Defence Research and Development Canada
Recherche et développement pour la défense Canada

DEFENCE R&D DÉFENSE

Traversability Analysis for Unmanned Ground Vehicles

Interpreting the Environment

J. Collier, G. Broten and J. Giesbrecht
DRDC Suffield

Technical Memorandum
DRDC Suffield TM 2006-175
December 2006

Canada

Traversability Analysis for Unmanned Ground Vehicles

Interpreting the Environment

J. Collier, G. Broten, J. Giesbrecht
Defence R&D Canada – Suffield

Defence R&D Canada – Suffield

Technical Memorandum
DRDC Suffield TM 2006-175
December 2006

Principal Author

Original signed by J. Collier

J. Collier

Approved by

Original signed by D.M. Hanna

D.M. Hanna

Head/AISS

Approved for release by

Original signed by Dr. P.A. D'Agostino

Dr. P.A. D'Agostino

Head/Document Review Panel

Abstract

Scientists at Defence R&D Canada – Suffield have been investigating autonomous operation of Unmanned Ground Vehicles (UGVs). In order to navigate unknown terrain effectively, UGVs must be able to create an accurate representation of the operational environment. This is typically done by constructing a geometric representation of the environment, called a Terrain Map, from exteroceptive and proprioceptive data streams. This Terrain Map can further be analyzed to provide a measure of the traversability of the terrain. The resulting Traversability Map can be utilized by path planning and obstacle avoidance algorithms to determine the "best" path to follow.

This paper discusses DRDC's *Traversability Map* as a method of world representation. The Traversability Map interprets geometric data by calculating statistics about the environment to determine whether an area is traversable or not. In doing so, the Traversability Map interprets geometry from a vehicle specific context, allowing for the unique mobility characteristics of platforms to dictate map parameters.

Résumé

Les scientifiques de R & D pour la défense Canada – Suffield ont étudié l'opération autonome de véhicules terrestres sans pilote. Ces véhicules doivent être capables de créer une représentation exacte du milieu opérationnel pour être en mesure de naviguer des terrains inconnus efficacement. Ceci est généralement obtenu en construisant une représentation géométrique du milieu, appelée carte morphographique, à partir de flux de données extéroceptives et proprioceptives. Cette carte morphographique peut être analysée plus profondément pour mesurer la possibilité de traverser le terrain. La carte de parcours traversable qui en résulte peut être utilisée par des algorithmes de planification de parcours et d'évitement d'obstacles pour déterminer le « meilleur » chemin à suivre.

Cet article discute de *la carte de parcours traversable* de RDDC comme d'une méthode de représentation du monde. Cette carte interprète les données géométriques en calculant les statistiques concernant l'environnement pour déterminer si une zone est traversable ou non. De cette manière, cette carte interprète la géométrie à partir du contexte spécifique d'un véhicule ayant les caractéristiques de mobilité toutes particulières des plateformes capables de dicter des paramètres cartographiques.

This page intentionally left blank.

Executive summary

Traversability Analysis for Unmanned Ground Vehicles

J. Collier; G. Broten; J. Giesbrecht; DRDC Suffield TM 2006-175; Defence R&D Canada – Suffield; December 2006.

Background: Scientists at Defence R&D Canada – Suffield have been investigating autonomous operation of Unmanned Ground Vehicles (UGVs). In order to navigate unknown terrain effectively, UGVs must be able to create an accurate representation of the operational environment. This is typically done by constructing a geometric representation of the environment, called a Terrain Map, from external and internal sensor data. This Terrain Map can further be analyzed to provide a measure of the traversability of the terrain. The resulting Traversability Map can be utilized by path planning and obstacle avoidance algorithms to determine the "best" path to follow.

This paper discusses the DRDC's *Traversability Map* as a method of world representation. The Traversability Map interprets geometric data by calculating statistics about the environment to determine whether an area is traversable or not. In doing so, the Traversability Map interprets geometry from a vehicle specific context, i.e. a particular area may be traversable for a large UGV but impassable for a smaller UGV.

Principal Results: Trials were conducted in the fall of 2006 to assess the performance of Traversability Mapping for point to point navigation with obstacle avoidance. A Koyker Raptor all terrain vehicle which had been modified for autonomous navigation was used as a test platform for the trials. The results are summarized as follows:

- The UGV was able to traverse 1.3km of gravel road terrain with minimal intervention.
- The Traversability Map correctly identified positive obstacles such as buildings, signs, etc.
- Negative obstacles such as excessively sloped ditches where correctly labelled as impassable.
- False obstacles often occurred due to errors in terrain data. In most cases, the system was able to recover and account for these errors.
- Vegetation would often appear as obstacles in the map regardless of whether it was traversable or not.
- The UGV followed a road between waypoints without prior definition of a road or its characteristics.

Significance of Results: Based on the results assessed above, it can be concluded that slope and step hazards are sufficient metrics to determine the traversability of simple terrain such as asphalt or gravel roads. Furthermore, the ability of the UGV to effectively road follow suggests that the Traversability Map could be used as input to a road following/recognition system. The inability of the map to accurately represent vegetation data indicates that the method may not work well for off-road terrain traversal though supplementing the Traversability Map with a terrain classification system may prove effective.

Future Work: Traversability Mapping work will focus on improving system robustness and increasing the accuracy of the maps. Currently, the UGV is limited to running at very slow speeds as a result of a mechanical error in the laser nodding mechanism which causes large errors in laser readings. Improvements to this mechanism should improve map generation speeds. In addition, sun-visors are being fabricated to reduce the instances of laser dazzle. Work will also continue with Traversability Mapping to determine the robustness of the algorithm. Currently, the obstacle avoidance algorithm only implements discrete traversability (traversable, impassable). The capability is already in place to use continuous traversability values between 0 and 1. This could potentially improve the effectiveness of the Traversability Map for obstacle avoidance as rough areas or areas near obstacles may be avoided. Other hazards such as roughness and border hazards should be evaluated to determine their effectiveness. Furthermore, the Global Traversability Map has yet to be tested with DRDC's D* Lite implementation.

Despite the successes that Traversability Mapping has achieved thus far, the approach does not work nearly as well in heavily vegetated areas such as those encountered in off-road navigation. In these cases the map is unable to differentiate between "real" obstacles such as rocks and "false" obstacles such as grass. In order to be successful in this environment this approach must be supplemented with a learning algorithm which would allow the map to distinguish between various types of terrain. AISS has been conducting research in *Learned Trafficability* for a number of years and as such is well positioned to make a worthy contribution in this area.

Sommaire

Traversability Analysis for Unmanned Ground Vehicles

J. Collier; G. Broten; J. Giesbrecht; DRDC Suffield TM 2006-175; R & D pour la défense Canada – Suffield; décembre 2006.

Contexte : Les scientifiques de R & D pour la défense Canada – Suffield ont étudié l'opération autonome de véhicules terrestres sans pilote. Ces véhicules doivent être capables de créer une représentation exacte du milieu opérationnel pour être en mesure de naviguer des terrains inconnus efficacement. Ceci est généralement obtenu en construisant une représentation géométrique du milieu, appelée carte morphographique, à partir de données de capteurs externes and internes. Cette carte morphographique peut être analysée plus profondément pour mesurer la possibilité de traverser le terrain. La carte de parcours traversable qui en résulte peut être utilisée par des algorithmes de planification de parcours et d'évitement d'obstacles pour déterminer le « meilleur » chemin à suivre.

Cet article discute de *la carte de parcours traversable* de RDDC comme d'une méthode de représentation du monde. Cette carte interprète les données géométriques en calculant les statistiques de l'environnement pour déterminer si une zone est traversable ou non. De cette manière, cette carte interprète la géométrie à partir du contexte spécifique d'un véhicule, comme par exemple, une zone particulière pouvant être traversée par un gros véhicule terrestre sans pilote mais qui serait impassable pour un véhicule plus petit.

Résultats principaux : On a conduit des essais durant l'automne 2006 qui évaluaient le rendement de la cartographie d'un parcours traversable pour naviguer d'un point à un autre en évitant les obstacles. Le Koyker Raptor, un véhicule tout terrain qui avait été modifié pour la navigation autonome avait été utilisé comme plateforme de test pour les essais. On a résumé les résultats comme il suit :

- Le véhicule terrestre a été capable de traverser 1,3 km de route gravillonnée avec un minimum d'intervention.

- La carte de parcours traversable a correctement identifié les obstacles positifs tels que les bâtiments, les signaux, etc.

- Les obstacles négatifs tels que les fossés excessivement profonds ont été relevés comme impassables.

- Des faux obstacles ont souvent été relevés surtout à cause d'erreurs dans les données de terrain. Dans la plupart des cas, le système a été capable de se corriger et de tenir compte de ces erreurs.

- La végétation apparaissait souvent sur la carte comme un obstacle qu'elle soit traversable ou non.

- Le véhicule terrestre a suivi une route entre des points de cheminement sans définition antérieure de la route ou de ses caractéristiques.

Portée des résultats : En se basant sur les résultats ci-dessus, on peut conclure que les dangers dû aux pentes ou autres sont des paramètres qui suffisent à déterminer la capacité à traverser d'un terrain simple tel que les routes gravillonnées ou d'asphalte. De plus, la capacité du véhicule à suivre effectivement la route suggère que la carte de parcours traversable pourrait être utilisée comme donnée d'entrée dans un système de poursuite et de reconnaissance d'une route. L'incapacité de la carte à représenter les données de végétation avec exactitude indique que cette méthode ne fonctionnera pas très bien pour traverser un terrain hors route bien que le fait de supplémenter la carte de parcours traversable avec un système de classification de terrain pourrait se prouver efficace.

Travaux futurs : Les travaux sur les cartes de parcours seront axés sur l'amélioration de la robustesse du système et de l'exactitude des cartes. Le véhicule est actuellement limité à se déplacer à des vitesses très lentes à cause d'une erreur mécanique dans le mécanisme de laser basculant causant de grosses erreurs dans la lecture du laser. Les améliorations apportées à ce mécanisme devraient améliorer la vitesse de génération de cartes. De plus, on est en voie de fabriquer des visières contre le soleil pour réduire les circonstances d'aveuglement du laser. Des travaux continueront aussi sur la carte de parcours traversable pour déterminer la robustesse de l'algorithme. L'algorithme d'évitement des obstacles n'implémente actuellement qu'une valeur discrète de la capacité à traverser (traversable, impassable). La capacité à utiliser des valeurs continues de capacité à traverser entre 0 et 1 est déjà en place. Ceci pourrait avoir le potentiel d'améliorer l'efficacité de la carte de parcours traversable concernant l'évitement d'obstacles en évitant les zones d'herbe longue et épaisse ou les zones proches d'obstacles. D'autres dangers tels que la rugosité ou les bordures devraient être évalués pour déterminer l'efficacité du système. De surcroît, la carte de parcours traversable globale doit être évaluée avec l'implémentation D* Lite de RDDC.

Bien que la carte de parcours traversable ait atteint un certain succès à ce point-ci, la méthode ne fonctionne pas aussi bien dans les zones très herbeuses telles que celles rencontrées lors de la navigation hors route. Dans ces cas-là, la carte est incapable de différencier entre les obstacles « réels » tels que les roches et les « faux » obstacles tels que l'herbe. Pour réussir dans un tel environnement, cette méthode devrait être supplémentée par un algorithme d'apprentissage qui permettrait à la carte de distinguer entre les différents types de terrains. La Section des systèmes autonomes conduit la recherche dans le domaine de *Traficabilité acquise* depuis un certain nombre d'années et est bien positionnée en tant que telle pour apporter une contribution méritoire dans ce domaine.

Table of contents

List of figures

This page intentionally left blank.

1 Introduction

Scientists at Defence R&D Canada – Suffield have been investigating autonomous operation of Unmanned Ground Vehicles (UGVs). In order to navigate unknown terrain effectively, UGVs must be able to create an accurate representation of their operational environment. This is typically done by constructing a spatial representation of the environment from exteroceptive sensors such as laser or stereovision sensors and proprioceptive sensors such as GPS and IMU sensors. These representations are utilized by path planning and obstacle avoidance algorithms to determine the "best" path to follow.

A popular world representation, particularly for outdoor mapping, is the Terrain Map, sometimes referred to as the Digital Elevation Map or the 2.5D map. The Terrain Map tessellates the environment into 2D grid-cells. Geometric data provided from range sensors is then accumulated into each cell in an effort to estimate the height of the terrain at the cell location. Stereovision cameras and/or nodding laser scanners are typical employed to provide the range data, although radar, sonar, etc. may also be employed.

Many Terrain Maps are further abstracted to provide a measure of traversability of the terrain by the UGV. Typically this is done by calculating various map statistics such as roughness, pitch, step height, etc. These statistics can then be compared to vehicle specific thresholds to determine if the grid-cell is traversable, impassable, or unknown. This abstraction allows easy integration into path planning and obstacle avoidance algorithms by reducing the data dimensions. Another advantage, is the portability of the algorithm to different platforms which only requires that the user change the vehicle specific parameters.

This paper discusses the generation of Traversability Maps from Terrain Maps. Section 2 provides background information into Terrain and Traversability Mapping, while Section 3 describes the algorithm employed in the Cohort project. Section 4 discusses software design and implementation issues. Section 5 provides results from trials held in the fall of 2006. Finally, Section 6 presents our conclusions and future work.

2 Background

2.1 Terrain Mapping

Robots employ many navigation strategies, based upon a variety of assumptions with respect to their operational environment [1]. Early research followed the sense, model, plan and act paradigm (SMPA) [2,3], where the robots environment was structured, predictable and assumed to be known. Real environments are unstructured and unpredictable and thus the performance of a deliberative SMPA approach can be poor. The reactive school of thought, pioneered by Brooks [3, 4], used the environment itself as the world model for the robot. This approach resulted in robust behavior for unstructured environments, but it did not yield useful application due to the inability to direct the robot's behavior. Current robotic research exploits both the SMPA and deliberative approaches by implementing a hybrid strategy. Like the SMPA paradigm, the hybrid approach requires that the robot create a representation of its environment. A common implementation for world representation is to view the world as a grid array of adjacent regions. The most simplistic of these is the Occupancy Grid [5–7] where each grid element is classified as either occupied, not occupied, or unknown based on 2D range data. This type of grid is useful for indoor environments where obstacles such as walls, bookcases or chairs are easily represented as either empty or occupied space.

For unstructured, outdoor environments the common world representation is the Terrain Map [8–12]. For Terrain Maps each grid element represents the elevation of the terrain at the grid element's location. The Terrain Map, shown in Figure 1, illustrates this grid based representation. A grid element is sized w x d with each element containing data such its average height and the variance. While the Occupancy Grid is actually a type of Terrain Map, the term is used here to refer to maps which make use of 3D range data.

It is not necessary that a map represent just elevation data. Indeed, many robotic maps are capable of representing obstacles and other features, such as hills, slopes, bumps and dips, found in outdoor environments. This is often done in an effort to reduce data dimensionality and provide more useful data to path planners. For the purposes of this paper, these reduced dimensioned mapping algorithms are referred to as Traversability Maps. While many algorithms encode traversability data within the Terrain Map, a clear distinction between the two is made for analysis purposes. In general, Terrain Maps encode the geometry of the environment, while Traversability Maps interpret that data into a useful metric for robot navigation and path planning.

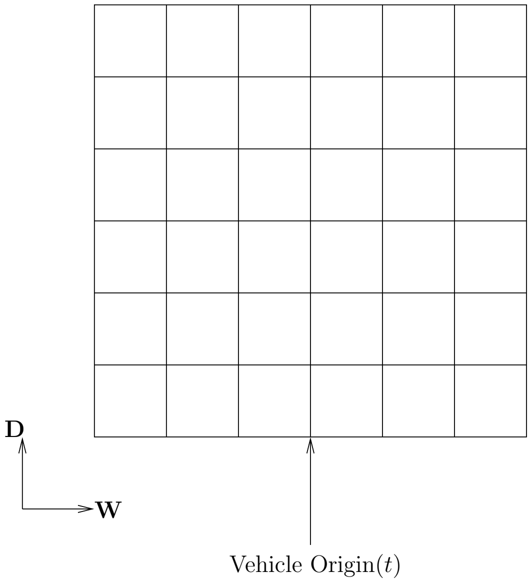


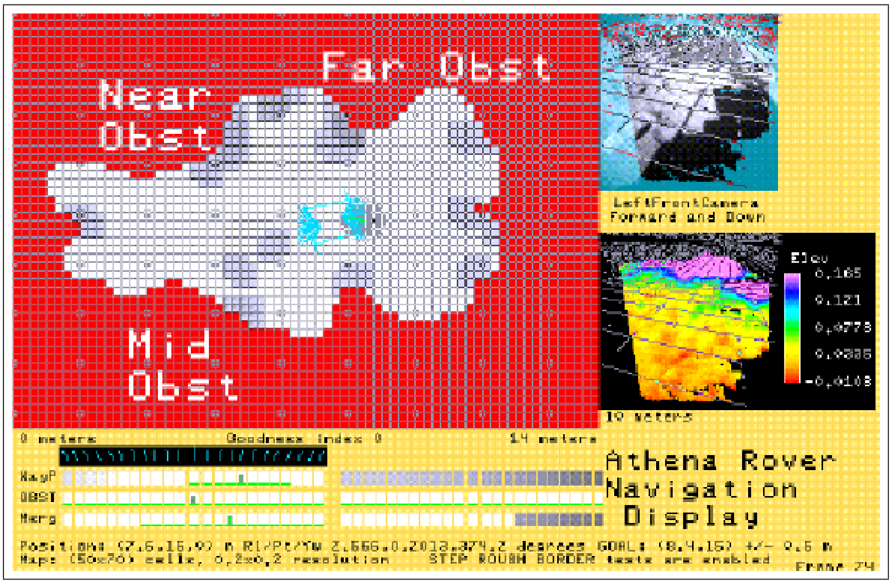
Figure 1: *Typical setup of a Terrain Map where each w x d grid represents the elevation of the terrain for that grid.*

2.2 Traversability Mapping

Traversability Mapping translates high dimensional geometric data into lower dimensional parameters which are applicable to navigation and path planning algorithms. Most implementations calculate cell statistics related to the cost of traversing the cell. In the simplest implementations, each cell can be classified as **traversable**, **impassable**, or **unknown**. In this way, the Traversability Map can be thought of as a 2.5D Occupancy Grid.

Systems such as MORPHIN [13] used a planar fit of terrain data to determine the pitch and roll of the terrain and residual data to determine the roughness of the terrain.

The Grid-based Estimation of Surface Traversability Applied to Local Terrain (GESTALT) [14] developed at JPL for the Mars rover missions tessellated the environment into a number of rover sized grids. Sensory data was collected into the grid cells and potential traversability hazards were calculated. Straight and curved paths from the rovers current position were then evaluated to determine the safest path that moved the rover towards its goal. An unique aspect of this algorithm is the ability to determine obstacles in a direction specific manner. In other words a slope may be a hazard when approached from one direction, but may be perfectly safe when approached from another angle. Figure 2 shows the navigation display used by GESTALT. Despite the effectiveness of the approach, the GESTALT system was implemented in a plan/move/stop/plan fashion which is well suited to high risk navigation of Martian terrain, but less well suited for continuous motion applications.



```
Position: (7.6,15.9) m Rl/Pt/Yw 2.666,0.2013,374.2 degrees GOAL: (8.4,15) +/- 0.5 m
Maps: (50x70) cells, 0.2x0.2 resolution    STEP ROUGH BORDER tests are enabled
```

Figure 2: *The Athena Rover Navigation Display depicting the Traversability Map generated using the GESTALT algorithm. The dark blue areas are impassable, the red areas are unknown, and the grey areas are traversable.*

In [9] researchers collected first and second order moment statistics about range points in each cell. The statistics were merged for a rover sized patch of cells and the best fit plane was determined. The plane was used to determine the following hazards:

- **Step Hazard** - The maximum height difference between any pair of cells in a patch.
- **Roughness Hazard** - Computed from the residual of the planar fit and compared to a threshold roughness factor.
- **Pitch Hazard** - If the slope of the planar fit is above a certain threshold then a slope hazard is present.
- **Border Hazard** - If the cell borders on an unknown cell then it has a border hazard.

Finally Hazard Arc votes were calculated from the hazard data and merged pairwise with waypoint arc votes to determine the best arc for the rover to travel.

In [15], Ye and Borenstein again used a planar fit to estimate roughness and slope hazards. They then calculated *Polar Obstacle Densities* which created a field of repulsion from obstacles. These obstacle vectors were summed for various angles relative to the robot thus creating a polar histogram from which the best steering angle could be selected. This is an extension of the well known Vector Field Histogram described in [16].

More recently, in [17] the Stanford Racing Team utilized a Traversability Map based on data from six laser scanners registered with pose from an Unscented Kalman Filter to classify grids as undrivable, driveable, or unknown. Unfortunately, pose error often led to a large error in the 3D data. To correct for this a Markov model was used to probabilistically test for the presence of an obstacle leading to an improved Traversability Map. In addition, parameters of the Markov model where tuned using a discriminative learning algorithm and data labeled through human driving, as seen in Figure 3. Data representing where the vehicle traveled was labelled as driveable while an area to the left and right of the vehicle was labelled as non-drivable. This significantly reduced the instances of false positives in the map. Finally, a mixture of Gaussians from RGB vision data was maintained for the driveable area of the Traversability Map. These Gaussians were used by an online learning algorithm to label data beyond the range of the laser map. Stanford's extension of the Traversability map represents perhaps the most sophisticated work in the area to date. However, it should be noted that the problem was formulated as a road following problem and has not been tested in off-road navigation scenarios.

3 DRDC Traversability Mapping

3.1 Algorithm Details

DRDC's traversability analysis maps a fine resolution Terrain Map, $\mathcal{T}$, to a coarser Traversability Map, $\mathcal{V}$. Similar to [18] and [9], the Traversability Map is composed of a grid where each element, denoted by the index (i, j), contains measures of *Traversability* $\mathcal{V}_{ij}$, the ease with which a UGV can navigate the given cell, and *Goodness* σ^2_{ij}, the accuracy of the data used to produce traversability. So for an element $\mathcal{V}_{ij}$:

$$\mathcal{V}_{ij} \equiv \left\langle \mathbf{V}_{ij}, \sigma^2_{ij} \right\rangle \tag{1}$$

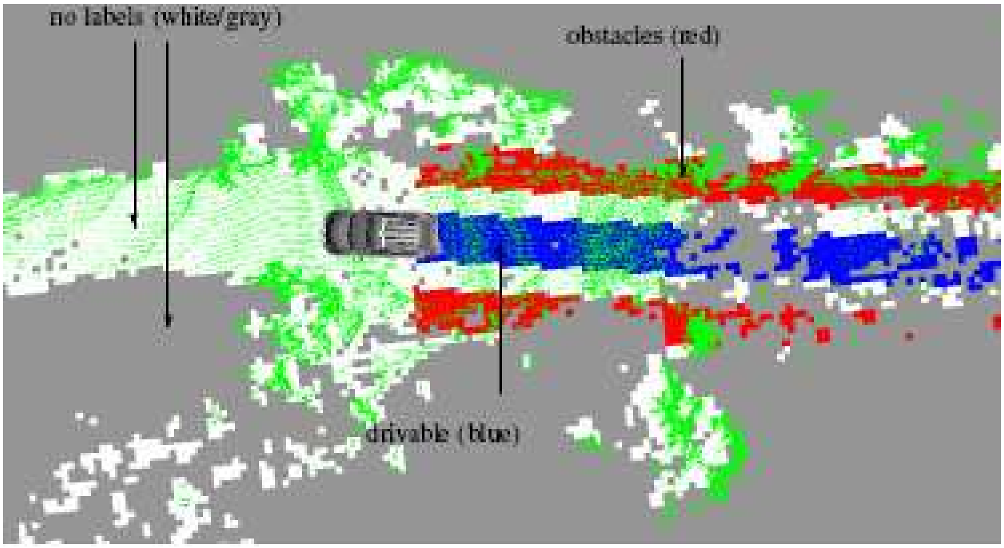


Figure 3: *Terrain labeling for parameter tuning for the Stanley robot. The areas are labeled blue which the UGV drives over whereas areas a fixed distance to either side of the UGV are labeled obstacles. This data is used to train a learning system to accurately predict whether terrain is traversable or not.*

This information can then be used by path planning algorithms to determine an optimal route through the map.

The Traversability Map is generated either each time the Terrain Map is updated or on a timed interval. Traversability Maps are non-cumulative in the sense that a new map is produced at every interval, but these maps are based on cumulative Terrain Maps data. Each traversability cell is constructed from a subset of terrain cells $\mathcal{S}_{ij}$ whose Cartesian coordinates lie within the bounding box of cell $\mathcal{V}_{ij}$:

$$\mathcal{T}_{ij}(x_t, y_t) \in S_{ij} : \begin{cases} x_v - 0.5w \leq x_t \leq x_v + 0.5w \\ y_v - 0.5d \leq y_t \leq y_v + 0.5d \end{cases} \tag{2}$$

where (x_v, y_v), (x_t, y_t) are the centroids of $\mathcal{V}_{ij}$ and $\mathcal{T}_{ij}$ respectively, w is the width of $\mathcal{V}_{ij}$ and d is the depth of $\mathcal{V}_{ij}$.

The subset $\mathcal{S}_{ij}$ calculates the traversability measure, $\mathbf{V}_{ij}$ ranging from 0, or fully traversable, to 1, indicating non-traversable terrain. In the event that $\mathcal{S}_{ij}$ has less than n_{valid} members containing valid terrain data, the traversability is marked as unknown, otherwise the following calculations are used to determine $\mathbf{V}_{ij}$:

Calculate Step Hazard

The step hazard, $\mathbf{H}_{ij}$, is defined as a change in elevation which the UGV cannot safely navigate and is calculated as follows:

$$\mathbf{H}_{ij} = \begin{cases} 0 & : \quad s_{max} < 0.5h_{obst} \\ \frac{s_{max}}{h_{obst}} & : \quad 0.5h_{obst} \leq s_{max} < h_{obst} \\ +1 & : \quad s_{max} \geq h_{obst} \end{cases} \tag{3}$$

Where s_{max} is the maximum elevation difference between any of the members of $\mathcal{S}_{ij}$ which contain valid data, and h_{obst} is the minimum step height the UGV can safely traverse.

Calculate Slope Hazard

The slope hazard, $\mathbf{D}_{ij}$, is determined by fitting a plane to the valid elements of $\mathcal{S}_{ij}$. If the plane's pitch p_{ij} or roll r_{ij} relative to vehicle's local frame is greater than the pitch or roll thresholds, p_{max} and r_{max} respectively, the slope hazard, $\mathbf{D}_{ij}$, assumes a value of 1, otherwise $\mathbf{D}_{ij} = 0$,.

$$\mathbf{D}_{ij} = \begin{cases} 1 & : \quad p_{ij} > p_{max} \text{ or } r_{ij} > r_{max} \\ 0 & : \quad \text{otherwise} \end{cases} \tag{4}$$

Calculate Traversability

The traversability of a grid cell $\mathbf{H}_{ij}$ is determined as follows:

$$\mathbf{V}_{ij} = \begin{cases} 1 & : \quad \mathbf{H}_{ij} = 1 \text{ or } \mathbf{D}_{ij} = 1 \\ \mathbf{H}_{ij} & : \quad \text{otherwise} \end{cases} \tag{5}$$

The Goodness of cell, $\mathcal{V}_{ij}$, is calculated as the sum of variances of elevation data σ_z^2 in $\mathcal{S}_{ij}$.

The Traversability Map is separated into two different regions, a near zone $\mathcal{Z}_1$ and a far zone $\mathcal{Z}_2$. $\mathcal{Z}_1$ includes any traversability cells which lie within a radius r_1 from the UGV and $\mathcal{Z}_2$ is the remainder. $\mathcal{Z}_1$ typically contains large amounts of valid terrain data and is of greater accuracy than $\mathcal{Z}_2$. To reduce false obstacles caused by inconsistencies in the Terrain Map, the step height threshold is modified as follows where o_{mod} is the obstacle height modifier:

$$h_{\mathcal{Z}_2 obst} = o_{mod} h_{\mathcal{Z}_1 obst} \tag{6}$$

3.2 Global and Ego Traversability Maps

DRDC's traversability algorithm is actually implemented as two separate maps, a Global and an Ego map. The Global map has a global reference frame with the center of the map corresponding to the UGV GPS location and is derived from the Global Terrain Map data.

As the reference frame is not local to the vehicle, pitch/roll hazards are not calculated as they are only relevant in relation to the vehicle pose. The Global map is utilized by a global path planner [19]. Figure 4(left) depicts a typical Global map.

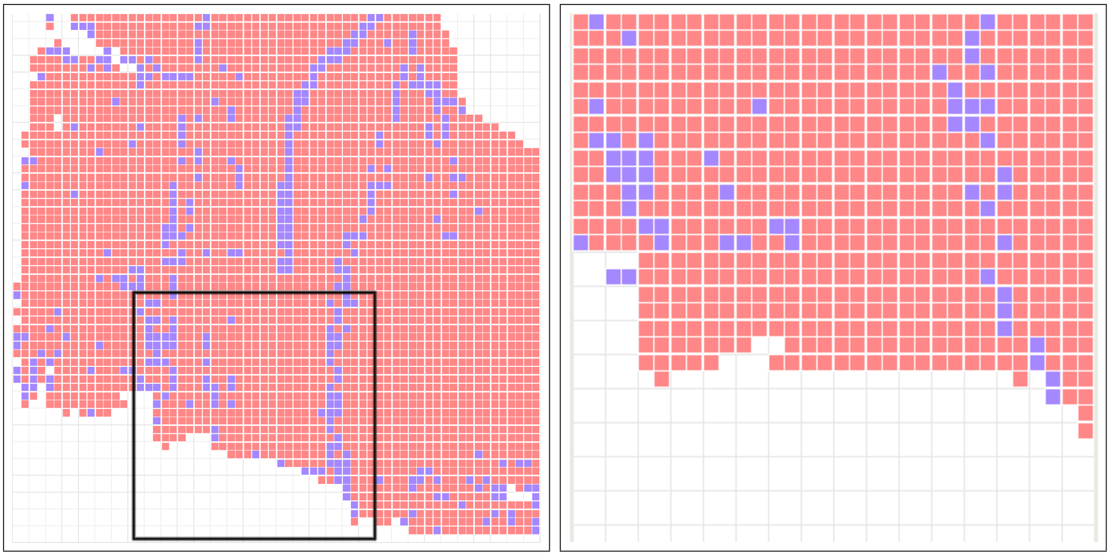


Figure 4: *Comparison of a Global (left) and Ego (right) Traversability Map taken at the same time in a trial. Blue, red, and white cells indicate impassable, traversable, and unknown cells respectively. The area enclosed in the rectangle roughly corresponds to the Ego map.*

The Ego map has its local reference frame at the middle of the front bumper of the vehicle and is created from DRDC's Ego Terrain Map. Here the step and/or slope hazards may be used in calculating the traversability of a given cell. The Ego map typically has smaller dimensions than the Global map as it retains no data which is behind the vehicle. This map is used for local obstacle avoidance. Figure 4(right) depicts a typical Ego Map.

4 Implementation

4.1 Miro

The Traversability Map has been implemented using the Miro framework adopted by the AISS researchers at DRDC – Suffield. Miro [20–22] is a framework that simplifies the process of building a robot by providing capabilities that are commonly used by robot systems. In general, each algorithm exists in Miro as a standalone module. These modules communicate through pre-established interfaces (IDL) in polled or event driven fashion. Each algorithm follows an established design pattern which encourages reuse by cleanly separating the interface from the algorithmic details. The Traversability map follows the **Subscribe-Publish Server** design pattern seen in Figure 5.

The Subscribe-Publish Server defines a Miro Server which receives events of type **A**, processes this event, and produces events of type **B**. In the case of the Traversability Map the

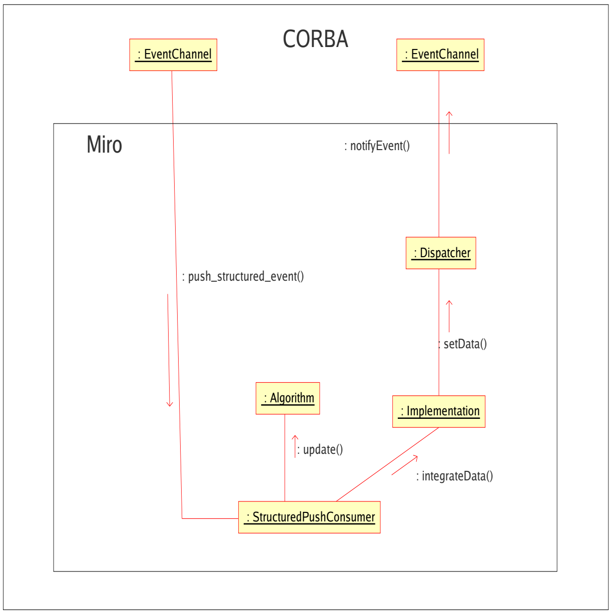


Figure 5: *The Subscribe-Publish design pattern. The StructuredPushConsumer class receives events of one type, process the data into another event type and send the event to the implementation. The event is then dispatched on the EventChannel via the Dispatcher class.*

Server responds to events of type **MapArrayEventIDL** and **EgoMapArrayEventIDL** and generates events of type **TravMapArrayEventIDL** and **EtravMapArrayEventIDL**, which correspond to the Global Traversability Map and Ego Traversability Map respectively. The **TravMapArrayEventIDL**, shown below, contains a number of important parameters. The **EtravMapArrayEventIDL** is similar in structure and thus has been omitted here.

```
typedef double TravMapArrayIDL[CONFIDENCE+1][TINDEX_DEPTH][TINDEX_WIDTH];

struct TravMapArrayEventIDL
  {
    //The time the map generated
    TimeIDL time;

    //The UGV pose when the map was generated
    PoseTransformIDL pose;

    //Value indicating the type of map
    long maptype;

    //Value indicating the depth of map
    long index_depth;
```

```
    //Value indicating the width of map
    long index_width;

    //X index in the map indicating the position of UGV in the map
    long x_curr;

    //Y index in the map indicating the position of UGV in the map
    long y_curr;

    //The Traversability data
    TravMapArrayIDL map;
};
```

4.2 Utilizing the Traversability Map

Currently the Traversability Map is used by two processes. The **ObsAvoid** module utilizes the Ego Map to avoid positive and negative obstacles and perform local path planning as shown in Figure 7. This is done by projecting a series of candidate arcs through the map. A cost for each arc is determined by the traversability of the grids which the arc is projected through. Arcs which pass through obstacles are vetoed. Finally an arbiter chooses the best non-vetoed arc to travel. Results utilizing **ObsAvoid** are presented in Section 5.

The Global Traversability Map is used by the **findPath** module which is a global path planner utilizing the D* Lite algorithm, an incremental heuristic search method implementing goal-directed robot navigation in unknown terrain. The algorithm seeks to minimize the cost of traversing from a start vertex to a goal vertex. This planner has not been fully tested as of yet.

5 Experimental Results

In the summer of 2006, field trials were conducted, under the Cohort project, to evaluate the effectiveness of Traversability Mapping for long range point to point navigation with obstacle avoidance.

Having already successfully demonstrated simple obstacle avoidance using the system the previous fall [23], all efforts were directed towards improving the accuracy and robustness of the mapping software. All algorithms were tested on the Koyker Raptor UGV, seen in Figure 6. The Raptor is a gas powered 25Hp all terrain vehicle with a hydrostatic drive-train which has been modified for autonomy. The platform was equipped with the following hardware [1]:

- One quad Pentium server

---

[1] Additional hardware available on the Raptor but not used in the field trials is not listed

Figure 6: *Raptor UGV used for Autonomous trials in the summer of 2006.*

- A Microstrain Inertial Measurement Unit
- A Sokkia GSR2600 GPS
- A Pacific Crest PDF RVR radio to provide DGPS corrections
- 2 SICK laser rangefinders with a custom nodding mechanism
- An MPC555 micro-controller for vehicle control

The UGV was given a series of GPS waypoints shown in Figure 10. As previously mentioned, a Traversability Map was generated using the process described in Section 3. This Traversability Map was used as input to the **ObsAvoid** candidate arc obstacle avoidance algorithm. The **PurePursuit** and **ObsAvoid** algorithms each voted on the set of candidate arcs. As can be seen in Figure 7, the ObsAvoid algorithm would veto an arc if an impassable cell lies within that arc, otherwise a costing function was used to calculate the cost of traversing the arc. The PurePursuit algorithm would vote for each arc based on its ability to steer the UGV towards the straight line path between waypoints. Finally an arc arbitration algorithm, **ArcArbiter**, selected the best arc from the competing votes. Figure 8 depicts the entire system. Details of the Pure Pursuit algorithm can be found in [24]. The ArcArbiter is similar to the DAMN architecture described in [25]. The ObsAvoid algorithm is similar to the MORPHIN and GESTALT systems described in [13] and [14].

The Traversability Map was configured with 50cm x 50cm cells, while the size of the map was 16m x 16m. Though the size of the map was 16m x 16m, data was inaccurate beyond $12m$ and thus the nodding SICK lasers were adjusted such they they did not nod beyond this distance. The maximum speed the UGV traveled was roughly $1m/s$. This was limited partially by the nodding rate of the lasers. Due to an issue with our stepper motors we were unable to nod our mechanism any faster than roughly 25 degrees/sec, as this would cause the stepper motor to jitter and produce noisy data.

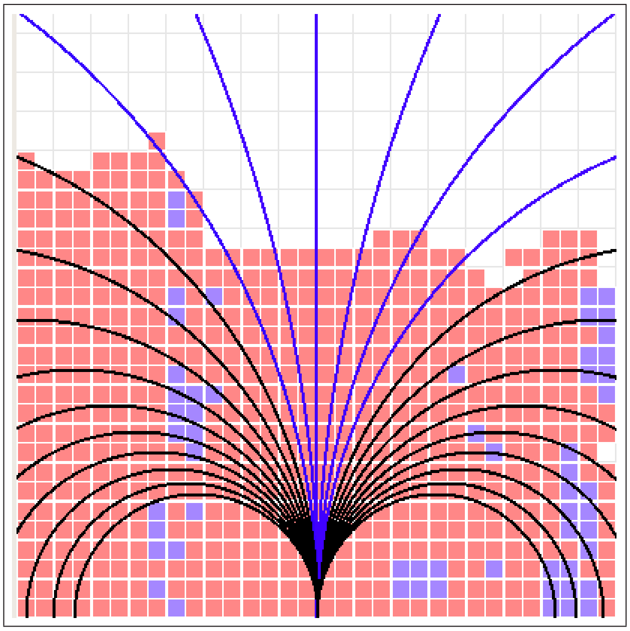


Figure 7: *Traversability Map with Obstacle Avoidance arcs overlayed. Vetoed arcs appear black while safe arcs appear blue.*

Step and slope hazard parameters where chosen as 25cm and 15 degrees respectively. The low slope and step thresholds were chosen such that even slight positive/negative obstacles such as road grades and ditches would appear as hazards. Terrain representative of the course can be seen in Figure 9.

The UGV was given a series of 5 waypoints to follow, as seen in Figure 10. These waypoints were located at various positions on a grid road bounded by a graded ditch and grassy areas. The UGV was able to navigate through all 5 waypoints with minimal intervention [2]. As can be seen in Figure 10, the actual trajectory taken by the UGV consistently followed the road. This proves that the slope and step hazard metrics are sufficient for detecting negative obstacles. In addition, two buildings (positive obstacles) were successfully avoided.

As the UGV was not explicitly road following it would sometimes exhibit undesirable behaviour which nonetheless was consistent with the algorithms employed. For instance, where the grade of the ditch was relatively flat (below the slope threshold) the UGV would travel through the ditch following a trajectory to the nearest waypoint. As the grade of the ditch steepened, the UGV would navigate back to the road as the ditch was once again classified as impassable. At one point during the run the UGV turned onto an approach and subsequently got stuck instead of continuing to follow the road. This suggests that a road recognition algorithm could be used in conjunction with the Traversability Map in order to explicitly label areas of the Traversability Map as road/non road.

---

[2] The UGV turned off the road twice in an effort to take a more direct approach to a waypoint. In addition, the UGV was halted once as vegetation was incorrectly classified as impassable

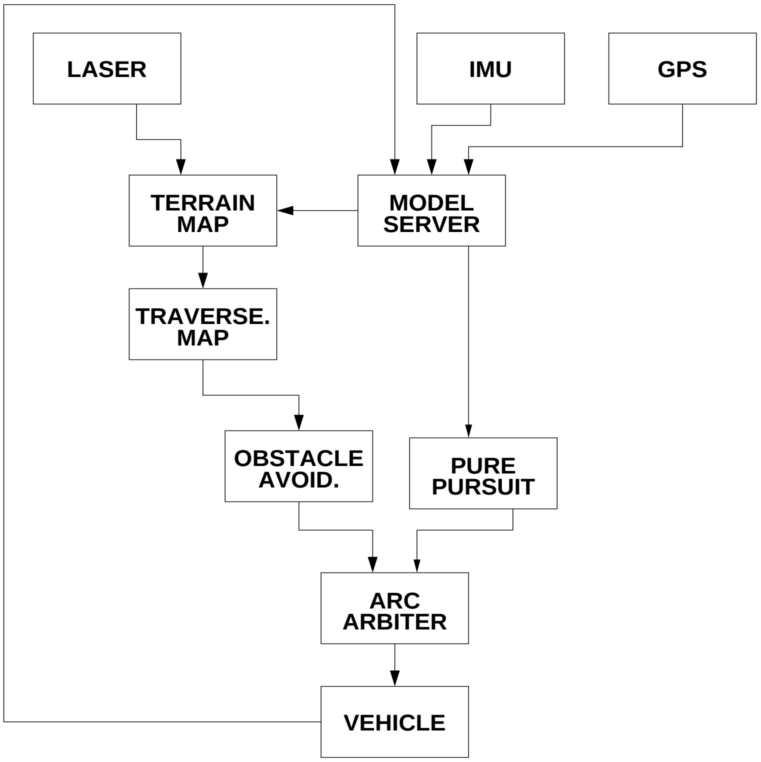


Figure 8: *Flow chart depicting the various modules involved in the 2006 Raptor trials. A pose solution from an IMU and GPS was used to convert laser data into a Terrain Map. This map was analyzed to produce a Traversability Map. An obstacle avoidance algorithm vetoed arcs based on traversability data, while the Pure Pursuit algorithm voted on the arc which would progress the UGV to its goal. Finally an arbiter chose the best arc among competing votes. These appropriate steering and velocity commands were then send to the vehicle.*

Due to Terrain Maps statistical nature, the derived Traversability Map sometimes detected false obstacles. This could cause the UGV to turn erratically or stop (if the obstacle appeared near the vehicle). Once the Terrain Map accumulated more sensor data, yielding a more accurate statistical representation, these obstacles usually disappeared. However, in early testing it was discovered that the vehicle could get caught if a false obstacle appeared close to the UGV outside the range of the laser scanners. In these instances no new range data was collected for the corresponding cell. In order to alleviate this problem, functionality was added which cleared the Terrain Map data, and accumulated new data for a number of seconds before resuming normal operation.

6 Conclusion

Traversability Mapping attempts to parametrize the geometry of the environment into useful metrics which a UGV may use for navigation or obstacle avoidance. DRDC has

Figure 9: *Terrain representative of that found on the trial site. (Far-Left) start area - The UGV would have to navigate around the building in the left side of the image. (Left-Center) steep ditches characteristic of the trial site. These were seen as obstacles by the UGV. (Right-Center) - harsh terrain which the UGV had to negotiate (Far-Right) - straight away bounded by sloped ditches on either side*

developed such a mapping system using generic range sensor data to generate a 2.5D Terrain Map. This Terrain Map is then analyzed to quantify traversable areas, thus yielding a Traversability Map. This map can then be used by obstacle avoidance and path planning algorithms. The Miro framework has proved effective in efficiently and reliably implementing the Traversablility algorithm.

In the summer of 2006 field trials were conducted to assess the effectiveness of Traversability Mapping for obstacle avoidance. Results have shown that this method is successful for recognizing positive obstacles such as buildings, trees, etc., and negative obstacles such as ditches. This allowed the test UGV to successfully navigate through a series of five waypoints on a 1.3km course. During testing, the UGV routinely chose to travel on the road without any knowledge of what a road is thus proving the statistics calculated are sufficient for recognizing safe corridors of travel.

7 Future Work

Future work in Traversability Mapping will focus on improving system robustness and increasing the accuracy of the maps. Currently, the UGV is limited to running at very slow speeds due in part to a mechanical error in the laser nodding mechanism which causes large errors in laser readings. Improvements to this mechanism should improve map generation speeds. In addition, sun-visors are being fabricated to reduce the instances of laser dazzle; an error which occurs when excessive sunlight causes the laser to fail. In addition, work will continue with Traversability Mapping to determine the robustness of the algorithm. Currently, the obstacle avoidance algorithm only works with discrete traversability (traversable, impassable). The capability is already in place to use a degree of traversability value between 0-1. This could potentially improve the effectiveness of the Traversability Map for obstacle avoidance as rough areas or areas near obstacles may be avoided. Other hazards such as roughness and border hazards should be evaluated to determine their effectiveness. Furthermore, as previously mentioned, the Global Traversability Map has yet to be tested

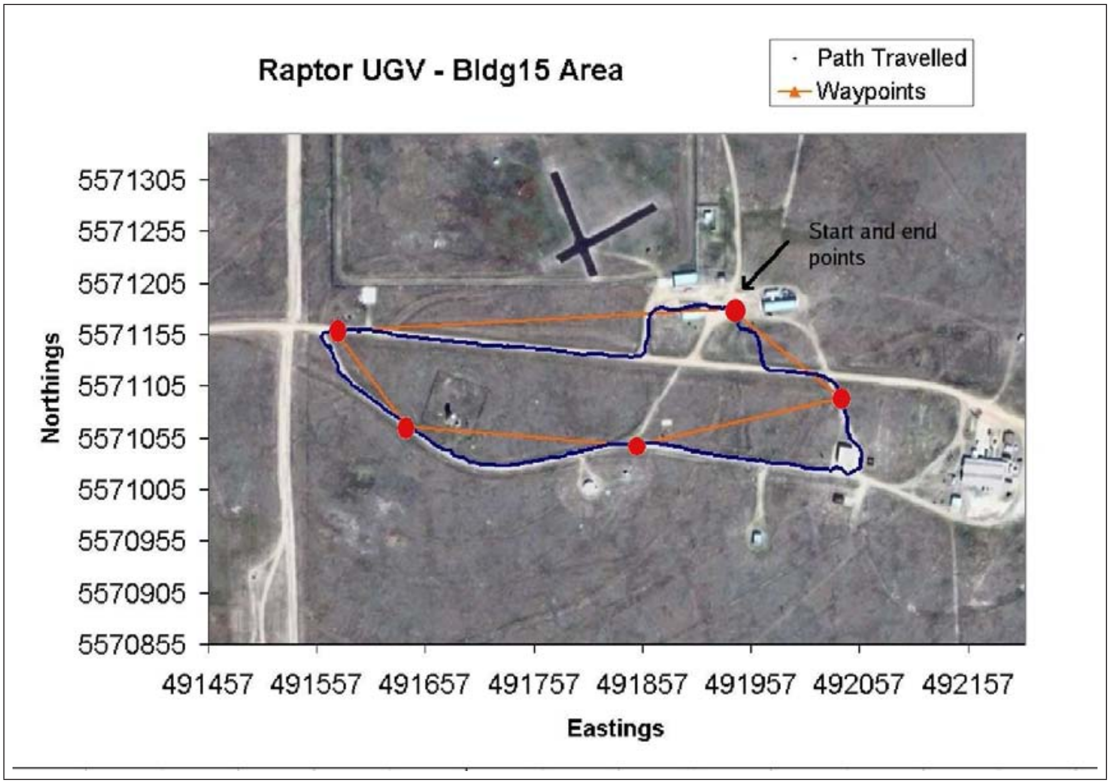


Figure 10: *Site of the Raptor autonomous road following field trials. The red points indicate the GPS waypoints which the vehicle must navigate. The orange track indicates the straight line trajectory which the UGV attempts to follow, while the blue track indicates the actual trajectory which the UGV followed as a result of obstacle avoidance.*

with DRDC's D* Lite implementation.

Despite the successes that Traversability Mapping has achieved thus far, the approach does not work nearly as well in heavily vegetated areas such as those encountered in off-road navigation. In these cases the map is unable to differentiate between "real" obstacles such as rocks and "false" obstacles such as grass. In order to be successful in this environment this approach must be supplemented with a learning algorithm which would allow the map to distinguish between various types of terrain as in [26] and [27]. AISS has been conducting research in *Learned Trafficability* for a number of years [28] and as such is well positioned to make be a worthy contribution in this area.

References

[1] Broten, G., Monckton, S., Giesbrecht, J., Verret, S., Collier, J., and Digney, B. (2004), Towards Distributed Intelligence - A high level definition, (DRDC Suffield TR 2004-287) Defence R&D Canada – Suffield.

[2] Nilsson, N.J. (1984), Shakey The Robot, (Technical Report 323) AI Center, SRI International.

[3] Brooks, R.A. (1991), Artificial IntelligenceMemo No. 1293: Intelligence without Reason, Massachusetts Institute of Technology.

[4] Brooks, R.A. (1986), A Robust Layered Control System for a Mobile Robot, *IEEE Journal of Robotics and Automation*, RA-2(1), 14–23.

[5] Elfes, A. (1989), Using Occupancy Grids for Mobile Robot Perception and Navigation, *Computer*, 22(6), 46–57.

[6] Thrun, S., Burgard, W., and Fox, D. (2005), Probabilistic Robotics, 1st ed, Toronto: The MIT Press.

[7] Thrun, S. (2003), Learning occupancy grids with forward sensor models, *Autonomous Robots*, 15, 111–127.

[8] Bellutta, P., Manduchi, R., Matthies, L., Owens, K., and Rankin, A. (2000), Terrain Perception for DEMO III, In *Proceedings of the 2000 Intelligent Vehicles Conference*, 326–331.

[9] Goldberg, S., Maimone, M., and Matthies, L. (2002), Stereo Vision and Rover Navigation Software for Planetary Exploration, Vol. 5, 2025–2036.

[10] Herbert, M. and Krotkov, E. (1993), Local Perception for Mobile Robot Navigation in Natural Terrain: Two Approaches, In *Workshop on Computer Vision for Space Applications*, 24–31.

[11] Kweon, S. and Kanade, T. (1992), High-Resolution Terrain Map from Multiple Sensor Data, *IEEE Transactions on Pattern Analysis and Machine Vision*, 14(2), 278–292.

[12] Lacroix, S., Mallet, A., and Bonnafous, D. (2000), Autonomous Rover Navigation on Unknown Terrains Demonstrations in the Space Museum "Cite de l'Espace" at Toulouse Automation, Albuquerque, USA, 1997, In *7th International Symp. on Experimental Robotics*, 669–683, Honolulu, HI.

[13] Simmons, R., Henrikson, L., Chrisman, L., and Whelan, G. (1996), Obstacle avoidance and safeguarding for a lunar rover, In *AIAA Forum on Advanced Developments in Space Robotics*, Madison WI.

[14] Biesiadecki, J., Maimone, M.W., and Morrison, J. (2001), The Athena SDM Rover: a Testbed for Mars Rover Mobility, *International Symposium on Artificial Intelligence, Robotics and Automation in Space i-SAIRAS '01.*

[15] Ye, C. and Borenstein, J. (2004), A Method for Mobile Robot Navigation on Rough Terrain, In *Proceedings of IEEE International Conference on Robotics and Automation*, Vol. 4, 3863–3869.

[16] Borenstein, J. and Koren, Y. (1991), The Vector Field Histogram - Fast Obstacle Avoidance for Mobile Robots, *IEEE Transactions on Robotics and Automation*, 7(3), 535–539.

[17] Thrun, S. (2005), Stanley: The Robot That Won The DARPA Grand Challenge, *DARPA Grand Challenge Website*.

[18] Singh, S., Schwehr, K, Simmons, R., Smith, T., Stenz, A., Verma, V., and Yahja, A. (2000), Recent Progress In Local and Global Traversability For Planetary Rovers, In *International Conference on Robotics and Automation*.

[19] Mackay, D. (2005), Path Planning with D*-Lite, (DRDC Suffield TM 2005-242) Defence R&D Canada – Suffield.

[20] Utz, H., Sablatnog, S., Enderle, S., and Kraetzschmar, G. (2002), Miro - MIddleware for Mobile Robot Applications, *IEEE Transactions on Robotics and Automation*, 18, 493–497.

[21] Department of Computer Science, University of Ulm (2005), Miro Manual, 0.9.4 ed, University of Ulm.

[22] Broten, G., Collier, J., Giesbrect, J., Monckton, S., and Mackay, D. (2006), The Architecture for Autonomy, (DRDC Suffield TM 2006-188) Defence R&D Canada – Suffield.

[23] Monckton, S., Collier, J., Giesbrecht, J., Broten, G., Mackay, D., Erickson, D., Verret, S., and Digney, B. (2006), The ALS Project: Lessons Learned, In *SPIE Defense and Security Symposium Unmanned Systems Technology VIII*, Vol. 6230, p. 12.

[24] Giesbrecht, J., Mackay, D., Collier, J., and Verret, S. (2005), Path Tracking for Unmanned Ground Vehicle Navigation, (DRDC Suffield TM 2005-224) Defence R&D Canada – Suffield.

[25] Rosenblatt, J.K. (1995), DAMN: A Distributed Architecture for Mobile Navigation., In *Proceedings of the 1995 AAAI Spring Symposium on Lessons Learned from Implemented Software Architectures for Physical Agents , H. Hexmoor and D. Kortenkamp (Eds.)*, AAAI Press, Menlo Park, CA.

[26] Wellington, C. and Stentz, A. (2004), Online Adaptive Rough-Terrain Navigation in Vegetation, In *IEEE International Conference on Robotics and Automation*, Vol. 1, 96–101.

[27] Rassmussen, C. (2002), Combining Laser Range, Color, and Texture Cues for Autonomous Road Following, In *IEEE International Conference on Robotics and Automation*, Vol. 4, 4320–4325.

[28] Broten, G. S. and Digney, B.L. (2003), A Learning System Approach for Terrain Perception Using Eigenimages, (DRDC Suffield TR 2003-165) Defence R&D Canada – Suffield.

This page intentionally left blank.

Distribution list

DRDC Suffield TM 2006-175

Internal distribution

DRDC Suffield

1 DG/DDG/Chf. Sci./SMO/HAISS

2 Lead Author

2 Other Authors (1 each)

2 Library – 1 hardcopy/1 softcopy

Other DRDC Suffield

1 DRDKIM (softcopy)

Total internal copies: 6 hard copies

Total copies: 6

This page intentionally left blank.

DOCUMENT CONTROL DATA

(Security classification of title, body of abstract and indexing annotation must be entered when document is classified)

1. ORIGINATOR (the name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's report, or tasking agency, are entered in section 8.) Defence R&D Canada – Suffield PO Box 4000, Station Main, Medicine Hat, AB, Canada T1A 8K6	2. SECURITY CLASSIFICATION (overall security classification of the document including special warning terms if applicable). UNCLASSIFIED

3. TITLE (the complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S,C,R or U) in parentheses after the title).

Traversability Analysis for Unmanned Ground Vehicles

4. AUTHORS (last name, first name, middle initial)

Collier, J.; Broten, G.; Giesbrecht, J.

5. DATE OF PUBLICATION (month and year of publication of document) December 2006	6a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc). 32	6b. NO. OF REFS (total cited in document) 28

7. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered).

Technical Memorandum

8. SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development. Include address).

Defence R&D Canada – Suffield
PO Box 4000, Station Main, Medicine Hat, AB, Canada T1A 8K6

9a. PROJECT NO. (the applicable research and development project number under which the document was written. Specify whether project).	9b. GRANT OR CONTRACT NO. (if appropriate, the applicable number under which the document was written).
10a. ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity. This number must be unique.) DRDC Suffield TM 2006-175	10b. OTHER DOCUMENT NOs. (Any other numbers which may be assigned this document either by the originator or by the sponsor.)

11. DOCUMENT AVAILABILITY (any limitations on further dissemination of the document, other than those imposed by security classification)

(X) Unlimited distribution
(   ) Defence departments and defence contractors; further distribution only as approved
(   ) Defence departments and Canadian defence contractors; further distribution only as approved
(   ) Government departments and agencies; further distribution only as approved
(   ) Defence departments; further distribution only as approved
(   ) Other (please specify):

12. DOCUMENT ANNOUNCEMENT (any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (11). However, where further distribution beyond the audience specified in (11) is possible, a wider announcement audience may be selected).

13. ABSTRACT (a brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), (R), or (U). It is not necessary to include here abstracts in both official languages unless the text is bilingual).

Scientists at Defence R&D Canada – Suffield have been investigating autonomous operation of Unmanned Ground Vehicles (UGVs). In order to navigate unknown terrain effectively, UGVs must be able to create an accurate representation of the operational environment. This is typically done by constructing a geometric representation of the environment, called a Terrain Map, from exteroceptive and proprioceptive data streams. This Terrain Map can further be analyzed to provide a measure of the traversability of the terrain. The resulting Traversability Map can be utilized by path planning and obstacle avoidance algorithms to determine the “best” path to follow.

This paper discusses DRDC’s *Traversability Map* as a method of world representation. The Traversability Map interprets geometric data by calculating statistics about the environment to determine whether an area is traversable or not. In doing so, the Traversability Map interprets geometry from a vehicle specific context, allowing for the unique mobility characteristics of platforms to dictate map parameters.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus. e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified. If it not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title).

2.5 mapping
robotics
perception