IN-AIR ROUTE PLANNING FOR MILITARY AIRCRAFT

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Abstract

At BAE SYSTEMS, Avionics, there is on-going research into three-dimensional (3D) route planning for military aircraft. The main aim of this work, called Terrain Avoidance (TA), is to provide a real-time optimum covert flight trajectory, accounting for terrain characteristics and aircraft capability. TA has been designed to give the pilot a directional cue on a Head-Up Display (HUD) that would enable the calculated route to be flown.

This paper describes the background of TA, why it is required, what advantages it brings and an overview of the algorithms used.

1 Contents

This section gives a general introduction to where TA has come from and why it is useful.

Section 2 describes the various methods of route generation considered for the terrain avoidance algorithm. Section 3 is a brief description of the Terrain Avoidance algorithm as it stands at present. Section 4 gives a description of some of the testing that was carried out. Simulated flight testing was performed on the demonstrator to see how the system coped with various types of terrain. Conclusions and a discussion of the further work that is planned for TA is contained in Section 5.

1.1 Introduction

The origins of route planning stretch back thousands of years. Over time man has developed strategies and tactics for attacking and defending known locations. During World War 1, when the first airborne conflicts began, reconnaissance missions were flown to gather intelligence data concerning enemy activity. During World War 2, wide area bombing was frequently employed but this tactic necessitated that bombers were used to get behind enemy lines and knock out supply routes, bridges and communications. Each mission would have been planned using paper maps and current intelligence data and was a time consuming process.

With the continuing developments in aircraft, missiles and munitions, air supremacy is seen as a key element in modern warfare. The inability of hostile forces to detect attacking forces is seen as key. Stealthy incursion into hostile territory has been used to good effect by the stealth fighter and bomber but this technology, whilst passive, is expensive. There are various ways of jamming enemy radar and confusing counter measure devices to avoid detection. However, the simplest solution to arrive at a destination without being either detected or fired upon is to use some form of route planning to mask the aircraft using the terrain.

1.2 Overview

The ability to find a route through a particular region is intuitive to someone looking at a map. The valley's low points can be chosen, and box canyons can be avoided simply by looking at the map. However, when it comes to planning a 3D route where the pilot wants to keep as low to the ground as possible but also potentially fly below radar defences, it could take a while for a navigator to find the best route. If the mission undertaken is aborted or some hitherto unknown threat is encountered, rapid re-appraisal of the programmed route may be required. If it takes perhaps 30 seconds to form a route using current mission planning software then this delay could be significant if in hostile territory. Another key element to the problem is that the pilots may not know accurately where they are; even if Global Positioning System (GPS) data is available, it has the potential to be jammed.

Thus some form of covert and autonomous navigation aid may also be required. Computers can be loaded with data stored in digital form such as Digital Terrain Elevation Data (DTED) and Digital Vertical Obstruction Data (DVOD). Threat and radar information can also be loaded. From all the information available, algorithms can be used to construct different possible routes through the terrain. Hundreds if not thousands of possible routes can be evaluated in a fraction of the time that would be required if a new route calculation was attempted by hand. This has been done in the past, but only off-line.

Terrain Avoidance has similarities with mission planning as a route is chosen that attempts to conceal the aircraft. Mission planning looks at the big picture, taking into account the whole mission, from take off to landing. Even when mission planning takes account of terrain it may not direct the pilot down, into a valley for example, as there may only be a limited number of waypoints possible for guidance.

TA is primarily used as a real-time navigator to direct an aircraft through the immediate terrain ahead of the aircraft. One of the main criteria to consider when planning the route is to keep the aircraft as low as possible on the assumption that when in hostile terrain it is better to fly down inside valleys, rather than just over them. This makes it less likely that the aircraft will be picked up by radar. Also the aircraft could be concealed even in areas covered by threats if flying in valleys. Figure 1 shows the steps in a TA route directly ahead of the aircraft. Following this route the aircraft will be masked by the terrain.

Low level flying is amongst the most dangerous of activities undertaken by a pilot. Instead of simply suggesting a valley to fly down, TA directs the pilot via the HUD with a three-dimensional steering cue, which

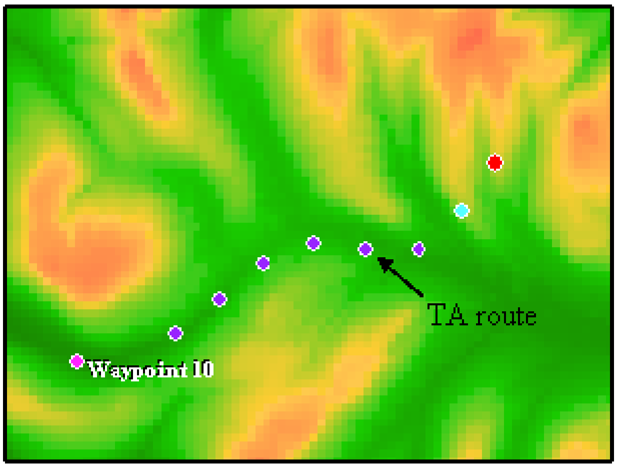

Figure 1 : Example of a TA route

will prevent the pilot from missing a turn, turning too early or turning too late. It also directs the pilot in the vertical plane via a terrain following function to avoid the aircraft ballooning over significant peaks. This will ensure that if the cue is followed the pilot will be able to easily navigate through the immediate terrain ahead therefore reducing the pilot workload. The system has also been set up so that if the pilot, for any reason, diverts from the pre-determined route, possibly flying into unfamiliar territory, TA will direct the pilot onto the best possible route to the next waypoint in order to get back on track.

1.3 Hosting of the Algorithms

One of BAE SYSTEMS current products, TERPROM®, uses inputs from an aircraft Inertial Navigation System (INS) and radar altimeter to provide estimates of the current position of the aircraft with respect to the underlying terrain via its Terrain Referenced Navigation (TRN). TERPROM® contains a digital terrain elevation database (DTED) and uses this database, the INS and the returns from the radar altimeter within an adaptive Kalman filter to provide accurate, autonomous position information.

TA uses the position information and the same terrain and obstruction database as the current TERPROM® system in order to achieve its purpose of navigating the aircraft with more stealth through a particular area of terrain.

Amongst TERPROM®'s other functionality, there is a Terrain Following (TF) mode which provides a vertical cue to the pilot in order to direct the aircraft along its current path at a pilot selected clearance height, taking into account both terrain and obstructions contained in the obstruction database (DVOD).

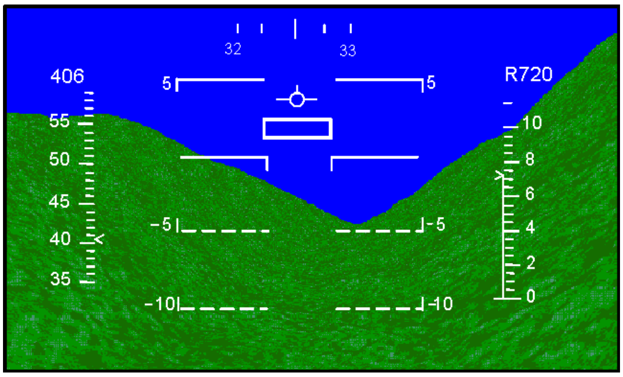

Figure 2 : HUD display showing TF symbology

Figure 2 shows a view out of the cockpit. The pilot must follow the rectangular box highlighted on the HUD to perform TF. Keeping the flight path marker in the box means that the pilot should be flying the TF profile.

2 Methods of Terrain Avoidance

There are numerous ways of finding 'the best' route through an area of terrain. The difficulty has been to determine what method or methods to use and how they interact in real-time. This section overviews some of the methods that can be used.

All the routes use nodes, which are points on a route, and can be thought of as an intermediate waypoint where information is stored.

2.1 Tree Search Algorithm

The traditional tree search extends branches from the current aircraft position to the next set of start nodes. From the new start nodes more branches are extended again until all the possible routes have been attempted and the target or waypoint has been reached. However this method requires too much processing power although it does yield good results. Even after 3 iterations it can be seen in Figure 3, that the number of routes soon gets unmanageable.

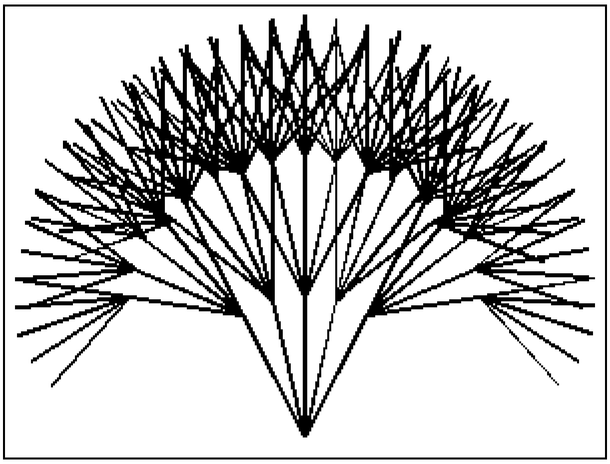

Figure 3 : Tree search after 3 iterations

2.2 A* Algorithm

The best-established algorithm for the general searching of optimal paths is A* (pronounced "A-star"). The idea is to search an area of terrain and find the shortest route to the next waypoint. All the nodes in this algorithm have three ratings used during the search, which are the cost of the node, an heuristic estimate and 'f', which is the total of the other two.

This was the first heuristic search considered, in that it takes into account domain knowledge to guide its efforts. It is similar to the tree search algorithm, except that instead of the nodes being scored by their distance from the start, they are scored by an estimate of the distance remaining to the goal. This cost also does not require possible updating as the tree search does. It combines the tracking of the previous path length of the tree search, with a heuristic estimate of the remaining path. The trouble with A^* is that it only produces one route. It can take a long time to produce and use a lot of processing power, although it is easily the fastest of methods described so far, heading in the most direct manner to the goal.

2.3 Networks

A network technique developed by BAE SYSTEMS was a simple, straight forward way to create a rough off-line route. The network consists of nodes that are reasonably evenly distributed throughout the region of interest, and can be formed before being restricted to any route or route calculation. They are constructed to be, wherever possible, along valleys in the region of interest.

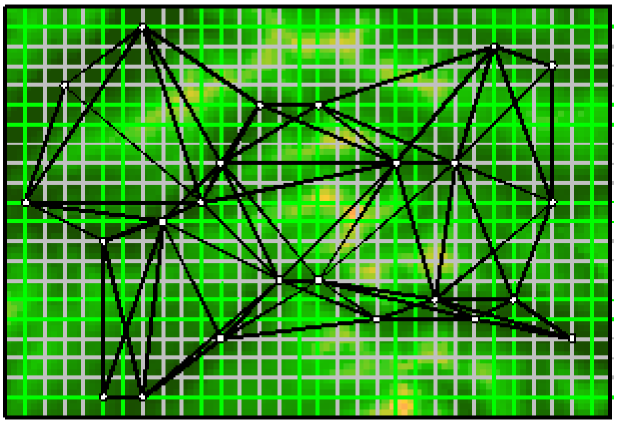

Figure 4 : Network structure

As only coarse (large scale) solutions were a concern, the amount of digital map data was reduced to one point each square kilometre. The 1km squares were then split into a 4x4 grid and the lowest post was chosen as a node. The nodes were joined to the surrounding nodes and a cost between them was generated. The costs were based on terrain height and a simple masking function. Figure 4 shows a small area of Scotland, but it can be seen that connecting the low points gives a reasonable rough route and picks out the valleys.

2.4 Conclusion on Method to be used

The main problem with all these methods is that they are not efficient enough to produce the best route in the time available, making them very static and not very dynamic. The whole point of creating the TA routes is that they should be flyable. The Tree Search technique is too processor intensive to be run in real-time although it yields good results. The network could be useful and would take little time to code and implement. Of the concepts addressed so far, the A* algorithm seems the best but still requires a lot of modification.

3 Terrain Avoidance Algorithm

3.1 Method

The implementation of TA used a highly modified version of the A* algorithm. Initially the routes were spread out using the tree search but all the routes are pruned to form an A* type route. At present the TA code uses the same terrain map as TERPROM® which is limited to 10km range ahead of the aircraft at any point in time.

3.2 Terms

Throughout TA, there are fixed length manoeuvres being projected onto the terrain ahead of the aircraft. The start and end points of these manoeuvres are nodes.

All the routes that are created use lists, made up of a node structure. The node structure was defined to have the following parameters included.

- Latitude
- Longitude
- Heading
- Target Distance
- Cost
- Acceleration

3.3 Creating Routes

The TA code has been set-up to have an interface with all the all the relevant information required e.g. current latitude, longitude, heading, pitch, roll, velocity, and waypoint latitude and longitude. The only other access TA needs is to the digital map to get the height of the terrain.

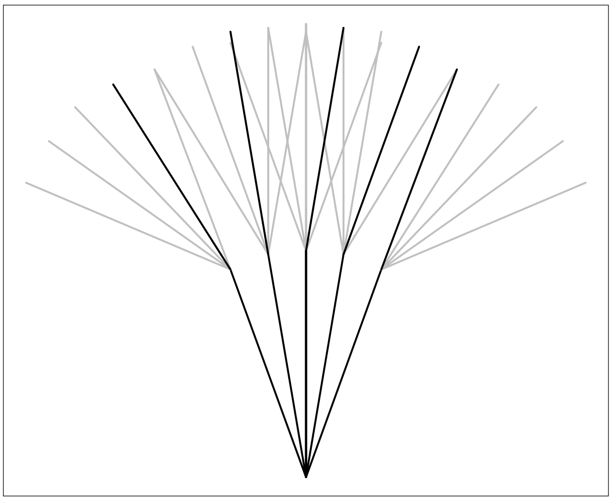

Figure 5 : Possible routes and pruning

The grey lines in Figure 5, show all the possible routes that could be taken from the current position. Turns of 1g and 2g horizontal acceleration were implemented to the left and right and a route to continue on the same heading was also used. The black lines represent the preferred routes due to cost implications. From the preferred routes, other branches are grown and the rest are discarded. This does mean that routes can be missed which is an issue that can be solved by considering more routes, or implementing a larger scale scan first to get a more general route. Making the code efficient enough so it can be run in real-time might then be a problem, as the workload would be significantly increased.

Using a traditional technique, where all possible routes are calculated, is wasteful in terms of processing time. The goal is therefore to calculate the minimum number of routes, whilst still maintaining reasonable flexibility in the chosen route.

3.4 Calculate Route Costs

The purpose of cost functions is to try and find the best compromise of a number of factors to find the shortest, lowest, most direct and efficient route from one waypoint to another.

3.4.1 Terrain Height

Along every branch the terrain height was averaged and compared to the current height of the aircraft. The difference was then multiplied by a height cost factor. If the actual height was used when the aircraft was flying in mountainous terrain, the terrain cost would become significantly more dominant than all the other costs which could force the route along valleys even when going in completely the wrong direction.

3.4.2 Maximum Height

There are dangers with choosing the lowest average terrain height. If the average is low but there is a peak or obstruction in the terrain then this could mean that the aircraft would be better served by following a different route. Once the branch has been completed, Figure 6 shows the height difference, between the maximum and minimum.

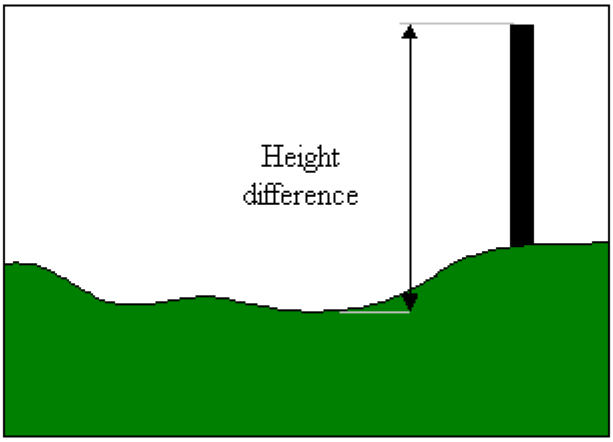

Figure 6 : Example of an obstruction on the route

The height difference is then multiplied by a maximum height cost factor. It can be clearly be seen that flying a route with obstructions would force the pilot to fly high over the terrain which is what TA is trying to avoid.

3.4.3 Distance To Target

The distance cost was designed to increase the further away from the target each branch went. The least cost is incurred when the aircraft was heading directly towards the waypoint, and the most when heading directly away. The distance cost is calculated from the difference between the distance remaining and the least distance, then multiplied by the distance cost factor.

3.4.4 Heading

The heading cost was introduced in order to ensure that the aircraft did not turn too far off course. The difference in heading was multiplied by the heading cost factor.

3.4.5 Distance Travelled

If the aircraft reaches the correct waypoint but takes too long to get there, then there was little point in choosing that route as the aircraft may run out of fuel en-route. The distance travelled cost is equal to the distance step travelled in metres multiplied by a factor. If the number of iterations is low the cost is low and visa versa.

3.4.6 Other factors to consider

Here are a just a few factors not yet taken into consideration, some of which could have dramatic effects.

- Exposure cost - the amount of terrain masking that the route gives.
- Climb cost - Combined TF/TA routes that take into account the change in gradient.
- Fuel cost - chosen to conserve fuel. This takes account of weight, speed, configuration etc. High g turns and sudden pull-ups cause more fuel to be used.
- Track cost - favours plans which meet any track constraints set on waypoints.
- Time cost - favours plans that arrive at a waypoint at the correct time.
- Speed cost - favour plans that allow aircraft to have the correct speed at a waypoint.
- No-go cost - a route, which flies through an area obstruction or designated no-go area.
- Threat cost - dependent on length of time and number of threat zones infringed. Takes account of terrain screening, threat ranges and threat density.

All these factors could be taken into account. Some are based on survival and range such as the fuel cost, though others are more concerned with mission planning criteria. In time these should all be added.

4 Testing

The developments described thus far were tested using a set of waypoints drawn on a map of Scotland. This was done to simulate the possible terrain that TA could encounter along a route. Some of the terrain is flat, and some is reasonably mountainous, giving a good variation of different types of terrain.

One of the main problems with testing a system such as this is that no two situations will be exactly the same. Many different combinations of situations have to be taken into account, much more than a simple 2D terrain following system. The code has been tested on simulators to test how flyable the 3D profile actually was. Additional special test cases will be required to show that TA can avoid obstructions, box canyons etc. Further development is required to implement additional costs as described in section 3.4.6, but the optimal set of costs to consider in order to limit the system and processor usage are not yet known.

4.1 Symbology

To demonstrate Terrain Avoidance without having to investigate the HUD symbology too thoroughly, the auto-pilot on the demonstrator was updated. The normal g produced by the aircraft was split into vertical and horizontal acceleration components being used for TF and TA respectively. The question of symbology is a contentious subject. There have been many investigations in the past into corridors in the sky for landing that are set on a route and then as long as the pilot keeps the aircraft in the box the aircraft will land safely. These are a perfect way to clutter the HUD of any aircraft. However to direct a pilot along a 3-dimensional TF/TA route will need some sort of roll and pitch symbology.

4.2 Simulated Flight Testing

Several tests were performed to show the difference between the direct route and the TA route generated. The map was of DTED square +56° Latitude, -6° Longitude, which is located on the west coast of Scotland, see Figure 7 for details.

The demonstrator used a fast jet aircraft model. With the auto pilot and terrain avoidance switched on, the behaviour of the system could be seen. The route flown showed a clear advantage of using the TA route compared to the normal auto pilot route. The aircraft was on average 25-30% lower using TA rather than the normal auto-pilot using just TF.

5 Conclusions

From this preliminary study it has been shown that a real-time Terrain Avoidance system integrated with TERPROM® is feasible. Although TA has been proved in simulation the algorithms still need development to yield insight into what costs have the greatest effect on the generated route and at what time during the mission they are critical. Further work is required to develop the system to a suitable standard for flight test.

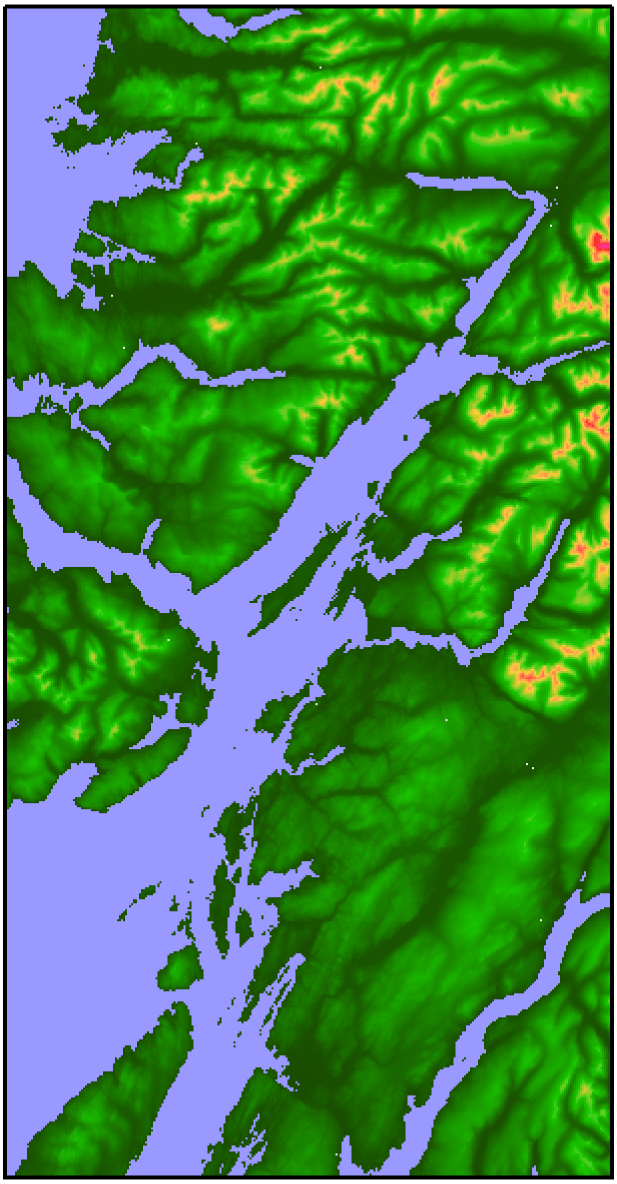

Figure 7 : Area of terrain used for testing