Highly Autonomous UAV Mission Planning and Piloting for Civilian Airspace Operations

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Summary: The last decade has seen a rapid increase in the development and deployment of Unmanned Airborne Vehicles (UAVs). Previous UAVs have been capable of useful missions with a limited degree of on-board intelligence. However, more on-board intelligence is required to fully exploit the potential of UAVs. The objective of this research is to increase the on-board intelligence in two areas: mission planning; and mission piloting. Thereby improving the integration of a UAV into civilian airspace and reducing operator workload.

This paper presents the research towards the development of the Intelligent Mission Planner and Pilot. The IMPP enables a UAV to autonomously plan and to perform missions within civilian airspace. The IMPP employs a novel multidisciplinary approach, exploiting robotics, 3D graphics and computer science techniques. Results are presented based upon testing using real world data from south-east Queensland. These results demonstrate the performance achieved by the mission planning and piloting algorithms.

Keywords: UAV mission planning, collision avoidance, high level communications, civilian airspace, 3D graphics, robotics.

Introduction

In the last decade UAVs have increased in sophistication, advancing from deployments as target drones for military operations to performing reconnaissance and strike missions in war zones. UAVs are now routinely deployed for civilian purposes with applications such as meteorological data collection and farming (eg. Yamaha's RMAX). However, a limit exists on how extensively current UAVs can be deployed within civilian airspace. Presently, the intelligence on-board UAV platforms is low. The consequence of this is that UAVs must be either deployed within a restricted area or must be continually monitored by trained personnel. This constrains the deployment of UAV platforms and denies access to the full capabilities of UAVs.

It is therefore desirable to increase the intelligence on-board UAVs to enable the full exploitation of their potential. The purpose of increasing the on-board intelligence is to increase the capabilities of the UAV and to reduce the workload placed upon its human operators. The research presented in this paper focuses upon the mission planning and piloting aspects of the on-board intelligence. In this context mission planning refers to the process of determining the path which the UAV needs to fly in order to meet the mission objectives. Similarly, mission piloting refers to the processes of collision avoidance and communications which must be performed during flight. The objectives of the research presented here are:

1. To perform 3D on-board mission planning for civilian airspace operations.
2. To plan efficient paths in terms of distance travelled, time required or fuel consumed.
3. To perform collision avoidance in civilian airspace in accordance with the applicable regulations and with an emphasis on preventing loss of life.
4. To define a vocabulary suitable for communicating with a UAV operating in civilian airspace and to identify the issues present in using this type of communications in civilian airspace.

A novel multidisciplinary approach has been adopted to achieve these objectives. This approach draws upon techniques from the 3D graphics, computer science and robotics fields. 3D graphics techniques have been employed to enable the UAV to construct and maintain its situational awareness. This situational awareness is used by the UAV to perform high level tasks such as mission planning and piloting. The mission planning algorithms have been adapted from techniques used within the robotics field for path planning. The combination of the 3D graphics and robotics techniques enables the UAV to plan its own missions and to do so with greater freedom (of movement) than previous approaches. Robotics techniques have also been used in conjunction with 3D graphics techniques to provide the collision avoidance capabilities. Finally, computer science techniques have been employed to develop the natural language based communications algorithms. The advantages of this novel multidisciplinary approach will be demonstrated using scenarios based upon airspace and terrain data from south-east Queensland, Australia.

The Autonomous Mission Planning Problem

The mission planning problem is, simply put, that the UAV is given a list of mission objectives which it must satisfy. To satisfy the objectives (ie. Solve the problem) a plan must be generated of how to reach the objectives given that there are obstacles which must be avoided. This section will examine the existing solutions to the problem and identify issues which prevent these approaches from fully exploiting a UAV’s potential. Based upon the identified issues a solution will be developed aimed at resolving these issues.

Currently most mission plans for UAVs are prepared by a human operator. This avoids the need to perform mission planning on-board, but at a cost. The human operator needs to be aviation trained and the process of planning the mission can take considerable time [1]. Naturally the more complex the mission the longer the time required for mission planning. There are three main issues with having a human operator performing the mission planning.

Firstly, the UAV is constrained to flying along the path which the operator has planned. During a mission the UAV cannot change the mission plan, this can only be done by the human operator. This makes it difficult for the UAV to adapt to changes within the environment during the mission. Secondly, the workload placed upon the operator is high [1]. This is especially true if the operator is required to replan large sections of the mission during a flight. Finally, the operator must be aviation trained in order to be capable of planning an appropriate path. This in turn raises the training and personnel costs for operating the UAV.

The presence of these issues therefore makes the transfer of mission planning to on-board the UAV a desirable action. By providing the UAV with an on-board planning capacity it can adapt to changes in the environment. Some UAVs have been developed which can perform their own mission planning. These systems have however focussed upon military operations within a war zone. They have therefore placed their emphasis upon factors such as minimising the size of the target presented to enemy RADARs and other similar military oriented attributes [2]. These systems, while capable, are not suitable for civilian airspace applications due to a number of issues.

Firstly, the previous approaches make no accounting for airspace boundaries or issues associated with them (eg. Being active only in certain hours). Secondly, many of the previous approaches only consider the planning problem in two dimensions (often a fixed height above ground is assumed). A two-dimensional approach is not suitable for the civilian airspace environment where stepped airspace boundaries (ie. A 3D shape) are commonplace. Finally, the previous approaches typically constrain the UAV to operations along specific paths. This limits the freedom of the UAV and potentially blocks out more efficient flight paths.

Current on-board UAV mission planning systems are therefore not suitable for operations within civilian airspace. A mission planning solution is required which addresses these issues. This paper describes the development of an Intelligent Mission Planner and Pilot (IMPP) designed specifically to address these issues. In order to provide the necessary mission planning capability the IMPP needs to:

- Operate based upon a fully 3D representation of the world
- Plan missions on-board the UAV in a manner suitable for civilian airspace applications
- Plan missions that optimise distance travelled, time required or fuel used
- Enable the UAV to fly anywhere within civilian airspace that a human pilot would be permitted to fly

These requirements define the framework for the mission planning research presented in this section. Consideration is not being given at this stage, of the research, to the sensing side of the problem. The assumption is made that the information required will be available. The research focuses upon using and representing the sensory information to assist with mission planning.

Consideration must also be given to the rules under which the flight will be conducted. The flight could be conducted under Visual Flight Rules (VFR) conditions, Instrument Flight Rules (IFR) conditions or a mix of both (ie. VFR during one part of the flight, IFR in another). VFR conditions impose the least constraints upon the operations of the UAV, which is one of the research objectives. Furthermore many civilian applications, such as crop dusting, are conducted under VFR conditions. Therefore the decision was made that the IMPP would plan missions assuming that the UAV was flying under VFR. This requires the IMPP to avoid entry into controlled airspace (typically VFR flights are not permitted into controlled airspace). The UAV must also fly at the appropriate hemispherical altitude based upon its heading.

In order to satisfy these requirements the IMPP will require a mechanism to store, represent and interact with information which describes the operating environment. The IMPP will also require mission planning algorithms which operate based upon the current information stored about the operating environment.

The proceeding sections will discuss, in detail, the multidisciplinary techniques which have been implemented in order to create the IMPP. The first aspect of which is the achievement of on-board situational awareness.

Achieving Situational Awareness

A human pilot operating an aircraft requires a high degree of situational awareness. The Intelligent Mission Planner and Pilot will also require an awareness of the environment in which it is operating. The situational awareness will need to contain sufficient information for the IMPP to plan its assigned mission. The IMPP will need to construct, update and interact with its awareness of the complex 3D operating environment.

Constructing a dynamic, complex, 3D digital world has historically been restricted to large dedicated high performance computing systems. However, with the rapid advances in computing technology, constructing such digital worlds is now possible on, what would be considered by today's standards, low-end computers. These advances have made it possible to construct a digital representation of the civilian airspace environment which incorporates terrain, airspace boundaries, weather and other aircraft. This digital world is the key to constructing the situational awareness required by the IMPP to perform on-board mission planning. As new sensor information is collected the digital world can be updated (eg. Add a new aircraft) to provide a snapshot of the current environment. The Intelligent Mission Planner and Pilot then interacts with the digital world. These interactions include determining if the straight line path between two waypoints intersects with an entity in the world (eg. Terrain). The interactions with the digital world are performed using techniques established in the 3D graphics and robotics fields which have been optimised for speed and numerical efficiency [3].

The first step in constructing this digital world is to identify exactly what the UAV needs to be aware of. The critical entities which must be represented are:

- Terrain
- Airspace boundaries
- Adverse weather (eg. storm cells)
- Other aircraft
- Tall buildings
- Navigation aid locations and types
- Runways
- Radio frequency zones

Other entities could be incorporated if the operational concept requires it, however the above list was considered to be sufficient to meet the research objectives of this project.

The above entities form an important part of the civilian airspace environment and the UAV needs to be aware of them. The majority of the entities (terrain, airspace, adverse weather, other aircraft and buildings) are ones which that a human VFR pilot would be aware of (through instrumentation, maps etc) and avoid. The other entities are either informational (navigation aids and radio frequency zones) or are mission start/end points (runways).

A number of sensing capabilities have been assumed for this research. In addition to standard attitude and position information, the UAV must be aware of the location of other aircraft and weather (eg. storms). A number of methods exist for obtaining this information, for example radar-based systems or the Airborne Dependent Surveillance – Broadcast (ADS-B) can provide the location and speed of nearby aircraft. Similarly, a weather-radar can also provide location information for adverse weather conditions. However, the focus of this paper is on how to represent and utilise the information that is assumed to be available. No further consideration is given as to what sensing capabilities must be implemented in order to provide this information.

Digital Representation of Airspace Entities

In addition to the location of the entities within the world, their dimensions must also be known. This means that for each entity within the world there needs to be a description of its dimensions. This description is necessary for the entities to be 'drawn' within the digital world. The creation (ie. Drawing) of, and interaction with, 3D models is an area which has been studied in detail within the 3D graphics field for both hardware and software applications.

The industry standard for rapidly representing 3D models is to use a mesh of triangles (triangular mesh) [4]. Triangles are a geometrically and mathematically simple shape. They are constrained within a single plane and are fast to interact with (eg. Detecting if a line intersects the triangle). Complex objects can be represented using triangular meshes, with the complexity limited only by the resources available for the storage of the mesh. Fast, efficient algorithms have been developed for interacting with triangles and by association triangular meshes [5]. The triangular mesh representation is used by the majority of 3D graphics hardware and software systems as the standard for rapid modelling of objects.

This approach has been used to model the entities within the digital world. It should be noted that this is a unique application of 3D computer graphics algorithms to provide situational awareness for a UAV operating in civilian airspace. Before lower level details of the creation of the situational awareness are provided a brief explanation of the terminology which will be used will be provided.

> *Entity* refers to an object from the civilian airspace environment. For example, terrain, airspace boundaries and other aircraft.
>
> *Model* is the digital representation of an entity. A model stores both the properties of the entity (eg. the type [airspace boundary, terrain etc]) and the shape of the entity.
>
> The shape of an entity is stored (digitally) using a *primitive*. A primitive is one of a group of pre-defined shapes which can be used to represent an entity.
>
> Finally, primitives are converted to a *triangle mesh* to facilitate fast interactions (eg. detecting if a straight line passes through the model of an entity) with them.

These terms are shown in the figure below.

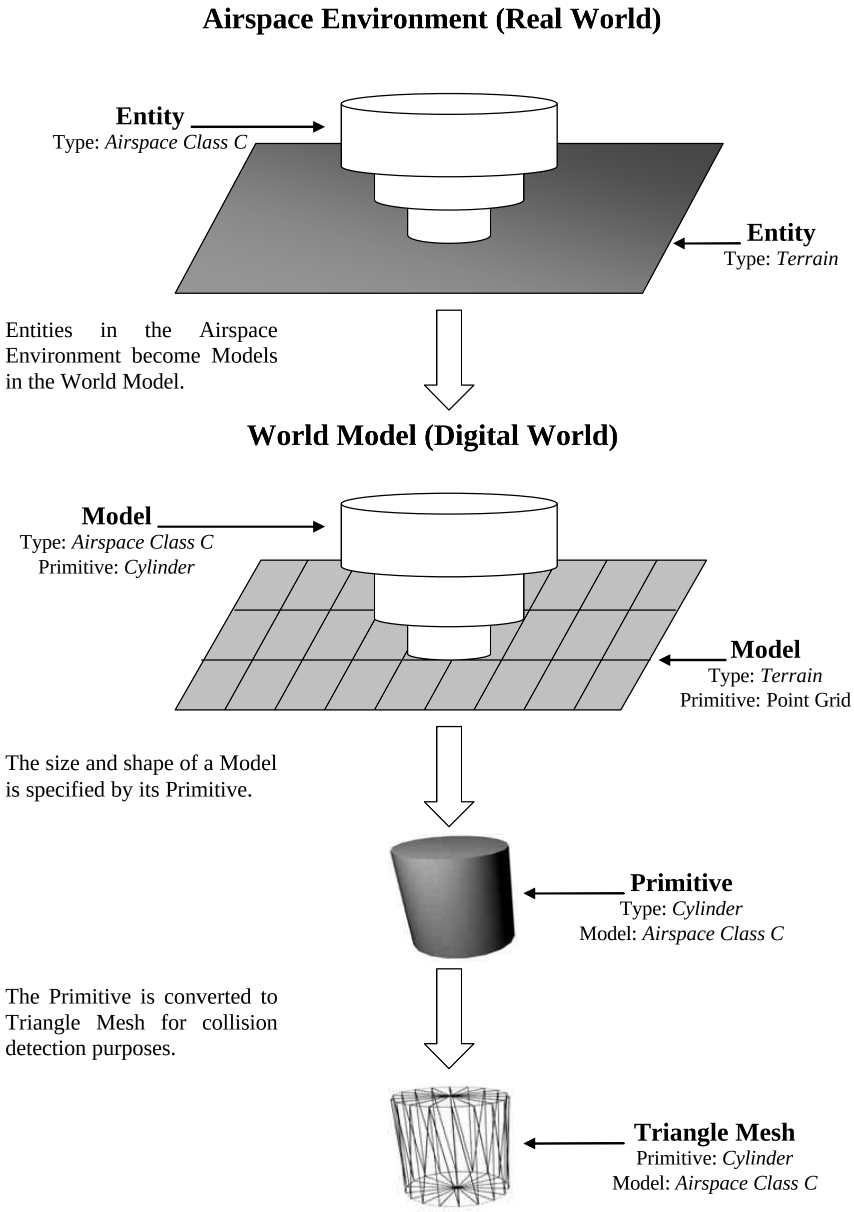


Fig. 1: World modelling terminology

Every entity is converted to a triangular mesh-based model with which the Intelligent Mission Planner and Pilot can interact. These interactions include detecting if the straight line path between two waypoints will collide with an entity and if a location lies within an entity.

This unique approach of using 3D graphics to provide situational awareness for mission planning in civilian airspace has been successfully implemented into the Intelligent Mission Planner and Pilot. A 3D digital representation of the airspace environment has been constructed using information from digital elevation models and airspace charts. The current digital world stores the terrain and airspace details for a section of the eastern coast of Australia. This section covers a region measuring 270 nm (east-west) by 240 nm (north-south) and contains over 70 airspace boundaries.

By continually updating the digital world based upon current sensor data the IMPP, and other UAV systems, can be provided a with high-degree of situational awareness. This situational awareness provides the foundation for the mission planning and piloting algorithms within the IMPP.

Autonomous Mission Planning

Once the digital representation of the world (ie. The situational awareness) has been created, high level activities such as mission planning and piloting can be performed. The autonomous mission planning algorithms are the core component of the Intelligent Mission Planner and Pilot (IMPP). These algorithms use both the mission objectives provided by a human operator and the on-board situational awareness to plan the mission. The planning process involves determining an efficient and collision free flight path which will achieve the assigned mission objectives. The output of the planning process is a series of waypoints (ie. Flight path) which the UAV must fly to (in sequence) in order to achieve the mission objectives.

The field of mission planning has been studied in depth by the robotics industry [6, 7]. Research to date can be divided into two categories: solutions where all information is known *a priori*; and solutions where either partial or no information is known *a priori*. Information in this case refers to the layout of the world and the locations and dimensions of entities within the world. Solutions which initially have a full awareness of the operating environment (ie. All information provided *a priori*) can develop a complete plan from the start to the end of the mission. These plans are known as ‘global plans’. As global plans cover the entire mission they can be made efficient over the entire course of the mission (ie. Globally efficient).

The disadvantage of developing global plans is that the mission planner requires a large amount of *a priori* information in order to develop the plan. The alternative approach is to plan for the near future (eg. 10 minutes). This uses only a partial awareness of the environment and requires less information. Solutions of this type can only develop plans for the immediate future (ie. Plan for 10 minutes into the future). These plans are known as ‘local plans’. Local plans have the disadvantage that they may not be capable of achieving the required goal as they can become lost or stuck due to their limited view of the world. Finally, as local plans cannot consider the entire mission at once they are not guaranteed to produce plans which are efficient over the entire course of the mission. Efficient local plans can only be developed for the immediate future, known as ‘locally efficient’.

For UAV mission planning it is possible to provide sufficient information *a priori* to enable the UAV to develop global plans. This information would include as a minimum the terrain and airspace boundary information. Short-term disturbances (eg. Avoiding a collision with another aircraft) can be accommodated through reflex-style algorithms that make local changes to the global mission plan. This mixed approach of global planning algorithms and reflexes will enable the IMPP to plan efficient paths within civilian airspace. The reflex-based collision avoidance algorithms are presented later in the paper.

A range of methods, for global planning in known environments, have been developed and proven by researchers in the robotics field. These methods range from algorithms which partition the world into grids then move from cell to cell, to artificial intelligence based path searches. The most common methods available are:

- Cube space (C-Space) algorithms where the digital world is divided into cubes [8]. These are a 3D extension of 2D grid worlds.
- Octree algorithms, which are a hierarchical representation of C-Space which enables the digital world to be viewed at multiple resolutions [7].
- Voronoi diagrams, which compute a graph of the free paths within the digital world [9].

Voronoi diagrams have previously been employed for UAV mission planning. They are typically combined with artificial intelligence based graph search algorithms [9].

Voronoi diagrams can be used to incorporate the concept of risk into the mission planning process by keeping further away from dangerous obstacles (eg. A military test range). The primary disadvantage with Voronoi diagrams is that the UAV is required to fly along the lines of the Voronoi graph (except when transiting to/from a waypoint). This prevents the UAV from flying close to obstacles and thus eliminates potentially more efficient plans. Previous UAV implementations [9] have only used Voronoi diagrams for two-dimensional mission planning. However the civilian airspace environment is three-dimensional and therefore demands a three-dimensional planning approach in order to provide a wider operating envelope.

Cube-Space Mission Planning

Cube-Space (C-Space) algorithms have been employed frequently within the robotics field to solve the mission planning problem [10]. To date C-Space algorithms have not been applied for UAV mission planning. The C-Space algorithms are based upon dividing the 3D world into cubes. The cubes are marked as either free or occupied. A cube which contains any part of an entity within the world (eg. A region of airspace) will be marked as occupied. As can be seen in the diagram below all cubes (in this case squares since it is a plan view) that overlap with the region of airspace are marked as occupied (shaded).

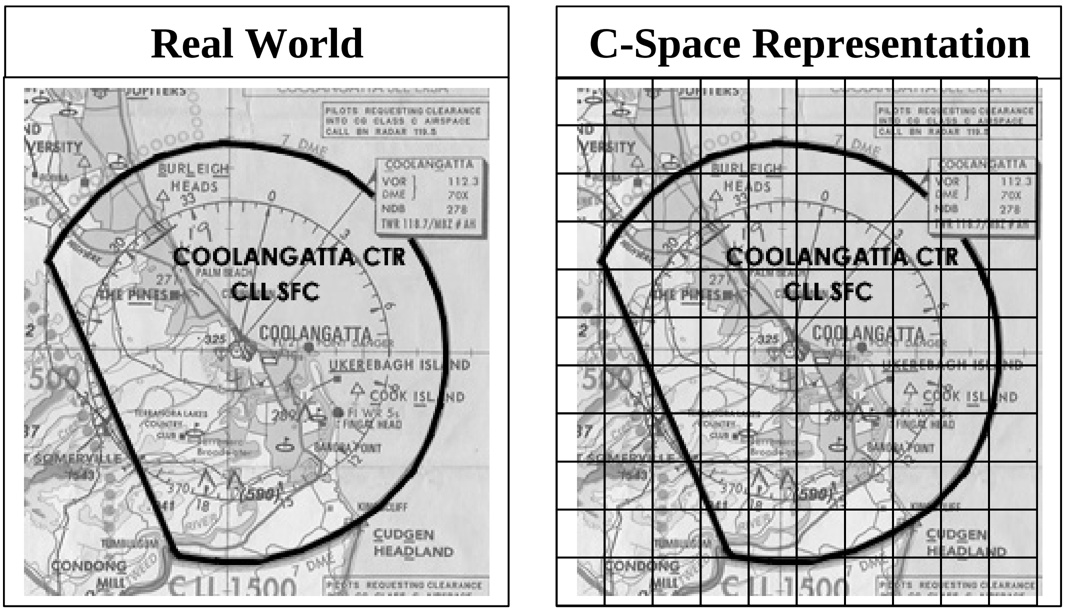


Fig. 2: Plan view comparison of real world and C-Space representations

Additionally each free cube is assigned a value, for example the distance from the cube to the goal (destination). The path (ie. Mission) is planned by jumping from cube to cube with the direction of the jump based upon the values assigned to the free cubes. This process is shown in the diagram below.

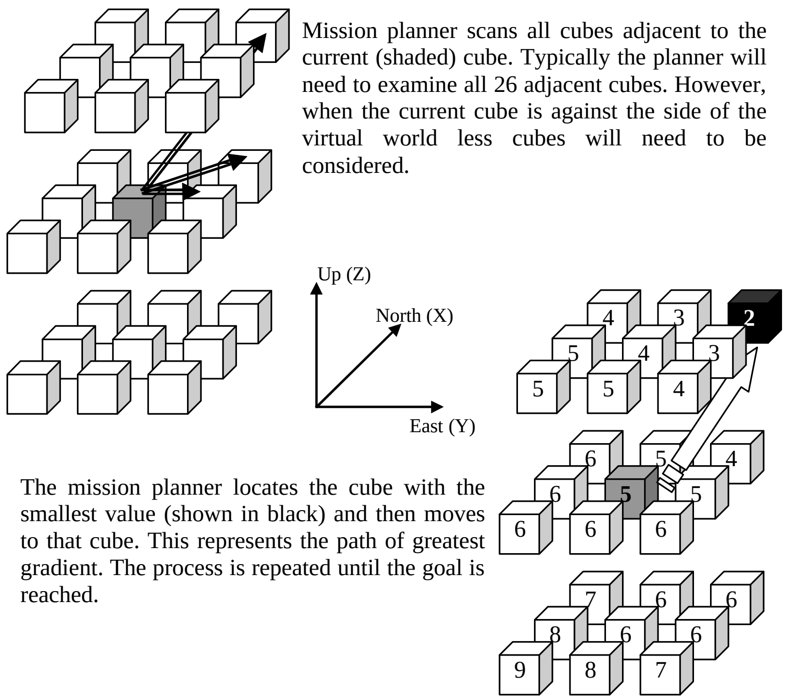


Fig. 3: Example of the scanning process performed by the mission planner

The critical part of C-Space based mission planning is the algorithm used to map values onto the free cubes. One commonly used mapping is to propagate a 3D wave from the goal (destination) marking each free cube with the distance to the goal [6, 7]. This can be viewed as a sphere expanding from the goal where the edge of the sphere is the wavefront being propagated. It is important to note that this is not the straight line distance from the cube to the goal. Instead it is the distance that the UAV would need to fly to reach the goal. This requires that the distance wave refract around obstacles so that each cube is accurately marked with the distance required to move from that cube to the goal. The mission planner then starts at the UAV's current location and scans the adjacent cubes. This process is shown in plan view in the figure below.

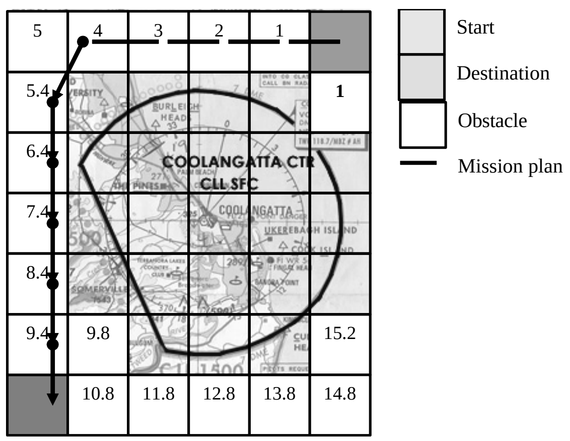


Fig. 4: Path planning process

After scanning the adjacent cubes the mission planner then moves to the cube closest to the goal. This approach is repeated until the goal is reached.

The distance wave mapping has been successfully employed in the past for autonomous ground vehicles [7]. However the disadvantage of the distance wave is that it does not factor in the time taken or energy (eg. Fuel) used to traverse the path. For example there is a significant difference between an aircraft flying a 50nm path at a constant altitude and flying a 80 nm path that requires the aircraft to climb and descend thousands of feet to avoid airspace boundaries. As part of the research two additional mappings have been developed to enable the generation of mission plans which are more consistent with the practices of a human pilot.

The first mapping estimates the effort, in terms of time, to fly to the goal. The effort wave mapping is applied by first applying the distance wave. Then, based upon the capabilities of the aircraft, the time to fly from each free cube to the goal is estimated. This is calculated by assuming different speeds based upon the direction in which the UAV would fly. The speeds were determined based upon simulated testing which examined the speed of the aircraft in different configurations (climb, descent etc). The diagram below shows the speeds used to determine the time to fly to each cube within the world.

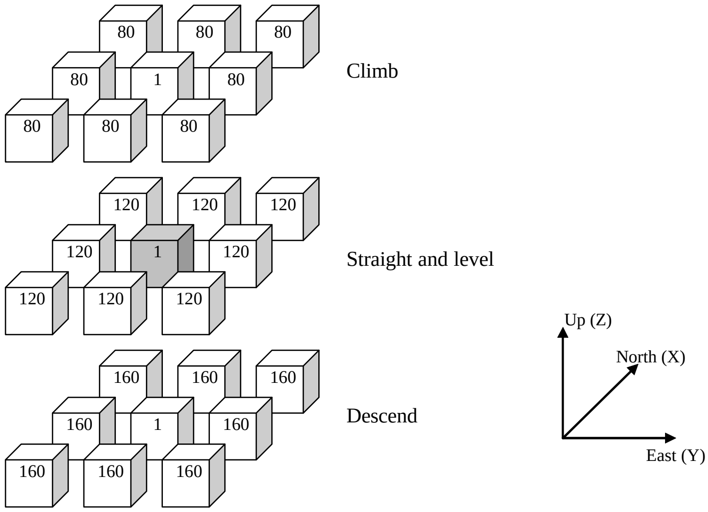


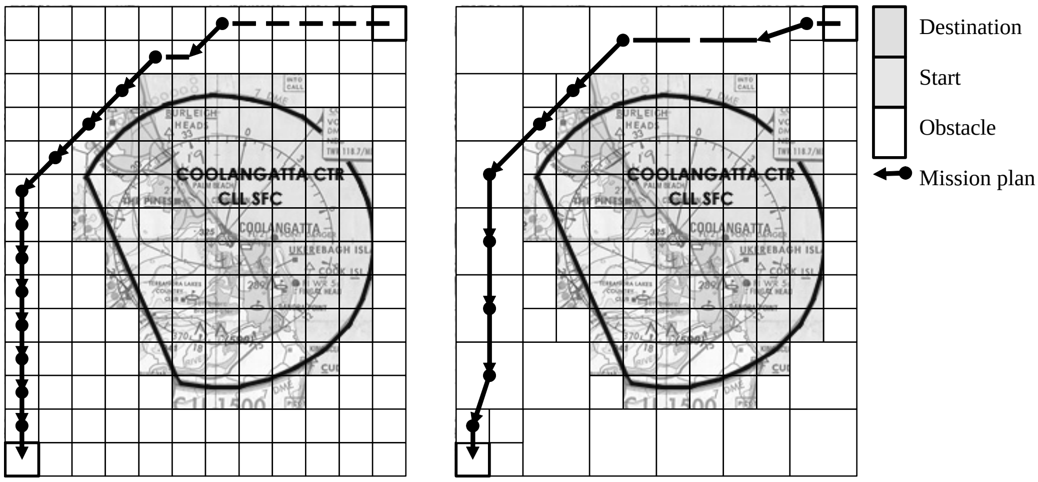
Fig. 5: Speeds (in knots) used for effort wave calculation. (Current cube is shaded)

The result of this mapping is that the decision between climbing, descending or making no altitude change is weighted appropriately. Very high penalties are assigned to pure vertical manoeuvres in order to prevent the path planner from choosing such a path. Ascending incurs a penalty in terms of speed, whereas descending incurs an advantage. The consequence of this mapping is that the UAV will fly the path of approximately shortest time. The UAV prioritises flying straight and level over ascending. Although an advantage is given to descent manoeuvres, the UAV will not descend to the lowest level possible and then ascend at the last minute. This is prevented by the penalty for ascending, which makes such a mission plan too costly. Determining the path with the effort wave mapping is identical to that for the distance wave mapping. The new mission plan is generated by following the path of greatest gradient.

The final mapping estimates energy required to manoeuvre the aircraft in terms of the fuel used. Unlike the effort wave, the fuel wave mapping does not build on top of the distance wave. The fuel wave factors in both the distance and the time to move that distance when the wave is propagated. The equation used to determine the fuel usage was based upon the engine model provided by the AeroSim Blockset [11]. First, a basic aircraft model is used to estimate the time the UAV would require to fly from one cube to another. This information is then used by the engine model to estimate the fuel which would be consumed in performing the manoeuvre. Consequently, the UAV will attempt to fly the most fuel efficient path. The method for generating the mission plan using the fuel wave mapping is identical to that for the distance and effort waves. Any of these mappings could be used to perform on-board mission planning by the IMPP. The performance of the different mappings will be compared further on in this paper.

Octree-based Mission Planning

The second type of mission planning method available is the Octree, which is an extension to the C-Space methods. Octrees are a hierarchical structure that represent the world at multiple resolutions [7]. The multiple resolutions make crossing large empty spaces more efficient than for a C-Space representation. Rather than moving from cube to cube, multiple cubes can be crossed at the same time. This is shown in the figure below.



C-Space mission plan requires **19** jumps   Octree mission plan requires **12** jumps

Fig. 6: Efficiency differences between C-Space and Octree representations

While this greater efficiency is beneficial, Octrees posses two major disadvantages. Firstly, they consume a larger amount of memory than C-Space methods. For example, consider the situation where a cube, with a side length of 16 nautical miles, is represented at a resolution of 1 nm. The C-Space representation will require 16x16x16 = 4096 data structures to represent it. An Octree representation would require 16x16x16 + 8x8x8 + 4x4x4 + 2x2x2 + 1x1x1 = 4681 data structures. This is a 14% increase in the storage requirement and as the dimensions increase (or the resolution decreases) this overhead will grow.

Secondly, the path planning process is made slower due to the greater overhead in traversing the Octree structure. This overhead results from the process of relocating to parent, child or adjacent nodes. This is slower than for C-Space which can be represented as a multi-dimensional array.

In the Octree method the blocks (called nodes) are marked as either fully-free, fully-occupied or partially-occupied. If a node is partially-occupied, by an entity, then it is possible to change to a finer resolution version of the node and then locate the free nodes within it. The mappings described for C-Space can also be applied for Octrees in the same manner. The path planning algorithms are also identical. The only change is that the planner can move to a partially-occupied node as well as a fully-free node. The Octree algorithms can provide more efficient planning, however the greater overheads frequently outweigh the performance gains, as will be shown in the results.

The C-Space and Octree algorithms mentioned in this section were implemented into the Intelligent Mission Planner and Pilot (IMPP). Both types of algorithms are capable of meeting the research objectives. The Voronoi diagram methods have not been adopted as they greatly restrict the freedom of the mission planner by forcing flights along pre-defined paths. The outlined methods enable the IMPP to perform global mission planning on-board the UAV for civilian airspace applications. Results of testing conducted on the planning algorithms will be presented later in the paper.

Collision Avoidance in Civilian Airspace

Collision avoidance is an essential area to address for a civilian airspace integrated UAV. Any aircraft operating in civilian airspace in the presence of other air traffic will require a collision avoidance capability. This section discusses the development of a collision avoidance capability for a UAV operating in civilian airspace based upon a unique fusion of 3D computer graphics and robotics techniques.

Collision avoidance is a two step procedure comprising of both collision detection and collision resolution. Collision detection is the process of detecting if a collision may occur. The development of a strategy to then prevent the detected collision from occurring is known as collision resolution. These two stages of collision avoidance will be dealt with separately. Consideration will first be given to the collision detection stage.

Collision Detection

Collision detection involves detecting if a collision may occur. In order to perform this detection it is necessary to be aware of the current location of the UAV and the locations of the entities in the world which must be avoided. For the purposes of this research it will be assumed that this information will be available through the on-board situational awareness created through the 3D graphics algorithms This section will focus upon the algorithms which utilise this information to determine if a collision scenario is present.

Before specific algorithms can be discussed it is necessary to identify what entities must be avoided as well as other constraints (eg. regulations) related to collision detection. The situational awareness, described earlier, is capable of storing details for the following types of entities.

- Terrain
- Airspace boundaries
- Adverse weather (storms and clouds)
- Other aircraft
- Navigation aids
- Runways
- Buildings
- Radio frequency zones

Of the entities listed there is clearly no need to avoid radio frequency zones, navigation aids or runways. The remaining entities (terrain, airspace boundaries, adverse weather, other aircraft and buildings) must be avoided. These are all entities which an aircraft operating in civilian airspace may encounter and which a human pilot would avoid. It is important to note that other aircraft and buildings will be deemed inhabited by the collision avoidance algorithms.

One of the key constraints upon the UAV is to prevent injury or loss of life to the fullest extent possible. To this end the UAV needs the capability to differentiate between inhabited and uninhabited entities to enable it to place greater emphasis on avoiding inhabited entities. The collision detection algorithms must therefore possess the means to make this differentiation. Finally, the collision detection procedure should be performed in accordance with the Civil Aviation Regulations. These regulations state that an aircraft is not required to perform avoidance manoeuvres when it is being overtaken. The criteria for if an aircraft is being overtaken is shown in the figure below.

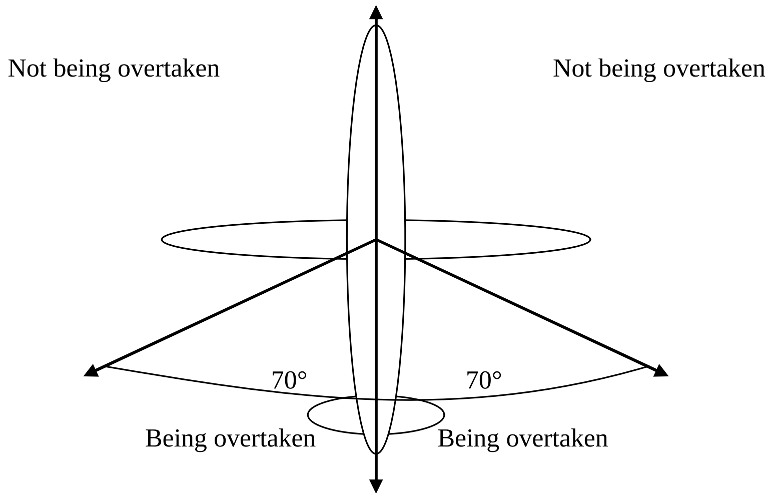


Fig. 7: Criteria for if an aircraft is being overtaken

As shown in this diagram if the other aircraft is in a region 70° either side of the tail of the aircraft then it is considered to be overtaking. There is no requirement to consider an overtaking aircraft for collision avoidance purposes. In this scenario the regulations permit the pilot discretion to determine if collision avoidance manoeuvres must be performed. For a UAV in the same situation the question is: how should the UAV decide what to do? It has been assumed that the UAV will have a full awareness of the location of the overtaking aircraft (intruder). Therefore the UAV will be able to calculate the distance between it and the intruder. This distance can be used to decide if collision avoidance manoeuvres are required. Beyond a set threshold there will be no reaction to the intruder. However, once within the distance threshold collision avoidance procedures will be enacted. The determination of this threshold will be discussed in the proceeding section.

Developing an Approach to Collision Detection

A significant body of research exists in the robotics field in the area of collision avoidance. The leading approach in this field is potential field theory. Potential field theory has been used on-board UAVs previously for collision avoidance purposes [12]. However, these applications have not considered operations in civilian airspace and the ensuing issues (eg. regulatory constraints) that result from operations in civilian airspace. There is therefore a need to extend this approach to encompass the additional issues which civilian airspace presents.

Firstly a brief overview of potential field theory will be provided. Essentially potential field theory operates by assigning a repulsive field to the entities which are to be avoided. This repulsive field exerts a force upon the UAV which 'pushes' the UAV away from the entity. The strength of the force is determined by the potential field magnitude (ie. How hard the field can push) and the distance from the entity. As the UAV gets closer to the entity the strength of the force exerted upon the UAV increases. Potential fields also posses shape and a zone of influence. Shape refers to the shape of the potential field being generated (eg.

spherical etc). The zone of influence is the distance beyond which the potential field strength is zero (ie. Has no effect). The zone of influence is used to reduce computational complexity.

The first step in using potential field theory to perform collision detection is to establish where the entities in the world are in relation to the UAV. The on-board situational awareness tracks the locations of all of the entities of which the UAV is aware. In addition to the location information the situational awareness can also identify the specific type of an entity (eg. building, other aircraft etc). The type information can be used to define the magnitude of the potential field which each entity generates. This is necessary in order for the UAV to place a greater emphasis on avoiding collisions with inhabited entities over uninhabited entities. Based upon this, priorities can be defined using the guidelines below.

- At the highest level are the inhabited entities (ie. Other aircraft and buildings). As these entities are inhabited the UAV must place the highest priority on avoiding these entities over all others.
- At the next level are the entities which are uninhabited but which will cause substantial damage to the UAV. This category includes only terrain.
- The next level includes entities which have the potential to cause damage to the UAV. Adverse weather conditions fall under this category.
- At the lowest level are entities which will not cause damage to the UAV. This includes airspace boundaries.

These guidelines can then be used when defining the magnitude of the potential fields which each entity will generate. By following these guidelines the constraint of emphasising preventing loss of life or injury can be adhered to. It is important to note that the formalisation of guidelines of this nature has not previously been performed for UAV collision avoidance using potential field theory. In order to define the magnitudes the guidelines must be used in conjunction with simulated flights. The simulated flights expose the collision avoidance algorithms to a range of collision scenarios which enables the potential field magnitudes to be tuned. The tuning is performed until the UAV maintains a minimum threshold from the other entities for each of the testing scenarios. For the purposes of this research the safety threshold has been set at 10 seconds for a head on, aircraft-on-aircraft collision.

In addition to the magnitude of the potential fields it is necessary to also consider both the shape and the zone of influence. The situational awareness stores the shape information for all entities which are detected. This information can therefore be requested from the situational awareness and used to accurately model the potential fields of the entities.

The zone of influence determines at what distance the potential field generated by an entity begins to effect the UAV. Increasing the potential field results in the UAV performing avoidance manoeuvres sooner than if the zone of influence was smaller. It is desirable for the zones of influence of large entities to extend further than for smaller entities. A larger zone of influence enables the UAV to make a more gradual (and shorter) avoidance manoeuvre around the entity. Entities such as other aircraft, which are small, do not require as large a zone of influence as a large airspace boundary. As the situational awareness stores the shape of every entity it is possible to use this information to describe how ‘large’ an entity is.

This section has, up to this point, detailed how the potential field can be defined for all of the entities which must be avoided by the UAV. The final aspect to consider is the process of combining this information into a usable form. This requires the determination and combination of the potential field forces exerted upon the UAV by all of the entities in the airspace environment. This process requires firstly that the potential field force from each entity be determined. This force possesses both a direction (which points away from the entity) and a magnitude (which indicates how strongly the UAV is being pushed away). The magnitude of the potential field force is calculated using the field equations below:

$$|F| = \frac{PF_S}{D} \quad for\ \ D \le Z_I$$
$$|F| = 0 \quad for\ \ D > Z_I \tag{1}$$

In the equation above **|F|** is the magnitude of the potential field force. $\mathbf{PF_S}$ is the strength of the potential field (which is assigned based upon type). **D** is the distance between the entity and the UAV. $\mathbf{Z_I}$ is the zone of influence. The direction of the potential field is calculated as the normal (pointing outward) from the surface of the entity at the point closest to the UAV. Combined with the magnitude this gives the potential field force exerted upon the UAV by that entity.

The final task is to combine the potential field forces of the individual entities. The combination of the forces yields a single force vector which indicates the direction furthest away from the entities. This vector is calculated as the summation of the individual potential field force vectors from each entity (except those where the UAV is outside of the zone of influence).

The combined force vector provides a distilled representation of the collision scenario which is present. The force vector indicates how close the UAV is to a collision (by its magnitude) and also indicates the most direct path away from the collision. Although the potential fields have been combined into a single vector, this does still factor in specific issues such as prioritising avoiding inhabited entities. An inhabited entity will generate a stronger field than an uninhabited entity. Therefore the stronger potential field of the inhabited entity will be the dominant component of the combined force vector. This will in turn lead to the UAV placing a greater emphasis upon avoiding the inhabited entity. e combined force vector is then the input to the collision resolution algorithms.

Collision Resolution

The combined force vector provides the basic information required to determine the appropriate collision avoidance manoeuvre to perform. The magnitude of the force provides an indication of how near the UAV is to a collision. The higher the magnitude the closer the UAV is to a collision. The magnitude therefore also indicates the severity of the avoidance manoeuvres which the UAV must perform. The direction information from the force vector indicates the most direct path away from the collision scenario.

However, the UAV cannot necessarily fly the most direct path. The Civil Aviation Regulations define specific procedures which must be followed when avoiding a collision with another aircraft. The established convention is that aircraft in a head on collision scenario turn right to avoid the collision. A right hand turn may not necessarily be the most direct path away from the collision. However, as it is a legal requirement placed upon aircraft operating in civilian airspace the UAV will need to adhere to this. The collision avoidance system must therefore take this into account. It is important to note that this regulation only applies to aircraft which are flying in opposite directions (ie. One aircraft is not overtaking the other). For the situation of avoiding an aircraft which is closing in from the overtaking position the UAV is not limited in which direction it will take to avoid the collision. Therefore the UAV can take a more direct path away from the collision. The diagram below represents how the UAV will react, in terms of heading changes, for different collision scenarios.

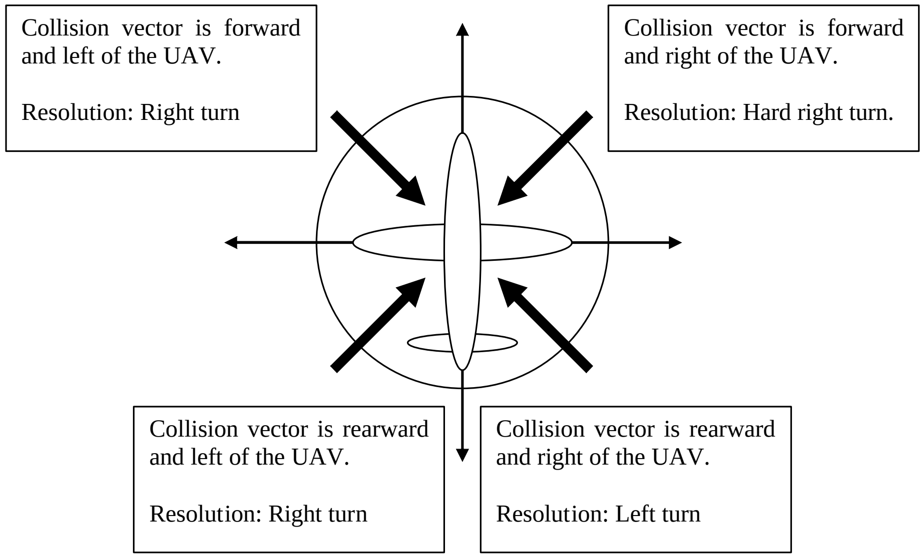


Fig. 8: Heading manoeuvres for collision resolution

Based upon the simulated testing which was conducted the following numerical values were assigned to the different types of turns which the UAV can perform to avoid a collision.

- Right turn – deflect current heading by 45°
- Hard right turn – deflect current heading by 135°
- Left turn – deflect current heading by -45°

The end result of employing this form of collision avoidance strategy is that the UAV will, in accordance with regulations, deflect its path to the right when faced with an oncoming aircraft. In the case of an overtaking aircraft, the UAV will manoeuvre out of the path of the overtaking aircraft in the most direct manner possible.

This far the discussion has focussed solely upon horizontal manoeuvres in response to a collision scenario. However, there is no reason to limit the UAV to only horizontal responses. The combined force vector provides sufficient information to also make a vertical manoeuvre in response to a collision scenario. The vertical (Z axis) component of the force vector indicates the location of the collision in the vertical axis in relation to the UAV (ie. Is the collision above or below the current UAV altitude?).

The magnitude of the force in the Z axis and the direction (up or down) therefore indicates whether the UAV should climb or descend and by how much. The equation below was determined empirically through simulations of various collision scenarios.

$$\Delta A = 2\,|F| \times sign\left(\vec{F}_Z\right) \tag{2}$$

In this equation the altitude deviation (**?A**) is calculated as double the combined force magnitude (|**F**|). The sign of the altitude deviation is determined based upon the Z component of the combined force ($\mathbf{F_Z}$). This equation will cause the UAV to climb or descend in order to move further away from the potential collision. The amount of altitude change executed will be proportional to the magnitude of the combined potential field force.

The combination of the altitude and heading avoidance manoeuvres affords the UAV a range of options for the avoidance of a collision. The novel approach which has been outlined enables the UAV to avoid a collision while also adhering to the applicable Civil Aviation Regulations. Testing results will be presented later in the paper. The next section presents the research conducted into the development of the on-board communications capability.

Natural Language Communications in Civilian Airspace

The final aspect to consider is the area of communications. Any aircraft operating in civilian airspace must communicate with a wide range of entities (eg. Air Traffic Control). Currently deployed UAVs rely upon a human operator to perform the communications required by the UAV. The human operator communicates either directly (to ATC etc) or alternatively the communications are relayed via the UAV. This places an additional burden upon the human operator who must act as a 'go-between' between the UAV and others.

It is therefore desirable to imbue the UAV with sufficient on-board intelligence in order for it to perform the required communications itself. This will facilitate a reduction in the operator workload and provide an increased capability for the UAV to integrate into civilian airspace. This section describes the development of a novel solution to the on-board communications problem based upon computing science techniques.

Overview of the Communications Problem

There are two main types of approaches to the problem of performing these communications. The first category of approaches use a proprietary digital transmission. Communications of this nature can be performed on-board the UAV without the need for human operator input. However, this type of communications mechanism can only be used to communicate with the UAV's operators. For ATC and others to communicate with the UAV they would require specific hardware. The adoption of a proprietary digital communications mechanism for civilian airspace UAV communications is therefore undesirable due to the large infrastructure changes which it would require.

The second category of approaches use an open communications standard, that is natural language (either spoken or written). This enables the UAV to communicate with a wide range of entities without the need for substantial infrastructure changes. An open communications standard is therefore preferable for a civilian airspace integrated UAV. Highly capable open communications approaches have been developed for both spoken and written natural language.

UAVs such as the Global Hawk perform their communications using spoken language [13]. However, the generation and interpretation of this speech is not performed by the on-board systems of the Global Hawk. Instead the Global Hawk acts as a relay to one of its human operators. The human operator communicates (via the Global Hawk) with Air Traffic Control (and others) and then issues updates to the Global Hawk. This provides the Global Hawk with the capability to communicate in the same manner as any other aircraft operating in civilian airspace. However, it places a higher burden upon the UAV's human operators especially during operations in congested airspace. Furthermore if the communications between the human operator and the UAV are blocked (intentionally or unintentionally) the UAV loses its ability to communicate. It is therefore undesirable for a civilian airspace integrated UAV to use a communications approach that is reliant upon a human operator.

However, written natural language based approaches have been developed which operate without the need of a human operator. The leading example of this is the natural language communications system developed by MIT [14, 15]. This approach by MIT enables a UAV to perform its own communications through a text based natural language interface. MIT have developed and applied these techniques to a UAV targeted towards defence applications. There are however issues which the MIT approach has not considered.

Firstly, the MIT approach has not given consideration to operations in civilian airspace. A UAV operating in civilian airspace will typically be in communication with a more diverse range of entities than a defence oriented UAV. Secondly, MIT have focussed solely upon using the natural language communications for issuing commands to the UAV. However, a UAV operating in civilian airspace can also use natural language to gain a heightened situational awareness of the operating environment.

This chapter will present a novel natural language based approach which addresses these issues. This approach will extend the previous approaches to provide support for civilian airspace applications. The new approach will enable a UAV to be issued both commands and updated situational awareness information. Finally this approach will cater for the differing communications from ATC, FIS, the UAV's operators and other aircraft. The novel aspects of this research are:

- Evaluation of natural language for civilian applications
- Adoption of natural language for situational awareness purposes in addition to mission planning
- Identification of a vocabulary suitable for communications with a wide range of entities of varying skill levels.

The proceeding section will discuss the details of the development of this new approach.

An Approach to On-board Communications

Communications to and from an aircraft during flight occur for a specific purpose. Identifying these purposes is an important first step in the development of a natural language based communications system as they provide a framework of the functionality which must be provided. A UAV operating in civilian airspace may be communicated with (or may communicate) for the following reasons.

- Communications to the UAV
    - From the UAV's operators
        - Updating mission plan
        - Updating situational awareness
    - From Air Traffic Control
        - Updating mission plan (eg. ordering a hold)
        - Updating situational awareness
    - From Flight Information Services
        - Updating situational awareness
    - From other aircraft

        - Updating situational awareness
- Communications from the UAV
    - To the UAV's operators
        - Advising of current status
    - To Air Traffic Control
        - Advising of current status
        - Requesting access to controlled airspace
    - To Flight Information Services
        - Advising of current status
    - To other aircraft
        - Advising of current status

For the purposes of this research consideration will only be given to the communications to the UAV. Communications from the UAV to others are beyond the scope of the research and will not be considered.

As can be seen from the list above the communications, although from a wide range of sources, fall into two basic categories. The first category encompasses all communications which are to enact changes in the mission plan. These changes could be to provide the UAV with a completely new mission plan or to request the UAV to perform a specific manoeuvre (eg. hold at a given location). The second category of communications includes all those which provide updated situational awareness to the UAV. For example the UAV could 'listen' to weather broadcasts and use this information to update the situational awareness which it is maintaining. Information may also come in which describes the intended flight path of other aircraft.

Based upon these categories the natural language communications system must provide the following functionality.

- Receive an updated mission plan (completely new or modified)
- Receive a manoeuvre command to be executed immediately (eg. hold at location)
- Receive updated situational awareness information (eg. location of adverse weather system)

These functional requirements provide the framework for the development of the natural language based communications system. They define the capabilities which must be provided. The next step in the development of the natural language based communications system is to define the vocabulary for the communications.

Civilian Airspace Vocabulary

An important component of using natural language for communications with the UAV is the vocabulary supported by the communications. The vocabulary in this context refers to the way in which commands and information updates are phrased. To date there has been no analysis of what vocabulary is appropriate for a UAV operating in civilian airspace. The vocabulary defines what terms the UAV will be capable of understanding and what meanings the UAV will assign to each term. When defining the vocabulary there are two main issues to consider: who will be talking to the UAV? And what applications will the UAV be being applied to. This section will answer these questions and in so doing define a suitable vocabulary for civilian airspace communications.

In the case of the first question the UAV will be talked to by its operators (which may have limited training in the case of commercially sold UAVs), Air Traffic Control, Flight Information Services and potentially other aircraft. This presents a substantial challenge from a communications perspective as the UAV will be receiving communications from a wide range of sources with varying skill levels. The operator of the UAV may not be aviation trained as the intent with this research is to reduce the need for highly trained operators. Therefore it cannot simply be assumed that using the standard civil aviation radio calls will be suitable. Furthermore the established radio calls are not designed for the simple commanding of common applications performed by civilian aircraft (eg. crop dusting). The vocabulary for the communications must therefore take this into account. A trade-off will be required between the need for a simple communications mechanism and the adherence to established radio procedures.

With respect to the second question the UAV will be applied to tasks common in the civilian airspace environment. For the purposes of this research a number of common tasks were selected as test cases. The chosen tasks were: crop dusting, skywriting and executing different holding patterns. These tasks were chosen as they are common in the civilian airspace environment and represent a diverse range of operational requirements. The communications vocabulary will need to cater for these tasks and reduce workload required by the operator to command the UAV to perform these tasks.

Based upon these considerations the vocabulary must both cater for a diverse range of skill levels in addition to a diverse range of tasks. The next step prior to defining the specific vocabulary for the communications is to consider the information which must be conveyed through the communications. In order to identify this information a number of examples of communications which the UAV may receive will be provided. The examples below have been defined based upon the tasks to which the UAV may be applied as well as other commands and information which may need to be communicated to the UAV.

- General Commands
  - Hold at **location**, **altitude** on **heading**
  - Circle at **location** at **altitude** and **turn direction**
- Task Commands
  - Skywrite **message** at **altitude** and **location**
  - Fly a grid pattern over **location** at **resolution**
- Situational Awareness Updates
  - Incoming aircraft currently at a **location 1** travelling to **location 2** at **altitude** and **airspeed**
  - Adverse weather system detected at **location** with **severity**

Considering these examples there are a number of elements common amongst the different commands and information updates. For all communications there are three key elements: the task to perform; the location to perform the task; and, extra parameters which define how to perform the task. In other words the communications all indicate what (ie. The task or information being updated), where (ie. Location to perform the task) and how (ie. Parameters for the performance of a task). Each of these elements (what, where and how) will be considered in turn and the vocabulary for each established.

The 'What' Element

Considering first the describing of what the UAV is required to do or what information is being updated. As previously stated the vocabulary used must be readily understandable across a range of skill levels. In order to make the communications more accessible the decision was made to adopt a very simple and descriptive vocabulary for the commands but one which remains comprehendible to aviation trained personnel. The list below shows common commands and information updates which the UAV may receive and the corresponding descriptive vocabulary. It is important to note that this is not an exhaustive list. It is a small subset of the range of commands which could be implemented. This reduced list provides a broad representative sample of communications which the UAV may receive.

- Commands
    - Takeoff from a specific location
        - Vocabulary**: Takeoff**
    - Fly to a specific location
        - Vocabulary**: Fly to**
    - Land at a specific location
        - Vocabulary**: Land at**
    - Circle a given location
        - Vocabulary**: Circle**
    - Execute a grid search (ie. Fly a grid pattern)
        - Vocabulary**: Execute a grid search**
    - Hold at a specific location
        - Vocabulary**: Hold at**
    - Fly a figure eight pattern
        - Vocabulary**: Perform figure eight**
    - Skywrite a specific message
        - Vocabulary**: Skywrite**
- Information Updates
    - Aircraft movement update
        - Vocabulary**: Traffic**
    - Adverse weather detected
        - Vocabulary**: Be advised of**

The vocabulary which has been identified for each of these communications is clear and unambiguous, both of which are important attributes for an on-board communications system. Furthermore, the clarity of the vocabulary enables it to be comprehended by persons with a range of different skill levels.

The 'Where' Element

The second element of the vocabulary to consider is the 'where' element. This defines either where an action is to be performed or where in the world the information update refers to. Traditionally when working with a UAV locations would be specified as a latitude, longitude and altitude. This approach is precise and is perfectly valid. However, it is not intuitive and it is not how locations are typically described for civilian airspace operations. For operations in civilian airspace it is more common to specific a location in terms of its name (eg. Brisbane airport) or its displacement relative to a known location (eg. 50 nautical miles south west of Caboolture). Location's specified by Air Traffic Control will be given using one of these manners. Therefore, the vocabulary must take this into account and must accommodate for the varied manner in which location information (ie. The ‘where’ element) may be communicated to the UAV.

Essentially there are two ways (excluding specifying latitude, longitude and altitude) in which the location information can be specified: absolute or relative. Specifying an absolute location means that the UAV is told the name of where it is to perform the task or where in the world the information update refers to. A relative location is comprised of both an absolute location (known as the reference) and a displacement relative to that location (known as the offset). Absolute locations can be readily accommodated through the usage of a location database. This database would store the names of various locations and their corresponding coordinates (ie. Latitude, longitude and altitude).

The list of locations would need to contain all those which the UAV may need during its mission. In order to define the contents of this list it is necessary to consider what locations a human pilot would need to be aware of during flight. For a human pilot the locations which they will fly with reference to will be a mix of established navigational points (eg. navigational beacons and airports) and custom locations (eg. a specific mountain). A UAV will therefore be required to possess a similar level of knowledge. There are freely available databases of all of the navigation aids existing within the world. These lists define the name, type and location of the navigation aid. These lists can in turn be used to populate the location database which the UAV will use in determining where a specific named location is. Custom locations such as mountains or the surveyed coordinates of a farmer’s crops can be added to the database dependent on the specific mission. When presented with a named location the UAV will then search the database to determine the latitude, longitude and altitude of the given location.

This location database can be used in part to process any relative locations which the UAV is given. The UAV will use the location database to determine the latitude, longitude and altitude of the reference point. After this the offset information must be interpreted in order to determine the specific location which the UAV has been given. The offsets in this case will be given in the form of “[**distance**] [**direction**] of …”. For example, “[50 miles] [south west] of …”. Considering the distance first, dependent upon who the communications have come from (ATC, human operator etc) the distance may be specified in different units. It is prudent therefore for the UAV to comprehend distances specified in the common units of nautical miles, miles and kilometres. There is no need for smaller units as it is unrealistic that the UAV would be asked, for example, to fly to 300 metres south of Brisbane. The final component of the offset is the direction. These directions are commonly specified using the terminology north, south, north east etc. The UAV will, in turn, be required to comprehend the common direction terms. The directions which the UAV will need to understand are shown in the figure below.

This section has defined how location information (ie. The ‘where’ element) can be communicated to the UAV in a manner which is both simplistic and consistent with established procedures.

The ‘How’ Element

The final element to consider is the ‘how’ element. This describes the manner in which the UAV is to execute the given or command or provides additional details for the information update. The list below shows the communications which are being used as the demonstrate set. For each of the communications the ‘how’ information is identified.

- Commands
    - Takeoff from a specific location
        - How Information**: None**
    - Fly to a specific location
        - How Information**: Altitude**
    - Land at a specific location
        - How Information**: None**
    - Circle a given location
        - How Information**: Altitude, direction, circle radius and number of circuits**
    - Execute a grid search (ie. Fly a grid pattern)
        - How Information**: Altitude, resolution, length and width of search area**
    - Hold at a specific location
        - How Information**: Altitude and heading**
    - Fly a figure eight pattern
        - How Information**: Direction (of first loop), altitude, radius and heading**
    - Skywrite a specific message
        - How Information**: Message, altitude and font**
- Information Updates
    - Aircraft movement update
        - How Information**: Aircraft ID, altitude and speed**
    - Adverse weather detected
        - How Information**: Type, severity and altitude**

The 'how' information which will be included in the majority of communications contains a number of common elements. These common elements are:

- Distance (altitude, resolution, radius and area dimensions)
- Direction (eg. clockwise)
- General numerical information (number of circuits and heading)
- General information (message to skywrite, aircraft ID and weather details)

It is necessary therefore to consider the vocabulary which will be used to communicate these elements to the UAV. In the case of distances the same vocabulary used for specifying relative location can be applied for consistency. The distances will therefore be comprised of both a numerical value and then the units for the numerical value. For example, distances can be given as '50 nautical miles'. However, in this case additional units will need to be supported dependent upon the parameter. For example altitudes are typically given in feet or flight levels (for altitudes above 11, 000 feet). The units which will need to be supported are listed below based upon the type of parameter.

- Altitude
    - Units: Metres, feet and flight level
- Resolution, radius and area dimensions
    - Units: Kilometres, miles and nautical miles

The remaining elements (direction, general numerical and general information) require the specification of only a single parameter (eg. a heading) rather than the two parameters (value and units) for distance measurements. Directions will be specified using the standard descriptions of clockwise, anti-clockwise, right and left. General numerical information would simply be communicated as the number (eg. 10 would indicate a heading of 10° or that 10 circuits are required, dependent upon the specific communications).

Finally the general information elements encompass all of the remaining non-numerical information such as the message to skywrite, the aircraft ID and the detected weather details. The message to skywrite will naturally be given simply as the text for the aircraft to write. In addition to the text the UAV will need to be provided with a font which will describe how the UAV is to write the characters which comprise the text. Aircraft ID information will be incorporated into the situational awareness in order for the UAV to be aware of the identity of aircraft which have been detected. Finally the communications will need to indicate the type and intensity of the weather system being reported. It is logical to use the common and unambiguous terms of cloud and storm to describe the different weather types. Similarly, the terms minor, moderate and heavy/severe can be used to describe the intensity of the weather system.

This is the first time that specific consideration has been given to defining a vocabulary suitable for natural language communications with a civilian airspace integrated UAV. The vocabulary which has been defined caters for the differing needs of Air Traffic Control (ie. The need to command holding patterns) and the UAV's operators (ie. The need to command the UAV to perform an assigned task). Furthermore, the vocabulary, through being clear and concise, can accommodate a range of skill levels.

Simulation Environment

Testing the algorithms presented in this paper required the usage of the QUT developed simulation environment known as the Aircraft Simulation And Testing Environment (ASATE) . ASATE provides a real-time simulation environment for an aircraft. In this case a Cessna 172 was chosen as it provides a proven stable platform.

The flight and sensor model components of ASATE are implemented in Matlab Simulink using the AeroSim blockset [16]. The AeroSim blockset provides a full nonlinear, six degrees of freedom simulation of an aircraft. The AeroSim blockset was chosen due to its ability to be used in a Simulink model, its support for standard aircraft formats (FlightGear model format) and its low cost (free for academic use). The flight and sensor models are executed in real-time on an Intel Pentium II 233 MHz processor with 64 MB RAM. The real time execution is achieved through the xPC Target component of Matlab Simulink. xPC Target compiles a Simulink model and executes it in real time on a second (target) computer.

The flight and sensor models (target computer) are connected via RS232 to a computer (host) running Microsoft Windows which is used to control (eg. change wind conditions) and to monitor the simulation. The Microsoft Windows computer publishes the flight information (location and orientation) via the World Wide Web for remote monitoring of simulations.

The IMPP is executed on a Pentium II 233 MHz processor with 64 MB RAM under the QNX Real Time Operating System (RTOS). QNX is a hard real-time operating system chosen for its high reliability. A RS232 link connects the flight hardware running the IMPP to the target computer running the flight and sensor models. This link is used to pass flight data to the IMPP and to pass control surface deflections to the flight and sensor models. The architecture of ASATE is shown in the figure below:

Aircraft Simulation And Testing Environment v4

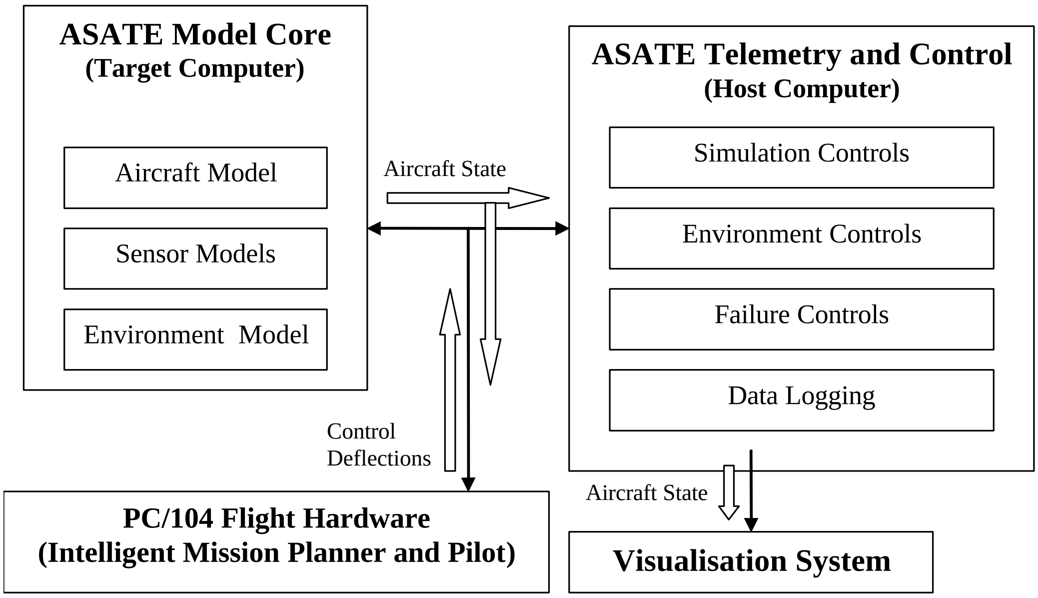


Fig. 9: ASATE System Architecture

The ASATE system can simulate a range of aircraft and has built-in support (via the AeroSim blockset) for any aircraft models designed for the open source flight simulation system, FlightGear. ASATE can be connected to either FlightGear or X-Plane for a 3D visual display of the aircraft's current position and attitude. ASATE possesses the capability to simulate the presence of other aircraft as well as various weather conditions (storm fronts, etc.).

The IMPP logs all flight (position, attitude etc) and algorithm (completion times) parameters in order to assess both the performance of the simulated aircraft and the mission planning algorithms. The testing regimes conducted are examined in greater detail in the proceeding section.

Testing Regimes

Three testing regimes were designed in order to evaluate the performance of the algorithms described within this paper. The aim of the testing regimes was to assess the ability of the outlined algorithms to meet the research objectives. The testing regimes required the Intelligent Mission Planner and Pilot (IMPP) to plan (for testing regimes 1 and 2 only) and then fly a given mission. All testing regimes were performed under the QNX Real Time Operating System (RTOS) using the ASATE simulation environment. The mission planning itself was performed under Microsoft Windows 2000 Professional on a Pentium 4 1.6 GHz processor computer with 256 MB of RAM. The testing was broken down into four testing regimes as shown in the table below.

Table 1. Testing regime summary

Testing Regime	Aspects Tested
1 – Plan Generation Time	Examined the time to generate a mission plan for (horizontal) resolutions of 5nm, 2nm and 1nm.
2 – In-Flight Performance	Compares the results (flight time, distance flown and fuel consumed) from simulated flights conducted at resolutions of 5nm, 2nm and 1nm.
3 – Collision Avoidance	Examines the performance of the collision avoidance algorithms for a number of randomly generated scenarios.

All testing was conducted using real world airspace and terrain information from South East Queensland, Australia, centred around Brisbane Airport (YBBN). The mission plan used in the first and second testing regimes required the aircraft to fly through a complex region of airspace over a total distance of 370nm. A picture of this testing scenario, from the software developed for the research, is shown in the image below.

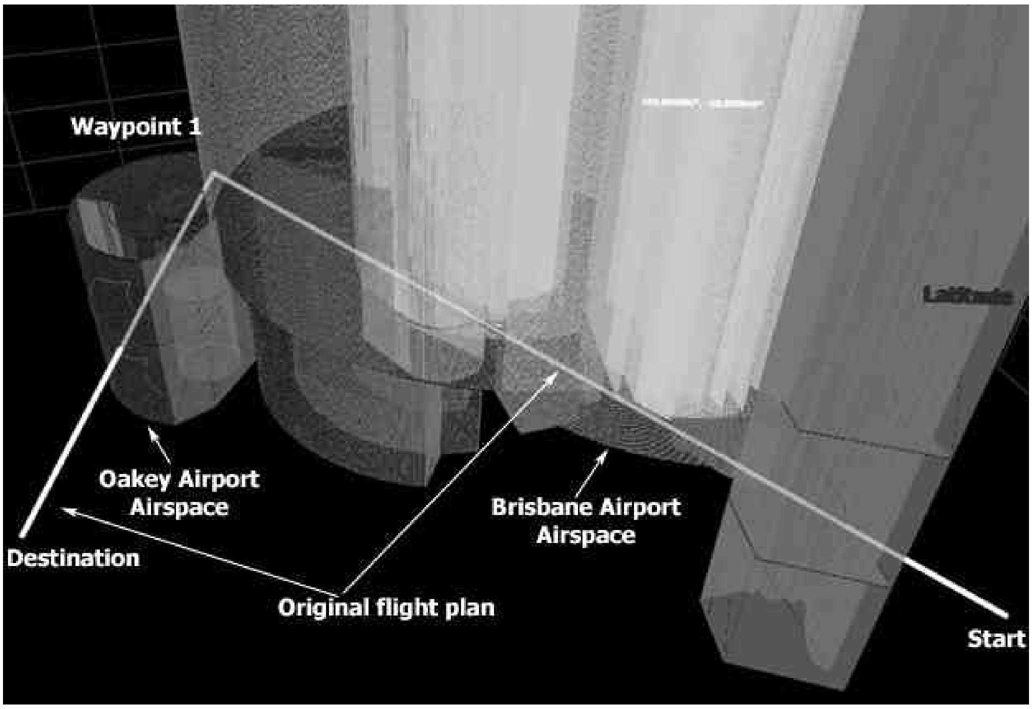


Fig. 10: Original Invalid Mission Plan

Test Results

This section presents the results obtained from the three testing regimes. The test results have been broken according to their regime as indicated below:

- Testing Regime 1 – Plan Generation Time
- Testing Regime 2 – In-Flight Performance
- Testing Regime 3 – Collision Avoidance

Testing Regime 1 – Planning Times

Testing Regime 1 examined the planning times for each combination of mission planning (C-Space or Octree) and wave mapping (distance, effort or fuel) algorithms. The table below shows the times (in seconds) taken to generate a mission plan for the scenario shown in ***Table 2***.

Table 2: Plan Generation Times

Planning Algorithm	Horizontal Resolution		
	5 nautical miles	2 nautical miles	1 nautical mile
Distance Wave – C-Space	**49.16 s**	**233.24 s**	**1013.72 s**
Distance Wave – Octree	49.72 s	235.38 s	1101.16 s
Effort Wave – C-Space	49.17 s	234.14 s	1015.17 s
Effort Wave – Octree	49.80 s	236.19 s	1089.56 s
Fuel Wave – C-Space	51.00 s	243.53 s	1067.37 s
Fuel Wave – Octree	<u>51.58 s</u>	<u>243.74 s</u>	<u>1112.39 s</u>

The fastest algorithm for each resolution has been highlighted in bold. The slowest algorithm has been underlined. A graphical representation of the results is provided in the figures below.

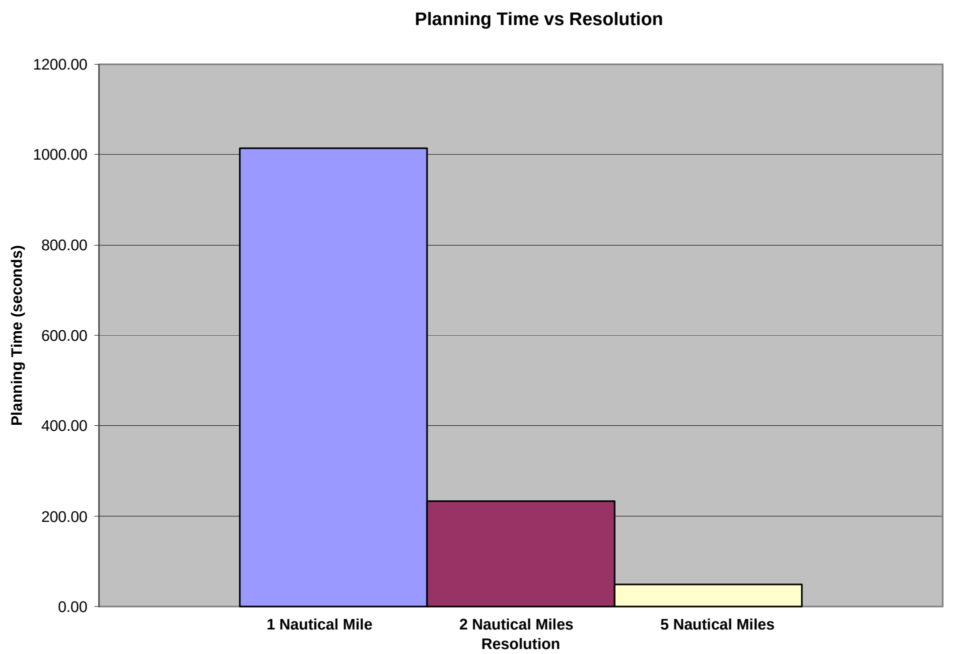


Fig. 11: Graph of planning time against resolution for the C-Space (Distance Wave) algorithm

A number of conclusions can immediately be drawn from these results. As expected the resolution has a significant impact upon the planning time. Reducing the horizontal resolution from 2 nm to 1 nm increases the number of cubes by a factor of four (from horizontal resolution of 2 nm x 2 nm to 1 nm x 1 nm, ie. Factor of four). This results in a corresponding increase in planning time by a similar factor.

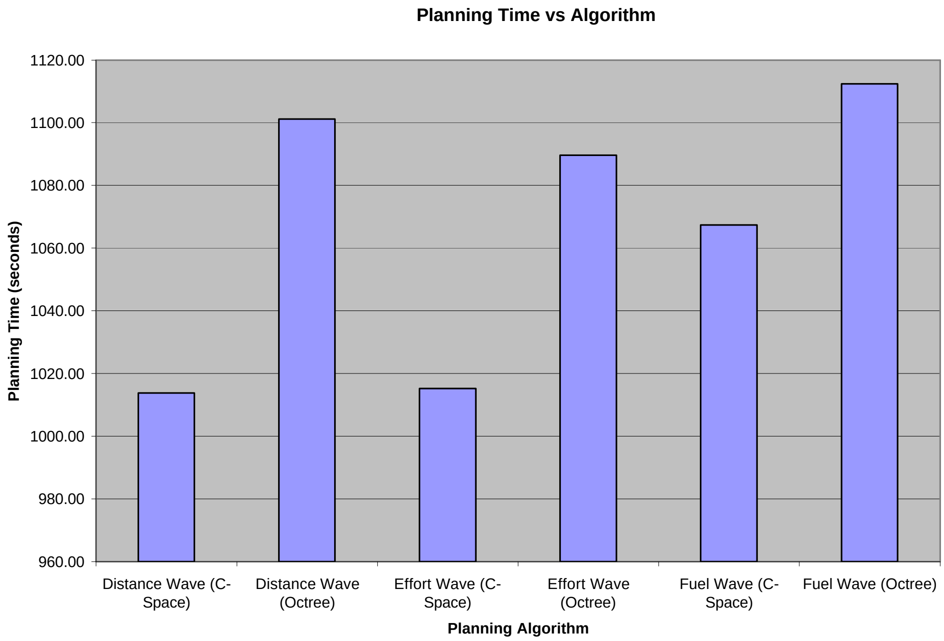


Fig. 12: Graph of planning time against planning algorithm for a resolution of 1nm

As shown in the figure above, the Octree algorithms are consistently slower than their C-Space counterparts. This is expected as the C-Space must be constructed prior to the Octree representation being constructed. The added overhead from the construction, and navigation (ie. Locating and moving to a new Octree node), of the Octree representation overshadows any performance gains achieved by skipping large sections of free-space. The relative speeds of the different algorithms can also be clearly seen. The fuel wave algorithms are consistently the slowest of the algorithms, this is due to their greater complexity. The greater complexity of the fuel wave algorithm results from its usage of both a flight and engine model which require multiple calculations to be performed to propagate the fuel wave.

The distance wave algorithms are consistently the fastest of the algorithms. This is expected as they are computationally the simplest of the algorithms. The distance wave algorithms only calculate the distance between cubes and do not use any dynamic models. The effort wave algorithms add a small extra step on top of the distance wave algorithms. Consequently, the planning times of the distance and effort wave algorithms are similar. Based solely upon planning times the Distance Wave – C-Space algorithm provides the best performance. However, there are other metrics to consider in identifying the optimal algorithm for mission planning in civilian airspace.

Testing Regime 2 – In-Flight Performance

The second testing regime analysed the flight time and distance to fly the generated mission plan. This provides verification of the previous efficiency results and an assessment of the quality of the generated plan. If large deviations are observed between the generated plan and flown plan then it indicates that the mission planner did not produce a plan within the aircraft's capabilities. The flight time provides a measure of the efficiency of the generated plan. The results were obtained using the real time simulation environment, ASATE. Both the flight time (in hours, minutes and seconds), the flown distance (in percentage overshoot from the original path) and fuel usage are shown in the table below.

Table 3: Simulated Flight Results

Planning Algorithm	Horizontal Resolution			Metric
	5 nautical miles	2 nautical miles	1 nautical mile	
Distance Wave – C-Space	3:40:09	3:36:10	3:14:32	Flight Time
	24.2 %	22.6 %	9.9 %	Distance Overshoot
	208.40 lb	205.38 lb	183.95 lb	Fuel Consumed
Distance Wave – Octree	3:41:13	3:39:6	3:16:19	Flight Time
	25.9 %	22.4 %	9.6 %	Distance Overshoot
	210.67 lb	207.04 lb	185.45 lb	Fuel Consumed
Effort Wave – C-Space	3:40:06	3:36:06	3:14:15	Flight Time
	23.3 %	22.2 %	9.3 %	Distance Overshoot
	208.36 lb	205.25 lb	183.80 lb	Fuel Consumed
Effort Wave – Octree	3:41:12	3:39:39	3:15:16	Flight Time
	24.6 %	22.6 %	9.5 %	Distance Overshoot
	210.65 lb	207.37 lb	184.84 lb	Fuel Consumed
Fuel Wave – C-Space	3:46:53	3:38:46	3:10:38	Flight Time
	26.5 %	18.8%	8.9 %	Distance Overshoot
	214.07 lb	203.73 lb	182.65 lb	Fuel Consumed
Fuel Wave – Octree	3:48:15	3:45:37	3:12:40	Flight Time
	27.3 %	23.6 %	10.4 %	Distance Overshoot
	215.35 lb	211.75 lb	184.44 lb	Fuel Consumed

These results demonstrate that the general trends of finer resolutions, and C-Space algorithms providing better performance have held true as shown in ***Fig. 13*** and ***Fig. 14***.

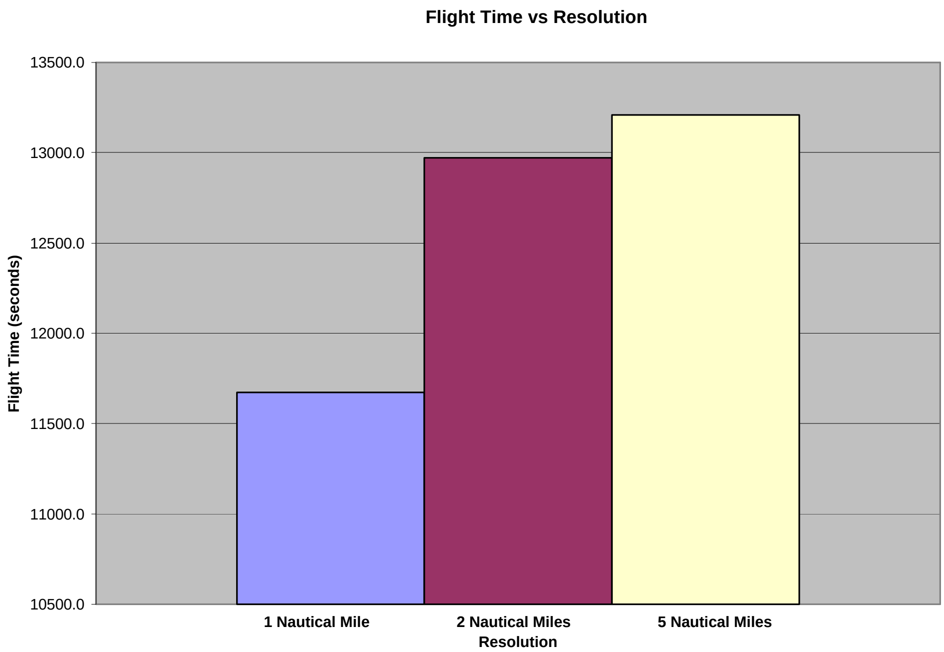


Fig. 13: Graph of flight time against resolution for C-Space (Distance Wave) algorithm

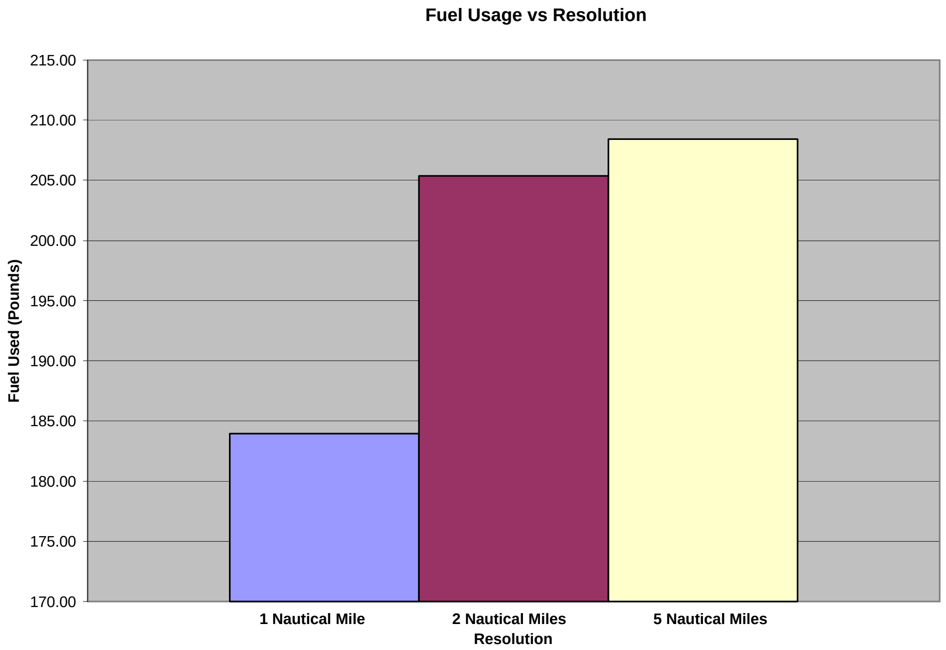


Fig. 14: Graph of fuel usage against resolution for C-Space (Distance Wave) algorithm

The key differences between the algorithms become clear upon an examination of the flight time and fuel usage. When these factors are examined the distance wave does not yield the best performance. In fact it provides the worst performance. This is because the distance wave looks only for the shortest path, it does not consider how long it may take to fly the path. Consequently, although the path's found using the distance wave are shorter because they have not factored in aircraft performance they take longer to fly.

As shown in ***Fig. 15*** and ***Fig. 16*** the fuel wave provides the best performance in terms of both flight time and fuel usage for this test case. The effort wave provides improved performance over the distance wave, however it does not perform as well as the fuel wave. The better performance of the fuel wave algorithm occurs even in cases where the path flown is longer than that of the other algorithms. However, although the path flown is longer it is more efficient providing benefits to time and fuel efficiency. These results show that the fuel wave mapping in C-Space is the most efficient of the algorithms, in terms of in flight performance. This contradicts the previous findings where the fuel wave was typically the least efficient algorithm. The reason for this contradiction is that the fuel wave algorithm has been designed to generate paths which, though they may be longer than for the distance or effort wave, are more fuel efficient.

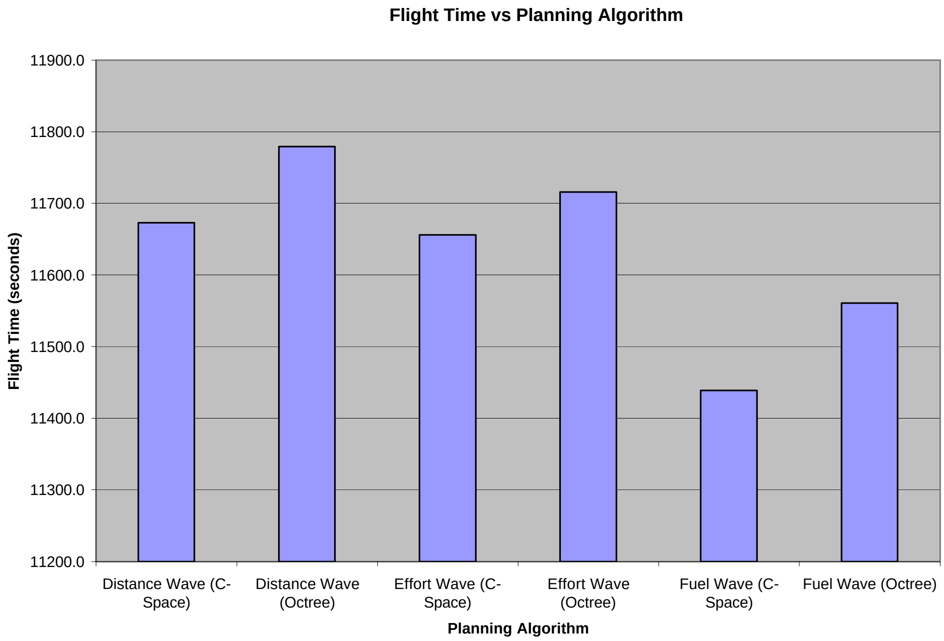


Fig. 15: Graph of flight time against planning algorithm for a resolution of 1nm

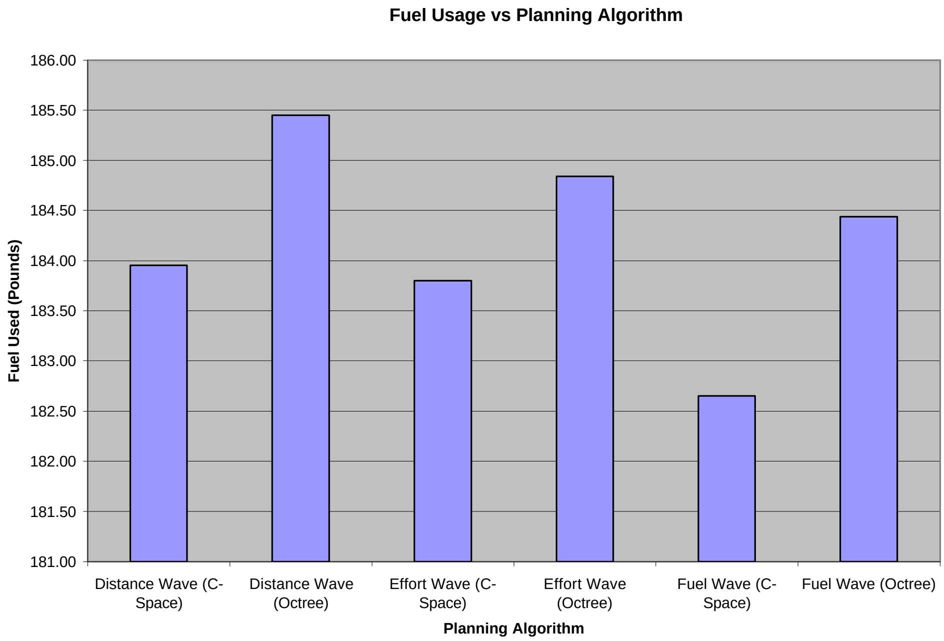


Fig. 16: Graph of fuel usage against planning algorithm for a resolution of 1nm

The results also show that while the effort wave yields faster flight times than the distance wave it is not faster than the fuel wave. This is a result of the effort wave using a very coarse model of the speed of the aircraft. As the fuel wave algorithm uses a more accurate, but slower, model of the aircraft's dynamics it is able to achieve better in-flight performance.

Visual inspection of the path flown by the aircraft indicates that the aircraft is readily able to fly the generated paths. There were no cases where the aircraft needed to loop around to reach a waypoint. This indicates the generated path did not exceed the limits of the aircraft. However, future research will be conducted to examine other factors such as the turn/climb rates required by the aircraft to gain a more detailed estimate of how achievable the mission plans are. The behaviour of the aircraft can be seen in the figures below which shows the original invalid desired mission plan, the planned path and the flown path. Note that in these figures the Class C and Class D airspace has been removed for clarity. The figures shown were generated using the distance wave (C-Space) planning algorithm operating at a resolution of 1 nm.

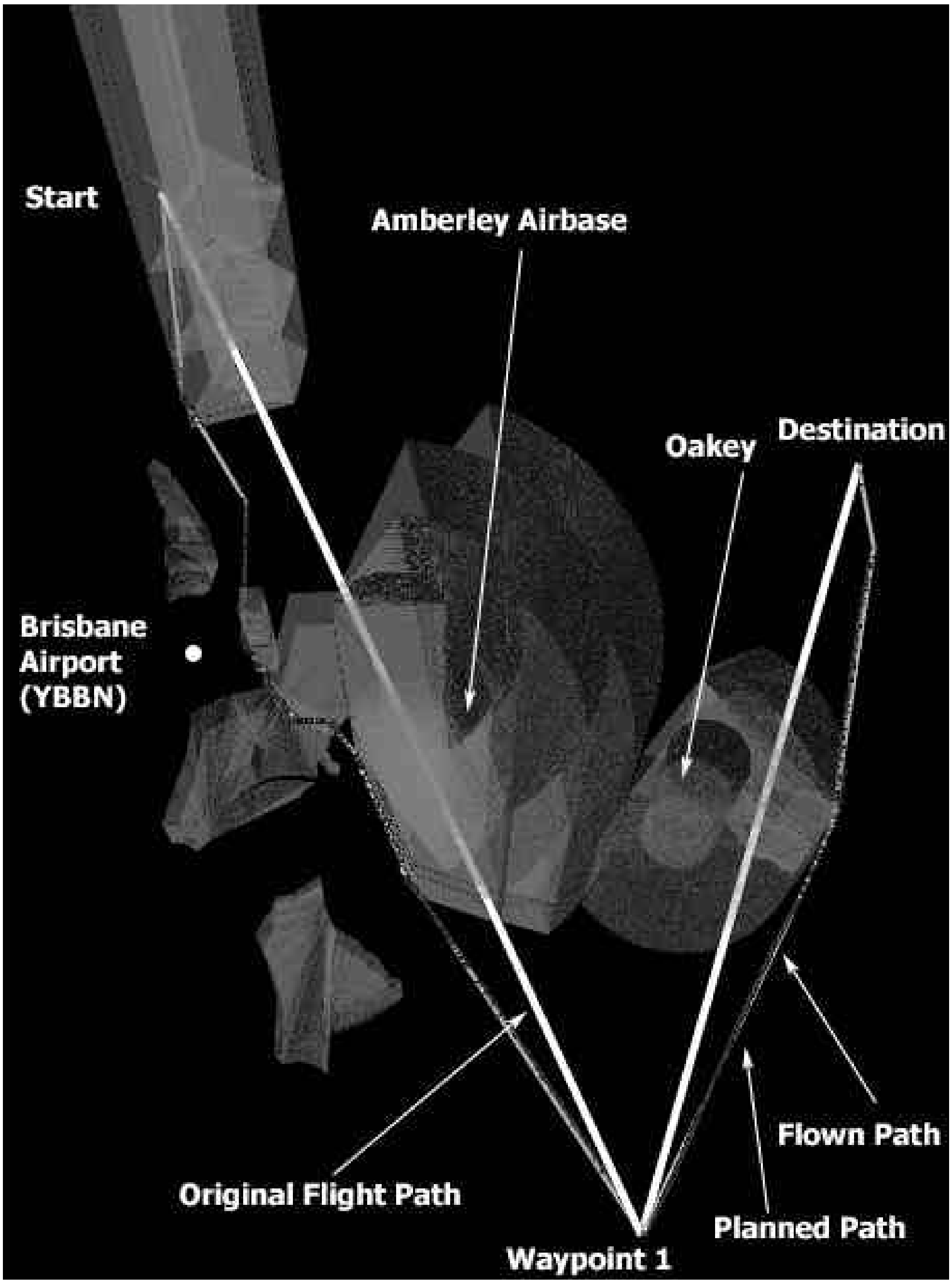


Fig. 17: Plan View of Mission Planning Results

This figure shows that the aircraft has found a small gap above a region of controlled airspace. The path found by the mission planner requires minimal altitude changes except where required. This is inline with the behaviour of a human pilot operating under the same conditions. The figure shows that the aircraft performs the planned ascents and descents faster than the planned path requires. This results from the design of the aircraft flight controllers. The controllers work to capture the next required altitude as soon as possible. Consequently the aircraft is capturing the required altitude sooner than intended. This is most obvious where large altitude change occurs. This has the potential to cause the aircraft to enter into controlled airspace or collide with another obstacle. This area can be addressed by modifying the flight controllers to fly precisely along the path laid out in the mission plan rather than attempting to capture the desired altitude immediately.

Throughout the flights the aircraft did not collide with any obstacles within the world as can be seen from the figure. This was verified based upon the flight data collected throughout the simulated flight. This fact combined with the proven ability of the aircraft to fly all of the given plans demonstrates that any of the planning algorithms can meet the research objectives.

Although the in flight performance of the algorithms was found to be good, the planning times are excessive. The majority of the planning time is occupied by constructing the C-Space (ie. Marking which cubes are free and which are occupied) and the propagation of the cost waves. These two process involve numerous complex calculations and as such are ideal candidates for optimisation.

Firstly, considering the construction of the C-Space, performance gains may be achievable through precomputation of the C-Space. The C-Space representations for airspace, terrain and buildings will not change over the course of a mission. This makes it possible to precompute and store the C-space representations for each entity. The precomputed representations can be imported into the digital world when needed rather than being generated on-board.

In order to test this theory a library of precomputed C-Space was constructed at varying resolutions. The mission planning algorithms were modified so that rather than constructing the C-Space online the C-Space representations of the entities were retrieved from the library. The table below shows the sizes of the C-Space libraries for a range of different resolutions.

Table 4: C-Space library sizes

Resolution (Nautical Miles)	Library Size (Megabytes)
1	87.8
2	23.2
5	4.4

The precomputed C-Space libraries are sufficiently small enough to be readily stored on-board a UAV. The availability of affordable and high capacity solid state storage devices (eg. Compact Flash cards) makes the storage of these precomputed libraries on-board a UAV readily achievable.

In addition to modifying the C-Space construction, changes were also made to the propagation of the different cost waves. In the previous results the cubes/nodes were marked with their true distance from the goal (for the distance and effort waves). Propagating the distance wave therefore requires that the equation shown below be used numerous times.

$$D = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \ \{\text{m}\} \qquad (3)$$

Logically, if this equation is being called a multiple times any optimisations made to the equation will speed the entire path planning process. It is in fact not necessary for the true distance to be propagated, instead the square of the distance can be used. The square of the distance still provides an indication of how far a cube is from the goal. However, it removes the need to perform a square root operation for every calculation which has the potential to improve the mission planning performance.

These optimisations were implemented into the Intelligent Mission Planner and Pilot and were subjected to the same testing scenario as the previous results. As the C-Space class of algorithms yielded the best performance previously (in terms of planning time and efficiency) the tests focussed solely upon the C-Space algorithms. This decision was driven by the intent to identify the best performing algorithm. The performance of the optimised mission planning algorithms (relative to the previous algorithms) are shown in the tables below.

Table 5: Non-Optimised planning times

Planning Algorithm	Horizontal Resolution		
	5 nautical miles	2 nautical miles	1 nautical mile
Distance Wave – C-Space	49.16 s	233.24 s	1013.72 s
Effort Wave – C-Space	49.17 s	234.14 s	1015.17 s
Fuel Wave – C-Space	51.00 s	243.53 s	1067.37 s

Table 6: Optimised planning times

Planning Algorithm	Horizontal Resolution		
	5 nautical miles	2 nautical miles	1 nautical mile
Distance Wave – C-Space	8.58 s	13.25 s	144.08 s
Effort Wave – C-Space	8.63 s	13.67 s	146.89 s
Fuel Wave – C-Space	17.80 s	69.50 s	378.32 s

As can be seen from these results the implemented optimisations provide a substantial improvement in the performance. Performance improvements between 60% to 80% were achieved for the different combinations of algorithms and resolutions. The addition of using the precomputed C-Space information and modification of the distance and effort wave propagation has clearly had a dramatic impact upon the performance. Distance and effort wave based mission plans can be performed at a 1 nautical mile resolution in under 2.5 minutes, compared to over 16 minutes previously. Fuel wave plans can be produced in under 6.5 minutes at 1 nautical mile resolution, compared to the previous time of over 17 minutes.

Testing Regime 3 – Collision Avoidance

This testing regime focussed solely upon the avoidance of other aircraft. The purpose of this testing regime was to verify the performance of the collision avoidance algorithms for other aircraft. For this regime the UAV flew a continuous circuit over a random location. Multiple random flight paths were generated for the other air traffic in the environment. These flight paths were generated such that they would intersect with the flight path of the UAV. The generated flight paths intersect the UAV’s flight at random headings and altitudes. The flights paths generated assume that the other aircraft will not perform any collision avoidance manoeuvres. This represents the worst case scenario where the UAV must avoid a collision without knowing the intent of the other aircraft.

Through the Aircraft Simulation And Testing Environment (ASATE) the UAV flew 10 campaigns. Each campaign exposed the UAV to a new randomly generated set of flight paths. For each campaign the proximity of the UAV to the other aircraft was recorded. This is the primary performance metric for the collision avoidance system. The table below shows the results for the testing campaign.

Table 7: Collision Avoidance Results

Testing Campaign	Closest Distance (ft)
1	5500
2	4000
3	5700
4	5500
5	4900
6	3900
7	4300
8	5800
9	3900
10	5600
Average	4900
Standard Deviation	800

Based upon these testing results the UAV maintains an average minimum separation of 4900 feet (with a standard deviation of 800 feet). This corresponds to an average of 12 seconds for a head on collision. This is within the safety margins defined for the collision avoidance system. It is important to note that these results have been obtained for the case of a strongly adverse collision scenario. In this scenario the UAV is faced with multiple aircraft flying a constantly changing trajectory. Consequently, this presents the UAV with a near worst case scenario. Even in the presence of this challenging scenario the UAV has maintained the minimum level of separation required.

Discussion and Conclusion

New trends are emerging in the field of uninhabited airborne vehicles. These trends are based around increasing the on-board intelligence of UAVs in order to more fully exploit their capabilities. This paper has focussed upon increasing the on-board intelligence in the areas of mission planning and piloting based upon a novel multidisciplinary approach.

The unique approach presented in this paper has been proven to satisfy the research objectives through simulated testing. These results have demonstrated that the approach outlined can be used provide a UAV with the onboard capability to plan and to execute its own missions. The mission plans can be optimised based upon distance travelled, time required or fuel consumed. The optimal algorithm was identified to be the Fuel Wave (C-Space) algorithm operating at a resolution of 1 nautical mile. This algorithm provided an acceptable planning time and high in-flight performance. Furthermore, when planning a mission the aircraft is given greater freedom of movement than previous approaches. This novel multidisciplinary algorithm therefore meets the established research objectives. Once a mission has been planned the UAV can fly the mission, avoiding collisions with other aircraft en-route. Finally, during the flight the UAV can be communicated with directly through the use of natural language.

The novel multidisciplinary approach uses a combination of algorithms from the 3D graphics, robotics and computer science field. 3D graphics routines are used to construct and maintain situational awareness of the operating environment. The situational awareness provides the foundation on which higher level actions such as mission planning can be based. The mission planning itself is achieved through algorithms drawn from the robotics field. These algorithms were implemented and tested using a scenario constructed from real world data. Optimisations were then made to the algorithms in order to enhance the performance. The collision avoidance algorithms were inspired by techniques frequently used within the robotics field. Finally, the computer science field provided the backbone for the natural language based communications.

The novel multidisciplinary approach presented in this paper enables a UAV to plan and execute its own missions. Human operators are only required to provide the UAV with its mission objectives and then the on-board systems will takeover. This therefore provides benefits in terms of increasing the on-board intelligence while also reducing the operator workload. The capabilities of the UAV can be more fully exploited as the UAV can re-plan its mission during a flight based upon a change in the environment (eg. Storm front, directive from Air Traffic Control etc). This in turn provides us with UAVs which are more capable and that require less ‘babysitting’ from their human operators.

The novel research presented here represents one step towards highly intelligent UAV platforms

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