

Strategy 3: The LHDs are still assigned to specific tunnels, but the order in which the drawpoints are visited, is determined dynamically. A cost function is used to determine the most appropriate drawpoint to visit. The value of the cost function is computed for every possible drawpoint, and the drawpoint that gives the lowest value is chosen as the next destination. The cost function contains a term describing the difference in levels between the drawpoint and adjacent drawpoints, as well as a term describing the tonnes drawn from the specific drawpoint. The distance between the drawpoint and LHD was considered as another term, but because the distances to the different drawpoints are fixed, only the nearest points will benefit from this term. The term was therefore not implemented because an important specification is that the ore level must be drawn evenly over the whole mine area. The terms of the cost function look as follow:

$$T_1 = \frac{\text{tonnes_drawn_today}}{\text{quota_per_day}} \quad (1)$$

$$T_2 = \frac{\text{adjacent_level_difference}}{\text{max_level_difference}} \quad (2)$$

(2) will be included four times in the cost function, because from figure 2 it can be seen that each drawpoint has four adjacent drawpoints. The maximum level difference between adjacent drawpoints was computed as 1449 tonnes for points in the same tunnel, and 2898 tonnes for points in adjacent tunnels. This was obtained from the fact that the maximum angular difference between the levels directly above the drawpoints must be 7°. The terms are normalized so that they can be added together.

The cost function then looks as follows:

$$J_k = T_1 + T_{2,1} + T_{2,2} + T_{2,3} + T_{2,4} \quad (3)$$

The subscript k denotes the specific drawpoint for which the cost function is computed. When an LHD has finished off-loading the cost function is evaluated for each drawpoint in the tunnel associated with the LHD. The drawpoint that produces the lowest value of J is set as the new destination for the LHD. The despatching of the trucks correspond to that of strategy 1.

Strategy 4: This strategy involves only the truck movements. The movements of the LHDs correspond to that of strategy 1.

The trucks still move in one direction around the truck loop, but they do not have to obtain their entire load from one transfer point, as was the case in all the previous strategies. A truck should however be fully loaded before it moves to the crusher. Because the trucks only move in one direction around the loop, a truck can only move from one transfer point to another until it reaches the last one in the loop. In the case of the simulation described in this paper the last transfer point would be number three, because only seven tunnels are active (see figure 2). A truck can only move to a transfer point with a higher number if that point is not occupied by another truck, or no other truck is already on its way to that point. When a truck reaches the last transfer point it must stay there until it is fully loaded.

More possibilities are created by combining different strategies. It is clear that strategy 1-3 all have the same despatching strategy for the trucks, and that strategy 4 uses the LHD despatching of strategy 1. Therefore some combinations of strategies are already implemented automatically. This is because the problem consists of two distinct despatching systems (for LHDs and trucks) which only interact at the transfer points. The only other possibilities for combinations of strategies are strategy 2 with 4, and strategy 3 with 4. These combinations are called strategy 2 + 4, and strategy 3 + 4, and were also simulated.

4. RESULTS

The main objective of a mine is to produce as much as possible each day to maximize profit, but also to ensure that maximal future production is possible. In the context of a blockcave mine this means that each active drawpoint must be visited as frequently as

possible while still keeping the ore level relatively even. The production must also be as even as possible throughout the time the mine is active. In practical terms this means that the crusher level must stay within its operation limits. This implies that the arrival of trucks at the crusher must be evenly spaced, not too far apart but also not too close together. If the crusher is empty for a specified time, it switches off, when a truck then arrives with a load it must be switched on again. An important performance measure is therefore the number of times the crusher is switched off. The results given in this section focuses on these factors. Tables 1 and 2 contains some of the relevant results obtained after one week of simulated production with each different despatching strategy, as well as the combinations of strategies.

Table 1. Crusher results. The total amount of ore dumped into the crusher throughout the week of production is given. The number of times the crusher had to be switched off is also given.

Strategy	Crusher total (tonnes)	Crusher stops
1	79785	24
2	83475	6
3	81270	13
4	73755	4
2 + 4	65880	4
3 + 4	74700	3

Table 2. Drawpoint results. The average amount of ore drawn per drawpoint, as well as the standard deviation from this average is given.

Strategy	Drawpoint average (tonnes)	Standard deviation (tonnes)
1	953	757
2	975	760
3	962	711
4	916	718
2 + 4	868	705
3 + 4	922	693

Figures 3 to 8 give a graphical representation of the ore level for the whole active area of the mine. The figures actually show the amount of ore already drawn. This means that the physical level in the mine will resemble the figures if they are turned upside down.

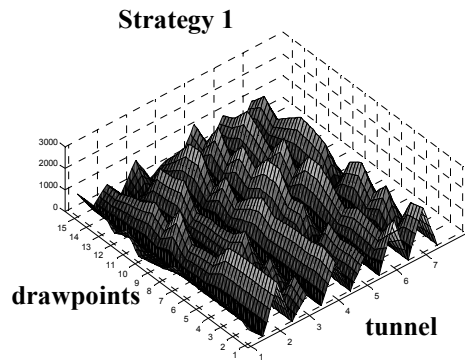


Fig. 3. Ore levels after one week of production with strategy 1.

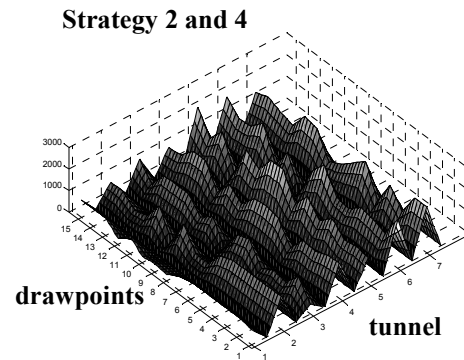


Fig. 7. Ore levels after one week of production with strategy 2 and 4.

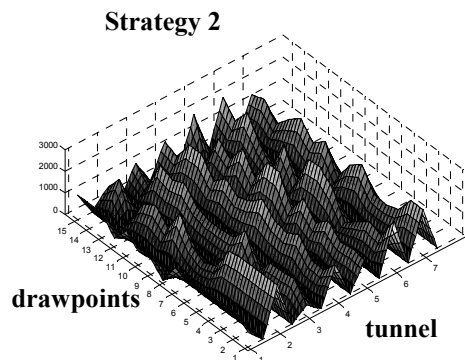


Fig. 4. Ore levels after one week of production with strategy 2.

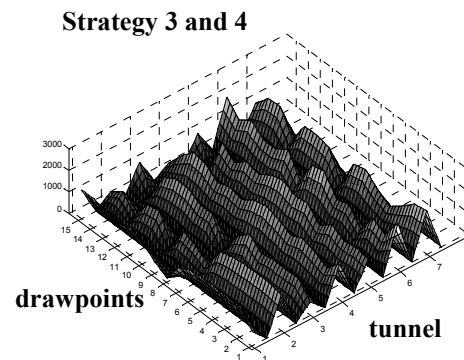


Fig. 8. Ore levels after one week of production with strategy 3 and 4.

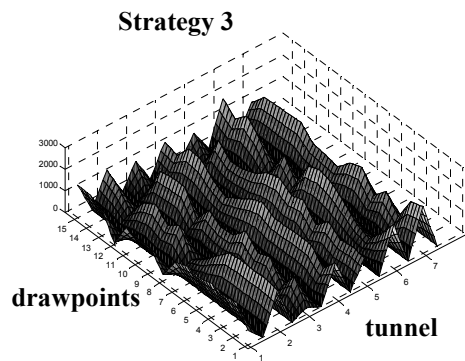


Fig. 5. Ore levels after one week of production with strategy 3.

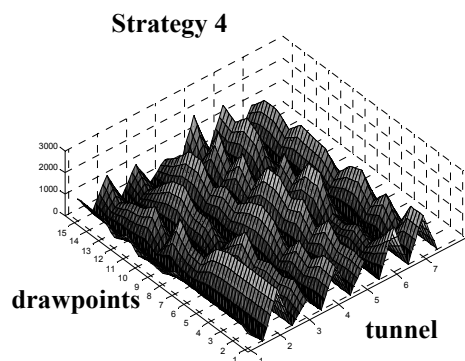


Fig. 6. Ore levels after one week of production with strategy 4.

5. DISCUSSION

From the results it is clear that strategy 2 performed the best in terms of total tonnes produced, and strategy 2 + 4 the worst. Strategy 2 also produced one of the smallest values for crusher stoppages, so in terms of the crusher results strategy 2 is by far the most effective. Strategies 1 and 3 produce more crusher stoppages. This is to be expected because strategy 3 is aimed at maximizing the tonnes drawn from the drawpoints and to keep the ore level as even as possible. It does not attempt to evenly space the arrival of LHDs at transfer points and therefore also not to evenly space the arrival of trucks at the crusher. In strategy 1 the LHDs progressively move to further drawpoints and this means that the travelling distances for the LHDs are almost the same at any time. The LHDs thus tend to arrive at the transfer points at the same time, and in between very few off-loading takes place. This causes the trucks to receive many loads in a short time, and at other times wait long for loads. The arrival of the trucks at the crusher is therefore not evenly spaced, and the crusher runs empty more often and has to switch off more. This problem is addressed by strategy 2 because the travelling

distance is different for adjacent LHDs most of the time. This is clear from the results in table 1.

The last three strategies produced low values for the total tonnes through the crusher, but on the other hand they produced the least number of crusher stoppages. This is because strategy 4 is aimed at spreading the arrivals of the trucks at the crusher evenly by reducing the travelling distances to the crusher if the truck is full as well as to the nearest transfer point if the truck is empty. The lower total tonnes produced could be due to the fact that the different strategies combined to obtain these results were developed in isolation with different goals in mind. It could therefore be expected that the strategies will not compliment each other.

Before the results of table 2 are discussed it must be kept in mind that some drawpoints became inactive due to the hang-ups generated. The standard deviation values therefore will not reflect the true potential of the strategies because large level differences between inactive and active drawpoints are inevitable. From the results in table 2 it can be seen that the average tonnes loaded from the drawpoints reflect the values of the crusher totals in table 1. This makes sense because all the ore loaded from the drawpoints must go to the crusher.

The values of the standard deviations indicate that strategy 3 improves on strategy 1. Strategy 3 therefore succeeds in keeping the ore level more even, whilst still maintaining a high level of productivity. The standard deviation results for the last three strategies can not really be compared to that of the first three due to the lower production values. The lower deviations therefore do not carry any weight and will not be discussed further. It is however worthy to note that the combination of strategy 3 and 4 produces the lowest deviation by far and still has a reasonable average value. These results could be expected because only strategy 3 is explicitly aimed at keeping the ore level more even.

6. CONCLUSIONS

Each strategy was developed to achieve a specific goal, and the success of each strategy was clearly indicated by the results. As already mentioned, however, these strategies were developed in isolation and not specifically to compliment each other. This is due to the physical layout of the mine. In reality two separate despatching systems must be optimized separately to achieve different goals. To obtain a more optimal solution when these two systems

interact will necessitate some trade-offs. The best solution will therefore depend on the specific priorities of the application. The strategy that produces the best results overall is strategy 3.

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