A Navigation System for Automated Loaders in Underground Mines

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Summary. For underground mining operations human operated LHD vehicles are typically used for transporting ore. Because of security issues and of the cost of human operators, alternative solutions such as tele-operated vehicles are often in use. Tele-operation, however, leads to reduced efficiency, and it is not an ideal solution. Full automation of the LHD vehicles is a challenging task, which is expected to result in increased operational efficiency, cost efficiency, and safety. In this paper, we present our approach to a fully automated solution currently under development. We use a fuzzy behavior-based approach for navigation, and develop a cheap and robust localization technique based on the deployment of inexpensive passive radio frequency identification (RFID) tags at key points in the mine.

Keywords: Mining vehicles, fuzzy logic, hybrid maps, behavior-based navigation, autonomous robots, RFID

1 Introduction

In underground mining, LHD (Load-Haul-Dump) vehicles are typically used to transport ore from the stope or muck-pile to a dumping point. A number of reasons have led to the desire to automate the operation of LHD vehicles, thus removing the need to have a human operator constantly on-board the vehicle. First, a mine is generally not offering the best environment conditions for humans. Second, the nature of this task is such that the vehicle and its operator are continuously subject to the risk of being hit or buried by falling rocks, since the load operation is performed in unsecured areas. Third, an automated LHD vehicle could allow reduced operation costs and increased productivity. Fourth, automatic control of the LHD vehicle could lead to less mechanical strain, which would in turn reduce the maintenance costs.

In some mines, tele-operation of LHDs is used to gain safety, but this often leads to reduced productivity since a remote operator is not able to drive the vehicle as fast as an on-board operator. In addition the maintenance cost of the vehicles tends to increase with tele-operation. These facts have led to the desire to automate the whole

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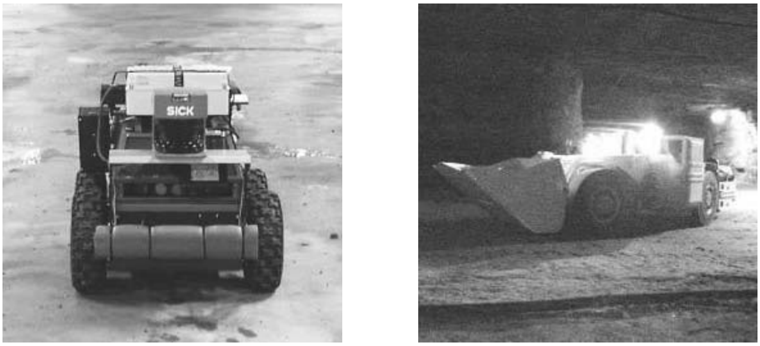

Fig. 1. Left: The ATRV-Jr research robot, carrying the two main sensors used in our experiments, the SICK laser scanner and the RFID tag reader (white box). Right: An LHD vehicle.

tasks performed by the LHD vehicles, or to use a combination of performing some tasks autonomously and others by tele-operation. Since the greatest part of the time in the work-cycle is spent tramming (moving or Hauling), this is the part that is most desirable to automate. This paper addresses the development of a control system that allows the autonomous navigation of an LHD vehicle in a mining environment.

In order to be commercially viable, any solution for the autonomous navigation of LHD vehicles should meet a number of requirements. The solution should require minimal setup and maintenance effort. It should require only little additional infrastructure on the mine, or possibly none at all. It should not require that an accurate geometric map of the mine is hand-coded into the system. It should afford navigation speeds comparable to the ones reached through a human operator (approximately 30 Km/h). Finally, it should guarantee extremely high safety and reliability, that is, faults should have low probability, and there should be mechanisms able to detect these faults and to stop the vehicle.

This paper, present our steps toward the development of a system for automated navigation of LHD vehicles in underground mines that satisfies the above requirements. Our system uses a coarse topological map to represent the mine, and a behavior-based approach to navigate inside the mine using a sequence of reactive follow-tunnel behaviors. No global metric localization is required. Instead, the vehicle uses data from a laser range scanner to maintain its relative position and orientation inside each tunnel, and an intersection recognizer to assess its topological position in the map. Intersections are recognized by a combination of odometry, laser signature, topological structure, and RFID tags. The two main features of this approach are: (1) small setup and maintenance costs, since it only requires to place a passive RFID tag at each tunnel intersection; and (2) high reliability, thanks to the redundancy of the information used.

Our development methodology is in two phases. In the first phase, with focus on localization, we develop our techniques and algorithms on a small research outdoor robot, starting from an existing framework for autonomous navigation [11]. The experiments in this phase are performed in long corridors inside a building, and in a test underground mine. In the second phase, we will port the developed algorithms to a real 30 ton LHD vehicle manufactured by Atlas Copco, and run experiments in the test mine. Figure 1 shows the two experimental vehicles used in our development. This paper reports about the first phase; the second phase will start in the next few months.

The rest of this paper is structured as follows. In the next section, we briefly overview some related systems for autonomous navigation in underground mines. In Sections 3 and 4, we discuss our approach to localization and to navigation, respectively. In Section 5 we present some preliminary experiments performed on the research robot in both the indoor environment and the test mine. Section 6 concludes.

2 Related Work

Several solutions have been suggested and evaluated for automation of the tramming (movement) of the LHDs. Some of these have been in use for quite some time now, while others have recently emerged pushed by the research in the area of mobile robotics.

2.1 Older Solutions

Several solutions to autonomous tramming have been used in mines around the world for quite some time now. These have all been based on some infrastructure that guides the vehicle. Independent of the type all infrastructure based guidance solutions have several drawbacks, such as installation cost, maintenance cost, and inflexibility. Examples of what has been used are inductive wires [5], light ropes and reflexive tape. Common to these examples are the time and cost of installation, while the light rope also suffer from maintenance cost, and unavailability due to damages created by blasting nearby.

These systems also suffers from another major drawback: none of them allows high speed tramming. A manual operator drives the vehicle at its top speed, which is usually somewhere between 20–30 km/h, while the guidance solutions above rarely or never provide possibilities to travel faster than fractions of the top speed. This is due to the fact that all of the line following systems have difficulty of gaining significant look-ahead, since they only sense the line at the current position of the vehicle or slightly ahead of the vehicle.

Experiments with infrastructure-less guidance using ultrasonic sensors to detect the tunnel walls have been performed successful at low speed [12], [10], but the difficulties to get the necessary high resolution look-ahead prevented this system from being able to do any high-speed navigation.

Finally none of the systems above utilizes any form of obstacle detection, which is another drawback in a sometimes unpredictable mining environment.

2.2 Current Products and Recent Solutions

A more flexible system of infrastructure based guidance is used in the LKAB mine in Kiruna, Sweden [13]. This system is based on a bearing only laser scanner that measures the angle to reflexive tapes on the tunnel walls, and allows the vehicle to operate at full speed. The drawback of this robust and highly reliable system is the need to install the reflexive tapes, and to measure the position of the same to be able to integrate them into the guidance map. This system is more flexible than the ones mentioned earlier since once the reflexive tapes are installed and integrated in the guidance map, the path to be followed by the vehicle can be changed in software.

An infrastructure-less guidance system is described in [8]. This system solely depends on dead reckoning, angle/distance laser scanner and the natural landmarks in the mine. During automatic tramming a five-meter section of the scanned tunnel profile closest to the vehicle is compared to a map with known profiles and the position can thus be established. The map, which is a polyline representation of the tunnel wall, on a specific height above the floor (the height the laser scanner is mounted on the vehicle) is created by a teaching procedure. During the teaching the vehicle is driven manually in the tunnel allowing the laser scanners to register the profile of the tunnel wall on each side of the vehicle. The scanner produces 181 measurements per scan, one each degree, but only the ten left- and rightmost are taken into account. These measurements are then fused into a polyline representation of the tunnel wall with the average distance of 10 cm between the points. With this system tramming velocity comparable with human drivers has been achieved with LHD and velocities up to 40 km/h have been tested on mine trucks. Although this system does not need any extra infrastructure for the navigation, it has the drawback that the vehicle has to be driven manually through every path, before it can run there autonomously.

In [4] and [9] an experimental setup of a test track, a mine created by shade cloth, is described and used to evaluate a reactive guidance and navigation system of a LHD. The guidance system utilizes laser range scanners and dead reckoning, together with a nodal map representation of the test track. The 300 m long test track consists of sharp corners, intersections, a hall, and a loop. No extra infrastructure to guide the vehicle is installed. The results of the experiments show that the combination laser range scanner and reactive guidance is a feasible way to perform mine navigation. The test vehicle successfully navigated through the test track for up to one hour at a time without human interaction. Regarding the important issue of speed the experiments showed that the control system is able to run the vehicle at the same speed as an experienced human driver. With this particular LHD the maximum velocity of 18 km/h was utilized at parts of the test track. The only situation in which the control system did not manage to equal the human driver was encountered at sharp intersections, where the control system could not see around the corner. Neither can the human operator, but after a few test runs the driver remembered what the tunnel looked like around the corner, and therefore could approach the corner more aggressively. This approach can obviously be implemented in the control system as well by adding driving hints to the map.

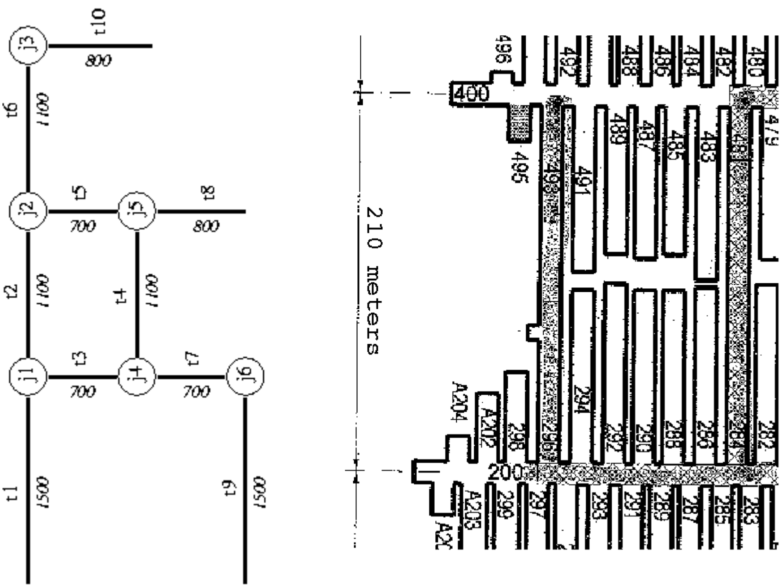

Fig. 2. Maps a) fragment of a sample topological map for a mine, b) fragment of metrical map of our test mine

The same vehicle used in the test track was also tested in a real mine environment. Again, the vehicle was able to operate at full speed through a typical production cycle without installed infrastructure or physical changes to the mine tunnel. The vehicles ability to navigate in previously unseen tunnels was also shown by driving the LHD up the access decline (a 4 km long 1:7 slope), where a human gave high level instructions to guide the vehicle through intersections. Duff et. al. [3] also shows that the control system works on a substantially larger mining machine (60 tonnes instead of the 30 ton LHD) with different hydraulics.

Although localization and navigation using only topological recognition of the environment is successful in many cases, there are some environments in which it proves much harder to localize using only topological information. This can easily be seen by considering, eg., the abandoned mine in which our trial runs have been made (see Figure 2b), where the high density of side tunnels (less than one tunnel width between each side tunnel) makes it difficult for humans to recognize the correct junctions without using further information such as the markings drawn on the walls. For this purpose we use an approach corresponding roughly to the marks used by human operators but more appropriate for automation — by using radio frequency identification tags to place artificial marks at key locations in the mine.

3 Localization

In order to fulfill its navigation task the autonomous vehicle needs some form of map, as well as some means of localizing itself within this map. Because of the cost and accuracy problems with a full metric map we choose to use a hybrid map which augments a topological map with some metric information [1]. This topological map consists of a number of nodes (junctions and positions in tunnels) and edges (traversable paths between the nodes). This topological map can also be augmented with some metric information such as approximate tunnel width and length *when available* but the system functions also without such information. For an example of such a topological map augmented with tunnel lengths see Figure 2a.

One of the strengths of using only a topological map is that it can be constructed at little cost and it can easily be updated when the environment changes. By only providing a topological description there is no constraint on the actual layout of the environment: the map provided in Figure 2a could just as well consist of nodes and tunnels through multiple levels of a mine.

The localization used within the loaders consists of two parts, a topological localization which gives information about which edge is currently being traversed or which node has just been reached, and a metric localization which indicates where the vehicle is positioned within the current tunnel. The purpose of the later is primarily for providing the needed parameters to the reactive behaviors used for tunnel traversal.

3.1 Metric Localization

We compute three types of metric information: longitudinal position along the tunnel, lateral position inside the tunnel, and orientation with respect to the tunnel. The former is used to increase the robustness of the topological localization; the latter are needed by the “FollowTunnel” reactive navigation behavior.

For the lateral localization and orientation within a tunnel we use a laser range scanner. The scanner produces 181 measurements per scan, one per degree and is mounted in the front of the vehicle. Our algorithm processes these scans to provide the rest of the system with the parameters of the detected tunnel segments, together with a certainty factor that depends on the number of reflected laser readings. In addition, our algorithm uses the laser data to detect obstacles for collision avoidance. Our target sampling rate for tunnel and obstacle detection is 75 Hz.

In order to achieve this rate, we have used a modified Hough transform [7] on the 1D laser data to identify pairs of line segments. By allowing some flexibility in the line segments it is also possible to operate in curved tunnels. By only checking for pairs of lines separated by 180 degrees and with a certain minimum and maximum separation it is possible to accurately identify tunnels around the vehicle. Our implementation yields execution times of about 2 ms, well within the requirements for fast navigation. The low execution time is achieved mainly by discarding irrelevant laser points before the Hough transformation is made, but the fact that we do not have to search the entire Hough space for tunnel walls also contributes. Apart from providing

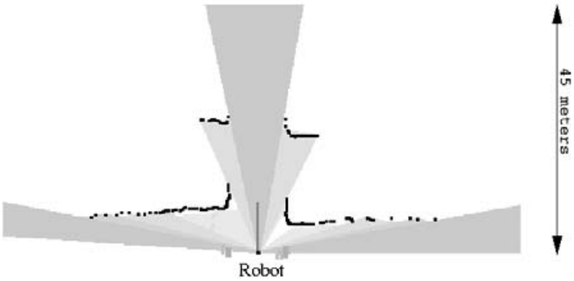

Fig. 3. Identifying open areas and tunnels with a laser range finder

information about the currently traversed tunnel these transformed laser readings are also used for identifying side tunnels which are used in the topological localization.

Figure 3 gives an example of extraction of the edges and direction of a tunnel from laser range data. The data refers to a situation in the test mine, where the robot was about to enter a new tunnel. In the figure, the robot is seen from the top, placed at the center bottom and pointing upward. Laser measurements shorter than the maximum range (80 m) are indicated by black dots. The light gray cones show the identified open areas. The dark gray line indicates the direction of the tunnel segment in front of the robot, found by our algorithm. Notice that the tunnel could be correctly identified even though its walls are interrupted by the entrances of many side tunnels.

The longitudinal position along the tunnels is computed by odometric update, where odometry is given by a combination of scan matching and wheel encoders. The encoder data are very imprecise since the wheel diameter can change by a large amount depending on tire pressure, loaded weight, and tire consumption. However, the combination with the topological localization gives sufficient accuracy for our purposes.

3.2 Topological Localization

The main input to topological localization is node detection and identification: this tells us that we have completed the traversal of one edge and arrived at a node.

To do node detection, we use a redundant combination of four sources of information: (1) longitudinal metric localization inside the tunnel, that tells us when we are near or past the next junction; (2) recognition of the laser signature of a junction from the laser data; (3) recognition of the topological structures, e.g., counting number of side tunnels; and (4) detection of an RFID tag. The latter also gives us the unique ID of the junction, which should match the one in the topological map.

For the first two sources of information (1), (2) we use standard robotic techniques with the normal caveats regarding robustness and deployment. Although by themselves these are not sufficient for our application we use them as a supplementary source of localization information to further increase the robustness of the two other techniques outlined below.

The third (3) source of information can be useful in areas in which the density of intersections is high. In practice, we identify the side tunnels through the laser system and compare the number of observed side tunnels with the topological map, much like a human driver would given the description “take the second turn on the left”. Note that failures may occur, e.g., if the entrance of a side tunnel is temporarily obstructed by another vehicle.

Perhaps the most peculiar of the above components is the use of RFID tags which is used in the last information source (4). This is a flexible and low cost solution for marking up the environment with standardized radio frequency identification tags.

These tags are a low cost, standardized solution for storing and retrieving data remotely in small tags that have found uses in various fields e.g.,. inventory tracking, automobile locks, animal tracking and quality control. There exists many different forms of RFID tags with sizes varying from 0.4 mm square and up, having reading ranges in the order of a few centimeters up to 8 m for passive tags. Battery powered (active) tags have reading ranges in the order of hundreds of meters and typical life lengths of a couple of years. Tags are available for as little as 0.40 USD and expect to drop in price to as little as 0.05 USD as the use of RFID tagging is growing in the industry.

For the application of autonomous navigation in mines we use passive RFID tags in key junctions and equip the LHD with a tag reader allowing us to verify the localization at key points. The deployment of tags can easily be done by untrained staff and noting the position of the tags in the nodes of a simple topological map of the environment is easy.

4 Navigation

The navigation system is organized in the three-layer hierarchical structure represented in Figure 4. The main idea here is to use a coarse topological planner to decide a sequence of tunnels and junctions to traverse, and a set of fuzzy behaviors to perform fast and robust reactive navigation within each tunnel segment.

The bottom layer includes the low-level control and sensor processing algorithms, including the odometry system and the processing of laser data described in Section 3.1.

The middle layer implements a fuzzy behavior-based system. Fuzzy behaviors are easy to define and they provide robustness with respect to sensor noise, and to modeling errors and imprecision [2]. The behaviors that we use were originally developed for indoor, low-speed navigation [11].

The main behavior used in our system is the “FollowTunnel” behavior, which takes as input the parameter (orientation and lateral position) of the tunnel extracted from the laser data as explained above. Other behaviors used in our development

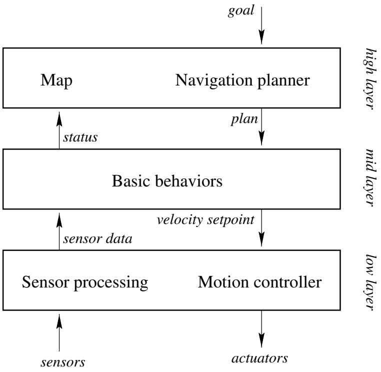

Fig. 4. Hierarchical structure of the control software

include “Avoid” to perform obstacle avoidance, and “Orient” to orient in the direction of the tunnel when entering a new one.

We only needed to modify slightly the original behaviors in order to make them work in our setup and to navigate at our robots topspeed 1.7 m/sec, or about 6 Km/h — the original behaviors were tuned for top speeds of about 0.3 m/sec. Thanks to their qualitative nature, fuzzy behaviors are prone to be transfered from one platform to another with few modifications, see [6]. However, we expect that major changes will be needed when we move to the real LHD vehicle, which is characterized by more complex dynamics and kinematics, less clearance on the sides, and speed up to 30 Km/h.

At the top level, the navigation planner relies on the topological localization described earlier, and decides what sequence of behaviors should be activated in order to reach the given target location. Our planner is based on standard search techniques, and it generates a reactive navigation plan in the form of a set of “situation → behavior” rules. These types of plans are called behavioral-plans, or B-Plans [11].

To exemplify the operations of the complete system we consider the topological map from Figure 2. Assume that the vehicle starts at at the junction `j6` facing in the direction of tunnel `t7` and is given the goal to move to `j5`. The topological planner will then generate the following behavioral plan which will be executed:

```
IF obstacle_near                        THEN Avoid()
IF nextNode(j4) AND NOT oriented(t7)    THEN Orient(t7)
IF nextNode(j4)                         THEN Follow(t7)
IF nextNode(j5) AND NOT oriented(t4)    THEN Orient(t4)
IF nextNode(j5) AND oriented(t4)        THEN Follow(t4)
IF nextNode()                           THEN Still()
```

Avoid, Orient, Follow and Still are fuzzy behaviors, activated according to the fuzzy predicates obstacle_near, nextNode and oriented. j4, j5, t4 and t7 are control system representations of objects in the map, for details see [11].

The laser scanner gives readings which are fed to the avoid-obstacle behavior and used to update the parameters of the current tunnel for the follow behavior. As the vehicle moves these two behaviors make the vehicle follow the center of the tunnel `t4` as long as the topological localization does not signal that the junction `j4` has been reached. When the junction `j4` is detected as described earlier another tunnel is added to the local expectations on the right side, and the laser is used for localizing its exact position and the orient behavior starts up. This behavior uses first odometric information and eventually the laser readings to orient toward tunnel `t4` and when oriented this new tunnel is traversed by the follow behavior.

5 Experiments

5.1 Indoor Trial Runs

In the initial stage we wanted to test the applicability of the system described above when navigating a set of interconnected corridors at a higher speed. For this purpose we staged a number of indoor trial runs using the ATRV-Jr research robot shown in Figure 1 above. These runs were performed in a basement consisting of a number of approximately 2 m wide corridors with a number of junctions, doors, 45 and 90 degree turns as well as a few slightly larger open areas. We started by setting up a simple topological map and placed RFID tags first on the walls and later in the ceiling of the important junctions (see Figure 5a).

Next, a number of runs between a starting point and a target point were made. During the first runs no metrical or RFID information was provided in the topological map, i.e. navigation was solely based on the information extracted from the laser data. This worked well in most corridors and intersections, but in the corridor that included the small open areas the system mistook the open areas as intersections and got lost. After this, two more sets of test runs were made, one using a map with RFID information, the other with coarse metric information added to the map.

By adding RFID information to the topological map the system was able to distinguish between the real junctions and the open areas and reach its target position. However the mounting of the tags turned out to be crucial. All of the runs when the tags were placed in the ceiling were successful and the robot could navigate these corridors at a speed of up to 1.7 m/s. As for the runs with the tags mounted on the walls we experienced a few failures caused by undetected tags since this mounting was outside the specification of the tag/reader combination.

Equal results were achieved with the map with metric information to it, the 150 m long path was travelled as planned in under 180 s despite disturbances as non modelled open doors and recycle paper trailers parked in the corridors.

5.2 Trials from Test Mine

In order to test the techniques in the target environment we have used an abandoned mine, used by Atlas Copco in the testing of LHD vehicles. The mine consists of a

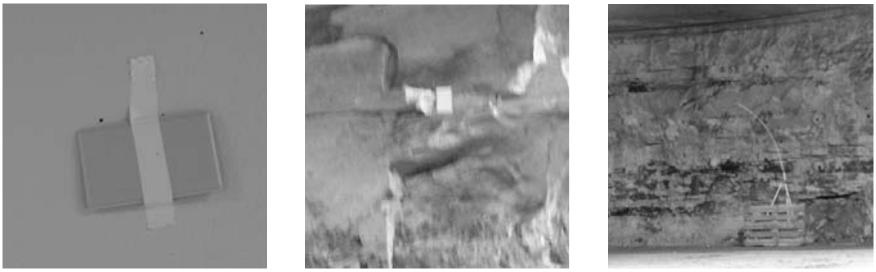

Fig. 5. RFID tags a) in basement, b) on the walls of mine and c) on a stand above center of junction.

number of 10 m wide and 5 m high tunnels with a fairly flat tunnel floor. In the setup of the tests we built a rough topological map consisting of five nodes which should be visited and in doing so a large number of junctions would be passed.[3] Since no accurate metric information where available, we placed RFID tags in the junctions either by placing them on the walls of the tunnels or (for practical reasons) using a 3 m high stand simulating placement in the ceiling. See Figures 5b and 5c for a picture of the tags and their stands.

We used the same ATRV-Jr research robot and control program as above for these tests, only parameter changes to enable detection of the much wider tunnels were made. We used odometry to update localization and RFID tags to re-localize and verify that the correct junctions were reached.

By using the corridor localization technique described in Section 3.1 it was possible to localize the tunnels, which was needed to correct from the large odometry errors caused by the uneven surface. As for the localization of the junctions this was achieved through the RFID tags when the robot passed within a radius of 3 m from the center point under the corresponding tag. By placing the tags higher up (in the ceiling) this radius would be increased sufficiently to make it impossible to miss the readings.

6 Conclusions

In underground mining the development of fully automated systems for the navigation of loaders is interesting for a number of reasons, including safety and efficiency. By combining standard robotic techniques such as fuzzy behavior based systems with some application specific techniques the robustness and usability of fully automated navigation systems for autonomous underground vehicles can be improved. In this paper we have investigated a few problems with implementing such navigation systems and presented a solution based on a hybrid metric-topological map with a number of redundant methods for localization which provides greater robustness than any one solution alone. Though still a project under development, the initial tests of this system in realistic environments look promising.

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[3] From the main tunnels there are side tunnels with a spacing of only about 10 m.

Acknowledgements

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