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Terrain Maps – Lessons Learned and New Approaches

A Global Implementation Using Egocentric Viewports

G.S. Broten, S.P. Monckton, J.A. Collier and D.J. Mackay
DRDC Suffield

Technical Memorandum
DRDC Suffield TM 2006-189
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Principal Author

Original signed by G.S. Broten

G.S. Broten, S.P. Monckton, J.A. Collier, D.J. Mackay

Approved by

Original signed by D. Hanna

D. Hanna

Head/Autonomous Intelligent Systems Section

Approved for release by

Original signed by Dr. Paul A. D'Agostino

Dr. Paul A. D'Agostino

Chairman/Document Review Panel

Abstract

In 2002 Defence R&D Canada changed research direction from purely tele-operated land vehicles to general autonomy for land, air, and sea craft. This research, conducted under the Autonomous Land Systems (ALS) project, developed the Raptor unmanned ground vehicle (UGV), which successfully demonstrated autonomous capabilities. A key capability developed under the ALS project was a terrain mapping technique for representing outdoor, unstructured environments. Although the original ALS terrain mapping technique performed adequately, extensive testing and experimentation revealed weaknesses in its egocentric approach, principally due to the rotation of the map when the vehicle executed sharp turns. To correct this weakness, it was replaced with a locally-referenced global map that scrolls relative to the fixed cardinal directions. The vehicle remains in the centre of the global map and the map scrolls as the vehicle moves. An egocentric view, required for obstacle avoidance, is derived from the global map using a viewport. Extensive testing on the Raptor UGV revealed the global terrain map's performance was superior to the egocentric terrain map approach. Using this technique, the terrain map more accurately represented and tracked terrain features. Additionally, since the vehicle remains at the centre of the global terrain map, this technique retains a record of recently traversed terrain, thus allowing for backup manoeuvres without requiring a rearward looking laser.

Résumé

R & D pour la défense Canada a changé la direction de sa recherche sur les véhicules terrestres purement télé-opérés, en 2002, pour l'orienter vers celle de l'autonomie générale d'embarcations terrestres, aériennes et maritimes. Cette recherche, conduite par le projet Systèmes terrestres autonomes (STA), a mis au point le véhicule terrestre sans pilote Raptor qui a fait preuve de ses capacités autonomes. Une capacité clé, mise au point par le projet STA, était une technique de cartographie de terrain destinée à représenter l'environnement extérieur non structuré. La technique de cartographie de terrain STA originale fonctionnait adéquatement mais des essais et des expériences ont révélé la faiblesse de cette méthode égocentrique surtout dû à la rotation de la carte quand le véhicule exécute des virages serrés. On a corrigé cette faiblesse en remplaçant cette carte par une carte globale ayant des références locales qui défilent relativement aux quatre points cardinaux fixes. Le véhicule demeure au centre de la carte globale et la carte défile en même temps que se déplace le véhicule. Une vue égocentrique, requise pour éviter les obstacles, est dérivée de la carte globale au moyen d'une fenêtre d'affichage. Des essais détaillés sur le véhicule Raptor ont révélé que le rendement de la carte de terrain globale était supérieur à la méthode de la carte de terrain égocentrique. Cette technique permet à la carte de terrain d'effectuer une représentation et un traçage de terrain plus exacts. De plus, le véhicule demeurant au centre de la carte de terrain globale, cette technique documente les terrains récemment traversés et permet ainsi d'effectuer des manœuvres de marche arrière sans avoir besoin d'un laser de vue arrière.

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Executive summary

Terrain Maps – Lessons Learned and New Approaches

G.S. Broten, S.P. Monckton, J.A. Collier, D.J. Mackay; DRDC Suffield TM 2006-189; Defence R&D Canada – Suffield; December 2006.

Background: Defence R&D Canada researches Autonomous Intelligent Systems as defined by the DRDC Technology Investment Strategy (TIS) where the TIS defines autonomy as *”...automated or robotic systems that operate and interact in the complex and unstructured environments of the future battlesspace”*. In order to conduct autonomous operations, an unmanned ground vehicle (UGV) must first sense and then represent its world. Under the Autonomous Lands Systems (ALS) project, Defence R&D Canada – Suffield developed a world representation based upon egocentric terrain maps. Using the egocentric terrain map implementation, the Raptor UGV could navigate around obstacles found in a low complexity environment and this capability was exercised during the ALS demonstration. Testing and experimentation revealed the original egocentric-only terrain map suffered from deficiencies. The most significant deficiency affected the map’s fidelity as the Raptor UGV conducted turning manoeuvres. Under certain circumstances, this degraded map fidelity could adversely affect the terrain representation, thus obstacles could be misrepresented. Additionally, turning manoeuvres had a smearing effect where an obstacle was not correctly tracked by the update process.

Principle Conclusions: To overcome the egocentric-only map’s limitation, a global map approach was proposed, implemented, and tested. The global map rectifies the ego-centric map issues, by referencing the map to the four cardinal direction, North, East, South and West. This eliminates the fidelity and smearing issues associated with turning manoeuvres since the global map’s fixed reference never require rotations.

Significance of Results: The global terrain map maintains its fidelity through all possible UGV turning manoeuvres, thus faithfully represents the world. This improvement translates into more consistent obstacle detection, tracking and subsequent avoidance. Extensive testing verified the performance benefits resulting from the global map implementation.

Future Results: Currently, the Raptor UGV does not support backup manoeuvres. At present, the single egocentric viewport, into the global map, extracts a forward looking representation. Given the global map implementation preserves a patch of traversed terrain that surrounds the vehicle, it is feasible to extract a viewport from an arbitrary viewpoint. Thus, the global terrain map can easily provide a rearward looking egocentric map and hence support backup manoeuvres that would allow the Raptor UGV to reverse directions.

Sommaire

Terrain Maps – Lessons Learned and New Approaches

G.S. Broten, S.P. Monckton, J.A. Collier, D.J. Mackay; DRDC Suffield TM 2006-189; R & D pour la défense Canada – Suffield; décembre 2006.

Contexte: R & D pour la défense Canada effectue des recherches sur les Systèmes intelligents autonomes (SIA) tels que définis par la Stratégie d'investissement en technologie de RDDC où autonomie est définie comme « *systèmes automatisés ou robotiques qui opèrent et interagissent dans les environnements complexes et non structurés des espaces de combat*. » Un véhicule terrestre sans pilote doit d'abord capter puis représenter le monde qui l'entoure pour être en mesure de conduire des opérations autonomes. Avec le projet des Systèmes terrestres autonomes (STA), R & D pour la défense Canada – Suffield a mis au point une méthode de représentation du monde basée sur les cartes de terrain égocentriques. L'implémentation de la carte de terrain égocentrique a permis au véhicule terrestre sans pilote Raptor de naviguer autour d'obstacles existant dans des milieux peu complexes et cette capacité a été exercée durant la démonstration STA. Les essais et l'expérimentation ont révélé que la carte de terrain, uniquement égocentrique, avait des inconvénients. L'inconvénient le plus important concernait la fidélité de la carte lorsque le Raptor effectuait des manœuvres de prise de virage. Dans certaines circonstances, la fidélité dégradée de la carte pouvait affecter négativement la représentation du terrain et mal représenter les obstacles. De plus, les manœuvres de prise de virage avaient un effet de lissage quand un obstacle n'avait pas été correctement dépisté par le processus de mise à jour.

Conclusions principales: Pour vaincre les limites de la carte uniquement égocentrique, on a proposé, implémenté et testé la méthode de la carte globale. La carte globale rectifie les problèmes de la carte égocentrique en utilisant les quatre points cardinaux nord, est, sud et ouest comme référence. Ceci élimine les problèmes de fidélité et de lissage associés avec les manœuvres de prise de virage parce que les références fixes de la carte globale n'exigent jamais de rotation.

Portée des résultats: La carte de terrain globale maintient sa fidélité au moyen de toutes les manœuvres de prise de virage possible pour un tel véhicule ce qui lui permet de représenter le monde fidèlement. Cette amélioration permet ultérieurement de détecter, dépister et d'éviter des obstacles d'une manière plus régulière. Des essais approfondis ont vérifié que l'implémentation de la carte globale résulte en un rendement amélioré.

Résultats futurs: Le Raptor ne soutient actuellement pas les manœuvres de recul. Le seul hublot égocentrique dans la carte globale n'extrait à présent qu'une représentation de marche avant. Étant donné que l'implémentation de la carte globale préserve la parcelle de terrain traversée entourant le véhicule, il est faisable d'extraire une fenêtre d'affichage à partir d'un point de vue arbitraire. La carte de terrain globale peut ainsi facilement fournir une carte de vue arrière et soutenir les manœuvres de marche arrière qui permettent au Raptor de reculer.

Table of contents

Abstract i

Résumé i

Executive summary iii

Sommaire iv

Table of contents v

List of figures vi

List of tables vi

1 Introduction 1

2 Original Egocentric Terrain Map 1

2.1 Background 1

2.2 Implementation 2

2.3 Deficiencies 3

3 Global Terrain Map 4

3.1 Implementation 5

3.1.1 Scrolling the Map 6

3.1.2 Fusing Data into the Global Map 6

4 Egocentric Map ViewPort 7

4.1 Implementation 7

5 Results 10

5.1 Egocentric Terrain Map Performance 10

5.2 Global Terrain Map Performance 11

5.3 Road Tests 12

6 Conclusions 13

References 17

List of figures

Figure 1: The Raptor UGV 1

Figure 2: Raptor UGV Control Block Diagram 2

Figure 3: Event Flows in the Terrain Map Component 3

Figure 4: Coordinate Transformation due to Rotation 3

Figure 5: Original egocentric terrain maps produced during straight line motion and when executing a sharp turn. 4

Figure 6: Global Map Grid 5

Figure 7: Co-ordinate System Transformations 6

Figure 8: Egocentric Terrain Map Reference 8

Figure 9: Global Map to Front-Centre Bumper Transformation 8

Figure 10: Default Viewport with Co-ordinate Locations 9

Figure 11: Egocentric Viewport overlaid on the Global Terrain Map 10

Figure 12: Egocentric Map Viewport from the Global Terrain Map 12

Figure 13: The global and corresponding egocentric terrain maps generated during a sharp turning manoeuvre. 15

Figure 14: Raptor Autonomous Trial 16

1 Introduction

Autonomous unmanned ground vehicles (UGVs), navigating unstructured outdoor environments, require an accurate world representation. For the 2005 Autonomous Land Systems demonstration, researchers at Defence R&D Canada – Suffield developed a $2\frac{1}{2}$D terrain map representation of the world [1], and this map was crucial for the successful demonstration of the Raptor UGV [2].

In addition to the ALS demonstration, this original egocentric terrain map was extensively tested under various field conditions and terrain types. These tests revealed a number of deficiencies in the original egocentric map implementation. Research, undertaken to address these deficiencies, resulted in the ultimate replacement of the egocentric terrain map with a global terrain map implementation. The original egocentric map is then extracted, from the global map, using a viewport approach.

This report is organized into 6 sections. Section 2 details deficiencies revealed during the testing of the original egocentric terrain map. Section 3 introduces the global terrain map concept and describes its implementation. The egocentric viewport's derivation is presented in Section 4. Experimental results are presented in Section 5 and the report finishes with the conclusions presented in Section 6.

2 Original Egocentric Terrain Map

2.1 Background

Defence R&D Canada – Suffield researchers developed an egocentric $2\frac{1}{2}$D terrain map world representation for its 2005 demonstration of autonomous UGV capabilities. This terrain map was one of a number of components developed, which together comprise the on-board control of the fully autonomous Raptor UGV. The Raptor UGV is shown in Figure 1.

Figure 1: *The Raptor UGV*

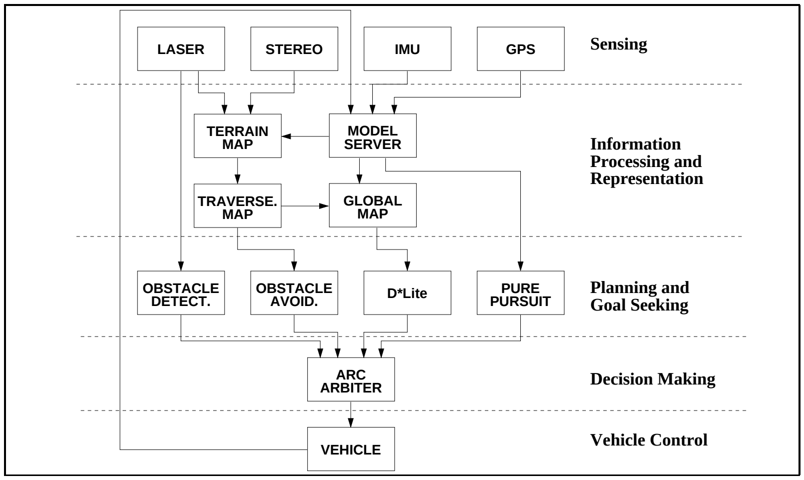

Figure 2: *Raptor UGV Control Block Diagram*

Figure 2 is a block diagram showing the components comprising the control of the Raptor UGV and the interconnections between them.

Figure 3 provides a detailed view of the *Terrain Map* component, in the context of its neighbouring services. As can be seen in this figure, the *Terrain Map* component acquires range sensor and pose events, and processes this data to create a coherent world representation. This world representation is then published as a *Terrain* event, which is acquired by the *Traversibility Map* component [3] for further processing.

2.2 Implementation

As described in *World Representation Using Terrain Maps* [1], the original terrain map implementation used a wholly egocentric approach. Under this approach, range data from the nodding laser [4, 5] was transformed into the egocentric map frame[1] before it was fused into the terrain map. Given that the laser frame and the egocentric map frame have a fixed geometrical relationship that co-aligns their respective orientations, the laser to map frame transform utilizes only the roll and pitch components of the vehicle's pose [6]. The egocentric technique must also handle changes in the heading/yaw component of vehicle's orientation. Under the egocentric implementation, a change in the vehicle's heading initiated a process that applied the delta yaw to each element in the terrain map. Figure 4 graphically illustrates terrain map rotation that occurs as a result of a change in heading. In this figure the grid element (i_{el}, j_{el}), with the positional co-ordinate of (x_{el}, y_{el}), experiences a rotation of θ_d to the new positional co-ordinate given by (x_{new}, y_{new}) and, thus, migrating to the (i_{new}, j_{new}) map element.

[1] The map frame is located at the vehicle's front, centre bumper and aligned with vehicle's direction of travel.

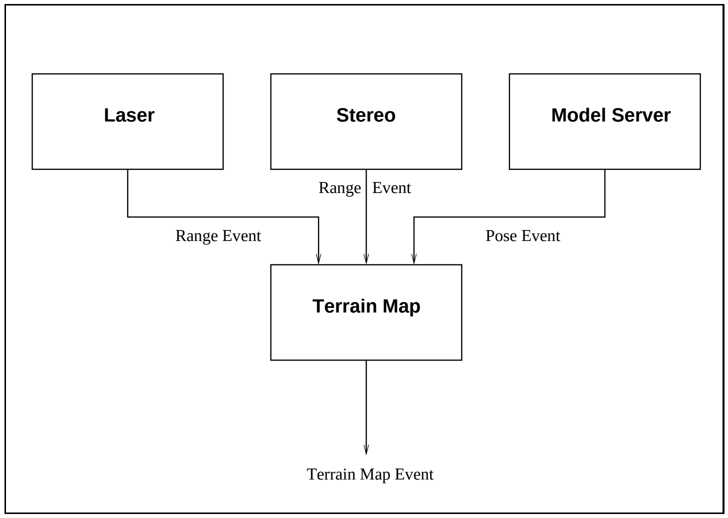

Figure 3: *Event Flows in the Terrain Map Component*

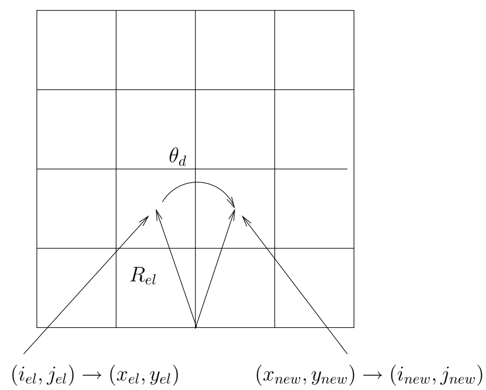

Figure 4: *Coordinate Transformation due to Rotation*

2.3 Deficiencies

Through extensive testing, the egocentric terrain map was found to suffer from a number of minor deficiencies and a single significant issue, namely: the map ends at the front bumper; map data is discarded during turning manoeuvres; and turning manoeuvres, in conjunction with data quantization, results in a loss of fidelity. Only one issue, the quantization effect that degrades the map's fidelity, had a significant impact on the map's performance. A grid of discrete elements, each with a size of $d \times w$, forms the basis of the terrain map. Thus, the conversion of an acquired range datum's position (x, y), into a pair of map indices (i, j), has a quantization effect due to a real, continuous number being *binned* into an integer value defined by the set N. The set of map indices, N, is defined by the map size, $(x_{\max}, y_{\max})$,

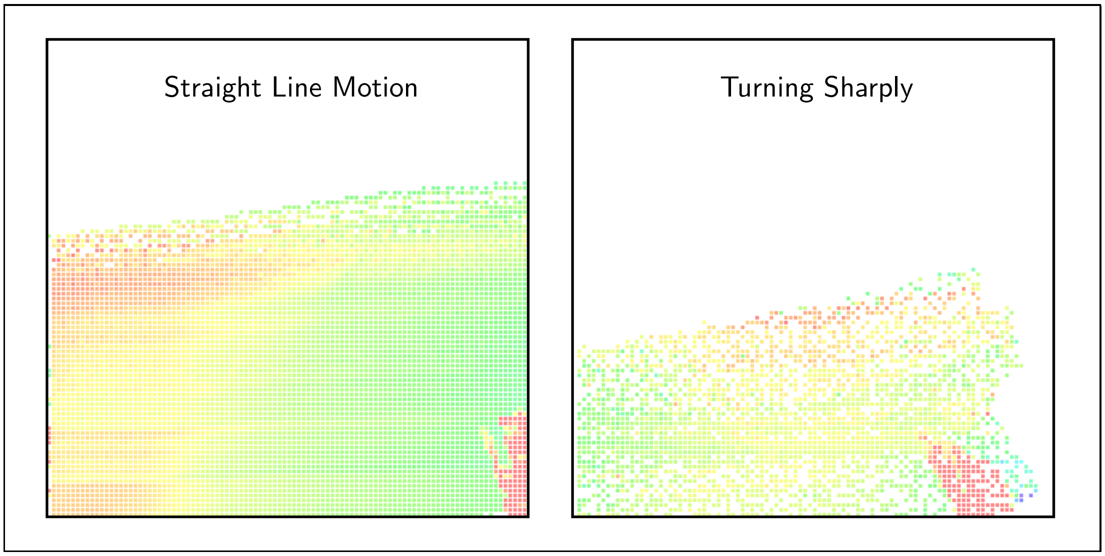

Figure 5: *Original egocentric terrain maps produced during straight line motion and when executing a sharp turn.*

and the grid element size[2], G_l, and is given by:

$$N = \left\{ (i,j) | 0 \geq i \geq \frac{x_{\max}}{G_l},\, 0 \geq j \geq \frac{y_{\max}}{G_l} \right\} \tag{1}$$

A map rotation requires the conversion of each grid element index pair, (i, j), to its corresponding real (x, y) distance from the vehicle's front centre bumper. This real position is then rotated by the change in heading, θ_d, and the resulting position was binned to determine the new map index pair. As happens with the fusion of range data into the map, the binning process yields a quantization error. Figure 5 presents a comparison between the terrain map produced as the vehicle traverses in a straight line, and one produced as the vehicle executes a sharp turn. Whereas the straight line motion map, shown on the left, has a uniform and consistent texture, the map produced while turning has a *salt and pepper* appearance with many unknown grid elements[3]. The root of this behaviour lies with discrete element nature of the egocentric terrain map and its incompatibility with real, continuous rotation angles.

3 Global Terrain Map

Although the egocentric terrain map used during the ALS demonstration was adequate, its performance was less than stellar. Consequently, researchers re-examined the imple-

[2]For a square grid element $G_l = d = w$.

[3]Unknown grid elements are displayed in white.

mentation of the terrain map and concluded that a new approach was required. Given the difficulties associated with maintaining a discrete, egocentric terrain map, researchers surmised a map implementation that was heading independent, requiring no map rotations, would provide a more accurate and consistent world representation. A heading independent terrain map can be achieved by referencing the map to the cardinal directions and thus, create a map that is global in nature.

3.1 Implementation

The global map implementation uses a fixed grid, aligned with the cardinal directions, that scrolls with the movement of the vehicle. The vehicle is located at the geometric centre of the global terrain map and the global terrain map's orientation is such that map index, i, aligns with North and map index, j, aligns with East. This is shown in Figure 6. Whereas the original egocentric terrain map implementation had a size of $(x_{\max}/G_l \times y_{\max}/G_l)$, the global terrain map has dimensions of $(2L_{\max} \times 2L_{\max})$. $L_{\max}$ is the the edge length of the map, in grid cells, expressed in terms of the lookahead distance in grid cells and given by $L_{max} = max(x_{\max}/G_l,\, y_{\max}/G_l)$. This larger map size is dictated by the fact the vehicle must maintain a look ahead distance of at least $L_{\max}$ and the assumption that the vehicle may reside at any orientation with respect to the map. The look ahead distance, $L_{\max}$, and the grid size, G_l, are also shown in Figure 6.

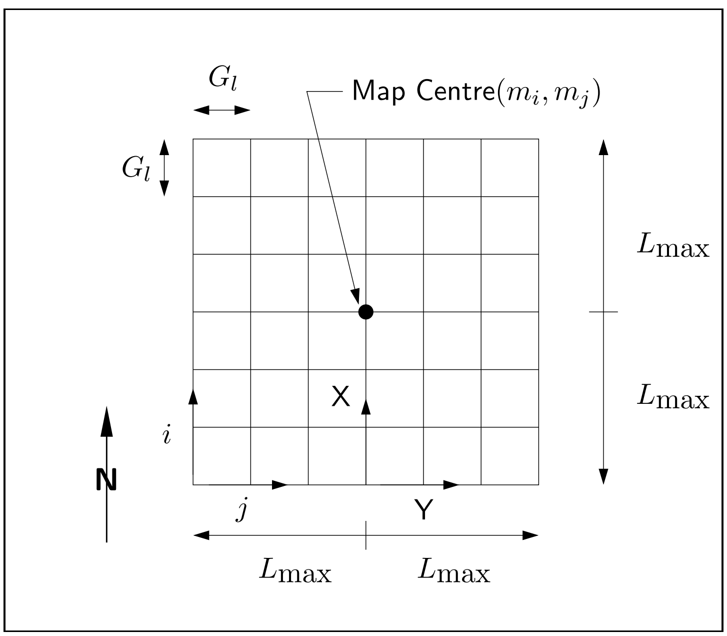

Figure 6: *Global Map Grid*

3.1.1 Scrolling the Map

The egocentric terrain map implementation wrapped only in the vehicle's **X** co-ordinate direction [1]. The global terrain map implementation, referenced to the cardinal directions, scrolls along both the North/South and East/West axes. This scrolling is a function of the vehicle's location in the global co-ordinate space, where the **X** direction is aligned with North and the **Y** direction is aligned with East, as shown in Figure 6. The following equations govern scrolling:

$$m_i = \begin{cases} m_{i-1}+1 & \text{if } x(t)-x(t-1) > G_l \\ m_{i-1}-1 & \text{if } x(t)-x(t-1) < G_l \\ m_{i-1} & \text{otherwise} \end{cases} \tag{2}$$

$$m_j = \begin{cases} m_{j-1}+1 & \text{if } y(t)-y(t-1) > G_l \\ m_{j-1}-1 & \text{if } y(t)-y(t-1) < G_l \\ m_{j-1} & \text{otherwise} \end{cases} \tag{3}$$

where m_i is the grid map index in the **X** direction, and m_j is the index in the **Y** direction. The values $(x(t), y(t))$ represent the vehicle's location, in the global co-ordinate system, at time t and the pair $(x(t-1), y(t-1))$ represent the vehicle's location at time $t-1$.[4]

3.1.2 Fusing Data into the Global Map

Data acquired by ranging exteroceptive sensors, such as laser rangefinders or stereo cameras, is fused into the $2\frac{1}{2}$ D terrain map. Before this fusion process can occur, the range data must first be transformed from the ranging device's local co-ordinate system into global co-ordinate system. Figure 7 shows the four relevant co-ordinate systems associated with the transformation chain, ${}^{L}T_M \rightarrow^{M} T_{FCB} \rightarrow^{FCB} T_G$.

[4]See World Representations Using Terrain Maps, Section 3.3 for a more in-depth description.

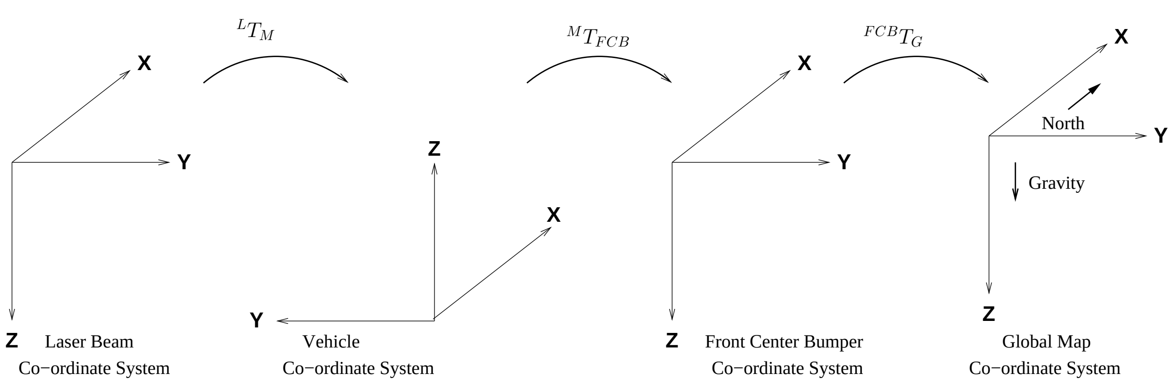

Figure 7: *Co-ordinate System Transformations*

Once the range data has been transformed into the global frame, it can be fused into the terrain map. The fusion process has two steps:

- The range data's (i, j) indices, into the grid map, are derived from the its (x, y) range components and current map indices, (m_i, m_j), as follows:

$$\hat{i} = \text{int}\left(\frac{x}{G_l}\right) + m_i \tag{4}$$

$$i = \begin{cases} \hat{i} & \text{if } 0 \geq \hat{i} < N_{max} \\ \hat{i} - N_{max} & \text{if } \hat{i} \geq N_{max} \\ \hat{i} + N_{max} & \text{if } \hat{i} < 0 \end{cases} \tag{5}$$

$$\hat{j} = \text{int}\left(\frac{y}{G_l}\right) + m_j \tag{6}$$

$$j = \begin{cases} \hat{j} & \text{if } 0 \geq \hat{j} < N_{max} \\ \hat{j} - N_{max} & \text{if } \hat{j} \geq N_{max} \\ \hat{j} + N_{max} & \text{if } \hat{j} < 0 \end{cases} \tag{7}$$

- Using the (i, j) map indices, the z component, representing the elevation, is fused into the terrain map as described in "World Representation Using Terrain Maps", Section 4.2.

4 Egocentric Map ViewPort

Although the global terrain map, described in Section 3, is directly applicable to the global navigation problem [7], its native format can not be used for local navigation. The local navigation module requires a vehicle-centric map [8] where the terrain map is centred on the vehicle's front bumper and its **X** axis is aligned with the vehicle's pose. The orientation of this egocentric terrain map is shown in Figure 8.

Figure 8 clearly shows that the egocentric terrain map's frame is aligned with the vehicle's front-centre bumper frame. As a result of this alignment obstacles, identified by the terrain map, are located in the vehicle's frame, thus simplifying the local navigation process.

4.1 Implementation

The egocentric terrain map is constructed by generating a viewport into the global terrain map, which is aligned with the vehicle's front-centre bumper frame. Figure 9 graphically shows the transformation, from the global frame to the front-centre bumper frame, that must occur to generate the egocentric viewport.

A default viewport location vector, aligned with global terrain map frame, is intially constructed. The viewport location vector, a 2-D array that contains the $(x, y, z, scale)$ coordinates for each grid element in the viewport, is shown in Figure 10.

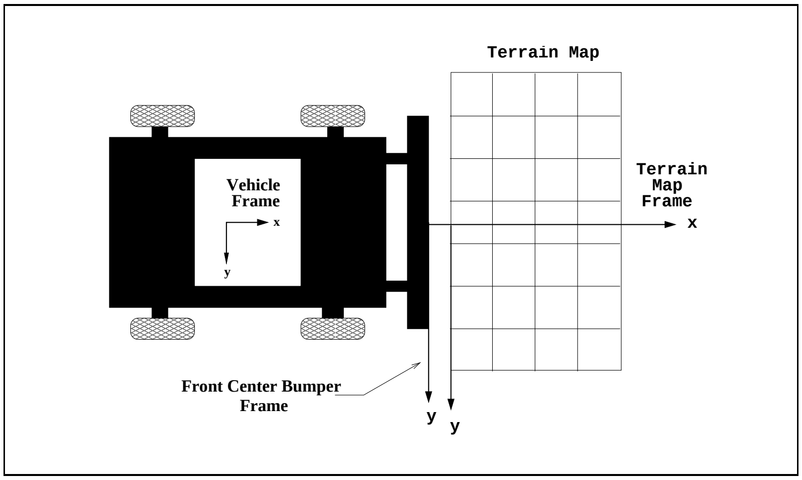

Figure 8: *Egocentric Terrain Map Reference*

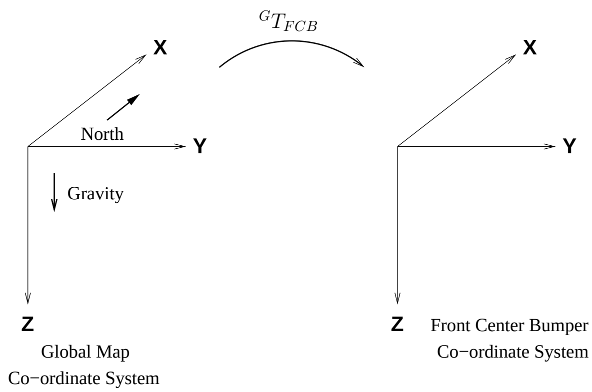

Figure 9: *Global Map to Front-Centre Bumper Transformation*

Using the standard $(x, y, z, scale)$ position representation, the location vector can be multiplied by a homogeneous transform; thus, transforming the location data from its default global map frame into an arbitrary frame. Given the global terrain map implementation uses (i, j) indices to access the map, the co-ordinates used to populate the default location vector are also indices in the form of $(i, j, 0, 0)$[5]. This usage of map indices, as opposed to true (x, y) co-ordinates, allows the transformation to operate directly on the map and eliminates the need to transform to and from true (x, y) co-ordinates.

The transformation, ${}^{G}T_{FCB}$, defines the relationship between the global terrain map and the egocentric viewport located at the vehicle's front-centre bumper. The value of the ${}^{G}T_{FCB}$ homogeneous transform is given by the current IMU heading. The relationship between the global terrain map and an example egocentric viewport is shown in Figure 11.

[5]Since neither the **z** co-ordinate nor the scale are required they are defaulted to 0.

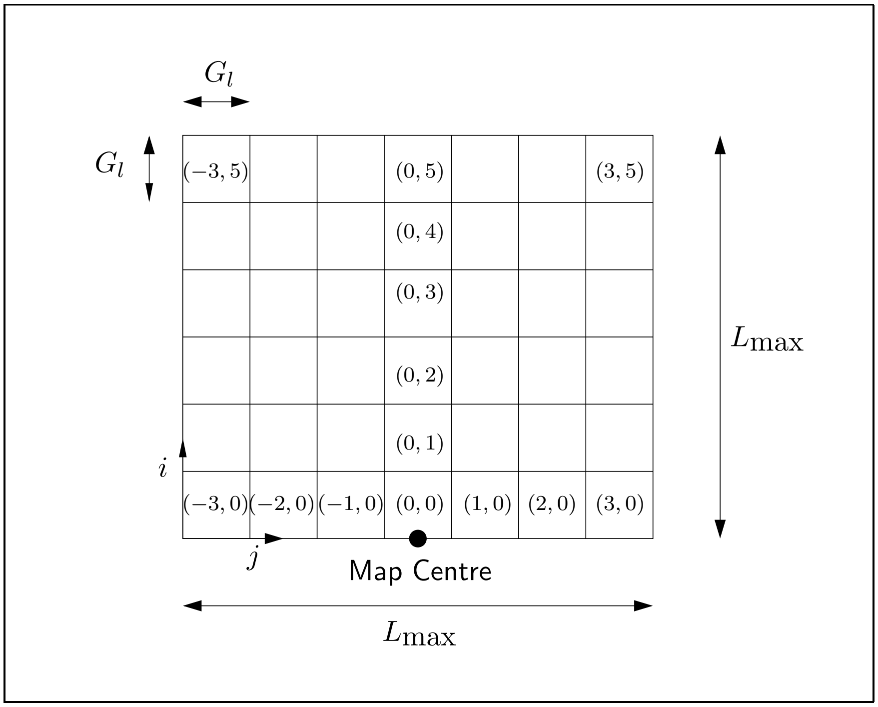

Figure 10: *Default Viewport with Co-ordinate Locations*

In this figure, with the IMU heading specified as 90 degrees, the large grid represents the global terrain map, and the shaded subgrid represents the egocentric viewport.

If the default viewport location vector is given by P_{Default} and the current IMU heading represented as a homogeneous transform is given by T_{Heading}, then the egocentric location vector, P_{Ego} is defined as:

$$\mathbf{P}_{Ego} = \mathbf{T}_{Heading}\mathbf{P}_{Default} \tag{8}$$

where the $T_{Heading}$, is a (4×4) matrix, $P_{Default}$ is a $4 \times L_{\max}$ matrix and the resulting matrix, P_{Ego}, also has the dimensions of $4 \times L_{\max}$. The egocentric location vector defines the indices, into the global terrain map, that extract the desired egocentric viewport. The egocentric map can then be constructed as shown in Listing 1. In Listing 1:

- Lines 2 through 5 index each and every individual grid element in the egocentric terrain map.
- Lines 8 and 9 determine the corresponding global terrain map index for the specified egocentric map indices. Given the global terrain map scrolls, these functions also account for the current map centre.

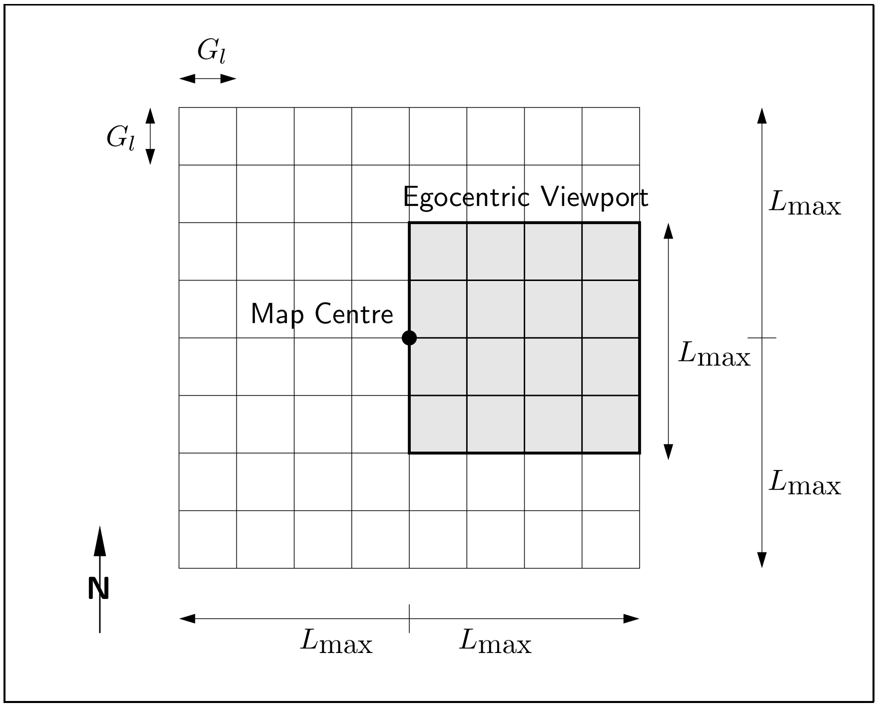

Figure 11: *Egocentric Viewport overlaid on the Global Terrain Map*

- The loop defined by line 13 specifies that all planes of the terrain map be used[6].
- Lines 15 through 18 copy the appropriate global terrain map data, using the defined indices, into the egocentric terrain map viewport assuming the data is located within the viewport region

5 Results

The global terrain map implementation was extensively exercised during the summer of 2006. Initially these tests verified the performance of the global terrain map implementation. Subsequent tests revealed this technique's performance was superior to the original egocentric terrain map implementation.

5.1 Egocentric Terrain Map Performance

The egocentric terrain map, a viewport into the global terrain map, was described in Section 4, and represents the terrain as seen from the front, centre bumper of the vehicle. Figure 12 shows the global terrain map, and the corresponding egocentric terrain map. Within the

[6] As detailed in "World Representations Using Terrain Maps" [1] a terrain map contains 7 planes of information, including the prerequisite z elevation.

```
inx = 0;
for (int x = 0; x < Miro::EGO_INDEX_DEPTH; x++)
{
  for (int y = 0; y < Miro::EGO_INDEX_WIDTH; y++)
  {
    // Determine the index into the global map using the ego_vector.

    j_n = indexToGlobalX( (int) ego_vector[0][inx], map.index_depth );
    k_n = indexToGlobalY( (int) ego_vector[1][inx], map.index_width );

    // Grab the data from the map, if it's valid.

    for (int q = 0; q < ZVAR; q++)
    {
      if ( inx < egoObj.size )
        ego_map.map[q][x][y] = map.map[q][j_n][k_n];
      else
        ego_map.map[q][x][y] = Miro::Map::INVALID_GRID_ELEMENT;
    }
    inx++;      // Next index
  }
}
```

Listing 1: *Egocentric Map Construction*

global terrain map, the embossed region represents the view from the egocentric viewport. For orientation purposes, in the global terrain map, the vehicle's heading is denoted by a vector extending from map's vehicle's position[7]. In this figure it is clear that egocentric terrain map represent a viewport into the global terrain map, as the world structures are identical for both views. As can be seen in this figure, red squares, representing lower elevations, are located to the left of vehicle, while the terrain in front of the vehicle, shown in green, represents the ground elevation. Both maps show a slightly elevated terrain patch, as indicated by the blue area, in front of and to the left/right of the vehicle.

5.2 Global Terrain Map Performance

As was detailed in Section 2.3, the egocentric map's performance deteriorated when the vehicle was subjected to a sharp turning manoeuvre. The global map approach, which doesn't subject the map to rotations, does not suffer from this problem. During turning manoeuvres the global terrain map retains its fidelity.

The global terrain map is shown at two points during the execution of a sharp 45 deg turn in Figure 13. This figure also shows the corresponding egocentric map. The top pair of maps where generated as the vehicle is beginning the turn and the bottom pair as the vehicle is completing the turn. As can be seen in this figure, the fidelity of both maps is

[7]Note: The vehicle is always located at the map centre, which is marked by the cross-hairs on the map.

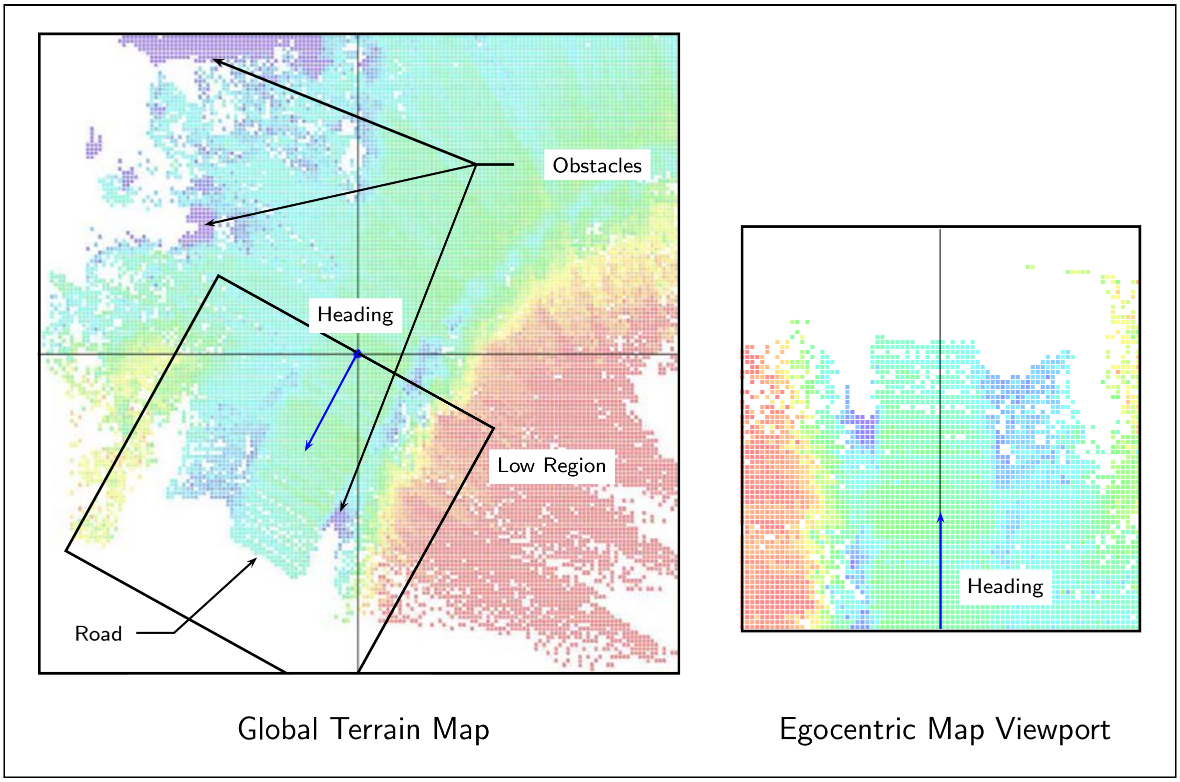

Figure 12: *Egocentric Map Viewport from the Global Terrain Map*

very good. In global terrain map the intersection, the roads, the ditches and obstacles are all easily identifiable. In comparison with Figure 5, the global terrain map is clearly a vast improvement over the original egocentric terrain map.

5.3 Road Tests

In the summer of 2006 the Raptor UGV used the global terrain map during a 1.3 km journey that exercised the Raptor's complete suite of autonomous capabilities. The Raptor was given a series of 5 waypoints to follow, as seen in Figure 14. These waypoints were located at various positions on a road bounded by a graded ditch and grassy areas. In this figure, the red points indicate the GPS waypoints that the vehicle must navigate, the orange track indicates the straight line trajectory that the Raptor attempted to follow, and the blue track indicates the actual trajectory, which the UGV followed as a result of obstacle avoidance. The Raptor UGV successfully navigated all 5 waypoints, requiring only minimal human intervention[8]. As can be seen in Figure 14, even though the Raptor was

[8]Vegetation, incorrectly classified as impassable, halted the Raptor's progress.

not specifically commanded to follow the road, but did so as this provided most traversible route.

6 Conclusions

A prerequisite of autonomous navigation is an adequate world representation. Under the ALS project, researchers developed and implemented an egocentric terrain map. This terrain map implementation was extensively exercised during the run up to ALS demonstration in the fall of 2005. These tests revealed a number of deficiencies in the egocentric terrain map implementation that impaired its performance. Of the three issues listed in Section 2.3, only the loss of map fidelity, due to quantization effects, had a significant impact on the map's overall performance. Under certain circumstances, this degraded map fidelity could adversely affect the terrain representation and lead to the appearance of *phantom* obstacles. Additionally, turning manoeuvres could have a smearing effect, in which an obstacle was not correctly tracked by the update process.

To overcome these deficiencies researcher's developed a purely global map approach. The resulting global terrain map is referenced to the cardinal directions and thus, does not require the map rotations that degraded the performance of the egocentric approach. Additionally, the global terrain map maintains a global terrain patch that surrounds the vehicle, which represents both terrain to be traversed and the terrain that is no longer in its sensors' fields of view. This short term *memory* capability could allow a vehicle to perform backup manoeuvres without requiring of rearward facing exteroceptive sensors.

Although the global terrain map is directly applicable to global navigation problems, it is poorly suited for the local navigation problem. The local navigation module requires a vehicle-centric map, centred on the vehicle's front bumper with its $\mathbf{X}$ axis is aligned to the vehicle's heading. The global terrain map technique, using a viewport, provides the required egocentric terrain map. The viewport implementation has the capability to provide an egocentric terrain map view at an arbitrary viewing direction. This new capabilitiy, in conjunction with the map's short term memory, facilitates backup manoeuvres.

Experiments, conducted in the summer of 2006, investigated the operation of the global terrain map and these tests revealed it performed as expected. The global terrain map scrolled correctly with the vehicle's translational motion. As was surmised by DRDC researchers, its fidelity was not degraded when the vehicle executed turning manoeuvres. These investigations also ascertained that the egocentric terrain map, extracted from the the global map using a viewport approach, faithfully represented the terrain encoded in the global terrain map.

The global terrain map, with the egocentric map viewport, was implemented under the MIRO framework. The MIRO framework allowed the map to simultaneously consume 3-D range data from multiple data sources while using the vehicle's pose to accurately update the global map. The terrain map's efficient implementation consumed relatively small amounts of computing resources. It could easily handle multiple nodding SICK lasers, as well as

320x240 stereo vision frames twice per second. This excess overhead means this terrain map implementation can be expanded to meet future requirements.

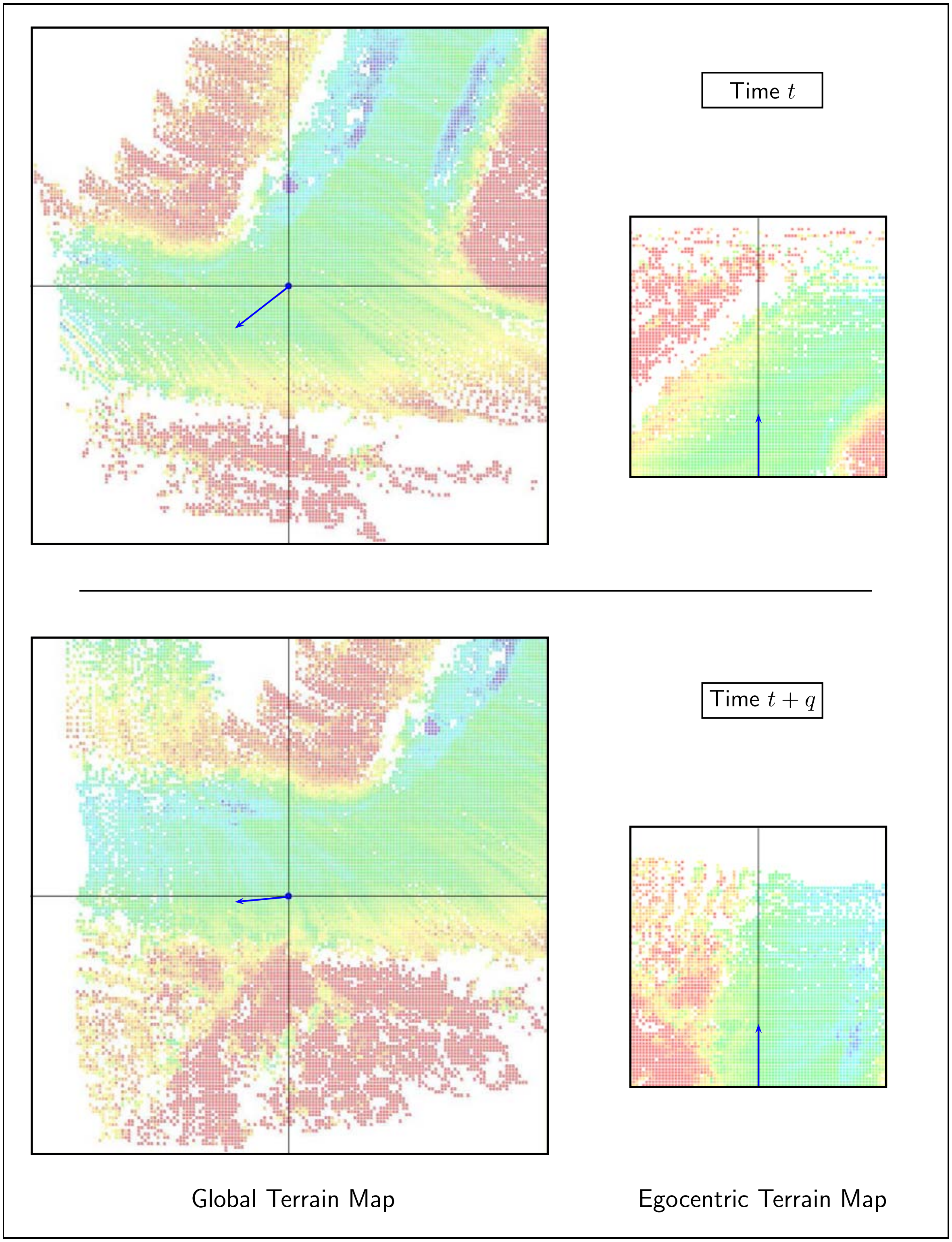

Figure 13: *The global and corresponding egocentric terrain maps generated during a sharp turning manoeuvre.*

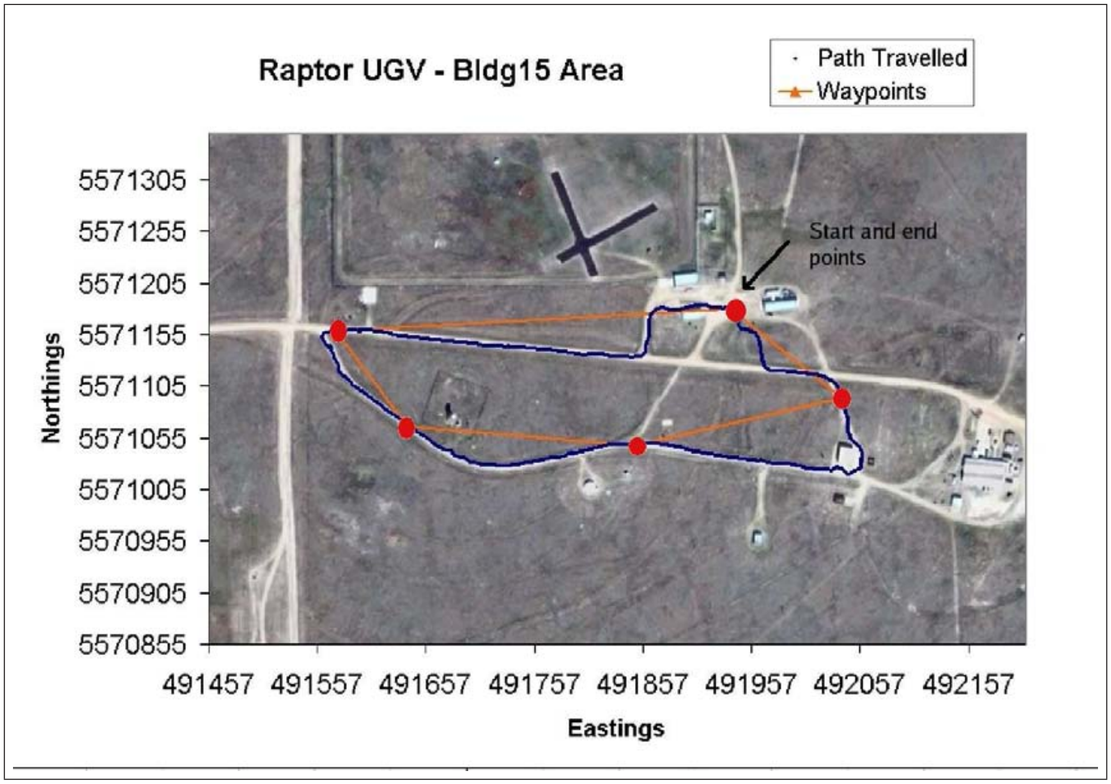

Figure 14: *Raptor Autonomous Trial*

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In 2002 Defence R&D Canada changed research direction from purely tele-operated land vehicles to general autonomy for land, air, and sea craft. This research, conducted under the Autonomous Land Systems (ALS) project, developed the Raptor unmanned ground vehicle (UGV), which successfully demonstrated autonomous capabilities. A key capability developed under the ALS project was a terrain mapping technique for representing outdoor, unstructured environments. Although the original ALS terrain mapping technique performed adequately, extensive testing and experimentation revealed weaknesses in its egocentric approach, principally due to the rotation of the map when the vehicle executed sharp turns. To correct this weakness, it was replaced with a locally-referenced global map that scrolls relative to the fixed cardinal directions. The vehicle remains in the centre of the global map and the map scrolls as the vehicle moves. An egocentric view, required for obstacle avoidance, is derived from the global map using a viewport. Extensive testing on the Raptor UGV revealed the global terrain map's performance was superior to the egocentric terrain map approach. Using this technique, the terrain map more accurately represented and tracked terrain features. Additionally, since the vehicle remains at the centre of the global terrain map, this technique retains a record of recently traversed terrain, thus allowing for backup manoeuvres without requiring a rearward looking laser.

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terrain map, digital elevation map, $2\frac{1}{2}$D map, world representation, global view, egocentric view