Constraint dependent, shortest path algorithms for real time vehicles movement in the coal mining industry towards Industry 4.0

Mohamed Sameer Hoosain
Department of Electrical and Electronic Engineering Technology
University of Johannesburg
sameer.hoosain@gmail.com

Babu Sena Paul
Institute for Intelligent Systems
University of Johannesburg
bspaul@uj.ac.za

Wesley Doorsamy
Department of Electrical and Electronic Engineering Technology
University of Johannesburg
za.wesley.doorsamy@ieee.org

Abstract

Industry 4.0 is knocking on South African miners' doors, with the introduction of a digital mine increasingly becoming seemingly important for their survival and success. In order for mines to remain competitive, digital innovations will be needed in the future to increase productivity. This paper looks at an artificial intelligent technique in order to assist in the control of shuttle vehicles in the coal mining industry. Since the bord and pillar mining technique is used, shuttle car movements are based on queuing, shortest paths and path constraints. A graphical user interface (GUI) was designed in order to assist mining operators. The algorithms used in this optimization of these cars are Dijkstra's shortest path algorithm, K-shortest path algorithm and discrete event simulation. In order to test this application, simulations and test results were carried out using Matlab.

Keywords
Industry 4.0, Dijkstra's algorithm, K-shortest path algorithm, discrete event simulation, artificial intelligence.

1. Introduction

Current mining processes do not possess the visibility to real time and accurate information. Therefore, the ability to track performance and increase equipment uptime is hindered. With the introduction of the fourth industrial revolution, industries will change the way they operate. Individuals, communities, but particularly organisations lives will be disrupted. Mines are no exception to this rule, with implications and important opportunities.

2. Brief History

Coal mining in South Africa can be traced back to the beginning of gold mining towards the end of the 19th century, the first coal being extracted on the Highveld coalfield close to the earliest Witwatersrand gold mines. As the country entered a period of industrialization during and following the second world war coal mining increased, which led to building off power stations.

Today Eskom South Africa's utility provider is constructing two thermal power stations, Medupi and Kusile, which are based on coal reserves in Mpumalanga and Limpopo provinces.

With 30 billion tonnes off available resources in South Africa:

- 3.5% of the world's coal resources are in South Africa.
- 6% of global exports.
- Coal provides 81% of the power generated by Eskom.
- Sasol mines gasification and conversion into liquid fuels.

Today there are over a dozen mining companies in South Africa, these include Sasol, Anglo American, Exxaro to name a few. With mining continuing on such a large scale, much more advanced mining equipment and technologies are required.

3. Coal Mining Techniques

Australia, the USA, and South Africa utilize similar mining methods. Bord and pillar and long wall mining in underground mining, opencast strip mines and truck-and shovel operations in surface mining. In this paper we consider the bord and pillar method.

Bord and pillar method consists of driving a series of narrow roads or pathways separated by walls of coal, parallel to one another, thereby creating a matrix or network. Selecting the perfect pillar size is key to the success off bord and pillar mining. This can be seen in figure 1 below.

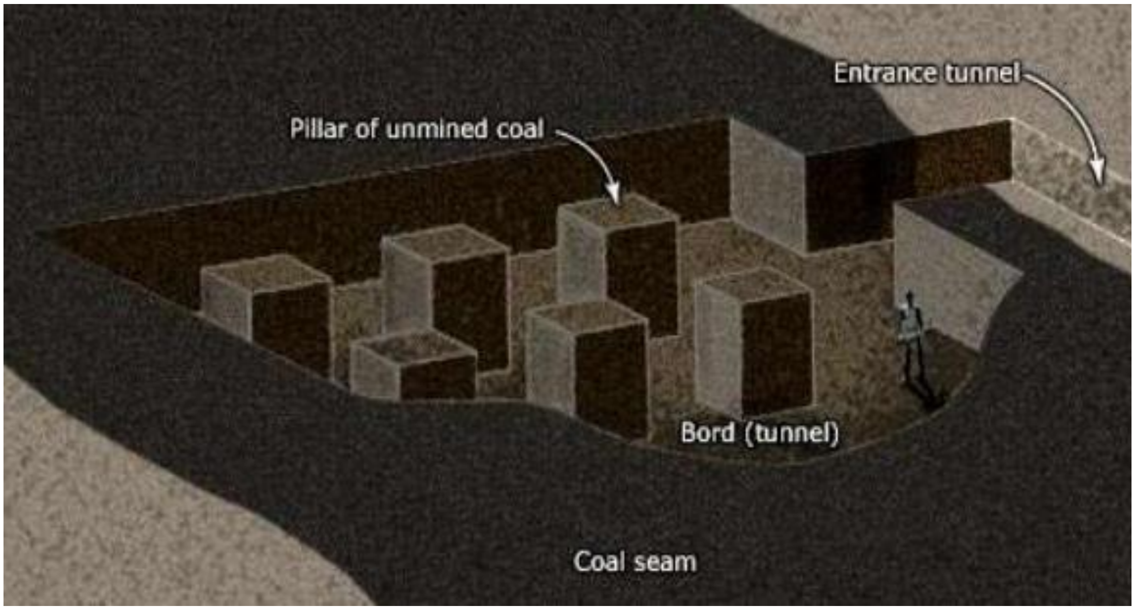


Figure 1. Basic principle of bord and pillar mining method.

In order to create such formations, specialized mining vehicles are required. Joy| Komatsu mining Corp. is continuously pursuing the optimal performance of their equipment fleets in the underground South African coal mining environment and globally. For the block and pillar equipment includes, entry drivers, continuous miners, bolting systems, haulage systems, feeder breakers, and loaders. In this paper, we specifically look at the haulage systems i.e. the shuttle cars that have a trailing cable for power, transport the coal from the mined area to the feeder breaker, the process can be seen below in figure 2.

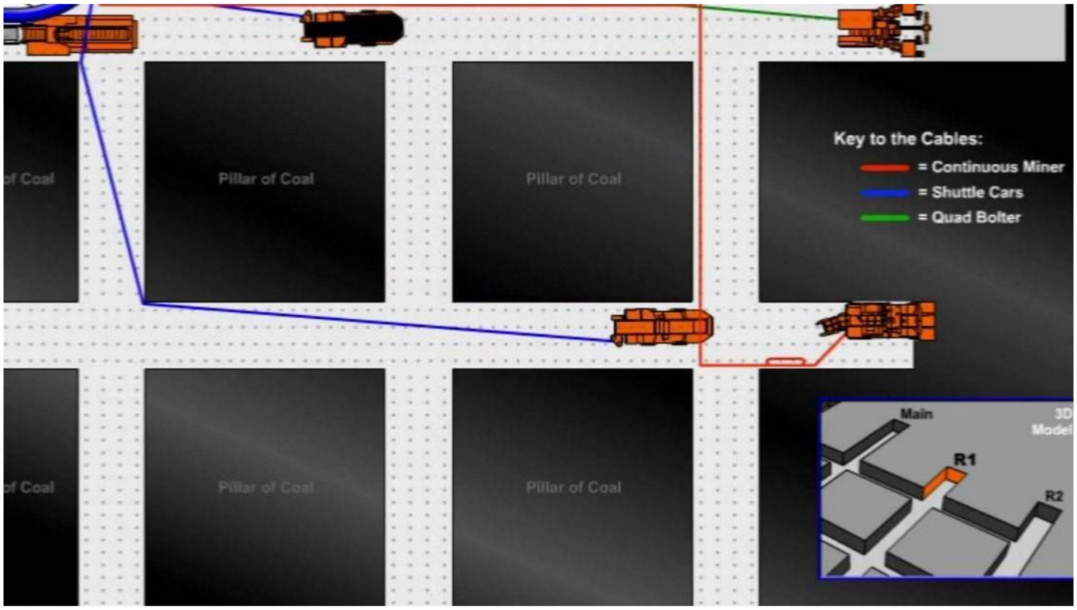


Figure 2. Basic operation of the mining process and shuttle car movements.

In a typical underground network, the mining area is a 7x3-matrix size or a 5x3-matrix size, with three shuttle cars operating at a time. Of course, this requires specialized operators to control paths and queuing of these vehicles. This paper looks at an artificial intelligent technique in order to assist in the control of these vehicles.

4. Background and Definitions

Pathfinding or shortest paths is an essential application which aims to provide computers with representations for understanding an environment and algorithms for navigating within an environment. Computers are designed to perform complex logical and arithmetic operations, and along these lines knowledge of the environment must be converted into a numerical representation, and the task of navigating that environment into a sequence of logical operations. Graphs are often used to model such environments. A graph is a mathematical abstraction modelling the relations between a group of nodes, or vertices. Relations are modelled as edges connecting two vertices together. A numeric value may be associated with edges, expressing the cost of travelling on them. Similar values may also be associated with nodes, to represent the cost of travelling through them. A typical example may be a road network, wherever graph edges represent roads, and graph nodes represent road intersections. Once this graph has been constructed, an algorithm can be designed to find paths within it. While it is possible for an arbitrary path to be chosen through the graph, it is usually more advantageous to select a path that optimises some metric. The shortest path is frequently chosen since it is generally desirable to save both time and energy when travelling. More formally, the shortest path between two nodes, consisting of linked edges, must minimise the summed edge costs.

The following definitions will be used in this paper and are often used in discussions on shortest path problems; we will also come to understand the concept of Industry 4.0:

4.1 Dijkstra’s Shortest Path Algorithm

Dijkstra’s algorithm was invented by Dutch computer scientist Edsger Dijkstra in 1956 and published in 1959. It is a graph based searching algorithm that solves the single source shortest path problem. It is applied only on positive weights graphs. This algorithm is used for finding the shortest path with minimum cost. This cost could involve distances or even constraints, based on its application.

One example would be if the vertices in a graph are cities and the edges are the links between these vertices, therefore the edges are the driving distances from one city to another city. This algorithm finds the shortest route from one city to another with the minimum cost. Dijkstra's original algorithm does not use a min-priority queue and runs in time O (| V |^2) (where |V| is the number of nodes). With some adjustments by Fredman & Tarjan in 1984, this algorithm is the fastest known single-source shortest-path algorithm for directed graphs with non-negative weights.

Another example would be in figure 3 below, given a weighted directed graph G = (V, E), source=s, destination=t. Find the shortest directed path from s to t. The result in this case would be:
S-2-3-5-t
=9 + 23 + 2 + 16
=48.

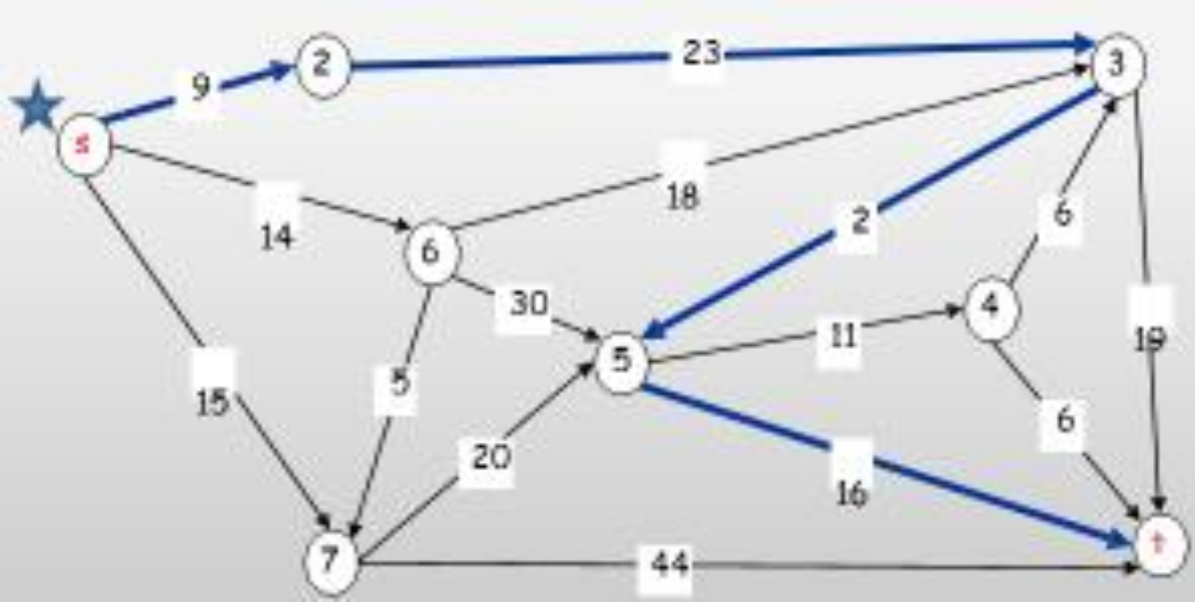


Figure 3. Shortest path example using Djikstra's algorithm.

4.2 K-Shortest Path Algorithm

Since Dijkstra's algorithm as explained above finds the shortest path from a source to a destination, what if for some reason this path is not available due to a constraint? Therefore, it is necessary to discover a second shortest path, and if this too is not available, a third path may be required, and so on. Thus, a series of these shortest paths are known as K-shortest paths, and represent the *first, second, third ... kth* paths typically of least length from one node to another.

Shortest path problems have been subject to research since the 1950's. In some applications shortest paths don't neccesararily refer to distance, rather it could also include factors such as cost, time, safety and weighting.

4.3 Discrete Event Simulation or Queuing

Since discrete event simulation spans across many concepts, the particular one discussed in this paper is queuing. Queueing deals with one of the most unpleasant experiences of life, waiting. Queueing is common in a number of fields, such as telephone exchange, pay points, traffic intersections, computer systems and networks, etc. The first problems of queueing was raised by telephone calls by Erlang in the beginning of 20th century.

The most commonly used laws are:
- FIFO - First in First Out: who comes first leaves first.
- LIFO - Last Come First Out: who comes last leaves first.
- RS - Random Service: random selection.
- Priority.

4.4 The Fourth Industrial Revolution or Industry 4.0

It is said that the Fourth Industrial Revolution is unlike anything humankind has experienced previously. We have to appreciate its endless possibilities and staggering technology breakthroughs in artificial intelligence (AI), the internet of things (IOT), 3D printing, and nanotechnology just to name a few. With this comes profound shifts in industry, mining, business models and innovation.

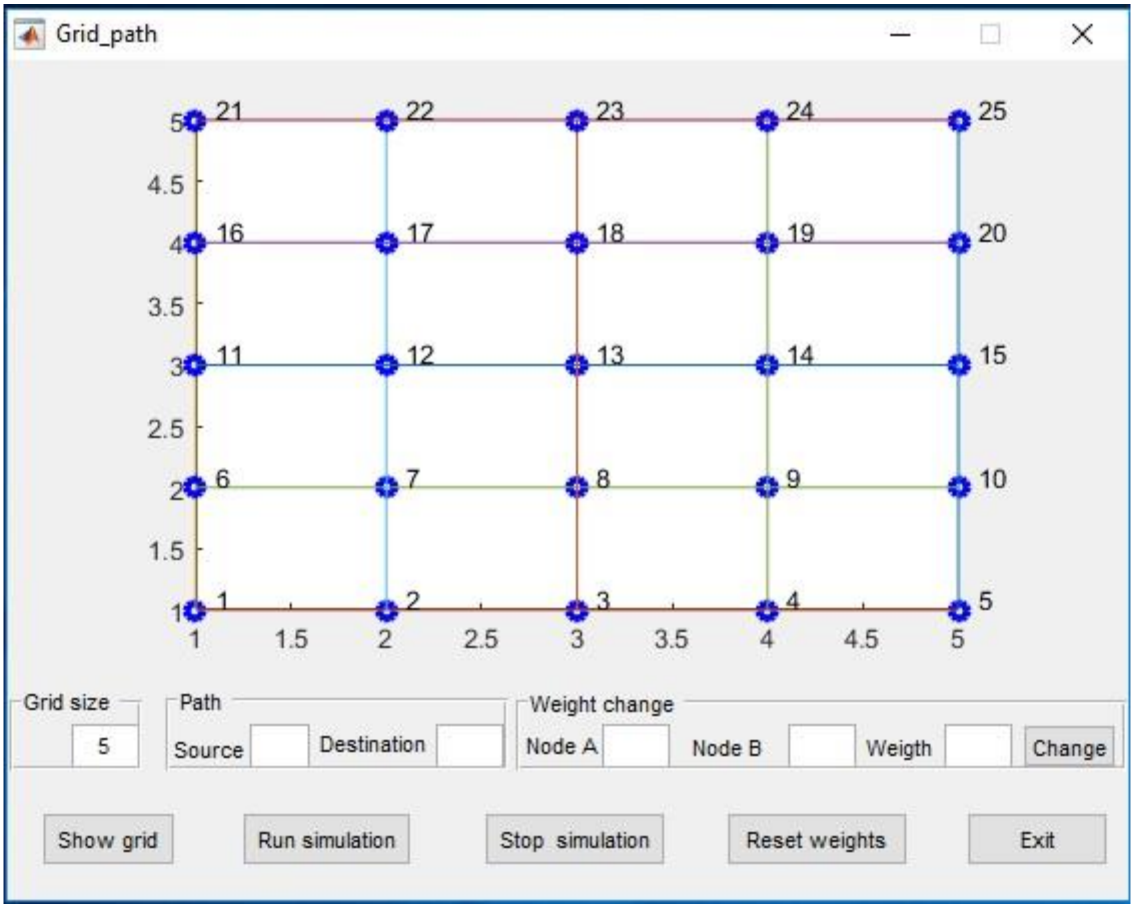
Looking back at the previous revolutions, the first industrial revolution began in England, which was also known as the age of steam and the use of thermodynamics. The second industrial revolution was also developed in Britain but were industrialised in the US. This was the age of electricity studies were done by Michael Faraday and formalised by James Maxwell. The third industrial revolution, gave us a transistor and ultimately computers and the electronic age. The fourth industrial revolution will give us cyber-physical systems, where human beings and machines will merge. Enhanced open innovation and people will be able to work on solutions together online. Furthermore, the fourth revolution will enhance internationalisation of universities. Communication barriers will be eliminated between students and academics as they work on solutions together online.

5. Methodology/System Model

In this section, the theory and the design of the concept that was investigated is discussed, namely: shuttle car movements based on queuing, shortest paths and path constraints in the coal mining industry.
We will look at each step taken to design a graphical user interface (GUI) assistive model for operators underground. Design and simulations were done using Matlab.

The first step was to design a layout of the mine. The best solution here was to create an adjustable square matrix. The most basic Matlab system is that the matrix: a two-dimensional, rectangular formed system capable of storing multiple elements of data in an easily accessible format. These data elements may be numbers, characters, logical states of true or false, or perhaps alternative structure sorts. Matlab uses these two-dimensional matrices to store single numbers and linear series of numbers additionally. In these cases, the dimensions are 1-by-1 and 1-by-n respectively, where n is the length of the numeric series. Matlab additionally supports data structures that have more than two dimensions. These data structures are referred to as arrays. For this application we initialize the grid below with the following code. By changing the value of N, we are able to set the square matrix size. In this case we used a 5x5 matrix size. Figure 4 below then depicts the output example.

```
%% GRID INITIALISATION
N = 5;
WeightMatrix = Inf*ones(N^2,N^2);
for i=1:N^2
   row = ceil(i/N);
   col = i - (row-1)*N;
   if i+1 <= N^2 && col ~= N
      WeightMatrix(i,i+1) = 1;
   end
   if i-1 >= 1 && col ~=1
      WeightMatrix(i,i-1) = 1;
   end
   if i+N <= N^2 && row ~=N
      WeightMatrix(i,i+N) = 1;
   end
   if i-N >= 1 && row ~= 1
      WeightMatrix(i,i-N) = 1;
   end
end
```



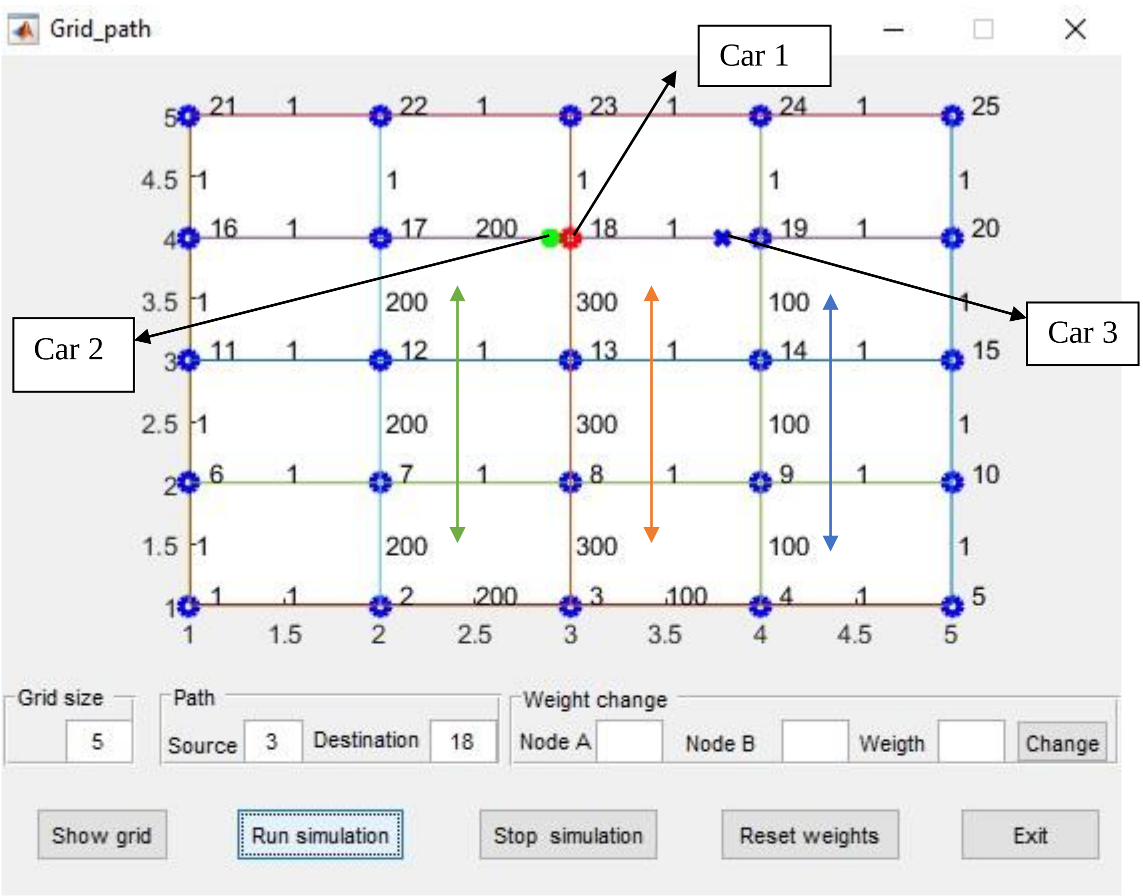
Grid size: 5

Figure 4. Initialization of a 5x5 matrix.

The second step was to create a weighting system between the nodes. Weighted graph assigns numeric values to each edge. These weights describe the values of a problem represented by the graph. For example, weights may describe the cost, distance or length of travelling along an edge, or an edge's capacity to handle traffic which is considered in this case.
The default weight when a path is free is equal to 1. This weight system was important, as it specified whether a path is blocked. Operators are able to manually insert weights between nodes, and the resultant paths change as per this adjustment. These weights can be any value greater than 1.

There was a second weighting system used in this application as well, this is known as a dynamic weight. Each of the three cars were assigned a specific weight value (car 1 (red)= 300, car2 (green)= 200, car3 (blue)= 100), this is important as it stops cars from crossing each other's paths. The second advantage of this dynamic weights are, we know the exact whereabouts of each car, if a car is between a particular node the weight is present, if not the weight returns to its original value.

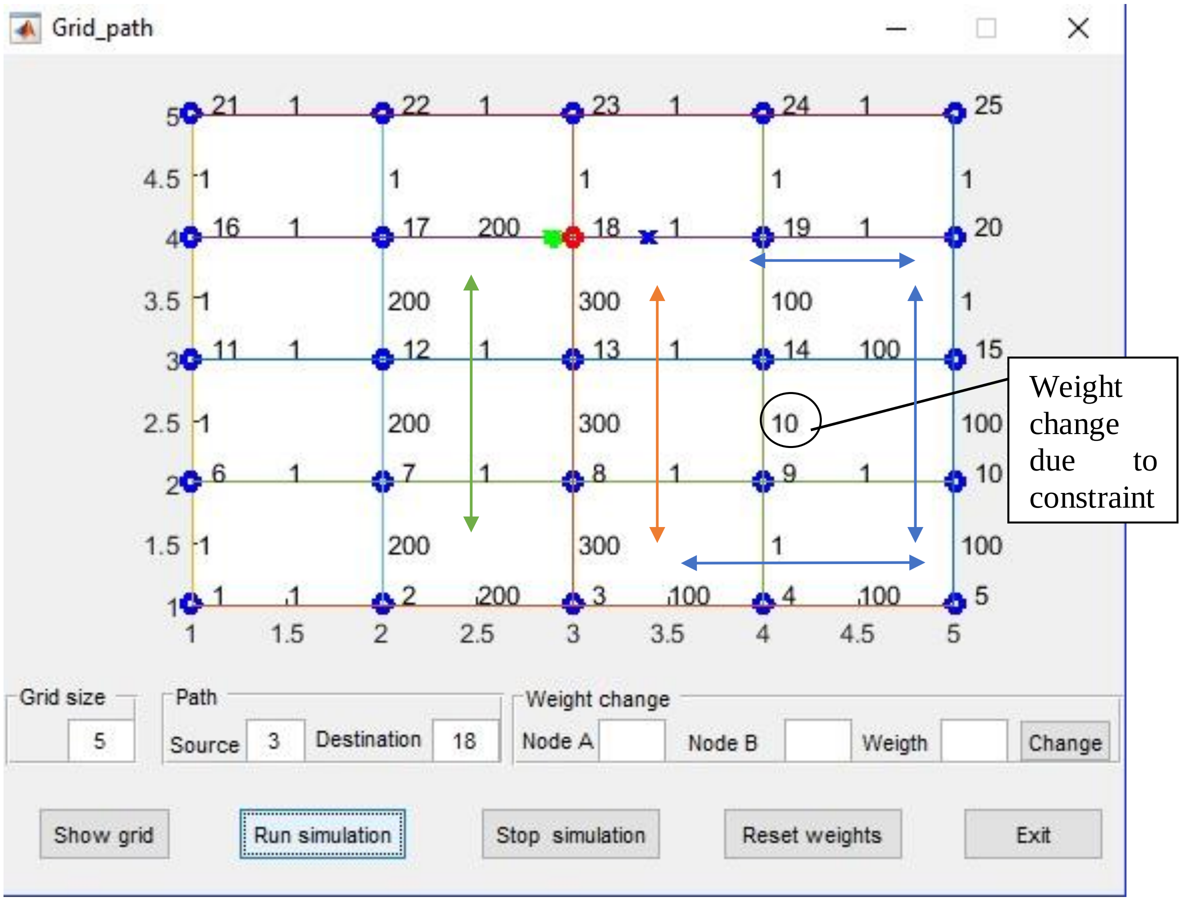
This weight system was important as Dijkstra's algorithm and K shortest path require the weights between nodes in order to calculate the three shortest paths. We see in figure 5 below a simple path demonstration with no constraints between paths. Source node = 3 and destination node = 18:



Grid size: 5
Path: Source 3, Destination 18

Figure 5. Demonstration of the paths selected (indicated by the three different color arrows and dynamic weights) with no constraints.

The same scenario was tested with constraints. Using the same source and destination, a constraint was added between nodes 9 and 14. By adding a higher value than 1 (in this case 10) the 3rd cars path is automatically adjusted accordingly in order to avoid the problem. Figure 6 below shows the resulting operation as compared to figure 5.



Grid size: 5

Path: Source 3, Destination 18

Weight change: Node A, Node B, Weigth, Change

Weight change due to constraint

Figure 6. Demonstration of the paths selected with a constraint (indicated by the three different color arrows and dynamic weights), and the new path is selected for car 3 (blue arrows).

The final step was to create a queuing system; this was done using discrete event simulation, this was important so that cars do not collide and since they have trailing power cables, damages to these cables could occur if the cars rode over them. In this case First-in-First-out, the 1st shuttle car arrives at the destination will leave first, the 2nd and 3rd shuttle cars would que near to the destination, and only once the destination is vacant the 2nd car will move into that space, once the 2nd car has left, the 3rd car will occupy that space. This process then continues as a cycle from source to destination, until the operator changes all inputs to the GUI to map a new route.

6. Conclusion

The development of shortest path algorithms to navigate through environments is a continuing area of research. When paths can be logically decomposed into a collection of routes and intersections, such environments can be represented by a graph. Edges of the graph can be assigned a cost, representing the expense of traversing a route between two graph nodes. Algorithms such as Dijkstra's shortest path operate on these graphs to find paths with a minimal summed edge cost. Thus, different routes can be favoured or avoided by weighting graph edges with some metric associated of the environment. The distance travelled along a route is the most frequently used, but other measures such as traffic congestion can also be used.

Many techniques to be employed for such applications are still being determined. Crucial tasks such as these are directly linked to operational efficiencies. The designed system in this paper is a positive step forward in solving this issue, at the same time taking steps to include the new industrial revolution. There is room for vast improvement to the concept such as the monitoring of real time data underground i.e. knowing the exact location of the shuttle cars, since GPS and other techniques are not readily available underground.

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References

Brander A.W., Sinclair M.C. (1996) A Comparative Study of k-Shortest Path Algorithms. In: Merabti M., Carew M., Ball F. (eds) Performance Engineering of Computer and Telecommunications Systems. Springer, London.

Chamberofmines.org.za. (2018). Coal - Minerals Council South Africa. [online] Available at: http://chamberofmines.org.za/sa-mining/coal [Accessed 9 Jun. 2018].

"Creating and Concatenating Matrices- MATLAB & Simulink." *Mathworks.com*. N.p., 2018. Web. 28 Aug. 2018.

Hardman, D. (1996). Coal-mining productivity in South Africa compared with Australia and the USA. The Joumal of the South African Institute of Mining and Metallurgy, pp.297-302.

I.ytimg.com. (2018). [online] Available at: https://i.ytimg.com/vi/yGawB7FZXjo/maxresdefault.jpg [Accessed 7 Jun. 2018].

Mining.komatsu. (2018). Room and Pillar / Entry Development - Underground Mining | Komatsu Mining Corp.. [online] Available at: https://mining.komatsu/underground-mining/room-pillar-entry-development [Accessed 10 Jun. 2018].

Njobeni, S. (2018). Digital mining future of Fourth Industrial Revolution | IOL Business Report. [online] Iol.co.za. Available at: https://www.iol.co.za/business-report/features/mining/digital-mining-future-of-fourth-industrial-revolution-13110058 [Accessed 5 Jun. 2018].

Perkins, Simon. "Field D* Pathfinding in Weighted Simplicial Complexes." Ph.D. University of Cape Town, 2013. Print.

Schwab, K. (2016). The fourth industrial revolution.

Segopolo, P. (2015). Optimization of shuttle car utilization at an underground coal mine. *Journal of the Southern African Institute of Mining and Metallurgy*, 115(4), pp.285-296.

Singal, P. and R.S.Chhillar, R. (2014). Dijkstra Shortest Path Algorithm using Global Position System. *International Journal of Computer Applications*, 101(6), pp.12-18.

Slideshare.net. (2016). Design of Bord and Pillar method in coal mines. [online] Available at: https://www.slideshare.net/aashutoshchhirolya/design-of-bord-and-pillar-method-in-coal-mines [Accessed 10 Jun. 2018].

Sztrik, D. (n.d.). Basic Queueing Theory. University of Debrecen, Faculty of Informatics.

Uj.ac.za. (2018). News & Events - Opinion: SA must connect to the fourth industrial revolution. [online] Available at:https://www.uj.ac.za/newandevents/Pages/Opinion-SA-must-connect-to-the-fourth-industrial-revolution.aspx [Accessed 9 Jun. 2018].

YouTube. (2018). Bord and Pillar mining by continuous Miner in HINDI. [online] Available at: https://www.youtube.com/watch?v=WUwdqSlxXuw [Accessed 7 Jun. 2018].

Ziliaskopoulos, A. And Mahmassani, H. (n.d.). Time-Dependent, Shortest-Path Algorithm for Real-Time Intelligent Vehicle Highway System Applications. *TRANSPORTATION RESEARCH RECORD*, 1408, pp.94-100.

Biographies

Mohamed Sameer Hoosain is a post-graduate member of the University of Johannesburg (UJ). He is a PhD candidate; his research is based on electrical engineering topics in regard to the 4th Industrial Revolution. His master's thesis in electrical engineering dissertation – is in the area of Energy Efficiency in Smart Homes Based On DSM. His manuscripts have been presented and published at local and international conferences and journals in his research field. He has qualified as an electrical engineer and has gained experience working in the academic sector and industrial sector. Engineering, Production management, Internal auditing (ISO 22000 FSSC 22000 including HACCAP) at an FMCG company. Among others, he has successfully completed an EPICS-in-IEEE project and is involved in ongoing projects at the University of Johannesburg (UJ) FEBE, and fosters collaboration with external parties, for instance, Engineers Without Borders (EWB), UJ chapter, Techno lab and Growing up Africa. Other areas include project management for Makerspace initiatives, compiling proposals for grants. He is a member of South African Institute of Electrical Engineers (ECSA) as a candidate engineering technologist en-route professional registration and a graduate student member with the Institute of Electrical and Electronics Engineers (IEEE).

Babu Sena Paul received his B.Tech and M.Tech degree in Radio physics and Electronics from the University of Calcutta, India. He was with Philips India Ltd from 1999-2000. He received his Ph.D. degree from the Department of Electronics and Communication Engineering, Indian Institute of Technology. He has successfully supervised several postgraduate students and post-doctoral research fellows. He joined the University of Johannesburg in 2010. He has served as the Head of the Department at the Department of Electrical and Electronic Engineering Technology, University of Johannesburg from 2015 to March 2018. He is the currently serving as the Director to the Institute for Intelligent Systems, University of Johannesburg.

Wesley Doorsamy received the B.Sc., M.Sc. and Ph.D. Degrees in Electrical Engineering from the University of the Witwatersrand in Johannesburg, South Africa in 2008, 2013 and 2015, respectively. He is currently a senior lecturer at the University of Johannesburg and is an active member of both the Institute of Electrical and Electronics Engineers (IEEE) and South African Institute of Electrical Engineers.