AN OVERVIEW OF THE AUTOMATION OF LOAD-HAUL-DUMP VEHICLES IN AN UNDERGROUND MINING ENVIRONMENT

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Abstract: This work is a survey on the automation of load-haul-dump trucks in underground mining. Background on the purpose of LHD vehicles is given and the need to automate LHDs discussed, with emphasis on the underground mining environment. Safety issues regarding mine personnel and mine vehicles are considered. Dynamic and kinematic modelling techniques including slip and no-slip models are discussed. Navigation of the LHD through the mine using absolute and reactive navigation are given and sensor technology is perused.

Keywords: LHD, load, haul, dump, slip model, no-slip model, safety, unmanned, robotics, autonomous, automation, underground mining, error model, extended Kalman filter, absolute navigation, reactive navigation, potential field methods, SLAM, CML

1. INTRODUCTION

Mining is an important global industry; however in today's economy it is essential that the mines remain as productive as possible in order to remain economically viable. Most of the productivity increases have been achieved through mechanisation making use of electrical and diesel powered machinery. In spite of this the mining industry has been slow to make use of robotics and automation technology (Duff *et al.*, 2002).

There is an increased risk of serious injury to humans having to work with heavy machinery in confined spaces as well as the long term injuries caused by inhalation of dust and exhaust fumes in poorly ventilated underground work tunnels or skeletal and soft tissue damage from machine vibration (Corke *et al.*, 1999).

Many underground mining tasks are also repetitious and tedious (Steele *et al.*, 1993). One such task is performed by an LHD (Load, Haul and Dump) vehicle that is used for the transportation of ore from the underground voids known as stopes, (where the ore is fragmented by blasting), to an ore pass from where ore is transported by gravity to another handling point. The LHD and its operator move back and forth along the mine tunnel, which is typically a few hundred metres long, hauling the ore. The more repetitions of this cycle that are completed within a shift the higher the production.

This survey focuses on evaluating robotic control and navigation schemes for practical implementation on an LHD as an autonomous mobile robot in underground mines.

This section poses the requirements of LHD vehicles as underground autonomous vehicles. Section 2 describes modelling techniques of the LHD for control design and section 3 describes navigation of LHDs in an underground mining environment.

1.1 Load-haul-dump vehicles

LHDs are produced by a number of manufacturers and are available in different models of various sizes using either diesel or electric power. The vehicles typically vary in length from 8 meters to 15 meters, and weigh between 20000 – 75000kg and have a transportation capacity of up to 25000kg. The vehicle's body consists of two parts connected together by means of an articulation joint.

The front and rear wheel sets are fixed to remain parallel with the vehicle's body and vehicle steering is achieved by means of hydraulic actuators altering the articulation angle of the vehicle.

An articulated vehicle is preferable in the narrow environment of an underground mine because of its higher maneuverability (Altafini, 1999). Altafini (1999) has also proven that the articulated truck can be modeled by a drift free nonlinear system, with two inputs, namely speed and articulation angle, which is controllable.

A characteristic of multi-axle vehicles is that during cornering the midpoints of their axles tend to follow different trajectories. The difference between these trajectories can be used as a measure of how cumbersome the vehicle is. Fig. 1 shows a comparison between the difference in trajectories of the midpoints of the axles (referred to as the off-tracking error) of a car-like vehicle and an articulated vehicle (Altafini, 1999).

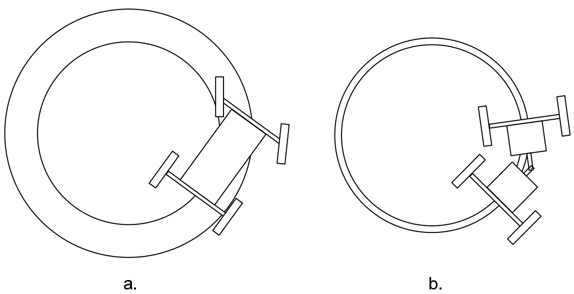

Fig. 1. Comparison between car-like vehicles (a) and an articulated vehicle (b).

1.2 The need for automation

LHDs are uncomfortable vehicles because they have a low profile for an on-board operator and visibility is made difficult by the fact that the operator usually sits almost at eye level with the top of the vehicle (Eger *et al.*, 2004). Several blind spots are created due to the bucket, extinguishers, well covers *etc.* Stereo vision using digital cameras have been studied to aid the visibility of the operator (Whitehorn *et al.*, 2003). The stopes from which the LHD is required to collect ore are hazardous due to the high rock stresses and the likelihood of rock-falls, making them inaccessible to humans. For this reason the LHDs are operated remotely at present, requiring the driver to alight from the vehicle every cycle, which increases the cycle time and the possibility of injury to the driver. In order to prevent this, some mines are now teleremotely operating the LHD vehicles for the entire cycle from above ground (Baiden, 2001; Steele *et al.*, 2001). While this has lead to improved safety, these systems unfortunately also lead to a decrease in productivity. The sensory perception of the drivers operating the vehicles from above ground is decreased causing running speeds to be lower, resulting in lower production levels and the additional economic overhead of the infrastructure required for teleoperation.

Several autonomously guided vehicle (AGV) systems have been tested in underground mines. Most of these systems have been based on AGV systems used in industrial environments and are optically guided by means of cameras that follow an optical guide made of a retro-reflective stripe or a light emitting rope in the tunnel roof (Hurteau *et al.*, 1992). A commercial high speed underground navigation system called Q-Navigator (Wigden and Tyni, 2004) is also available which makes use of retro-reflective tape mounted on holders on the tunnel walls and a rotating laser scanner. The angle of the rotating head of the scanner is recorded when the beam is reflected back into the scanner. The measured angles together with a map of the reflector positions are used to determine the position and heading of the vehicle in order to navigate.

This approach has proven very effective in industrial manufacturing environments and has also proven to work in the underground mine environment. Unfortunately, due to the ever changing and unstructured environment of the mine tunnel, this approach is not desirable as a large amount of extra infrastructure is required to be installed (Makela, 2001*b*).

As described by Makela (2001*b*) the navigation system should be on-board the vehicle and require no extra infrastructure in the tunnel, and allow the LHD to drive at full speed so as not to lose productivity. It should also be simple and take a short period of time to take a new route or change an existing route. Makela (2001*b*) also suggests that teleoperation should be an integrated and seamless part of the navigation system.

These requirements are very challenging to meet as mines place a high demand on reliability in a harsh physical environment that is often hot, occasionally dusty and wet.

1.3 The robotic environment

Mobile robotics research can be divided into indoor and outdoor environments and there is a large amount of literature available in both areas. It is therefore necessary to consider which category the underground mining environment resembles more closely so as to make use of the wealth of previous research in these fields.

The outdoor mobile robotic environment is typically characterized by rough terrain, where knowledge of the vertical elevation of the terrain is necessary to plan a path. Global positioning system data is also usually available for use in outdoor navigation, which is not the case for navigation of underground mine vehicles (Dragt *et al.*, 2003). In contrast, the indoor environment consists of rooms, corridors and a planar floor, allowing navigation techniques to be developed which treat the world as a two dimensional environment. Typically sensors can be employed to follow walls and look for openings such as doorways to move through. As the walls are smooth, flat, and vertical it is possible to assume that the space the sensors detect at their height above the floor, also exists at the ground level. It is therefore safe for the robot to navigate through the area.

The underground mining environment in which the LHD vehicles have to operate, although physically harsh and time varying due to ongoing mining activities, resembles the indoor robotic environment more closely. This is due to the fact that they have a floor, ceiling and walls much like a corridor. The only small difference is that the floor of a tunnel is usually dirt that is not as smooth or entirely flat like that of a corridor.

In general, however, each level of an underground mine can be considered as a horizontal plane, although in some places spiral ramp roads are used to link different levels. Maps of each level are readily available and due to the approximately rectangular cross section of most underground tunnels it is possible to use indoor mobile robot navigation techniques for the automatic navigation of underground mine vehicles (Roberts *et al.*, 2002).

1.4 The requirement for underground automation

Automation of LHDs has been studied for at least the last fifteen years (Makela, 2001*b*). The study has concentrated on automatic navigation in a tunnel, which is often referred to as guidance, which requires both positioning of the vehicle as well as kinematics and dynamics to keep it on a reference trajectory. Automatic loading of the bucket has also been studied but this has proven very challenging and is beyond the scope of this survey.

There have been two main approaches in research on a navigation system for an LHD, namely absolute navigation, in which the position of the vehicle is referenced to some fixed real world coordinate system, and reactive navigation in which the LHD reacts to something in its environment in order to continue moving forward.

There are generally four main tasks that need to be completed by an autonomous vehicle in some form or another in order to achieve successful autonomous navigation, namely sensing the environment, building its own representation of the environment, locating itself within the environment and finally planning and executing efficient routes in this environment (Madhavan *et al.*, 1998). These tasks are more significant in an underground mine for reasons of safety and efficiency.

1.5 Safety considerations

Safety is a critical issue for all autonomous vehicles. The most significant issues as outlined by Corke *et al.* (1999) are:

- Safety to personnel. In an underground mine environment this is straightforward as access to the work area can be restricted by means of electronically guarded access points. Should it be necessary for a worker to enter the operating area of the autonomously guided vehicle they can be fitted with active or passive tags to notify vehicles of their presence
- Vehicle obstacle. Detection is necessary as a last-resort mechanism to protect the vehicle from colliding with other vehicles or personnel. However, the vehicle dispatching system and the personnel access control systems should normally negate such situations. Obstacle detection is also necessary for preventing collisions with rock falls, broken down vehicles, or dangling overhead pipes.

- Breakdown detection. A fail-safe method of determining a vehicle breakdown is required. In the event that a serious failure prevents the vehicle from communicating with the supervisory system the location of the vehicle may need to be inferred from its last reported position. A repair or recovery crew would then need to be dispatched and the other autonomously guided vehicles whose path is blocked by the broken down vehicle need to be rescheduled or rerouted. A severe failure, such as fire, should activate an on-board fire suppression system and communicate with the mine ventilation system.

From these safety requirements it is clear that the navigation system of the autonomously guided vehicles is required to integrate with the mine management and vehicle dispatching systems. In order to implement such a system—according to Baiden (2001)—automation is only one component of a much larger system with the following fundamental components:

- Telecommunications
- Positioning
- Software
- Electronics
- Mining Engineering
- Organization

2. LHD MODELLING

In order to design a navigation system for an autonomous vehicle it is necessary to have a vehicle model (Genta, 1997) that describes the vehicle's position and other vehicle parameters as a function of time. There have been two main approaches in modelling the LHD vehicle, the first is derived from rigid body and rolling motion constraints. The second model is based on the first but introduces two slip variables which are chosen to represent the angle between the kinematic velocity perpendicular to the vehicle axles and the true velocity of the vehicle. The former is commonly referred to as the *no-slip* (or kinematic) model and the latter the *slip* (or dynamic) model.

There has been some debate as to which model is required in order to implement an autonomous navigation system (Ridley and Corke, 2001) as the increased complexity of tyre slip, suspension effects *etc.* increases the computing power required on the actual vehicle in order to implement the navigation systems. There have been several mathematical models developed. Hemami and Polotski (1996) and Polotski (2000) present a no-slip model with experimental results, but their models have however not been tested on the navigation of a physical mining vehicle as is the case with the works of *e.g.* Scheding *et al.* (1999) and a physical articulated truck as in Chen and Tomizuka (1997). LHD vehicle models generally exclude tyre dynamics (see Baraket and Fancher (1989) for an extensive treatment of tyre dynamics) and suspension.

2.1 No-slip model

Due to the confined nature of the environment the LHD vehicles usually operate at relatively low speeds, typically below 28 km/h. For this reason the path-tracking problem can be based on the kinematic model only. This is due to the fact that the dynamics of the vehicle and tyre deformation have little effect and may be neglected at these speeds (Hemami and Polotski, 1996; Polotski and Hemami, 1997)

These models are based on the assumption that the front and rear wheel velocities of the LHD are identical and that the articulation angle remains constant. However, the drive-train of most LHDs delivers equal power to both the front and rear sets of wheels through the transmission. This requires that wheel slip must occur when the rate of change of the articulation angle is not zero. This means that the rolling motion constraint of requiring that there be zero velocity in the direction of the axles is not valid, causing the model to overestimate the rate of change of orientation or heading.

2.2 Accounting for slip

In order to take into account that the vehicle will slip during motion, Scheding *et al.* (1999) have introduced two slip variables, α and β (using single-line or bicycle models). These variables represent the angle between the kinematically represented velocity, which is perpendicular to the axles and the true velocity and are therefore referred to as the slip angles. Any deviation between the true and kinematic velocities is by definition dependent on slip.

In deriving their model Scheding *et al.* (1999) reference all quantities to the rear of the vehicle as this is the position where the sensor array was located on their physical vehicle, and as they consider the articulation angle to be an uncertain parameter in their model, this makes co-ordinate transforms from the front to the rear of the vehicle a non-trivial task. In order to obtain the model they determine the velocity of the rear of the vehicle in the direction perpendicular to the velocity of the front of the vehicle and equate it to zero.

It is evident that the vehicle moves in the direction given by the sum of the slip angle and the heading angle. The rate of change of the heading angle is dependent on the slip angles, the articulation angle and the time derivative of the articulation angle.

2.2.1. Effects of inclusion of slip When comparing the no-slip and slip models it is quite evident that the two models are significantly different. The no-slip model overestimates the turning rate of the vehicle, causing the navigation system to have to continuously correct for the modelling error (Scheding *et al.*, 1999). The slip model is far more accurate if the slip angles are known. However, it is not possible to directly measure the slip angles and hence an Extended Kalman Filter (EKF)—as described by Brown (1983)—is used to estimate the unobservable parameters of the model (see also Lindgren *et al.* (2002)). In order to use the EKF to estimate the states it is necessary to derive an error model for the system.

2.3 Error model

The main sources of error for the no-slip model are due to the time varying parameters such as the articulation angle, rate of change of the articulation angle, slip variables and angular velocity of the wheels. Errors in these parameters propagate directly to the states, however the articulation angle, rate of change of the articulation angle and angular velocity of the wheels represent well known control inputs and it is therefore not required to estimate these parameters using the EKF.

It is necessary to estimate the slip parameters as well as the effective wheel radius, R, of the vehicle. Due to loading and wear, a typical LHD tyre may vary in radius by as much as 20cm (Scheding *et al.*, 1999), which can lead to excessive errors if a constant wheel radius is assumed for the entire life of the tyre.

Therefore, the states that need to be estimated are the position, orientation or heading, the slip angles as well as the wheel radius. The errors in the control inputs are modeled as additive noise about the respective means at time t.

The errors in the radius and slip angles are however more difficult to model as they involve a combination of other parameters which are fundamentally dependent on vehicle dynamics such as the slip angle changing with varying vehicle speed, mass and tyre-terrain in a non-linear manner. For this reason a compromise is used and the errors are modeled as random walks, or Brownian motion (Brown, 1983).

The noise sources are assumed to be zero-mean, uncorrelated, Gaussian sequences for the purposes of the design of the EKF. Although in practice these parameters may not evolve in a Brownian manner. The Brownian model reflects the growth in uncertainty in their true value and the rate at which their true value is expected to vary.

The observation model used as well as the complete derivation of the EKF and the discrete time vehicle model is available in Scheding *et al.* (1999) for their specific case.

3. NAVIGATION OF LHDS

The first generations of mobile robots developed in the ‘60s, ‘70s and ‘80s followed rail type guides in the environment such as buried wires in the floor or painted lines to aid navigation (Roberts and Corke, 1997). These systems perform well and are extremely reliable; however, they are designed for factory type situations in which speeds are low and the floor is smooth and flat. The route to be traveled also remains fixed for long periods of time in the factory environment and it is therefore possible to justify the economic expenditure of installing the navigation infrastructure. This is not the case in the underground mine environment. As described earlier the underground mining environment lies somewhere between the traditional indoor and outdoor mobile robot environments and it is undesirable to install large amounts of infrastructure due to the changing nature of mine tunnels and the hazardous environment in which humans have to work to install such infrastructure.

3.1 Navigation Techniques

3.1.1. Dead Reckoning Dead reckoning is the most widely used navigation technique for determining the pose of a mobile robot. It provides good accuracy in the short term, is inexpensive to implement and allows high sampling rates (Makela, 2001*a*). An additional advantage of dead reckoning is that all navigation equipment can be contained on-board the vehicle. As described by Makela (2001*a*), dead reckoning measures the two dimensional or three dimensional motion of the vehicle and determines the position by integrating the speed vector. The length of the speed vector is the distance travelled and the direction is in the direction of the motion during that sampling interval.

There are several methods of determining the distance travelled by the mobile robot. The simplest method being to measure the rotation of the wheels of the robot. Alternatively ground speed radar can be used which is based on the Doppler effect. Another alternative to determine the distance travelled is to double integrate the acceleration of the robot.

Odometry The simplest form of dead reckoning is called odometry. As the name suggests the motion of the robot is measured by measuring the rotation of the wheels. Odometry requires instrumentation such as optical encoders directly coupled to the wheels axles or proximity sensors to detect cogs on the wheel. The heading can be calculated by measuring the distance travelled by the left and right hand side wheels which is called differential odometry (Makela, 2001*a*). Borenstein *et al.* (1996) lists the typical error sources related to odometry namely:
Systematic errors:

- unequal wheel diameters
- average wheel diameter differs from nominal wheel diameter
- misalignment of wheels
- finite encoder resolution
- actual wheelbase differs from nominal wheelbase

Non-Systematic errors:

- travelling over uneven surfaces
- travelling over unexpected objects in the ground
- wheel slippage due to:
  - slippery terrain
  - over acceleration (wheel spin)
  - fast cornering (skidding)
  - non-point contact with the ground
  - external forces (interaction with external bodies)

A distinction between systematic and non-systematic errors is of great importance for odometry error reduction. Systematic errors are serious because they accumulate over time. Non-systematic errors occur unexpectedly and typically result in large position errors. There are techniques which can be applied in order to reduce odometry errors as described in Borenstein *et al.* (1996). However in the best case the odometry error is in the region of 0.1%-0.5% of the distance travelled. There is unfortunately no upper limit to the error (Makela, 2001*a*).

3.1.2. Inertial Navigation An Inertial Navigation System (INS) is an entirely self-contained navigation system. The system measures accelerations in each of the three directional axes. These accelerations are integrated over time to obtain the velocity, position and attitude of the vehicle. Inertial navigation makes use of gyroscopes and accelerometers to measure the state of motion of the robot by noting changes in the state caused by accelerations, (Makela, 2001*a*); in this way by knowing the starting point of the robot one can keep track of its current position. Although inertial navigation seems less prone to errors in comparison to odometry, as it is not dependent on ground conditions, inertial navigation systems are very prone to drift. This is because the position measurements are dependent on double integrations of the accelerations. Regardless of the sensitivity of inertial navigation systems to drift it is possible to obtain sufficiently accurate systems. However, the price is prohibitive to the practical implementation in the autonomously guided vehicle industry (Borenstein *et al.*, 1996). According to Borenstein *et al.* (1996), a high-end INS package for ground applications with an accuracy of 0.1% of the distance travelled would cost approximately \$100 000 to \$200 000. The main challenge for inertial navigation in the future is to manufacture accurate gyroscopes and accelerometers at a reasonable price.

3.1.3. Data Fusion Methods Data fusion methods refer to navigation techniques which make use of an approximate estimate of the vehicles position and heading, provided by means of dead reckoning, and a method to update the estimate periodically. The vehicle will typically make use of a map of the environment and a sufficient means of sensing natural or artificial beacons. Knowing the position of the beacons on the map and measuring the distance and heading to the beacons it is possible to reduce the dead reckoning error and improve the estimate of the vehicles position and heading. Typically a Kalman filter would be used for this data fusion (Makela, 2001*a*).

Artificial Beacons Artificial beacons are objects placed in known positions within the environment for the purposes of navigation. The installation of the beacons requires, however, a large amount of building and maintenance work. Active beacons also have a further disadvantage in that they require a power source for each beacon. Artificial beacons do have the advantage that they can be designed in such a manner that they are easily and reliably detectable in the particular operational environment in comparison to natural beacons.

In order to calculate the pose of a vehicle in two dimensions either the distances or bearings to three beacons can be measured and used to calculate the position and heading of the vehicle by simple geometry. This process is referred to as trilateration if it is based on known distances or triangulation if it is based on known bearings (Makela, 2001*a*). The distance measurement methods can be divided into the following groups, (Makela, 2001*a*):

- Triangulation
- Time-of-flight
- Phase shift measurement
- Frequency modulation
- Interferometry
- Swept focus
- Return signal intensity

Triangulation is in this case a range measurement method which obtains the range to a beacon based on angle measurement. An example of this is stereo vision systems in which two cameras in a known configuration pointed at the same scene and image analysis are used to find common objects in the image. The displacement between the objects common to both images is inversely proportional to the distance. Systems that measure the bearing to several beacons can be divided into the following groups,

- Rotating laser
- active beacons detected by camera with special optics
- radio location

Details of various artificial beacon navigation techniques are given in Makela (2001*a*), which includes global positioning system (GPS) navigation techniques as an artificial beacon based method which has the advantage of not requiring beacons to be installed in the environment. GPS navigation is however only useful in outdoor navigation environments and therefore is not suitable for underground mine vehicles.

3.2 Absolute navigation

In this navigation scheme the absolute position of the autonomous vehicle is known at all times relative to some fixed real-world co-ordinate system. In this technique the path for the vehicle is defined in this same co-ordinate system and the vehicle attempts to remain on the designed path as accurately as possible. This path-tracking problem for an articulated vehicle is addressed by Hurteau *et al.* (1992) and Bolzern *et al.* (1998).

In order to implement an absolute navigation system it is necessary to estimate the absolute position of the vehicle, which is referred to as localization. This is usually achieved by means of fusing data from on-board sensors such as inertial measurements and heading angle measurements and external measurements such as odometry. Unfortunately, such measurements are prone to errors which accumulate over time and it is therefore necessary to periodically correct the position estimates by means of artificial beacons such as radio tags or reflective markers. The position estimate together with a map of the tunnels is used to navigate the robot through its environment. Collisions are avoided by means of range sensors being laser, or ultrasonics, which need to be capable of detecting the tunnel walls and any obstacle that may occur in the tunnel.

Autonomous vehicles that navigate by means of the data fusion algorithm are more flexible in their use as they do not require expensive rail guides. Such vehicles are still limited by the coverage of the available maps and artificial beacons. However, maps are readily available in the underground mining environment and there are a number of navigation systems that operate using this type of architecture.

The first absolute navigation system discussed is that of Q-Navigator. This is an absolute navigation system that is commercially available and has been implemented on over 700 autonomously guided vehicles (Roberts and Corke, 1997).

Q-Navigator is a High Speed Underground Navigation System, (HUNS) which is based on the navigation system developed by the University of Luleå in Sweden from 1986 to 1989. The HUNS consists of a rotating laser scanner and a navigation computer. The laser scanner rotates an infrared laser at 12 revolutions per second. The laser is reflected back to the laser scanner from retro-reflective targets mounted on holders on the tunnel walls. The angle of the rotating head is recorded when the beam is reflected back into the scanner. The measured angles together with a map of the target positions are used in the navigation algorithm to determine the position and heading of the vehicle. The high sampling frequency of the laser is said to make the system insensitive to model errors such as wheel slippage.

Unfortunately, the system requires a rather large overhead of installed infrastructure as the system needs at least four reflectors to be visible at any one time. The reflectors are also affected by dust as this decreases their visibility and can be a potential safety hazard.

Madhavan *et al.* (1998) propose a similar absolute localization and navigation scheme, but which does not require artificial beacons. The system they propose uses a minimal-structure algorithm for computing accurate estimates of the vehicles pose for the navigation of an LHD based on an existing map of the underground tunnel. The map used consists of a series of short line segments, referred to as poly-lines, which represent the approximate geometry of the mine tunnel walls. The map is constructed from data obtained by a scanning laser-range finder using the time-of-flight principle. Range data obtained from the range finder is then matched to the segments of the existing map, based on the minimum distance principle. An extended Kalman filter (EKF) is then used to account for uncertainty in the motion estimation. The EKF employs a nonlinear process model to account for effects of slipping as well as a nonlinear observation model for the range measurements provided by the laser scanner. This observation model is derived from the basic principles of analytic geometry and vector calculus. The Iterative Closest Point (ICP) algorithm (Besl and McKay, 1992) is then used to solve the problem of obtaining correspondence to the pre-existing map. Details of the ICP algorithm can be found in Madhavan *et al.* (1998).

Another LHD navigation technique which relies on absolute navigation, or an approximation thereof, is that described by Makela (2001*b*). The emphasis on this approach has been to design navigation systems that require no extra infrastructure to be installed in the mine tunnel. The navigation system is based on learning the route segments by having a human operator drive the vehicle through the route initially and recording the environmental model while model learning is taking place. Laser scanners are then used to correct the drift of dead reckoning positioning while the vehicle drives in automatic mode. The navigation system is based on the fusion of dead reckoning (odometry) and position measurement using the natural features of the tunnel walls. All the navigation equipment, which consists of a Pentium level computer running the QNX operating system which runs the navigation program that consists of 16 tasks being executed in parallel, an articulation angle sensor, an odometer, a gyroscope and two laser scanners, all entirely contained on the LHD. The odometer, articulation sensor and gyroscope are used in determining the pose of the vehicle by means of a discrete kinematic model that does not include slip. The odometer, however, is mounted on the cardan axle of the vehicle allowing it to measure the mean of the distance traveled by the left and right hand side wheels, allowing a resolution of better than 5mm and a practical accuracy in the region of 0.5-2% depending on the terrain.

A new path is taught to the navigation system by having an experienced driver steer the route in both directions. This approach has the advantage that when the vehicle is driving in automatic mode it will take into account the local conditions of the path, as the experienced driver did. When the route is driven in automatic mode the vehicle follows the reference trajectory by correcting its heading when necessary. This is accomplished by the navigation system constantly measuring the position and heading of the vehicle using dead reckoning. Due to the drift of dead reckoning the position and heading estimates must be corrected frequently. This is done by using the environmental model obtained during learning to estimate the drift in the dead reckoning accuracy, which is then corrected. This system also has the added advantage that the system records the position of the bucket during learning and this can then be used during automatic driving as well. In this way the system addresses the requirements set by Makela (2001*b*) that an underground vehicle navigation system should meet in order to be practical and economically viable as follows:

- The navigation system requires no extra infrastructure in the tunnel, as all navigation equipment is on board;
- the navigation system allows the LHD to drive at full speed;
- taking a new route into use is simple and takes a short period of time;
- changing an existing route is also simple and fast;
- teleoperation is integrated as a seamless part of the navigation system;
- moving of the boom and bucket is taken care of by the navigation system to synchronize their motion to the position of the machine.

The logical ideal for the absolute navigation paradigm is Simultaneous Localization and Map Building (SLAM) (Guivant *et al.*, 2002) or Concurrent Mapping and Localization (CML) (Thrun *et al.*, 1998) where no prior map is required and the map is generated as the robot moves around the environment for the first time, without the need for prior training. Although SLAM and CML are currently topics of much research (Williams *et al.*, 2002; Kurz, 1995); these techniques have, as yet, not been implemented in the underground mining environment (Roberts *et al.*, 2002).

3.3 Reactive navigation

Reactive navigation is a simple type of navigation which has been used since the '60s (Roberts *et al.*, 2002), in which the autonomous vehicle reacts to objects in its immediate environment in order to continue moving forward. Examples of a reactive navigation system used in the underground mining environment are those that follow painted lines, retro-reflective strips or light emitting ropes on the tunnel floor or roof, one such example is described by Hurteau *et al.* (1992).

These navigation systems typically use CCD cameras to detect the relative position of the line being followed immediately above the vehicle. These systems offer very little look-ahead and thus heading changes that need to be made cannot be anticipated which is not suitable for driving at high speeds.

For the case of an LHD vehicle operating underground the essence of the driving task is to stay in the middle of the mine tunnel and avoid collision with the tunnel walls. This can be achieved by application of wall following which is a technique that has been popular in indoor mobile robotics. Ultrasonic sensors and laser range finders have been used successfully for determining the distance of the vehicle from the mine tunnel (Roberts *et al.*, 2002; Lane and King, 1994; Madhavan *et al.*, 1999), provided that it is possible to attain significant look-ahead to detect the walls ahead of the vehicle (Roberts, Duff and Corke, 2002). A reactive navigation system was also developed by Lane and King (1994) for the automation of an articulated underground mine truck which used ultrasonic range sensors to perform environment mapping and wall following.

The advantage of reactive navigation is that the robot does not need to *know* where it is within its environment with respect to a global co-ordinate frame of reference, it is only necessary to keep track of obstacles in its immediate vicinity. Two popular techniques used in wall following are potential field and neural network methods.

3.3.1. Potential field methods Potential field methods have been used for navigation by robotics researchers since the 1980s (Roberts *et al.*, 2002). The principle is to treat the vehicle as a particle that is attracted by a potential field radiating from its intended destination and repulsed by potential fields radiating from obstacles. A local path plan is then constructed by applying a force based on the sum of the potential fields to a general desired path whose end is fixed to the vehicle. This is normally an iterative process and hence suffers from the limitation that the vehicle may become trapped in a local minimum and be unable to reach its goal (Roberts *et al.*, 2002).

3.3.2. Neural network methods Neural networks have the advantage that they are fast to execute and can therefore be applied to high-speed autonomous vehicles. A vehicle can be taught to steer using a neural network by making an association between the sensor data and steering angle allowing the vehicle to steer through previously unseen terrain (Roberts *et al.*, 2002).

3.4 Path planning and decision making

A reactive navigation system does not perform any path planning on a global scale. A pure wall following LHD vehicle will move along a tunnel until it encounters a dead end where it will stop. In order to complete a useful mission the vehicle needs to be able to plan a path to its destination. In the underground mine environment the decision process is quite limited as there is only a choice of going forward or backward along the mine tunnel. However, it is necessary to choose the correct path to take at intersections. This leads to two problems, firstly identifying which intersection it is and secondly what action to take at the particular intersection.

In an absolute navigation environment the autonomously guided vehicle has a global map of its environment, and localization information is available and it is possible to make a decision. The localization accuracy does not need to be accurate; it is only necessary to determine which junction the vehicle is approaching and from which direction. Beacons, such as radio tags or bar codes, may also be placed at intersections to obtain absolute positional information (Roberts *et al.*, 2002).

A relative route can also be applied where the autonomously guided vehicle is given a sequence of instructions to follow in order to reach its goal. For example the vehicle may be told to drive 100m and turn left at the next T-junction, in a manner similar to the way in which humans verbally describe a route to another person. Such a technique has been implemented successfully in combination with reactive wall following (Roberts *et al.*, 2002).

3.5 Obstacle detection

A reliable obstacle detection system for an autonomously guided mining vehicle is essential to enable the detection of obstacles that could potentially be dangerous to the safety of the vehicle itself, other vehicles or personnel while navigating through the mine. Obstacles could include people, other vehicles, or objects such as fallen rocks or pipes hanging from the tunnel roof with which the vehicle could collide.

The development of reliable autonomous vehicle navigation systems is difficult in the harsh environment of an underground mine. The operating environment could include dust, mud, high humidity, diesel fumes, extremes of temperature, severe vibration, and bright light sources.

There are two distinct approaches to obstacle detection namely direct obstacle detection and terrain-mapping and navigation (Roberts and Corke, 2000). In direct obstacle detection the obstacles themselves are detected by actively illuminating a scene and waiting for reflections. This approach merely detects obstacles and passes the information to the actual navigation system.

In terrain mapping and navigation, obstacles are not explicitly detected but rather the free-space or navigable area in front of the vehicle is sought and everything that is not navigable is considered an obstacle. The location of the free space is then sent to the navigation system.

Obstacle detection systems are also categorized by the type of sensors they use. The four most commonly used sensors are radio tags, radar, lasers, and cameras for computer vision.

3.5.1. Sensors Laser based systems have proven to be effective in both direct obstacle detection and terrain-mapping navigation techniques. Laser based systems do however suffer significant limitations due to a lack of penetration through dust and fog. Dust and fog effects vary with the laser wavelength. Additional limitations are imposed by eye safety concerns in areas where humans are present, as well as the reliability of mechanical scanning systems. These consist of moving parts which need to be robust enough to survive extreme vibrations encountered in the mining environments (Roberts and Corke, 2000).

Radio tags are probably the simplest and cheapest form of obstacle detection. All site personnel and vehicles would carry a tag. The tag can be either active or passive. In the case of passive tags the autonomous vehicle carries both a radio transmitter and receiver; the vehicle transmits a signal to all tags in range and the tags reply. If active tags are used the vehicle is only fitted with a receiver and each tag transmits its own signal. These systems suffer from three fundamental problems:

- The range of the radio signal varies depending on the terrain and is therefore unreliable;
- obstacles which do not have tags such as fallen rocks;
- non-functioning tags which it is not possible for the autonomous vehicle to detect which could lead to accidents (Roberts *et al.*, 1999).

Radar based collision avoidance systems have been developed by a number of research groups as part of various Intelligent Vehicle Highway Systems (IVHS) (Konno and Koshikawa, 1997). Most of these system are designed to work in an environment where the vehicle will not pitch and roll significantly, however this is not the case for mining vehicles and hence it is unlikely that any of the current automotive systems would be suitable for the mining environment. Systems have however been developed in which targets placed on obstacles are used to reflect the radar energy back to the receiver much like the radio tag system (Roberts *et al.*, 1999).

A number of computer vision systems using cameras have been developed however they also suffer from poor performance due to fog and dust as with laser based systems. The computer vision systems also require good lighting, which can be a problem in the underground mining environment.

3.5.2. Fail-safe systems An obstacle detection system should ideally be a fail-safe system in order for the autonomous vehicle navigation system to be accepted in the field. In the case of direct obstacle detection for an autonomous vehicle navigation system the decision to move forward is based on null information, in other words that no obstacles were found in the vehicle's path. There are two possible sources of null information. Firstly that there is indeed no obstacle present and secondly that the obstacle detection system failed to detect an obstacle for some reason. Hence trying to detect obstacles in the unstructured underground mining environment can never be made fail-safe (Roberts *et al.*, 1999).

According to Roberts *et al.* (1999), it may be possible to create a fail- safe system using the terrain mapping and navigation technique in which the vehicle seeks free-space in front of the vehicle because this method is based on positive information confirming the presence of a navigable area rather than null information. Any failure in such a system will produce null information, which is invalid and hence the system will know when a failure has occurred.

4. CONCLUSION AND FUTURE WORK

The previous sections described the automation of LHD vehicles, modelling of LHD vehicles and navigation of LHD vehicles.

As yet, a full dynamic model of a practical LHD has still to be developed in the research community. Further modelling efforts include tyre modelling (Dragt *et al.*, 2004)—especially for LHDs—tunnel modelling and better sensors and sensor models. Very little could be found on low level control of LHD vehicles (see Sampei *et al.* (1995)). This is probably because more focus is on the navigation and modelling problems. Another issue is the question regarding where the location of sensors either within the tunnel and/or on the vehicle should be. Other research topics dealing with LHDs are truck modelling and automatic guidance, LHD loading (Petty *et al.*, 1997; Hemami, 1994), dispatching (Saayman *et al.*, 2003) and scheduling.

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