NAVIGATION OF AUTONOMOUS UNDERGROUND MINE VEHICLES

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Abstract: This paper gives a summary of the current state of the field of autonomous underground mine vehicle navigation. Various navigation schemes used in mobile robotics are evaluated for practical implementation on a Load-haul-Dump (LHD) vehicle as a mobile robot in the challenging environment of an underground mine. A simulation of a reactive navigation scheme based on a simplified kinematic model of an LHD is performed and the results discussed and analysed.

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. In spite of this the mining industry has been slow too make use of robotics and automation technology, (Roberts *et al.*, 2002). Most of the productivity increases have been achieved through mechanisation, making use of electrical and diesel powered machinery.

While the increased levels of mechanisation have led to improved productivity it has also lead to safety concerns. There is an increased risk of serious injury caused by humans having to work in such confined spaces with heavy machinery as well as the less dramatic 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).

For safety reasons as well as potential productivity reasons it is desirable to automate the repetitive and tedious tasks of underground mining. One such task is performed by a Load-Haul-Dump vehicle or LHD in trackless mining operations. The LHD vehicle is used for the transportation of fragmented ore from the stopes to an ore pass where it 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.

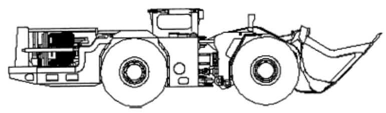

Fig. 1. An example of a typical LHD.

2. VEHICLE MODELLING

LHD vehicles as shown in figure 1 are produced by a number of manufacturers and are available in various models using either diesel or electric power and in various sizes. Typically the vehicles vary in length from 8 to 15 metres, weigh between 20000 - 75000kg with a transportation capacity of up to 25000kg. The vehicle's body consists of two parts connected 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 tunnel because of its higher maneuverability. Altafini (1999) shows that the difference in the trajectories followed by the midpoints of the vehicle's axles, referred to as the off-tracking error, is in fact zero for a vehicle of this type if the front and rear halves of the vehicle are the same length.

In order to design a navigation system for an autonomous vehicle it is necessary to have a vehicle model that describes the vehicles position and other vehicle parameters through time. Altafini has proved that the articulated vehicle can be

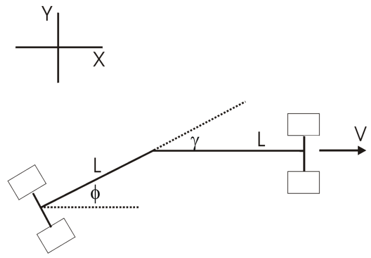

Fig. 2. LHD kinematic geometry.

modelled by a nonlinear system, with two inputs, namely speed and articulation angle, which is controllable. There is however some debate as to the complexity of the model required to successfully implement an autonomous vehicle navigation system, as increased model complexity places more stringent requirements on the computing power required on the actual vehicle to implement the navigation systems.

The main difference between the vehicle models is whether or not to account for slip during the vehicles motion. Due to the confined nature of the underground mining 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,(Polotski and Hemami, 1997). This assumption greatly reduces the complexity of the vehicle model as it is not possible to measure the amount of slip which has occurred during the vehicles motion. Hence the amount of slip has to be estimated using an Extended Kalman Filter (EKF) as described in Brown (1983). Figure 2 shows the kinematic vehicle geometry used by Scheding *et al.* (1999) to derive the model in (1) from rolling motion constraints.

$$\begin{aligned} \dot{x} &= V cos\phi \\ \dot{y} &= V sin\phi \\ \dot{\phi} &= \frac{V tan(\frac{\gamma}{2})}{L} \end{aligned} \tag{1}$$

where x and y denote the position of the vehicle relative to some fixed global co-ordinate frame of reference, and L refers to the distance between the front and rear wheels of the vehicle and the articulation joint which is referred to as the half-length of the vehicle. The angle ϕ is the orientation of the vehicle with respect to the x-axis also referred to as the heading and γ is defined as the articulation angle of the vehicle. These equations are based on the assumption that the front and rear wheel velocities of the LHD are identical and that the articulation angle remains constant. The drive-train of most LHD vehicles deliver equal power to both the front and rear sets of wheels through the transmission.

3. NAVIGATION OF THE LHD VEHICLE

The first generations of autonomous underground mine vehicles followed rail type guides in the environment such as buried wires in the floor or painted lines to aid navigation. These systems 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 travelled in an underground mining environment does not remain fixed for long periods of time and it is therefore not possible to justify the economic expenditure of installing the navigation infrastructure.

The underground mining environment in which the LHD vehicles have to operate is physically harsh as it is often hot, occasionally dusty and wet. The environment is also time varying due to ongoing mining activities.

In spite of the harsh nature of the underground environment, navigation techniques developed for indoor mobile robots have been found to be more suited to this environment. This is due to the fact that mine tunnels have a floor, ceiling and walls much like a corridor. The only 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 each level of an underground mine can be considered as an horizontal plane, although is 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).

Due to the hazardous nature of the underground mining environment 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.

There are two main approaches to deal with navigation in the underground mine environment based on research in the field of mobile robotics, namely reactive and absolute navigation, (Roberts *et al.*, 2002). In an absolute navigation scheme the absolute position of the autonomous vehicle is known at all times relative to some fixed real-world co-ordinate system, while in a reactive navigation scheme the autonomous vehicle reacts to objects in its immediate environment in order to continue moving forward.

3.1 Absolute Navigation

In order to implement an absolute navigation system it is necessary to estimate the absolute position of the vehicle within the fixed real-world co-ordinate system, which is referred to as localisation. This is usually achieved by means of fusing data from on-board sensors such as inertial 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 most successful commercially available absolute navigation system Q-Navigator's High Speed Underground Navigation System (HUNS) has been implemented on over 700 autonomously guided vehicles, (Roberts and Corke, 1997).

HUNS 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 there visibility and can be a potential safety hazard.

Madhavan *et al.* (1998) proposed a similar absolute localisation 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 vehicle's 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 is then used to solve the problem of obtaining correspondence to the pre-existing map.

Another LHD navigation technique which relies on absolute navigation, an approximation there to, is that described by Makela (2001). 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 teaching the route segments by having a human operator drive the vehicle through the route initially and recording the environmental model while the teaching 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, an articulation angle sensor, an odometer, a gyroscope and two laser scanners, is entirely mounted 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 travelled 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 to 2% depending on the terrain.

A new path is taught to the navigation system by having an experienced driver drive 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 which is done by using the environmental model obtained during teaching 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 teaching and this can then be used during automatic driving as well. In this way the system addresses the requirements set by Makela (2001) 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
- 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 synchronise their motion to the position of the machine.

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

3.2 Reactive Navigation

Reactive navigation is a simple type of navigation which has been used since the 1960s, (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 hitting 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 by King and Lane (1994) provided that it is possible to attain significant look-ahead to detect the walls ahead of the vehicle. A reactive navigation system was also developed by King and Lane (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 coordinate 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.

Potential field methods have been used for navigation by robotics researchers since the 1980s. 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).

Neural network methods 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).

4. SIMULATION

A purely reactive navigation scheme based on a wall following approach is illustrated in this section through simulation. The simulations where performed using Matlab based on the simplified kinematic model (1) and the results are shown in a graphical format.

The simulation performed in this section of the report is based on physical characteristics of the Atlas Copco Wagner ST-3.5 6 ton capacity Scooptram LHD. The maximum speeds that the vehicle is capable of in each particular gear are given in table 1 , assuming that the vehicle is on level terrain.

Table 1. Gear verses maximum speed.

Gear	Speed
1st	4.7km/h
2nd	9.5km/h
3rd	18.3km/h

For this particular vehicle the distance from the articulation joint to the centre of the front and rear axles is equal, and hence the off-tracking error given is in fact zero.

As an LHD is a low speed vehicle as stated by Polotski and Hemami (1997) it is possible to neglect the dynamic forces that cause slip, which implies that an analysis based on kinematics is sufficient. For this reason the no-slip simplified kinematic model given in (1) is used in this simulation of the underground navigation system, with L=1.449m and the maximum steering angle(ϕ) being 85° ,(42.5° in each direction). The effect of the dynamics, (slip) of the steering system can be added in future work.

The environment used in the simulation is a two dimensional area of 220 units by 220 units. The simulations have been created in such a manner that each unit is equivalent to one metre. Within the two dimensional environment boundaries have been defined in order to simulate underground tunnel walls. The tunnel layout consists of a straight line movement in the x direction (from left to right) for 100m, then a 90° left turn followed by a straight line movement in the y direction (upwards), this is followed by a curvature of constant radius from left to right.

Due to the nature of the simulation it was decided to implement a reactive navigation scheme in which the vehicle navigates through the environment by means of a wall following algorithm. A block diagram of the system is shown in figure 3. As noted by Steele *et al.* (1993), the system is different to the typical closed loop control systems since the loop is closed around the environment. In figure 3 y_d refers to the desired wall following distance while y_a is the actual wall following distance and γ is the steering angle of the vehicle used to control the wall following distance.

Although this model is in fact nonlinear, it was found in this simulation that it was possible to control the wall following distance, using a

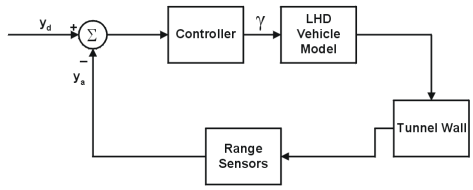

Fig. 3. Loop diagram of sensor based control system.

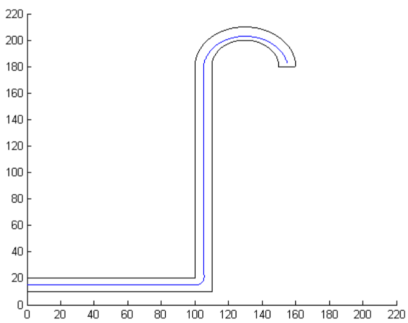

Fig. 4. Plot of simulation results showing tunnel walls and the trajectory followed by the vehcile

linear proportional, integral and derivative (PID) controller. The velocity form of the PID controller was used due to its ease of implementation and added advantage of not suffering from integral windup.

The simulation results show that the vehicle is able to navigate a tunnel with both a 90° corner and a curvature of constant radius. The vehicle should therefore be able to cope with most cornering demands that would occur in a typical mine tunnel layout. In performing the simulations there where a number of shortcomings noted and conclusions that can be made about a reactive navigation scheme. A reactive navigation scheme is similar to the way a human operator would drive the vehicle. That is the navigation system guides the vehicle by avoiding the tunnel walls rather than using a predetermined map of the tunnels layout as in absolute navigation. There is one critical difference in that a human operator while driving the vehicle is capable of looking ahead and positioning the vehicle correctly within the tunnel for the upcoming corner. This is a short coming in a purely reactive navigation scheme in which the vehicle navigates by remaining in the centre of the tunnel or at a constant distance from one wall. An efficient underground vehicle navigation system needs to have sufficient "look-ahead" to allow the vehicle to be aware of the upcoming corners and position itself correctly within the tunnel as a human operator would position the vehicle. This could be achieved by using improved sensors or by making use of some absolute navigation techniques such as using beacons to inform the vehicle's navigation system of the upcoming corner.

5. CONCLUSION

The autonomous navigation of underground mine vehicles is an important and challenging problem which involves a number of engineering disciplines including telecommunications, software, electronics as well as mining engineering. A practically feasible and economically viable underground autonomous navigation system has a number of safety and economic benefits.

The information in this paper is a brief overview of work already done in the field of autonomous navigation of underground mine vehicles. The simulations described in the previous section of this paper incorporate components from different sources, in order to give a clearer picture of the performance of certain existing methods. The results obtained in the simulation confirm and reenforce what is expected and has been found by previous research such as the need for significant look-ahead on the autonomously guided vehicle, which could be achieved by improved sensing or a navigation scheme making use of both reactive and absolute navigation techniques similar to the opportunistic localisation technique described by Roberts *et al.* (2002).

The work presented in this paper is a first step towards the development of a full dynamic model of an LHD, including effects such as slip and tyre deformation. Using this model it will then be possible to develop control strategies including necessary safety considerations such as obstacle detection and collision avoidance. This will also necessitate more accurate sensor models and a realistic and efficient tunnel model for the purposes of software simulation.

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