Obstacle Detection for a Mining Vehicle using a 2D Laser

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Abstract

This paper discusses a number of key issues for the development of robust obstacle detection systems for autonomous mining vehicles. Strategies for obstacle detection are described and an overview of the state-of-the-art in obstacle detection for outdoor autonomous vehicles using lasers is presented, with their applicability to the mining environment noted. The development of an obstacle detection system for a mining vehicle is then detailed. This system uses a 2D laser scanner as the prime sensor and combines dead-reckoning data with laser data to create local terrain maps. The slope of the terrain maps is then used to detect potential obstacles.

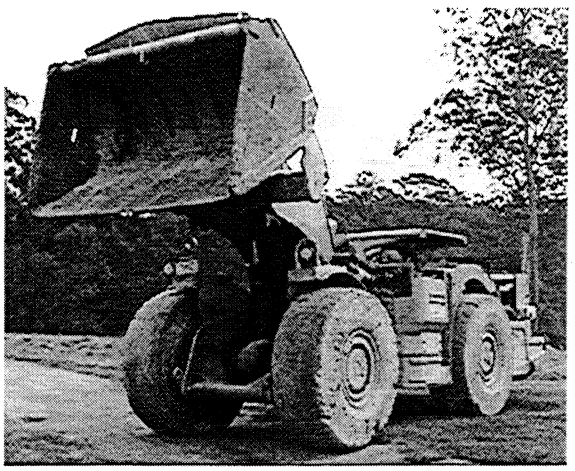

Figure 1: The experimental Load-Haul-Dump truck.

1 Introduction

Reliable obstacle detection is an essential element of an autonomous mining vehicle system. An autonomous vehicle must be capable of detecting potentially dangerous obstacles that would endanger the vehicle itself, other vehicles, personnel or expensive site infrastructure while navigating through the mine. Autonomous vehicles will not be deployed in the field alongside manned vehicles until robust obstacle detection systems have been developed.

The development of robust obstacle detection systems for these vehicles is difficult because of the relatively harsh conditions encountered in mining environments. The operating environment could include rain, dust, mud, high humidity, diesel fumes (small particles), extremes of temperature, severe vibration, extreme vehicle pitching and rolling, and bright light sources (e.g. the sun).

This paper presents work-to-date on an obstacle detection system for a mining vehicle (Figure 1) using a 2D-laser scanner. The system builds 3D terrain maps from the 2D laser data using knowledge of the vehicle's motion as it moves along.

1.1 Structure of the paper

The remainder of this paper is structured as follows. Section 2 discusses strategies for obstacle detection and defines what an obstacle is and talks about the two distinct approaches to obstacle detection. Section 3 reviews the state-of-the-art in obstacle detection using laser scanners. An obstacle detection system based on a 2D laser scanner is then discussed in Section 4. Finally, Section 5 lists some conclusions and possible future work.

2 Strategies for obstacle detection

2.1 What is an obstacle?

It is important to define what an obstacle is before we discuss how an obstacle may be detected. We define an obstacle as something that will cause dangerous or undesirable behaviour if hit by the host vehicle (the vehicle on which the obstacle detection system is mounted). Three general classes of obstacles are:

1. people,
2. other vehicles and
3. other roadway obstacles.

The third class of obstacles can include anything from a rock lying in the middle of a mine haul road to a mobile lighting

tower at the side of a haul-road.

An object should only be considered an obstacle if the host vehicle will probably collide with that object in the near future. For example, on a regular suburban road, parked cars are not obstacles, but the slow moving vehicle in-front is. This rather obvious statement has a very significant implication for an obstacle detection system. i.e. an obstacle detection system must have some idea of how its host vehicle will move in the future in order to declare a detected object an obstacle. A large object, such as a building, may be detected by the system ahead of the host vehicle. However, if this detected object is not in the actual path of the host vehicle, then it is not an obstacle. Figure 2 shows the problem. Here, the host vehicle is driving on a road way on the surface. Directly ahead of it is a building which is not an obstacle if the vehicle remains on the road. There is also a large rock, which is an obstacle, in the middle of the road way where the road starts to curve. However, the sensor employed by the obstacle detection system "sees" the building and does not see the rock.

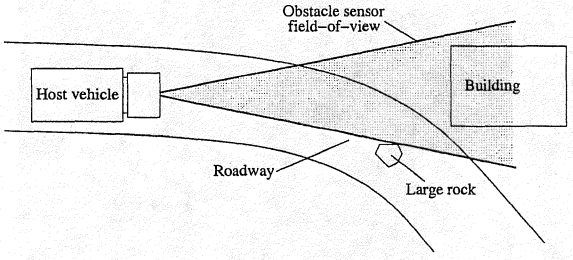

Figure 2: The building is not an obstacle and the large rock is. However, the sensor "sees" the building and not the rock.

This leads to the conclusion that an obstacle detection system must work in conjunction with a navigation system in order to reduce the number of false-alarms triggered by things such as parked vehicles, road-side structures, etc. The problem is even worse in an underground environment where there are potential obstacles all around, i.e. the walls. Figure 3a shows the situation where a Load-Haul-Dump (LHD) truck equipped with an obstacle detection sensor is approaching a T-junction. The system must be "told" ahead of time to ignore the wall of the T-junction. Figure 3b shows the problem encountered where an LHD is weaving along the tunnel. At this point in time, the LHD is heading towards the right-hand wall (an obstacle?). However, a moment later, the LHD will correct its path and turn to the left slightly to miss the wall.

The situations described above imply that in the general sense, an obstacle detection system will not work on a manually operated vehicle unless the future direction or path of the host vehicle can be predicted accurately. This is not a problem on a fully autonomous vehicle since the future path of the vehicle is know. Another solution would be to automatically identify certain features (such as tunnel walls) and then disregard them. This is a poor strategy since a tunnel wall is an

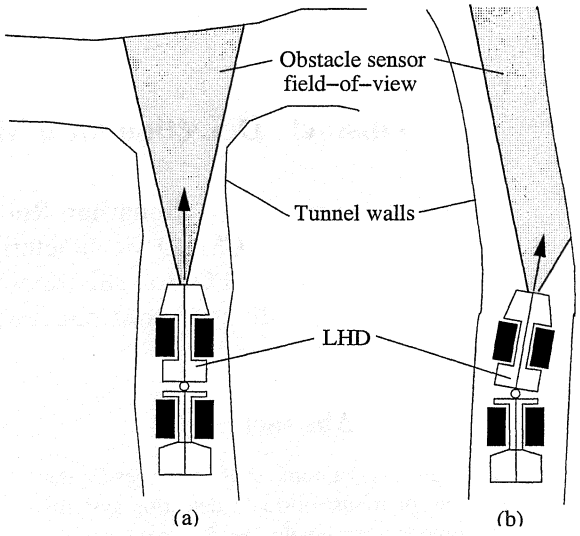

Figure 3: (a) Problems at a T-junction and (b) problems with a weaving vehicle.

obstacle in certain situations.

2.2 Approaches

There are two distinct approaches to the obstacle detection problem.

- Direct obstacle detection. Here, the obstacles themselves are detected by either actively illuminating a scene and waiting for reflections, or by passively receiving energy from potential obstacles. This approach does not attempt to navigate the vehicle, but simply detects obstacles and then passes this data to the actual navigation system.
- Terrain-mapping and navigation. Here, obstacles are not explicitly detected, instead the free-space, or navigable area, in-front of the vehicle is sought. Here, anything that is not navigable is considered an obstacle. This is a local terrain mapping problem. The location of free-space may then be sent to the navigator.

It is clear from the literature that both of these approaches are referred to as obstacle detection or obstacle avoidance, even though only the first approach directly detects obstacles.

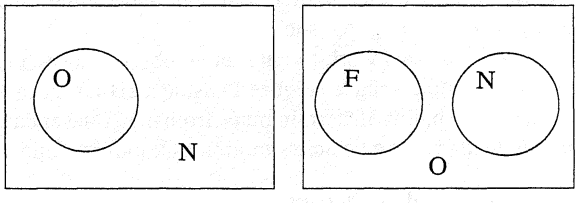

Figure 4: Left: direct obstacle detection. Right: the terrain-mapping approach.

An important distinction between these two approaches is how *null* information is used[1]. The lack of a return signal from an active system, or the lack of any radiated energy in a passive system is referred to as null information, or a null return.

Figure 4 shows some Venn diagrams of the situation to highlight the key difference between the two approaches. In the first approach the set of non-null returns is classified as the set of obstacles, O.

$$O = N' \tag{1}$$

where N is the set of null returns.

However, the second approach detects the set of free-space, F, and also has a set of null returns N. Here then, the set of obstacles, O, is given by:

$$O = (F \cup N)' \tag{2}$$

The two approaches normally require different sensor placements. The first approach normally requires sensors to be mounted on the front of the vehicle, typically low down so as not to miss any short obstacles. The sensors are normally aligned with the direction of travel of the vehicle (Figure 5). The second approach (terrain mapping) requires an elevated sensor position to view the local terrain. Most laser-based systems also require additional sensors giving positional data to aid with the integration of successive scans in order to build the map.

3 The state-of-the-art

Obstacle detection may also be categorised by the sensor(s) used. The four most commonly used sensors being:

- radio tags,
- radar,
- lasers and
- cameras (computer vision).

[Roberts *et al.*, 1999] discusses the state-of-the-art of all four categories of system. The remainder of this section will discuss the merits and problems of laser based system only.

3.1 Laser based systems

Lasers have been used frequently by researchers for obstacle detection for highway driving. Examples may be found in [A. Najmi et al, 1995; Doi *et al.*, 1994; Kaneko *et al.*, 1997]. These systems attempt to directly detect potential obstacles by scanning the laser beam in-front of the vehicle. As with many of the radar systems, the flat-world assumption is made [Roberts *et al.*, 1999], and hence significant vehicle pitch or roll will degrade the system's performance.

[1]This is important when considering the robustness of a system (see [Roberts *et al.*, 1999])

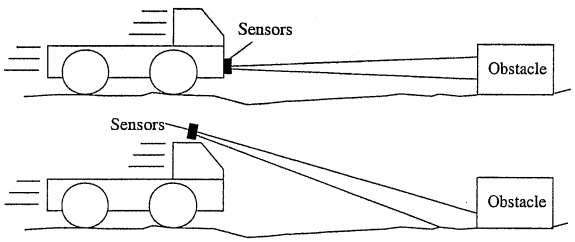

Figure 5: Top: direct obstacle only detection. Bottom: the terrain-mapping approach.

Free-space finding laser-based systems have also been developed. A famous use of such an obstacle detection system was that of the Sojourner Mars rover [Matthies *et al.*, 1997]. This system mapped the local terrain ahead of the rover using a laser and diffraction grating and a CCD camera. The diffraction grating produced 15 points/spots 50 cm ahead of the rover. This system had no moving parts and was hence very robust. Since it relied on the forward motion of the rover to move the line of spots across the scene, odometry was required to integrate the data.

The European Panorama project [Van den Bogaert *et al.*, 1993] also developed a successful free-space finding laser-based system. Here, a scanning laser rangefinder was used to scan ahead of the vehicle. Like the Sojourner system, the motion of the vehicle moved the scanned laser beam across the scene. Accurate odometry, inertial data and GPS was available to accurately integrate the data. A similar configuration was used with the highly successful Navlab 4 off-road vehicle [Hebert *et al.*, 1997].

It is clear from the literature that in general free-space finding systems are used on slow to medium speed applications such as off-road driving where both navigation and obstacle detection are performed as one. Direct obstacle detection system are typically used on high-speed applications such as highway driving where the navigation is performed by a separate system.

Laser based systems do have some significant limitation including:

- lack of penetration through fog or dust (this is wavelength dependent);
- some lasers are not eye safety (this is a function of power and wavelength) — this may be an issue when humans are near by;
- moving parts — the mechanical scanning systems must be robust enough to survive the extreme vibrations encountered in the mining and construction environments.

4 An experimental obstacle detection for an LHD

In 1996 our group, in conjunction with the University of Sydney, mounted an array of sensors to an LHD used in un-

derground metal mines [Scheding *et al.*, 1997]. Data were collected for the purpose of developing algorithms for both navigation and obstacle detection for the vehicle. The results of this exercise were very promising and a full-scale industry sponsored project to fully automate the driving and dumping functions of an LHD commenced in July 1998 (Figure 1). CSIRO Manufacturing Science & Technology separately funded work to develop an obstacle detection system for the LHD.

The definition of an obstacle (for the purposes of this work) was defined as terrain with an unacceptably high value of longitudinal slope. Figure 6 shows a side elevation of some terrain. The area where the ground suddenly increases in slope should be classified as an obstacle by the system. The system does not know why the ground suddenly increases in slope, and hence cannot classify or recognise obstacles, it simply detects them.

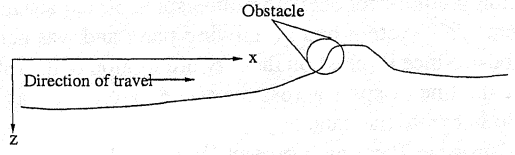

Figure 6: An obstacle is defined as terrain with an unacceptably high value of slope.

The proposed obstacle detection system uses a 2-D scanning laser range finder. The particular scanner used was a PLS laser scanner manufactured by Sick, Germany. The idea is to place the 2-D laser scanner on the vehicle such that the vehicle's motion sweeps the scanning plane across the ground ahead. Figure 5 (bottom) shows the idea.

The Laser scanner was mounted on the back of our experimental LHD (Figure 7). Its scanning plane was tilted down 20 degrees resulting in the plane intersecting the roadway about 5m away from the vehicle. It should be noted that it is not possible to mount the laser on the front of the vehicle in such as way as to scan the road due to the presence of the loaded bucket. However, the issue of obstacle detection on an LHD moving forwards (bucket first) is not as significant as when moving backwards (engine first) as it is standard mine practice to drive forwards with the unloaded bucket down to "scoop-up" any fallen rocks.

4.1 Dead-reckoning

In order to create a terrain map from successive laser scans, it is necessary to know how the vehicle moves between scans. In the case of a vehicle on a rough roadway, it may be necessary to have accurate estimates of all six degrees of freedom of motion in order to generate an accurate enough terrain map. However, certain degrees of freedom are more significant than others. In the case of a mining vehicle, pitch (rotation along the y-axis) and forward motion (motion along the x-axis) are the most significant. It maybe possible to ignore a

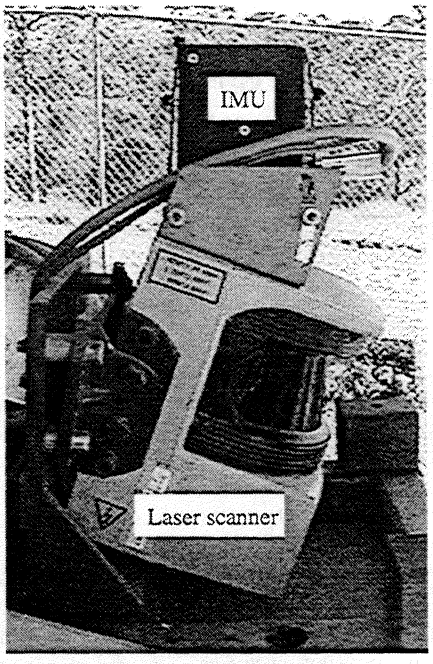

Figure 7: The IMU is mounted on-top of the Laser scanner.

number of degrees of freedom and still achieve the detection performance required.

Localisation data were obtained from a dead-reckoner software module. This module implements a basic vehicle localisation capability using an IMU and drive-line odometer. A Crossbow IMU (DMU-VG) was rigidly attached to the PLS, but was mounted level with respect to the vehicle[2] (Figure 7).

The output of the dead-reckoner is vehicle pose and position. The position and heading angle (yaw) are measured with respect to a real-world coordinate frame and estimates of these quantities drift with time. Roll and pitch are given with respect to the gravity vector. Note that the origin of the localisation co-ordinate system is initialised when the dead-reckoner module starts up and is coincident with the vehicle origin at that point in time.

4.2 Terrain map generation

A moving window of N scans is used to generate the terrain map. As each scan is read into the system the Cartesian position (X, Y, Z) of each scanned point is calculated with respect to the laser's origin at that point in time. The terrain map is then created from the latest scans point-of-view. Hence, the position of all the other $N-1$ scan's points are transformed into the latest scans co-ordinate frame. The position and orientation (from the dead-reckoner) of the laser at each scan is used to calculate a rotation and translation matrix for each scan. A raw terrain map generated this way is shown in

[2]Other automation sub-systems used the raw data from the IMU and they assumed that it was level.

Figure 8. This map was generated from data collected in a straight section of tunnel while the LHD was travelling at approximately 8km/h. The individual size of the cells that make up the map were 0.4m (x direction) by 0.2m (y direction). The walls of the tunnel are clearly visible. The characteristic slope (in the x direction) of the two walls is due to the plane of the laser.

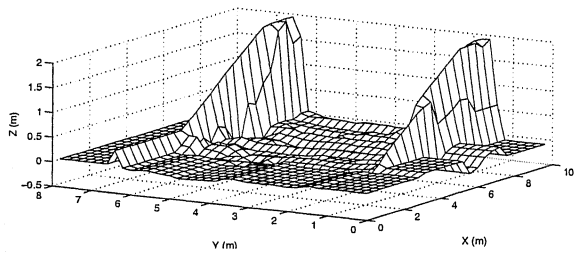

Figure 8: A terrain map of a section of straight tunnel.

There are areas in the terrain map where no data were collected. This is undesirable and will cause problems when calculating the slope of the terrain where the unmapped region meets the mapped region. Hence, the terrain map is linearly interpolated in both x and y directions (in that order). This also fixes the problem of occasional missing data in the middle of the mapped section.

4.3 Obstacle detection

Potential obstacles are then found by calculating the slope of the terrain in the x direction and thresholding the result. Figure 9 shows the results from a test performed with a small box (size 30cm x 40cm x 30cm) which was placed in the centre of a straight section of tunnel.

4.4 False-alarms versus sensitivity

In the example shown in Figure 9 a slope threshold of 0.4 was used to determine potential obstacles. It should be realised that a trade-off must be made between the minimum size of an obstacle that is detectable versus the speed/roughness of the vehicles motion. Because the correction for vehicle motion is not perfect (Section 4.1), severe motion will cause noise in the terrain map, and hence in the slope map. A small value for the threshold will result in a large number of false-alarms during rough/fast motion. To reduce the number of false-alarms, the threshold could be modified based on vehicle speed. This does however mean that it is only possible to detect small potential obstacles when moving slowly over smooth ground, and only relatively large obstacles when moving at speed over rough ground. Experiments suggest that obstacles of a height of 30cm are detectable during smooth medium speed motion, but only 60cm when moving at speed over bumps in the roadway.

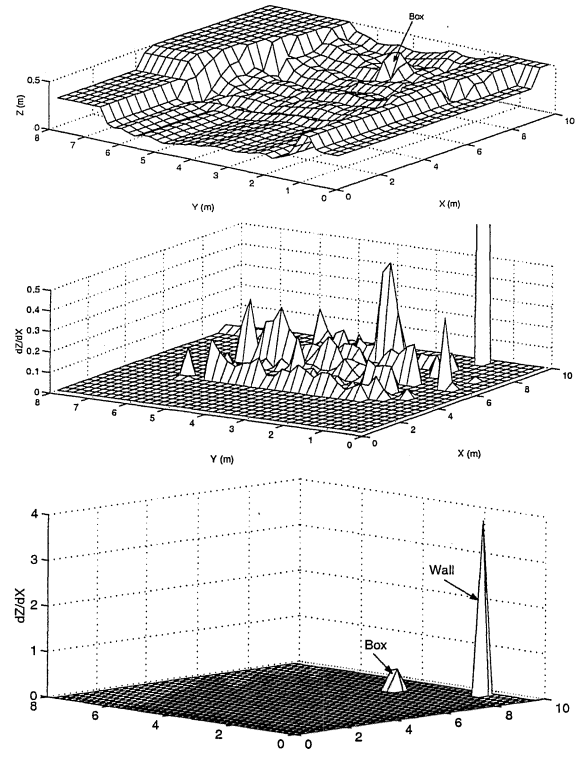

Figure 9: Top: A terrain map of a section of straight tunnel with a small obstacle (a box) placed on the roadway (The height has been cropped at 0.5m to help reveal the box). Middle: The slope in the x direction from the same section of tunnel. Bottom: Thresholded slope (potential obstacles).

5 Conclusion and Future Work

In this paper we have discussed a number of key issues for the development of robust obstacle detection systems for autonomous mining vehicles. Strategies for obstacle detection have been described and an overview of the state-of-the-art in obstacle detection for outdoor autonomous vehicles using lasers has been presented. The development of an obstacle detection system for a mining vehicle was then detailed. This system used a 2D laser scanner as the prime sensor and combined dead-reckoning data with laser data to create local terrain maps. The slope of the terrain maps was then used to detect potential obstacles.

Note that we have up-to-now stated that the system is capable of detecting *potential* obstacles. This is because the system has no notion of how the vehicle will move in the immediate future (Section 2.1) and hence it is currently impossible to classify potential obstacles as real obstacles. The situations shown in Figure 3 occur in our experimental test mine using our experimental LHD. The next stage of this work is therefore to integrate the navigation and obstacle detection systems on the LHD in an attempt to reduce the number of

false-alarms.

Although we have used a 2D laser scanner as the primary imaging sensor for our work, this may not be the best choice of sensor in the future. Using a 2D sensor to generate 3D terrain map data is difficult when the motion of the vehicle is not smooth. The effective resolution of the system degrades as the motion becomes more severe because the motion compensation is not perfect. A true 3D sensor such as a stereo camera may be more appropriate to this application. It has recently become possible to generate range information from stereo cameras at frame rates using relatively low-cost/light-weight hardware [Dunn and Corke, 1997][Kagami *et al.*, 2000]. Such a system will be immune to the effects of severe motion since the data is collected at one instant in time and is not integrated over time. Future work will therefore investigate the use of stereo vision for obstacle detection on mining vehicles.

Acknowledgments

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