Autonomous Control of Underground Mining Vehicles using Reactive Navigation

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Abstract

This paper describes how many of the navigation techniques developed by the robotics research community over the last decade may be applied to a class of underground mining vehicles (LHDs and haul trucks). We review the current state-of-the-art in this area and conclude that there are essentially two basic methods of navigation applicable. We describe an implementation of a reactive navigation system on a 30 tonne LHD which has achieved full-speed operation at a production mine.

1 Introduction

In underground mines ore is fragmented by blasting in voids known as stopes. Articulated wheeled vehicles known as Load-Haul-Dump or LHD units (Figure 1) are typically used to move (or tram) ore from the stope to a crushing plant or truck. The rock stresses in the stopes make rock-falls likely, so for safety reasons they are inaccessible to humans.

Typically, ore "flows" from a stope to a safe area where it can be collected by a manually controlled LHD. However, at a certain stage of the mining process, it is necessary for the LHD to enter the stope. This is done by tele-remote or line-of-sight remote control of the LHD. In the latter case, this necessitates the driver having to alight the vehicle each cycle which contributes to increased cycle time and the potential for accidents. For these reasons, some mines are now tele-operating [1] the vehicles for the entire cycle. Whilst they have gained in safety, they have often lost productivity compared with manned LHDs. A tele-remote operator is not able to drive the vehi-
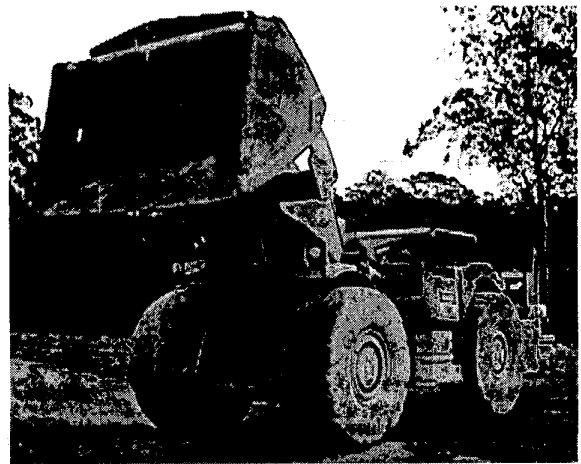

Figure 1: Our experimental Load-Haul-Dump truck.

cle as fast as a driver on board due to limited remote sensory perception.

The full or partial automation of LHDs is therefore a very attractive proposition. There is the potential to increase productivity above tele-remote and remote control levels and to improve safety by removing people from the vehicles altogether. One remote operator could conceivably control or "manage" a small fleet of largely autonomous LHDs. It is expected that the cycle time for autonomous LHDs will be the same as for manned LHDs, but automatic LHDs can operate longer and within design specification.

A strong and recurring theme in the robotics research community is the idea that mobile robots move through *indoor* or *outdoor* environments. There is a wealth of research into mobile robotics in both application areas. It is therefore useful to consider whether

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the underground mining environment is indoors or outdoors in the robotic sense.

The outdoor mobile robot environment is usually assumed to have rough ground of varying slope. It is often assumed that the outdoor world is fairly sparsely populated with objects/obstacles that are randomly distributed. An example of this is the research carried out in the area of planetary exploration [2]. Here it is crucial to obtain 3D terrain maps covering the potential path of the vehicle in order to plan a safe trajectory.

Tunnels in underground mines are somewhat like corridors in an office building in that they have a floor, ceiling and walls. Many of the navigation techniques developed by researchers for indoor applications treat the world as a 2D environment. Typically they employ sensors to follow the walls and look for openings (doorways) to move through. The surfaces in mine tunnels are not smooth and flat like those of an office corridor.

However, for the purposes of navigation we consider the underground mining environment to be similar to the indoor robotics environment in which the areas that LHDs are to operate are highly controlled. Maps are readily available at all underground mines making the indoor comparison even stronger. The aim of this paper is to consider the application of indoor robotics techniques to the automation of underground mining vehicles.

2 Navigation for LHDs

The first generation of Autonomously Guided Vehicles (AGVs) were developed in the '60s, '70s and early '80s. These AGVs followed rail-type guides placed in the environment to aid navigation. Popular techniques included following buried wires or painted lines in or on the floor. Other robots used a rotating laser to find the bearing to fixed reflective strips placed around the work place. Robots like these are now in common use around the world. These systems work very well and are extremely reliable. They were designed for factory type situations where speeds are low, floors are smooth and flat, and more importantly, where the route or routes remain fixed for long periods of time (sometimes years) and can thus justify the expenditure on installation and continued maintenance of navigation infrastructure.

2.1 Absolute navigation

A common navigation technique used in both the indoor and outdoor environments is that of *absolute* navigation. Here, the absolute position with respect to some fixed real-world coordinate system is known at all times (known as localisation). A path for the vehicle to follow is given in the same coordinate system and the vehicle attempts to maintain the desired path as accurately as possible. The control problem is using estimated pose to keep the vehicle following the predetermined path. Examples of path following control for LHDs may be found in [3] and [4].

The estimated absolute position of the vehicle is normally obtained by fusing data from on-board sensors, such as inertial navigation systems (INS), odometery and heading angle data, etc. The estimated position is periodically updated (corrected) by means of an external absolute position measurement. This measurement may come from GPS in the case of outdoor vehicles, or from the detection of artificial beacons (e.g. retro-reflectors or radio transponder tags) or natural features (e.g. unique tunnel profiles if using a laser scanner, etc) in the case of indoor vehicles. Data is typically fused using a Kalman filter.

Makela, et al. [5] described a navigation system for an LHD which used dead reckoning (incorporating odometry, a ground-speed radar and a fibre optic heading gyro) which was periodically corrected at least every 50 m using passive LC resonators or retro-reflective circles attached to the roof (detected by a row of optical switches).

In 1997 Q-Navigator [6] tested their system, based on a bearing laser scanner and retro-reflectors, on an LHD in Kiruna mine, Sweden. They used odometry and an articulation angle encoder, but no heading gyro. They successfully demonstrated full automatic driving of the LHD at the vehicle's top speed (22 km/h). The Q-Navigator system was based on a navigation system by NDC for AGVs that has been installed on more than 700 AGVs in factories around the world since 1991.

Madhavan, et al. [7] proposed an absolute localisation system that achieved position correction without the use of artificial beacons. They used a map consisting of short line segments which approximated the geometry of the tunnel walls. The map was constructed using a 2D laser range finder and the same laser was used to generate on-line tunnel profiles to match to the map.

A fundamental failing with the absolute navigation methods described above is that they are actually "blind" to their environment. Instead of "looking"

around and "seeing" where to go, they rely totally on the fact that their estimated position is very accurate and that the path that they are following is also accurate.

2.2 Reactive navigation

A simple type of navigation which has been used since the 1960's is that of *reactive* navigation, in which an AGV simply reacts to something in its immediate environment in order to continue moving forwards. These systems normally couple the sensor(s) with the steering actuators at a very low-level.

Reactive navigation can be thought of as *relative* navigation. Reactive navigation is a form of "active perception" [8] which says that instead of consulting a model of the world, consult the world with appropriate sensors. For the robot to move through the environment, it does not need to "know" with any accuracy where it is in the environment with respect to some global co-ordinate frame. It only needs to "know" where it is relative to the navigation infrastructure or local objects. Reactive navigation systems do not need to perform any path planning at the global scale and may not even need path planning at the local scale.

An example of a reactive navigation system is that found on an AGV that can follow a painted line on a factory floor. Such systems are common place today and can be constructed using a few photo-detectors placed in a row with the aim being to keep the centre of the detection row over the painted line. Little "intelligence" is need to follow the line.

Systems based on this basic principle, using retro-reflective lines, or lines of lights, on the ceilings of tunnels have been tested in mines [9, 10] and some are available commercially. These typically use CCD cameras to detect the relative position of the line. The automotive industry have also investigated navigation methods based on following the painted lane markings found on the road [11, 12].

A weakness of the line-following approach in mining AGVs is the difficulty in gaining significant look-ahead. Look-ahead is crucial if high-speed autonomous motion is to be achieved. All the currently available line-following systems sense the line immediately above, or slightly ahead of the vehicle. The difficulty of driving at speed using this approach can be comprehended when it is realised that this is equivalent to driving your car by following a line on the road by looking through a hole in the floor!

In the case of an LHD, the most logical way to stay in the middle of a tunnel, and the way a human driver does the job, is to observe the tunnel walls and avoid

hitting them. Significant look-ahead can be achieved by sensing the walls ahead of the vehicle. Wall following has been popular with the indoor AGV community for the past decade. Many of the robots used ultrasonic sensors, laser rangers or radar for wall detection. The (lateral) control problem is now one of keeping the vehicle in the centre of the tunnel and not hitting the walls. Wall-following techniques based on ultrasonic [13–15] sensors have been described for underground mining applications. Two techniques that seem suited to wall-following in the underground mining environment are *potential field* and *neural network* methods.

2.2.1 Potential field methods

Potential field methods of navigation have been described by robotics researchers for a number of years [16]. The general idea behind the methods is to treat the vehicle as a particle that is attracted by a potential field radiating from its goal and repulsed by potential fields radiating from obstacles. A local path plan may then be formed by applying a force, based on the sum of the potential fields, to a general desired path whose end is fixed to the vehicle. Such schemes are normally iterative in nature and are hence amenable to real-time implementation. Asensio et al. [17] developed an AGV based on the Labmate robot that used a potential field method to move around an office environment. Their system used a scanning laser rangefinder to detect the walls and perform wall-following. Scheding et al. [18] described a local path planner based on a popular potential field method. The local path was created by applying the summed potential field to a straight line segment that began at the vehicle and pointed in the direction of the goal. Potential field methods are very similar in principle to the *active contour* methods described by Blake and Isard [19] which are commonly used in image processing and computer vision applications to segment scenes.

2.2.2 Neural network methods

Reactive navigation systems based on neural networks are also amenable to the wall-following problem and are also fast to execute and hence appropriate for use on high-speed AGVs. Pomerleau [20] described how a vehicle was taught to steer using a neural network. An association between sensor data and steering angle was made which allowed the vehicle to steer through previously unseen terrain. Learning in this case took place off-line. Dubrawski and Crowley [21] presented a neural based navigation method that enabled an AGV

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to learn on-line using a trial-and-error method. Their AGV was equipped with 24 ultrasonic range sensors and an odometer. A goal position was set by a human supervisor or by an external path planner.

2.3 Which way do I go?

At some point in time on its journey, an AGV using a reactive navigation system will encounter a situation in which it needs to *decide* which way to go in order to reach its *goal*. An example of this is when an LHD reaches a Y or T-junction in the tunnel. However, the structure of these decision points makes their detection easy [22]. There are two solutions to this problem both based on human methods:

1. *Absolute position information and a map.* If an AGV has a global map of the mine and it has localisation information, then it is possible to make a decision. Note that localisation accuracy does not need to be high, but only good enough to determine that it is approaching junction A, or junction B from a particular direction. The human equivalent of this situation is being given a map of a city and being told where you are and where to go. Beacons such as radio tags or bar codes located near the decision points (normally intersections) can be used to obtain absolute position information. Natural features may also be used as localisation beacons. Asensio et al. [17] demonstrated an AGV that could move around offices and through doorways while avoiding obstacles in its path. They used a scanning laser rangefinder to relocated the position of the AGV with respect to the doorway and hence reset any drift accumulated during odometry based position estimation.

2. *A relative route map.* An AGV can be given a sequence of instructions in order for it to reach to its goal. For example, it may be told to drive 100 m and turn left at the next T-junction, continue for 230 m and turn right at the next intersection, and finally stop after 50 m. This method is analogous to the way in which humans verbally describe a route. Such a technique was used by Tsubouchi et al. [22] to guide a vehicle in an office building environment. They used laser scanners to perform low-level reactive wall-following.

2.4 Summary

Both absolute and reactive navigation techniques have been, and are being developed to guide au-

tonomous vehicles in mine tunnels. The data fusion (absolute) and wall following (reactive) navigation systems described above have a significant advantage over the rail guide following approaches (reactive) in that they require considerably less infrastructure, only needing beacons to reset their position estimates every 10 to 50 m, or requiring no beacons at all. This leads to lower installation and maintenance costs which can be significant over large areas of a mine.

3 Our project

3.1 The approach

Since July 1998 our group has been developing an autonomous navigation system for an LHD. Our testbed includes a 30 tonne LHD and an artificial test mine constructed out of shade-material. The LHD is an ex-mine machine with on-off steering control (new LHDs have proportional steering control). The test mine has approximately 300 m of tunnels and contains sharp corners, intersections and a loop.
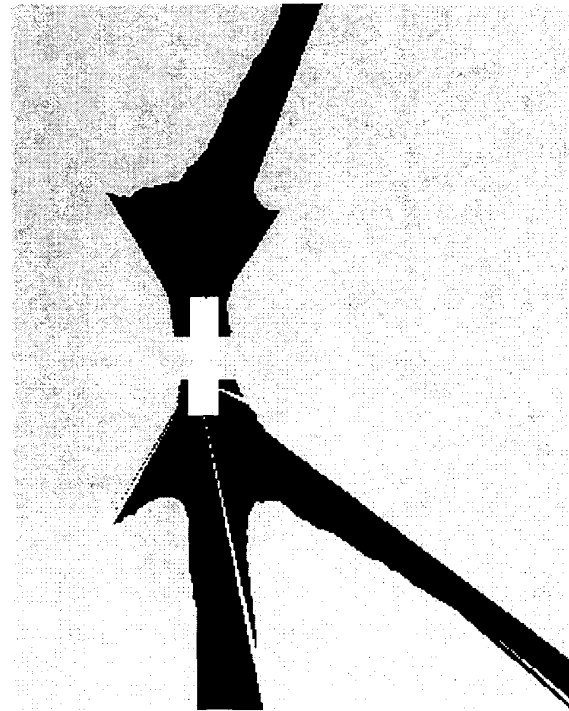

Figure 2: Data from front and rear 2D laser scanners.

In 1996 a joint CSIRO/University of Sydney (ACFR) team, under the auspices of the CMTE, ex-

plored sensing options for LHD navigation at Mt Isa Mines in Queensland [23]. Data were collected from a number of sensors mounted on an LHD with the aim of determining which sensors performed best underground. This project led directly to the current industry funded project including the same researchers.

We have developed a reactive navigation approach based on wall following and we are using a laser scanner as our primary sensor (Figure 2). Wall following alone is not sufficient to guide the LHD to its goal (Section 2.3). We are therefore using a relative route-map to guide the LHD to its destination. The route-map can be defined as a list of nodes that the vehicle must pass through. The nodal-map can be constructed from a physical map of the mine, or it can be constructed by driving the vehicle along the path and parsing the observed data. The identification of nodes is also based upon range data from the laser scanner used by the wall-following algorithm.

3.2 Results

The results so far are very promising. Since May 1999 our LHD has been able to drive at full-speed around the test mine. Sharp corners can be accomplished with ease. In July 1999 the LHD was taken to a real mine for testing. Again, the vehicle was able to operate at full-speed through a typical production cycle without installed infrastructure or physical changes to the mine tunnels. Simple route-maps we generated containing high-level navigation commands such as turn left after 100 m, stop after 54 m, etc, in a similar fashion to Tsubochi et al. [22].

Figure 4 shows the distance to the tunnel wall during a 30 second section of an automated run. Note that data from Figure 2 were obtained 13 seconds into the run. Figure 3 shows both steering angle and velocity over the same 30 second autonomous run. The potential to use these techniques on autonomous haul trucks was also explored by autonomously driving the LHD up the access decline (a 4 km long 1:7 slope). Instead of a pre-calculated route-map, a human gave the high-level instructions at intersections. This demonstration showed the ability of our system to navigate in previously unseen tunnels.

4 Conclusions

We have described how many of the techniques developed by the robotics research community over the last decade may be applied to a class of underground mining vehicles (LHDs and haul trucks). We consider
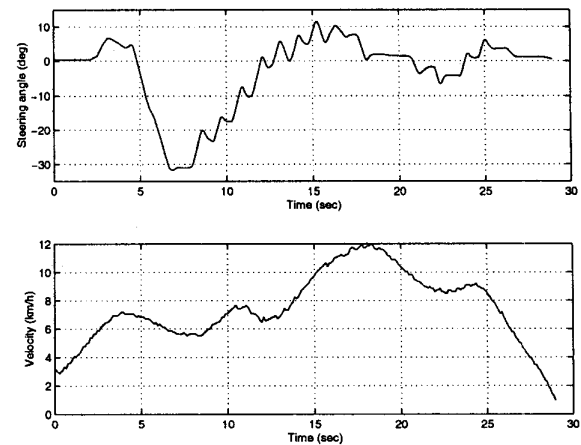

Figure 3: Top: steering angle vs. time, bottom: velocity vs. time.
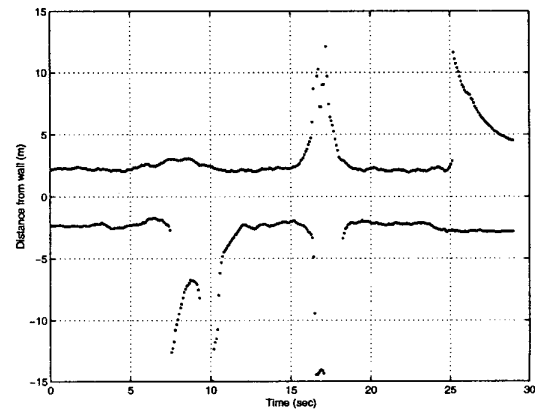

Figure 4: Distance from the wall vs. time.

the underground mining environment has similarities with the traditional indoor robotics environment and have hence investigated the use of indoor navigation methods to the mining environment. We have developed and implemented a reactive navigation system on a 30 tonne LHD. Full-speed performance of the autonomous LHD has been demonstrated at both our artificial test mine and at a production mine. The ability to navigate long distances (4 km) through previously unseen tunnels has also been shown.

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