Gathering Atmospheric Data
Using an Unmanned Air Vehicle

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March 13, 2014

Abstract

This report looks at three dimensional energy based path planning for unmanned air vehicles in a predetermined area, with particular consideration to quality of data produced.

Contents

1 Introduction

The following section outlines the process in which a minimum cost route through a sample space can be obtained which provides the best data collection quality

2 Aims

The aim of this project is to research, design and implement a UAV path planner that minimises energy consumption while maintaining optimal spread and depth of data collection. The approach taken in this project to tackling this aim requires a path planner that suffices both of these requirements.

- Initial path planning given a defined area of interest.
- Path planning to provide a minimum energy path given required waypoints.

3 Objectives

The following objectives define the measurable goals of the project required to fully complete the aim. The objectives are listed in the order in which they are to be completed, where each objective is a prerequisite to the next.

1. Design a model to calculate the energy costs of flight between two points in a time invariant wind vector field. This model will output the predicted energy required from the: work done against drag and the change in gravitational energy.

2. Implement an algorithm that uses the energy model to calculate the most efficient ordering of given waypoints to result in the least energy consumed over the tour.

3. Test the resulting algorithm using a number of data sets with the aim of reducing both the energy consumed and statistical maximum volume within the area of interest that does not have a data point.

4. Design a flight planning algorithm that uses the initial way-point order as a basis to optimise on the same parameters as objective two and return an exact flight path that adheres to the UAV properties (max range and minimum turn radius.

4 Problem Outline

The troposphere is the lowest atmospheric layer and of significant interest to meteorological researchers as "almost all weather develops in the troposphere" [Geographic, 2013]. The section of the troposphere that is closest to the earth is the atmospheric boundary layer, in this layer the atmospheric conditions are affected by the surface of the earth. These affects mean that modelling this section is much more complicated than other layers of the atmosphere, therefore "the boundary layer is still not represented realistically" [Teixeira et al., 2008]. Developing a greater understanding and thus better modelling of the atmospheric boundary layer will only improve the ability to: correctly predict weather forecasts or pollutant dispersion, to name but a few.

To collect atmospheric data a number of approaches are available, "many years before the use of radio-controlled aircraft, the collection of in-situ measurements was primarily done with balloons, towers, and tethersondes" [Bonin, 2011]. These options are limited as they are not able to move within the area of interest to build a model. UAVs operate with "reduced human risk, but also reduced weight and cost, increased endurance, and a vehicle design not limited by human physiology" [Pepper, 2012] in comparison to their manned counterparts. This means they provide a cheap and mobile data collection platform.

There are 5 main classes of UAV for different requirements [Sarris and ATLAS, 2001] the class of UAV best suited to collecting atmospheric data of a limited area is the close range class. This class of UAV: "require minimum manpower, training, and logistics, and will be relatively inexpensive" [Intelligence et al., 1996]. These benefits allow a greater number of researchers to have access to mobile data collecting platforms. Most small UAVs are "not capable of reaching above 5,000ft [1524m]" [Weibel, 2005] with their standard operating level generally not exceeding 350m and their maximum range being less than 10km [van Blyenburgh, 2000]. %See appendix **??** for more information on UAV classes.

The ideal solution to the problem of collecting atmospheric data will take a form where the limited energy contained within the UAV is maximally utilised to ensure the best possible sampling of the area of interest. In addition due to the atmospheric irregularities present in the lower boundary layer the energy consideration of the planning element will have to utilise a non-uniform vector field.

5 Literature Review

To achieve the objectives presented in this project pre-existing material on path planning, tour planning, energy routing and sampling plans has to be considered.

[Dubins, 1957] and [Boissonnat et al., 1993] consider the shortest path of a vehicle with a bounded turning radius in two dimensions: given a trajectory and location for the beginning and end points. Both papers found that the minimum path is comprised of maximum rate turns and straight line segments. This initial work on shortest paths is extended by [Chitsaz and LaValle, 2007] to take a third dimension into account: for low altitude ranges the shortest path is the Dubin path in the x-y plane and a constant rate altitude climb. High altitude climbs diverged from the Dubin path due to helical climbing component however this is not relevant as only low altitude climbs are considered in this project.

[McGee et al., 2005] and [Techy and Woolsey, 2009] apply Dubins shortest path in uniform wind. This is done by considering a ground reference frame and wind reference frame which results in the Dubin minimum path being calculated in the wind reference frame. The maximum rate turns in the air frame of reference "correspond to trochoidal paths in the inertial [ground] frame" [Techy and Woolsey, 2009]. Assuming uniform and time-invariant wind leads to potential inaccuracies which are considered through using "a turning rate less than the actual maximum turning rate" [McGee et al., 2005]. Both papers considered utilise different approaches to obtain a final optimal path, thought the resulting optimal paths are both comprised of a combination of trochoidal path sections and straight line sections. These papers are limited in there application to this paper as they only consider a set of two points in two dimensions.

[Bigg et al., 1976], [Held et al., 1984] and [De Berg et al., 2010] calculate minimum length tours of more than two points through applying the travelling salesperson problem (TSP). The TSP is concerned with "finding the shortest path joining all of a finite set of points whose distances from each other are given" [Held et al., 1984]. The TSP problem considered in these papers uses the euclidean distance where the "euclidean distances satisfy the triangle inequality" [De Berg et al., 2010]; "The triangle inequality implies that no reasonable salesman would ever revisit the same city: Instead of returning to a city, it is always cheaper to skip the city and to travel directly to the successor city" [De Berg et al., 2010]. Given the euclidean distances the solutions obtained do not correspond to the shortest path for a Dubin vehicle as the turning angle at nodes is not considered.

[Savla et al., 2005b], [Savla et al., 2005a] and [Le Ny, 2008] consider the Dubin travelling salesperson problem (DTSP). The basic approach considered in all papers is in the form of the alternating algorithm which requires calculation of a minimum tour using euclidean distances for an initial ordering. From the initial order the heading at nodes is given by the direction of either the vertex before the node or the vertex after the node. With the order, location and heading defined at each point the Dubin shortest path can be calculated. [Savla et al., 2005a] goes on to consider stochastic DTSP where the points are normally distributed and puts forth a bead tilling algorithm to improve the performance which is an important consideration for the initial planning aspect of this paper. [Le Ny, 2008] however goes beyond the scope of this paper in considering variable vehicle dynamics.

[Al-Sabban et al., 0], [Chakrabarty and Langelaan, 2009] and [Langelaan, 2007] look into the minimum energy paths through non-uniform wind vectors by considering the total energy of the UAV and attempting to minimise the reduction in energy. [Al-Sabban et al., 0] uses a markov decision process to plan a route through time varying wind vectors which have a degree of uncertainty. [Chakrabarty and Langelaan, 2009] and [Langelaan, 2007] however use a predetermined knowledge of the wind with the aim to exploit atmospheric energies. The given equations of energy and considerations of optimal routes through complex wind fields applies directly to this paper however attempting to tap into soaring flight is not feasible given the limited research area.

[Forrester et al., 2008] and [McKay et al., 2000] consider efficient sampling plans for black box experiments to improve the quality of the model produced. Both papers present latin hypercube sampling to be an improvement on random sampling as they ensure "that each of those components is represented in a fully stratified manner" [McKay et al., 2000] where those components refers to input dimensions. [Forrester et al., 2008] extend this by optimising latin hypercubes to result in the plan with best space fillingness. The sampling plans provided can easily be utilised in the primary planning component of the UAV tour in this project.

6 Plane Properties

Wingspan	3m
Turn Radius	0.1m

Table 1: Table of Plane Properties

To considere th minimum cost of circumnavigating a particular route the specifications of a plane must be considered in table 1 the plane detailed in this table is the plane that is used for the entire report

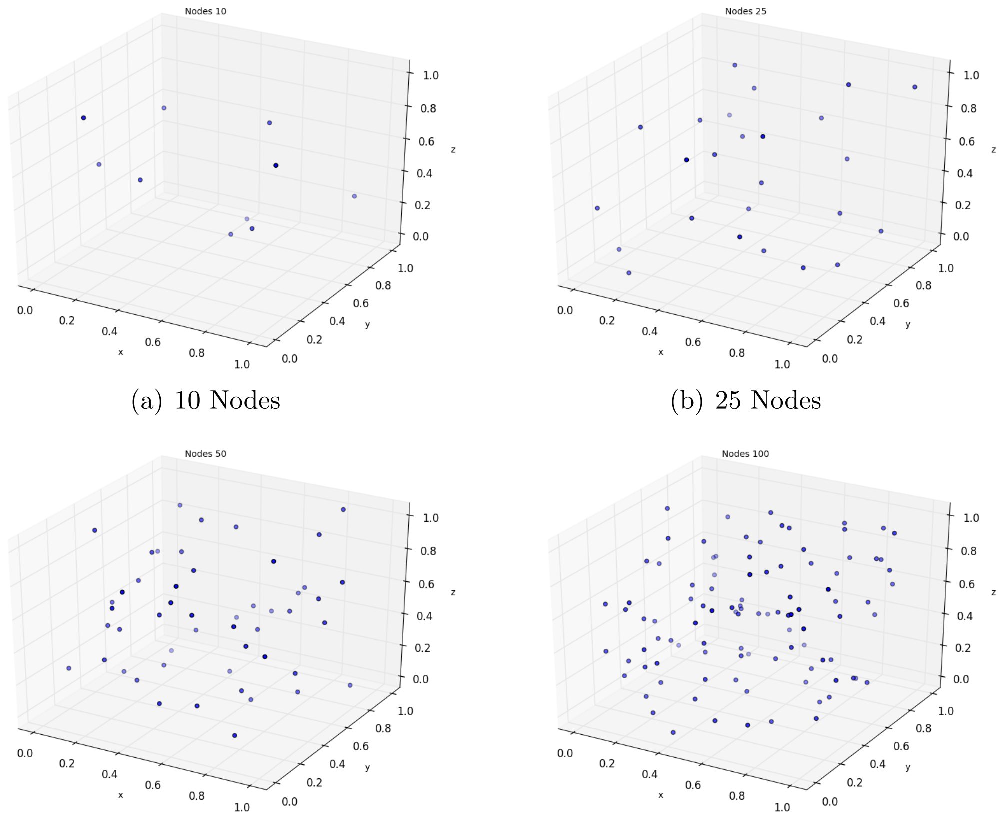
7 Energy Model

$$E = \alpha D + \beta H \tag{1}$$

From these plane properties the following energy model has been definened in equation 1 where α and β are coeficients that are determined by the plane. For the current plane shown in table 1 α and β take values of 10 and 6 respectively.

8 Latin Hypercubes

Latin hypercubes are sampling plans that provide the best space fillingness while limiting the total number of sampling points required. This is generally applied to testing of computer similations where the collection of each point is expensive. In this situation however the travel bertween the points is the expensive component.



(a) 10 Nodes

(b) 25 Nodes

(c) 50 Nodes

(d) 100 Nodes

Figure 1: Latin Hypercubes with Varying Numbers of Nodes

Figure 1 shows latin hypercubes with varying numbers of nodes. All the Latin Hypercubes are within a unit cube. For collection of data in a required area these cubes can be stretched to fill the desired space. This does not provide an even spacing in each direction however means that each vertex of data collection is equally considered in terms of spacing.

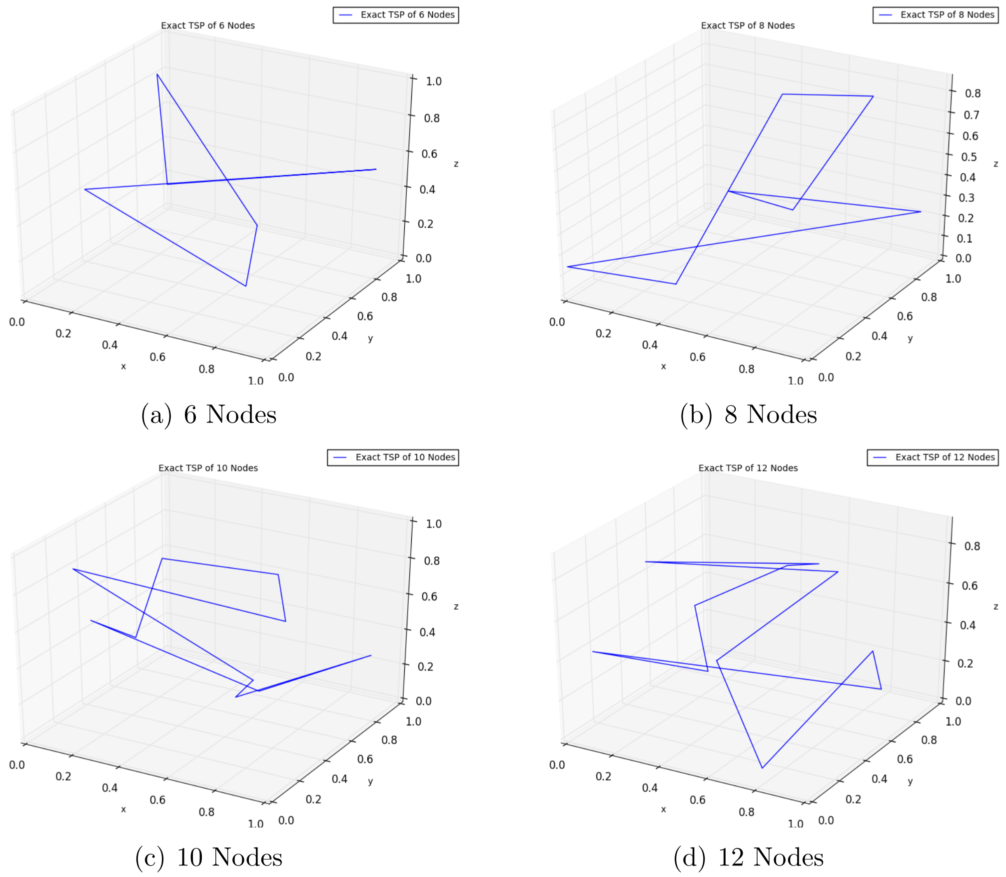
For this project the idea is to follow this logic to utilise Latin Hypercubes:

1. Specifiy area of interest to researcher
2. Estimate number of nodes able to be circumnavigated given the UAV total energy and the area of sample space
3. Fit Latin Hypercube of given nodes to sample area
4. Calcualte least energy route through the sample space
5. After first flight asses areas of encertainty to plan route through for next flight

9 Route Planning

Given a set of nodes within a sample space the next stage of the proceedings is to compute the least cost route through these nodes. This problem presents itself in the forn of the travelling salesman problem. The travelling salesman problem is the problem of finding the least cost route through a set of nodes. There is lots of work done on the elicidean travelling salesman problem and introducing heroustics to improve the time taken to compute. This is due to the problem being an NP hard problem (the computing time required increases exponentially with the number of nodes in the route)

9.1 Exact Travelling Salesman



(a) 6 Nodes

(b) 8 Nodes

(c) 10 Nodes

(d) 12 Nodes

Figure 2: Exact routes calculated by travelling salesman

Figure 4 shows the optimal routes for differnt numbers of nodes. These optimal routes are found by computing the exact cost of each and every route option. Although this yield the shortest routes this approach is not efficient in terms of the computation time required. To enable calculation of a 12 node route the start and end points of the route is defiend by the two lowest nodes. This is due to the nature of a UAV flight commencing and finishing at ground level

Number of points	6	8	10	12
Number of possible routes	24	720	40320	3628800
Computation time (ms)	0.0	7.0	411.0	43056.0
Best route cost (J)	106.71	91.53	108.76	99.96

Table 2: Comparison of route calculation

Table 3 shows the number of possible routes and the resulting computation time given different numbers of nodes. For a standard travelling salesman problem the number of possible routes is defined by $n!$ however in this case the number of route options is equivilent to $(n-2)!$ where n is the number of nodes in each case. This is due to the start and end node being defeined, thus the complexity is reduced by two nodes. The number of routes directly realtes to the computation time.

The computation time of the exact TSP is far exceeeding what would be practical for this project therefore the performance has to be increased to producee workable routes from the number of nodes required. These approaches involve producing a best guess and improving upon that which is call heroustics. The approach taken in this project is taken from considering the best routes in figure 4 generally comprise of a climbing component and a decending component.

9.2 Improving Travelling Salesman

The progressive travelling salesman is an approach to computing a best guess route for the least energy route for a number of points. The computation process is as follows

1. Order the nodes by there vertical location from lowest to highest
2. Consider a subset of the lowest nodes for routingCompute all permutations to two routes through the subset
3. Compare all to return the least cost combination
4. Add first nodes of both routes to final route
5. Consider a subset of the lowest nodes that are not in the final route and reitterate
6. Work through all nodes until no nodes are left without a route

Nodes in each route	2	3	4	5
Computation time (ms)	2.0	5.0	78.0	8277.0
Best route cost (J)	126.02	116.27	116.74	103.96

Table 3: Comparison of route calculation

Table 3 shows the varying computation time for routes through a 12 node latin hypercube that have a differnet numbers of nodes in each subset. Where subset refers to the number of nodes that are consideered in each progressive itteration of the code.

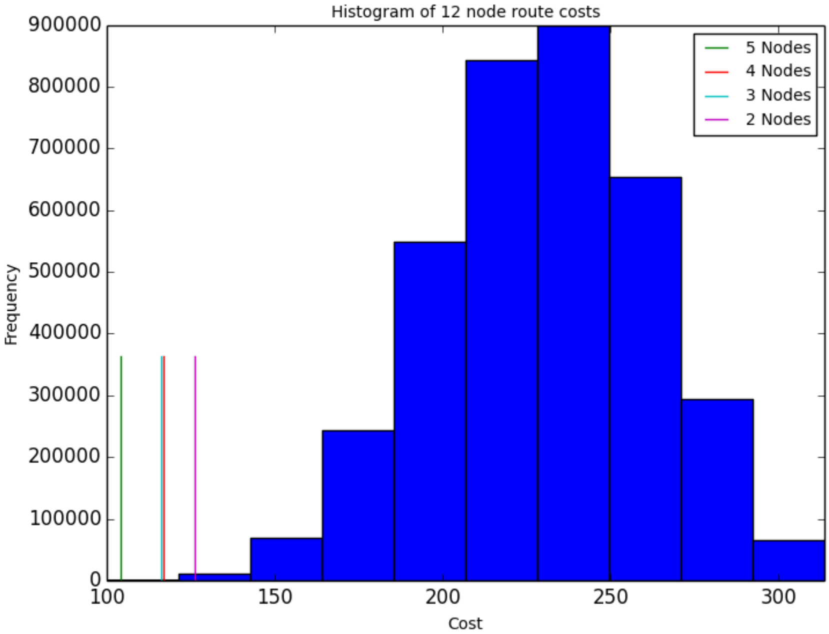
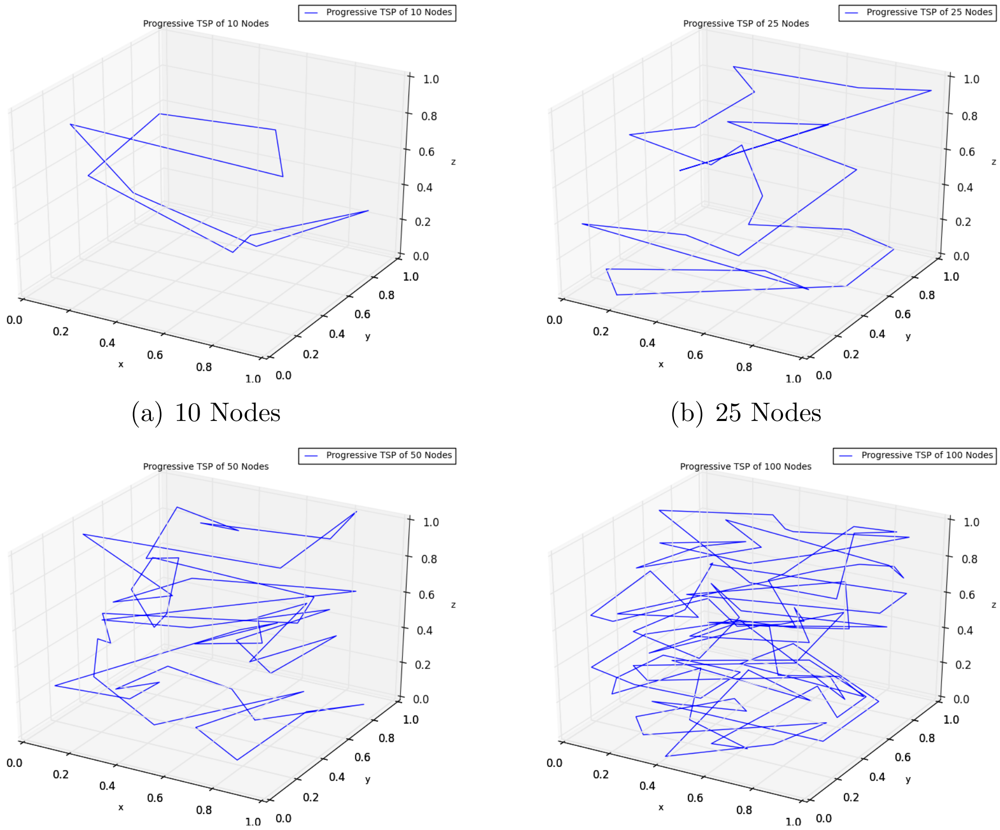


Figure 3: Histogram of 12 node route costs

Figure 3 shows a histogram of differnt route costs for a 12 node latin hypercube. The lines on this histogram plot represent the best cost routes with different numbers of nodes in the subset. It can be seen that the more nodes considered in the subset the closer the result is to that of the exact travelling salesman problem.

9.3 Progressive Travelling Salesman

In section 9.3 a best guess approach to the travelling salesman was presented and compared with the exact results. Given the results were close enough to the optimum even when the progressive algorithem only considered 2 nodes in the route it can be brought forward to be considered in reference to larger route problems. In these routes 4 nodes are considered for both the up route and the down route are used at each stage of the progressive algorithm.



(a) 10 Nodes
(b) 25 Nodes
(c) 50 Nodes
(d) 100 Nodes

Figure 4: Exact routes calculated by travelling salesman

Figure 4 shows a number of optimal routes for varing numbers of nodes whos order is defined be the progressive travelling salesman algorithm. Though the 100 node route is difficult to see the exact routing the other routes show a logical approach to the routing problem. These routes are around the same Latin Hypercubes as seen in Section 8.

Number of points	10	25	50	100
Computation time (ms)	52.0	234.0	586.0	1325.0
Best route cost (J)	115.48	136.76	185.14	302.64

Table 4: Comparison of progressive route calculation

Table 4 shows the computation time and route cost for the diffemt routing situations. The computation time is far bellow that of the exact travelling salesman algorithm due to the complexity of this problem being broken down into 4 node chunks. Therefore 8 nodes were considered in each subset. Looking at the computation time this is a sustainable method for computing routes through greater numbers of nodes as the time required does not grow exponentially.

10 Path Planning

The least energy route through a number of nodes has been defined however this route assumes that the UAV is able to turn on the spot and is not constricted by turning radius. Therefore to compute the actual energy cost of circumnavigating a route the turning radius of the UAV needs to be considered. Dubins paths are the minimum distance paths given a start and end direction.

Duibins paths ar comprised of maximum rate turns and straight line segments. The following defines all the routes that are possible made op of maxiumum rate turns and straight line segments

- RSR - Right Turn, Straight Flight then Right Turn
- RSL - Right Turn, Straight Flight then Left Turn
- LSR - Left Turn, Straight Flight then Right Turn
- LSL - Left Turn, Straight Flight then Left Turn
- RLR - Right Turn, Left Turn then Right Turn
- LRL - Left Turn, Right Turn then Left Turn

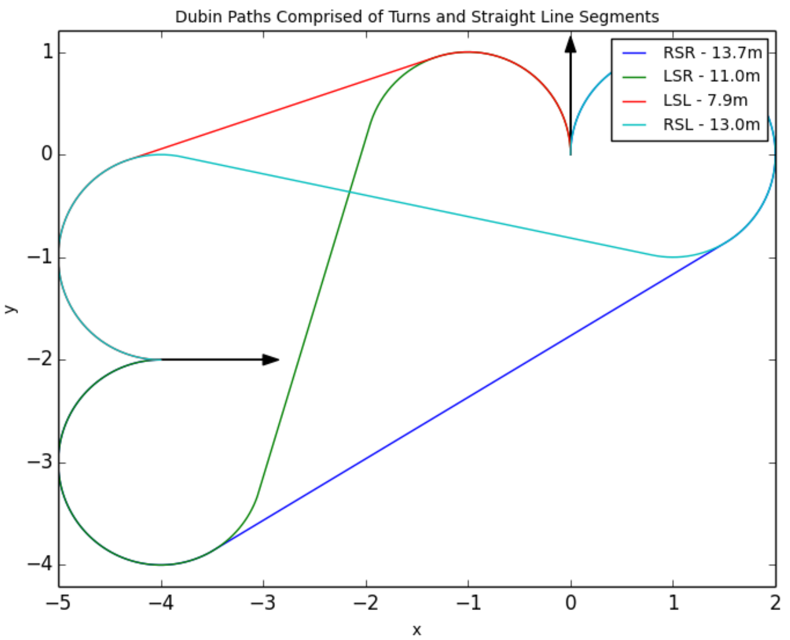


Figure 5: Dubin Paths Comprised of Turns and Straight Line Segments

Figure 5 shows the possible routes from the point (0, 0) in direction (0, 1) to the point (-4, -2) in direction (1, 0). The arrows symbolise the start and end headings and the different coloured route symbolise the different routes. In this example the routes comprise of maximum rate turns of radius 1 and straight line segment. At close proximity these routes are not always possible

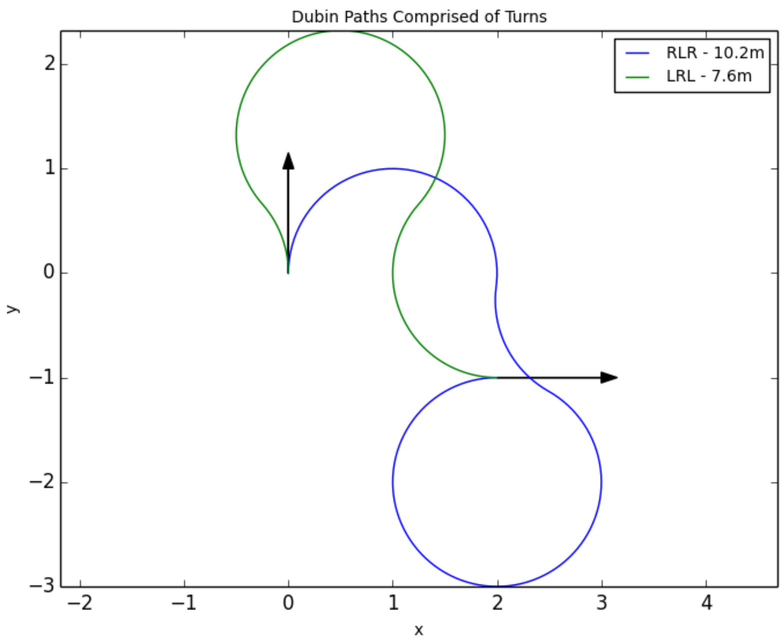


Figure 6: Dubin Paths Comprised of Turns

Figure 5 shows the possible routes from the point (0, 0) in direction (0, 1) to the point (2, -1) in direction (1, 0). The arrows symbolise the start and end headings and the different coloured route symbolise the different routes. In this example the routes only comprise of maximum rate turns of radius 1. These routes are only viable when the distance between points is $D < 4r$ where D symbolises the distance.

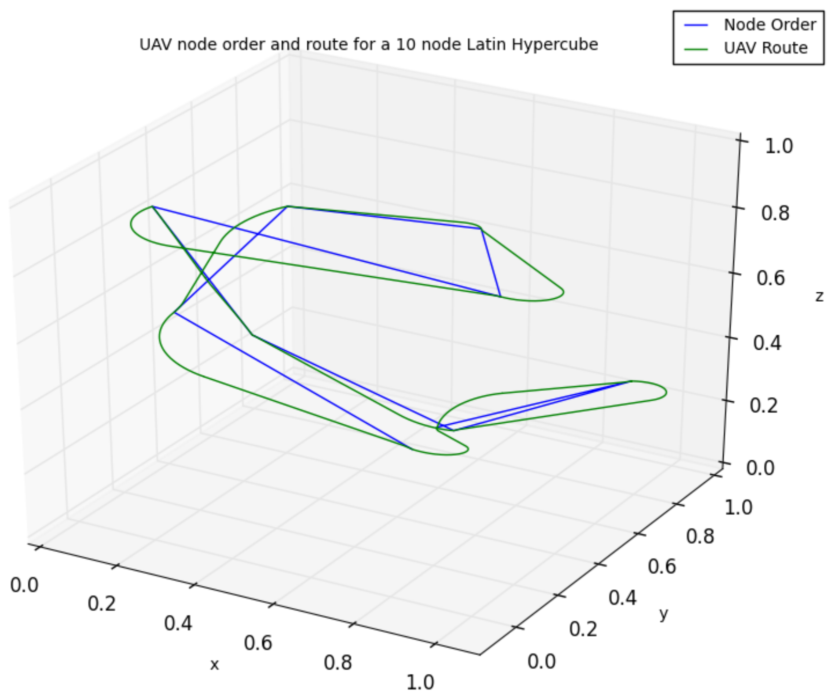


Figure 7: UAV node order and route for a 10 node Latin Hypercube

Figure 7 shows the optimal path and route for a UAV to circumnavigate a 10 node Latin Hypercube. The route is calculated before the path and then the path is calculated from the heading at each node in the route.

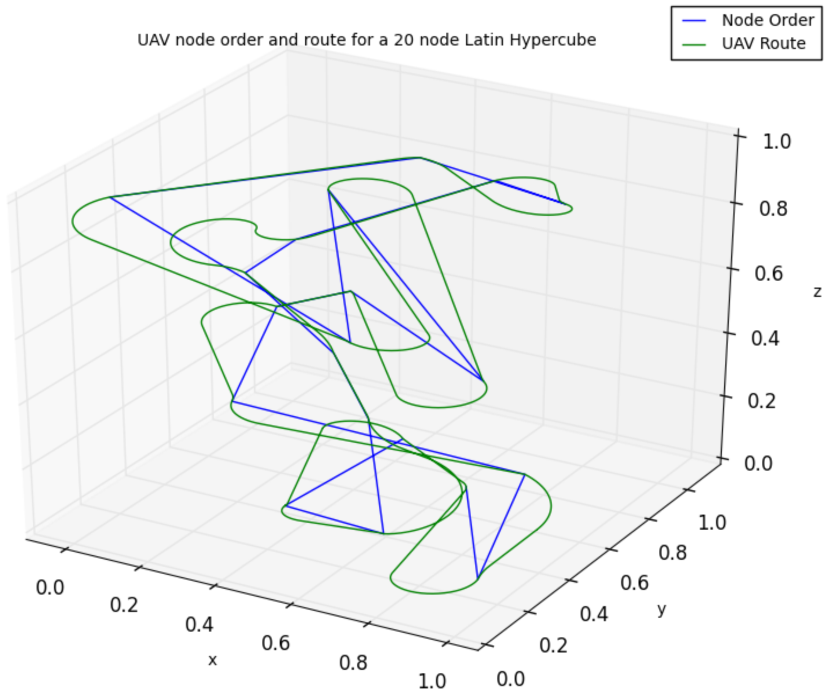


Figure 8: UAV node order and route for a 20 node Latin Hypercube

Figure 8 shows the optimal path and route for a UAV to circumnavigate a 20 node Latin Hypercube. The route is calculated before the path and then the path is calculated from the heading at each node in the route.

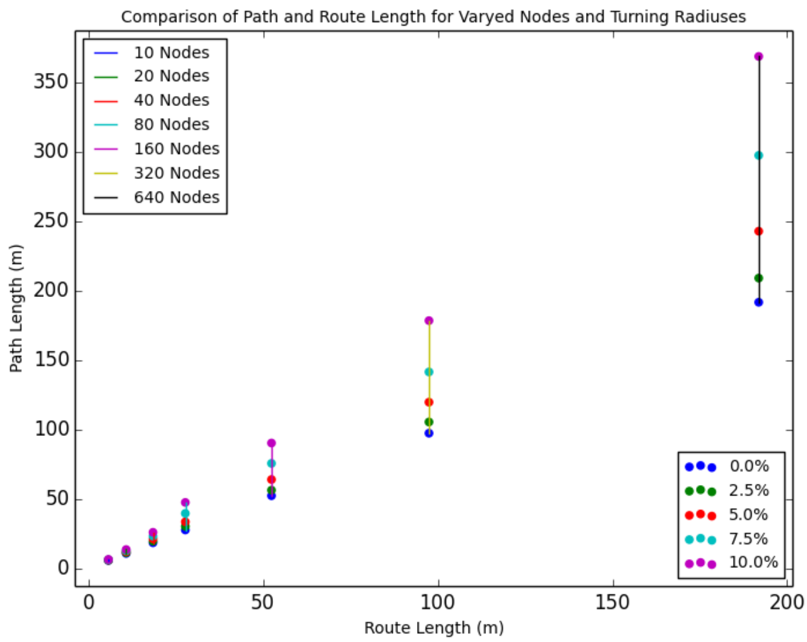


Figure 9: Comparison of Path and Route Length for Varyed Nodes and Turning Radiuses

Figure 9 shows the relationship between the route length and path length for a number of diffrent latin hypercubes. For each latin hypercube the distance of the shortest route (route through of nodes that does not take into account the flight charactersitics of the plane) is calculated and a number of shortest paths (path through ordered nodes that takes into account the maximum turning radius of the airplane). The shortest paths are considerede with turning radiuses varied between 0% and 10% of the length of the side of the area that is being explored. For this analysis the area of interest is a unit cube and the percentage value represents the maximum turning radius of the plane over the length of one axis.

It can be seen from figure 9 that as the number of nodes in the latin hypercube is increased (vertical coloured lines indicate a set of tests on a single latin hypercube) the afect of increased turing radius (turning radius is indicated by sets of coloured points) also increases. For the case where the turning radius is 0% the path length and route length are the same as the UAV can affectively turn on the spot.

$$L_P = (9.52R + 0.90)L_R \tag{2}$$

Equation 2 shows the relationship between route length and path length given varied turning radiuses. This equation should not be relied upon for exact path planning however is sufficient to see the relationship between the route and path length. Given the linear relationship it can also be determined that the route length is sufficient to calculate when considering the initial costs of paths.

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