Potential Functions for En-Route Air Traffic Management and Flight Planning

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Abstract:

This paper proposes an object oriented methodology and use of potential functions for efficient solutions to en-route air traffic management and flight planning in a complex airspace system. In this object oriented methodology, different objects, e.g., weather, Special Use Airspace (SUA), traffic, etc., and their attributes, e.g., weather orientation, SUA geometry, traffic density, etc., are defined by using potential functions. The interaction of the object of interest (host aircraft) and environment is modeled through an artificial potential field, whose interaction model is simple and well defined. This helps in framing a simple algorithm and produces efficient and complete solutions. The path planning and conflict detection and resolution algorithms developed for this methodology provide efficient solutions in the comprehensively defined environment model in which uncertainty is very limited. The algorithms have been implemented in a low-level flight planner. Results to validate the operation of the algorithm and feasibility of the methodology will be provided and a functional layout of the flight planner is provided.

Introduction:

The Distributed Air/Ground – Traffic Management (DAG-TM) concept [*8*] for Free Flight has been well defined for all phases of flight. The free flight in en-route airspace not only represents the largest portion of flight but also the most critical component to maintain continuous traffic flow in the National Airspace System (NAS). The DAG-TM Concept Elements (CE) 5, 6 and 7 dealing with en-route airspace has provided clear definition of the concept, requirements and solutions [*3,5,6,7*]. The problem in en-route air traffic has been believed to be issuance of inefficient resolution and difficulties in conformance to traffic flow management (TFM) constraints. The root cause for these problems has been identified as uncertainty in the trajectory information, lack of user preference and workload limitations [*5,6,7*]. The DAG-TM concept element 5, 6 and 7 proposes various efficient solutions by using decision support tools and collaboration.

The decision support tools being developed for these problems should consider many factors that influence a problem and bring out efficient solutions that do not result in further complexity. One approach this paper suggests is an object oriented approach. Problems in a complex system like airspace can be best solved if an object oriented approach is applied. In this paper, potential functions are used which provide a convenient way to do this. Artificial potential fields have been used extensively in both robotics and air traffic [*11,12,13,14,15,16*]. Dynamic force fields have also been used, which are similar to potential functions and they carry more information than potential functions [*10*].

A methodology, named as potential functions methodology, will be introduced to use the potential functions to model the airspace in an object oriented approach. Potential functions of different shapes and strengths are used to represent various objects and their attributes in the airspace. The host-centric interaction between the host aircraft and the environment is modeled by using an appropriate potential charge, which exerts the force of attraction and repulsion. The 4D information of a potential function (3D shape and strength) is enough to formulate any problem which provides 4D trajectory information (3D location and time).

Based on this methodology, two path planning algorithms are developed. One for flight route planning and the other for conflict detection and resolution and local trajectory generation. Many Conflict Detection and Resolution (CD&R) algorithms have been developed [*3,4*], but few have implemented coordinated resolution methods [*1*]. The CD&R algorithm developed under this methodology exhibits a rule based implicitly coordinated decision making for conflict resolution.

The algorithms have been implemented in a low level flight planner, which features the basic functions of flight planning. This shows the efficiency of this methodology and how an object oriented approach helps in framing efficient solutions for complex systems.

This preliminary work has been done with few assumptions: Only en-route airspace is considered, and aircraft provide only lateral resolution. Parameters and indexes such as aircraft trajectory modifier and airport busyness index are introduced, which efficiently represent attributes such as airport delay, user preferences, etc., in this methodology. The tools discussed in this paper generate a trajectory optimized for safety and comfort. A rule based implicitly coordinated decision making logic has been implemented for the CD&R algorithm. MATLAB® has been used for programming and obtaining results.

Using Potential Functions for en-route Air Traffic Management:

Under free flight, objectives for en-route air traffic management concept elements problems are clearly defined as free maneuvering, trajectory negotiation and collaboration to mitigate Traffic Flow Management (TFM) constraints. An object oriented approach simultaneously poses solution for all the 3 objectives. It helps by allowing free maneuvering when fully equipped, for utilizing all the services provided by DAG-TM, and produces a trajectory that satisfies all the constraints and preferences. A better object model using potential functions includes all the information, thus waiving the necessity for collaboration.

For TFM in en-route, the airspace is categorized into two types: Constrained Airspace and Transition Airspace. The constrained airspace is the subset of the en-route airspace that contains flights not headed to the same destination but share the same region. The transition airspace is the subset of the en-route airspace containing aircraft headed to the same destination and sharing the same airspace. While the problems in both the type of en-route airspace are caused by loss, gain of airspace and re-routing request, the solution varies in both the types. The potential function approach provides a generic solution for the en-route airspace.

Objective Oriented Approach and Careful Analysis of the en-route Problem:

The en-route airspace has various TFM constraints depending on the airspace type. The constrained airspace has weather, SUA, sector complexity problems, and the transition airspace has terminal congestion problems. All the constraints can be satisfied by creating an efficient 4D (Lat/Lon/Alt, Time) trajectory profile satisfying all constraints and preferences and meeting objectives. While the potential function can influence the Lat/Lon of the aircraft with 2D potential function (and Lat/Lon/Alt in 3D potential function case), the strength of the potential can influence the speed (time). Thus potential functions useful for passing constraint information that influence the 4D (Lat/Lon/Alt, Time) trajectory.

Apart from the constraints discussed above, the problem in en-route airspace is also caused by the objects not in the en-route airspace, such as destination airport. These kinds of objects are also included in this paper's approach. The discussion on potential functions methodology will provide more details.

Potential Functions:

Potential functions have been explored in Refs. [*11,12,13*] for robotic path planning. They became very popular in path planning for their inherent character of attraction and repulsion, and for use in continuous systems. The potential function value due to a unit charged potential at (x_0, y_0) has a general expression:

$$\Phi_{point} = (Charge\ Strength)*[1/((x-x_0)^2+(y-y_0)^2)]$$

at any location (x, y). Variations of the above expression can be created to represent several types of objects in the airspace. Variations can be made by providing different shapes to the potential functions and different strength to the potential fields.

Strong Potential Function: The potential field can be made to have a stronger value by placing a high charge instead of unity (Charge Strength >>1). The value of charge can be determined relatively by comparing to the aircraft which has a unit potential value. For example, very severe weather can be given high values proportionally as many times larger than an aircraft, thus creating a larger boundary around the weather and similarly to the SUA and high density areas.

Different shapes of potential fields: Another character of the potential function being exploited in this paper is the shape of the potential function. While the general expression above refers to the circular potential field, an elliptical potential field can be created by using the expression:

$$\Phi_{point} = (Charge\ Strength)*[1/\{(x-x_0)/a^2+(y-y_0)/b^2\}]$$

and $a \neq b$. The constants *a*, semi-major axis, and *b*, semi-minor axis, can be suitably chosen depending on the entity. This provides a more realistic representation of the data in the airspace as not all objects can be assumed to have a circular boundary. Weather, SUA, high density airspace can have different shapes which necessitates different shapes for potential function that can be achieved.

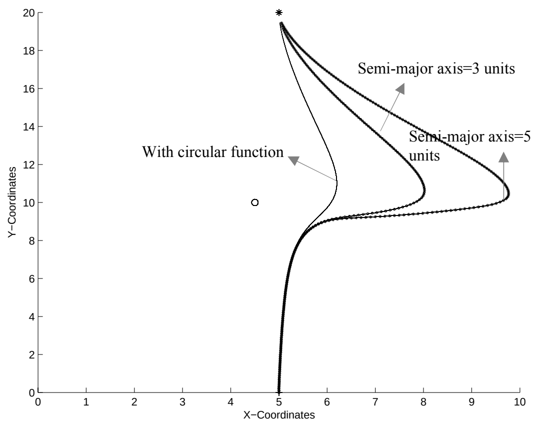

Figure 1: Effect of potential function shape on the trajectory

Though exact representations cannot be made, an usable representation can be achieved using axisymmetric shapes such as ellipses, cardioids [*20*], etc. Figure 1 shows the effect of elliptic potential functions and the trajectory generated avoiding it. Axisymmetric and asymmetric shapes can be built easily and used in potential functions which ease the issue of representing different data in the airspace. The potential functions are also attractive for the amount of information implicitly conveyed when they are used. The next sections will explore the use of potential functions in path planning and conflict avoidance.

Potential Functions and Path Planning:

Generally, in path planning using potential functions the goal is represented as an attracting potential and the obstacles as repelling potentials. The algorithm is constructed to minimize the cost function which will be a combination of path cost, repulsion of obstacle and attraction of goal. An optimized path is obtained as a result which avoids an obstacle and reaches the goal by satisfying the path cost constraints.

Research has explored more in the path planning by using different shapes differential force fields and different contour potential functions. While most of the applications have been developed for robotics, potential functions can be applied to air traffic management by adopting a methodology to model the problem. Using potential functions also suits an object oriented approach, which this paper explores.

Potential Functions Methodology:

The potential functions methodology is presented by using potential functions in an object oriented approach. Unfortunately, potential functions cannot be directly used for representation and dissemination of all the information in the airspace. While the variety of potential functions provides ample flexibility to do so, a careful methodology will enable efficient representation and modeling of information. An example of such a case is to apply constraints for safety and comfort level of an aircraft when solving the path planning by applying potential functions, where safety and comfort levels cannot be represented directly through potential functions but through some other parameters. Thus a distinct methodology is needed when the defining variables for the environment are potential functions.

In this methodology, information is passed as potential function strength and shape, the processed information is provided as indexes and the preferences are processed into a parameter. Every parameter and index is represented through an object. All the factors affecting an object are categorized and their interdependencies analyzed while creating parameters and indexes.

Table 1: Comparison of data representation in standard approach and objective oriented approach

Data Category	Direct Approach	Objective Oriented Approach
Information	Weather, traffic, SUA, airport location, etc	Combination of *potential function shape and strength*
Processed Information	Sector Complexity, TFM procedures (MIT, GDP, etc), etc	*Index* for every objective eg. Airport Busyness Index
Preferences	Priority, fuel/time efficiency, comfort, safety	*Parameter* unique for each aircraft based on preferences eg. Aircraft Trajectory Modifier

Elements of Potential Functions Methodology:

In the potential functions methodology, different elements have to be created to solve a problem. The basic elements are Object Information, Indexes and Parameters. Table 1 provides a comparison of information categorization in a direct approach and an object oriented approach.

Object Information: Object information is defined by different objects in the environment of the problem. These include weather, traffic, SUA, airports, etc., in the air traffic problem. The object information is represented using potential functions.

Indexes: Indexes are attributes of an object that is exhibited while interacting with other objects, such as the sector complexity, TFM constraints, etc. In this methodology an entirely new set of indexes have to be created to define data which are not objects, such as delays, TFM constraints, etc. The information that cannot be considered as objects but are associated with an object are categorized and are applied to the object in the form of the index. The index is globally valid. For example, the airport is an object that can be defined using potential functions, but an associated delay which is not an object can be represented as an index. This results in an Airport Busyness Index which modifies the value of the object information.

> *Airport Busyness Index (ABI)*: Based on the airport availability for aircraft arrival, a value is assigned to the airport which reflects the effects of terminal congestion, GDP, bad weather, etc. The ABI determines the shape and strength of the goal potential function for that airport which will be available everywhere as object information. Thus ABI is passed as an attribute to the airport.

Parameters: Parameters are indexes which are not valid globally but are object specific. For example, the safety of an aircraft and priority of the flight are not objects and are not valid globally. They form a category called parameters. Aircraft Trajectory Modifier is a parameter.

> *Aircraft Trajectory Modifier:* Based on different user preferences associated with an aircraft, a value is assigned for the modeled parameter, e.g., The Aircraft Trajectory Modifier determines the trajectory for the aircraft satisfying the user preferences on safety, comfort, etc.

Thus these elements form the basis for a problem formulation using potential functions. The algorithm built to operate in this methodology efficiently interprets the information passed by various elements of this methodology to provide an optimal solution.

Path Planning Algorithms in Potential Functions Methodology:

Exploring potential functions helps in building simple algorithms for path planning which can be solved in realtime and provides usable solutions directly. The path planning algorithms presented in this paper have a structure that includes the cost function and constraints, which are embedded in the object elements. Minimizing the cost function determines the initial trajectory which will be the direct route to the destination.

The algorithm tries to minimize the cost function while satisfying the constraints. Intuitively, it avoids the obstacles, defined as objects with attributes, and satisfies the object parameter defined, which generates the solution trajectory that satisfies the user preferences and the NAS constraints as well (which are in the form of the index in potential functions methodology).

This paper presents two algorithms for implementation using potential functions methodology: the Global Route Planner (GRP) and the Local Trajectory Generator (LTG). Both the algorithms are functionally similar, except the LTG is an implementation of a universal rule based upon implicitly coordinated decision making. This is primarily used as a CD&R algorithm.

Global Route Planner (GRP):

As the name implies, this algorithm calculates the route from departure to destination. This algorithm is a general path planning algorithm, which considers any object other than the aircraft (traffic) and provides a route which is optimal. The route generated is the flight plan which is obtained in the form of 4D trajectory information over large intervals of time or closer intervals if significant changes in the trajectory information occurs. The algorithm is also designed as an open system, hence enabling a user to modify the inputs anytime and also enhance the features of the algorithm.

In the absence of obstacles the algorithm calculates the ideal path towards the goal, which is predefined through the cost function. In this paper, the cost function is the distance from the goal which provides the shortest path when no obstacles (undesirable objects) are present in the path. When obstacles are present in the ideal route the negotiation is performed as: the obstacles repel the host aircraft and the maneuver direction is calculated as the resultant of the potential functions of the obstacles in conflict after weighting every obstacle avoidance direction with the preference parameter (parameter used to implement user preferences while generating optimal path) at the current location. The resultant direction is scaled to the maximum turn rate and maximum deviation from the ideal path allowed, thus the path planning algorithm directly provides the trajectory. Once the host aircraft is out of conflict the algorithm takes the shortest path towards the goal.

When the fuel and time constraints are represented in the cost function, the ideal trajectory generated will be fuel and/or time optimal and the algorithm will produce a trajectory further satisfying other constraints and preferences. For example, the turn rate constraint in each time step considering passenger comfort is set as 20 deg/sec and the maximum heading deviation from the original direct route heading is set as 90 deg, which produces a trajectory for passenger comfort as well as with limited deviation as shown in Figure 2 and the cost function is the distance to destination.

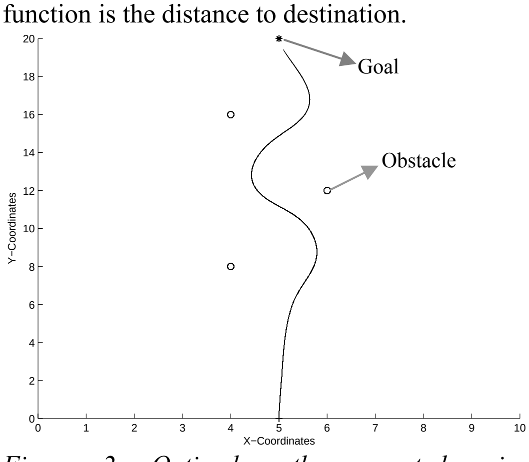

Figure 2: Optimal path generated using potential functions with turn rate constraints

Algorithm for path planning:

Step 1: Input the information of the airspace entities:

a. Starting point of the travel
b. Destination of the travel
c. Elements of the airspace – Object information, indexes and parameters

Step 2: Calculate the potential function and the gradient values for all the objects

Step 3: Calculate the direction of the negative gradient to the goal. When no obstacle is present this will be the direction of travel.

Step 4: When an obstacle collision is encountered, if the potential value due to an obstacle is greater than the threshold, a conflict maneuver is executed. The conflict maneuver direction is calculated from the general expression below:

Conflict avoidance direction = (1-∑Aircraft Trajectory Modifier)*Goal direction + degree of deviation.
Degree of deviation = ∑ (Aircraft Trajectory Modifier)*(Negative gradient direction of the obstacle) and is limited to a maximum value by scaling.

Step 5: The conflict avoidance direction is the direction of heading of the aircraft for the next time step. The conflict avoidance direction may be more than the maximum turn rate of the aircraft, thus the direction is scaled down using the general expression:

Final change in heading = Current heading – Conflict avoidance direction.
Turn Rate = Final change in heading/sampling time and is limited to a maximum value by scaling.

Step 6: The turn rate is now updated using a coordinated turn model [*20*] of an aircraft and the linear velocity of the aircraft is unchanged.

Figures 3 and 4 show the effectiveness of the path planning algorithm in tackling convective weather. The weather is represented as a point obstacle with circular boundary and moving in the direction shown in the figure.

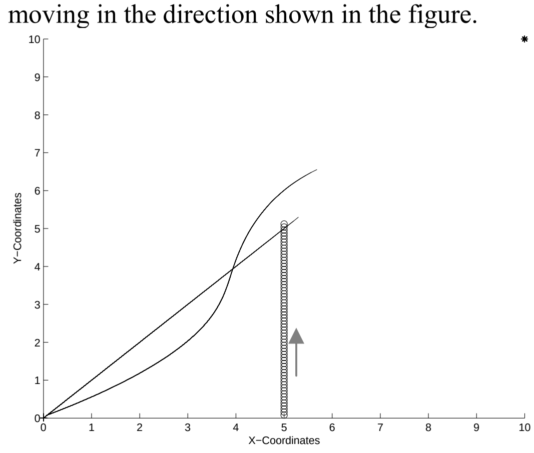

Figure 3: Shortest route and deviation from the normal due to convective weather starting at (5, 0) and moving in + y direction

The use of a parameter, defined in potential functions methodology to implement user preferences is made. The parameter shapes the trajectory for safety and comfort of the aircraft. The Aircraft Trajectory Modifier can take into consideration the turn rate of the aircraft, level of safety (allowable proximity to the obstacle) required, and efficiency.

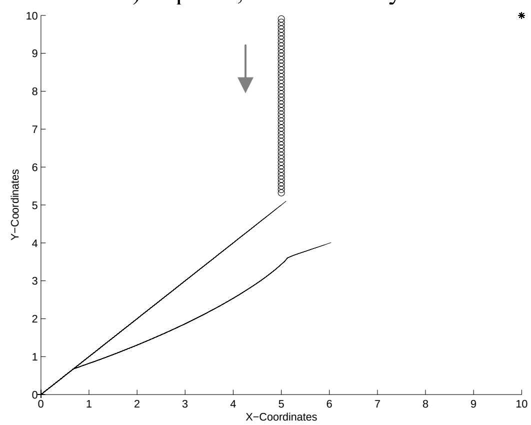

Figure 4: Shortest route and deviation from the normal due to convective weather starting at (5, 10) and moving in –y direction

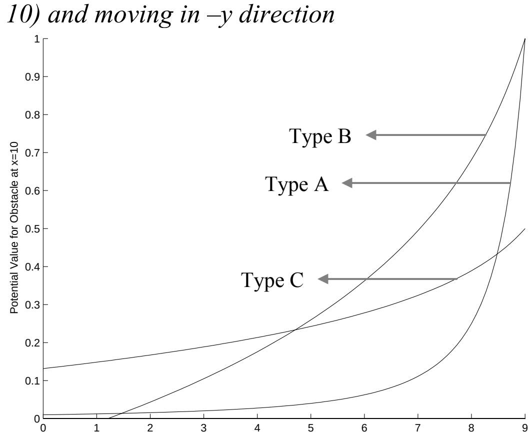

*Figure 5: The change in potential value for obstacle at (5,10) shown between y=0 to 9 and x=5. Modifier Type A corresponds to the actual potential function value with no modification. Modifier Type B is scaled as 0.23*log(potn_val)+1 and Modifier Type C as 0.08*log(potn_val)+0.5*

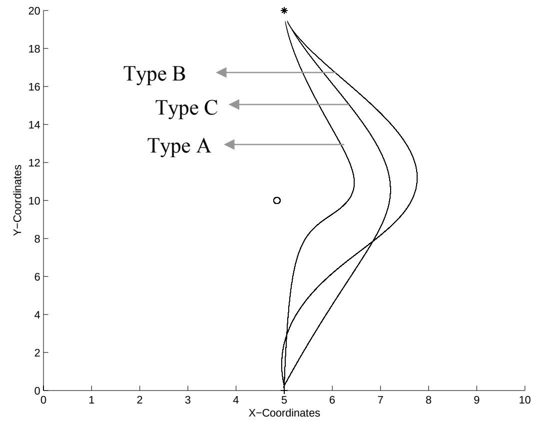

Figure 6: The different trajectories for different Aircraft Trajectory Modifier

Figure 5 shows different Aircraft Trajectory Modifiers. The trajectory it generates is shown by figure 6. A few interpretations made on the trajectories generated are provided in Table 2:

Table 2: Interpretations of different Aircraft Trajectory Modifier

Type	% increase in total distance	Total turn effort = $\int \omega .dt$ for $[0\ t_{final}]$
A	1.53	1.42 rad
B	4.6	1.8 rad
C	2.56	0.95 rad

The interpretations explain the effect of the parameter in implementing preferences in the trajectories generation. Each one has different levels of safety, efficiency and comfort level. The utilization of these variances will be made in the flight planner, where the user selects the type of modifier based on their combination of preferences.

Another feature of the potential functions methodology is the use of an index for objects. As mentioned before the index defines the character of the object and is valid globally. An example of an index, Airport Busyness Index, is demonstrated in the algorithm. This index is applied on the airport potential, an object in the potential functions methodology.

The ABI defines the character of the object and airport, which depends on various other factors. The degree of preparedness of an airport varies on factors such as integrity of the arrival/departure schedule, runway availability, weather in terminal airspace, etc. All the above factors affect the route of the aircraft related to that airport as an arrival or departure terminal. The ABI value reflects these factors in the shape and strength of the potential. Thus an index is created which can be applied on an object, the airport. This index will induce a combination of path stretching and speed change in the approaching aircraft

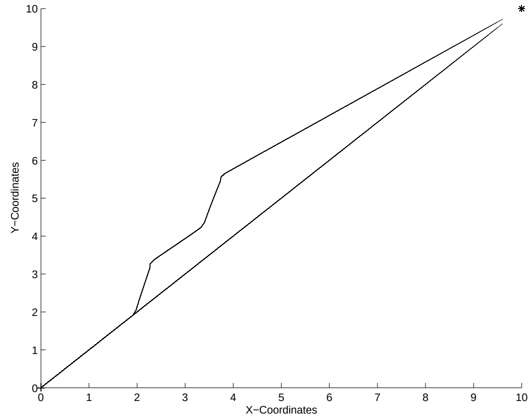

Figure 8: Comparing direct route and the route with path stretching implemented, achieved by varying ABI over time

Table 3: Aircraft arrival scheduling and ABI

Time	Aircraft Arrival Sequence Actual	ABIndex (Actual)	ABIndex (Modified at 00:20)	Aircraft Arrival Sequence after Modification
00:20	Axx	5	5	Axx
00:30	Bxx	5	On priority	Cxx
00:40	Cxx	5	3	Dxx
00:50	Dxx	5	3	Bxx
00:60	Exx	5	5	Exx

The Table 3 explains the effect of ABI and aircraft arrival scheduling. The table presents a scenario, when aircraft Bxx is informed of a delay by unpredicted weather around 00:20, which causes the index to be lowered to 3 for the next time period and the delayed aircraft will arrive on priority. This causes the next flights to arrive earlier as the ABI increase strengthens the airport potential attracting the aircraft scheduled to arrive at that time proportionally. Thus dynamic modification of the ABI mitigates the congestion problem, by maintaining a nominal traffic in the terminal airspace.

Local Trajectory Planner (LTG):

While the GRP creates a global route for the aircraft, the LTG complements the task of aircraft trajectory planning by generating the continuous trajectory information between the intervals of GRP. The LTG considers the objects not considered in the GRP, which is traffic. The LTG adopts a universal rule and implements it for implicitly coordinated decision making in the CD&R scenario. The rule based decision making makes the LTG algorithm different from the GRP.

Rule plays an important role and its effect in reducing chaos can be envisioned in a pair wise case easily. When a universal rule is adopted by every aircraft, they make coordinated maneuvers adhering to the universal rule while in conflict. The conflict will be resolved with effort from both the aircraft in the collision path, bringing a reliable and robust feature to this system. The assumption made here is that all the aircraft in the airspace follow the universal rule.

In this work, a universal rule which says 'turn anticlockwise around any obstacle' is adopted. In free flight airspace, the complexity increases as aircraft can travel in any direction. Under pilot control, the aircraft can maneuver in an unpredictable way in critical situations, which may lead to chaos. The problem lies here. When two aircraft are headed on a collision trajectory and flying in autonomous mode, each aircraft has a set of maneuvers that can be performed to avert collision. Which one is exercised depends on the pilot who controls it. By allowing full flexibility, the human decides arbitrarily, which is unpredictable and can lead to uncertain scenarios.

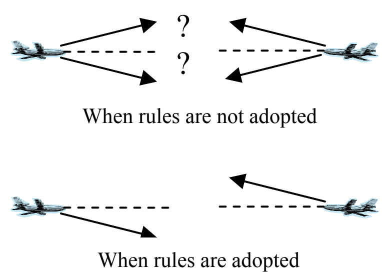

Figure 10: Rule dissolves the chaos in an aircraft pair case

Figure 10 illustrates a case where only horizontal resolution is allowed. In this case when a pair of aircraft are in conflict, more than one solution exists for each aircraft. Which solution will be adopted depends on the human operating the aircraft. When a universal rule is adopted, the solution for each aircraft is limited to one, which allows the human operating the flight no choice but to follow the rule. This explains how a rule can reduce the chaos in a complex environment.

Limitations to the Rule:

The rule adopted in this algorithm: 'Turn anticlockwise around any obstacle' has some limitations. The algorithm with turn rate constraints can make cases, where the obstacle is on the right side of the aircraft velocity vector, infeasible due to the inability of the aircraft to make sharp maneuvers. Enhanced conflict detection of this scenario can provide solution to this limitation, which has also been implemented in the CD&R algorithm. The algorithm and the rule based solution fail only when both the aircraft involved in the conflict fail to detect each other, which is highly impossible. This rule applies only to generation of lateral maneuvers, hence applicable to only case of aircraft in constant altitude.

Local Trajectory Planner Algorithm Conforming to the Universal Rule:

Step 1: Input information of the goal and other aircraft location, velocity and their fixes.

Step 2: Propagate the state forward in time and check for conflicts. The method of propagation used is a combination of the nominal and worst case.

Step 3: Calculate the set of aircraft in conflict and set them to conflict resolution mode.

Step 4: Calculate the coordinated conflict resolution with an estimate for the other aircraft in conflict mode.

Step 5: Obtain the traffic data and update the states of the other aircraft.

Step 6: Repeat Step 2 for every time step.

Step 7: Reset the conflict resolution mode after a minimum distance of separation achieved.

Step 8: Update the goal information if a current destination reached.

The algorithm is similar to the general route planning algorithm, but the only difference is the final turn rate is always positive making the aircraft fly in an anti-clockwise direction around the obstacle. Figure 11 shows the functioning of the LTG algorithm where 8 aircraft approach same point, thus in conflict, take a roundabout conflict resolution maneuver.

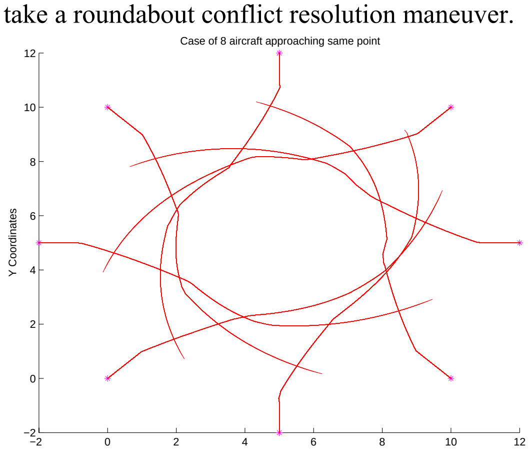

Figure 11: Example of 8 aircraft approaching a point in roundabout maneuver to avoid collision, generated by rule based CD&R algorithm

Implementation of Potential Functions Methodology to Flight Planning:

Pre-departure flight planning has various objectives, such as reducing the already congested airspace, exercising priority, planning for unexpected changes, calculating payload, fuel required, flight duration, etc. In the free flight concept, with the availability of global weather, SUA status, high traffic density regions and near airport traffic, pre-departure planning can be made more effectively with more information. Major decisions of the pre-departure planning stage are flight route determination and calculation of duration of flight, fuel required, etc. The automated flight planner built on the potential functions methodology uses potential functions, indexes and parameters and the GRP and LTG algorithms to provide a solution.

The flight planner presented here follows the potential functions methodology to solve the flight planning problem. The functional diagram of the flight planner in *Appendix B* shows the flow of information through the network for en-route traffic management. The flight planner offers the following features:

- Availability of traffic information to the NAS network, thus availability to the flight Deck (FD)
- Availability of weather, SUA, airspace complexity, airport status, TFM constraints, etc., to the NAS network, thus availability to the FD
- Input of user preferences anytime to the flight planner and updating changes in the NAS network
- Availability of the preferences of the other aircraft
- Updating the NAS network of any route or trajectory changes

The above features make all the object information and its attributes, developed using the potential functions methodology, available to the flight planner. The flight planner with information on the environment and its attributes provided with the host preference parameters produces the 4D-trajectory for the flight which brings equilibrium with the user preferences. This means an optimal feasible solution is obtained that satisfies various constraints as well as the user preferences.

The sequence of operation of the flight planner is as follows:

On Ground (Pre-Departure):

Step 1: The flight planner is initialized with flight information like flight performance information, flight destination and preference parameter, and global airspace information such as weather, SUA and traffic with associated indexes.

Step 2: The flight planner now has the environment with associated indexes and host information with associated preference parameter, which is now sent to the GRP.

Step 2: The GRP generates a route modified from the ideal route that satisfies the constraints and preferences. The user can review the route and make any changes, regenerate the route and assign them for entire flight with priority level once satisfied.

Step 3: The flight plan is added or updated to the NAS network, which updates the various indexes that are related to the flight plan. They may include, for example, change in traffic density along the flight route, airport arrival/departure schedule, airport busyness index, etc.

Step 4: The flight duration, fuel required, alternate destination, etc., are calculated.

The conflict of the aircraft with others is not considered at this level, which will be dealt by the LTG when encountered. The conflict avoidance maneuver is not large enough to affect the flight duration significantly.

In-Flight (en-route):

Step 1: The flight planner is activated when the flight leaves the departure terminal airspace region, after obtaining clearance from the ATC.

Step 2: The GRP provides the next fix on the route and assigns it as a goal to the LTG.

Step 3: The traffic information of the en-route local airspace is input to the flight planner through an Automatic Dependent Surveillance Broadcast (ADS-B) or a satellite. Other information are received automatically from a satellite or through an Air Traffic Service Providers (ATSP) and are input manually.

Step 4: The LTG uses the CD&R algorithm to predict the conflict and satisfies the user preferences on safety and comfort.

Step 5: When the current goal is reached the GRP provides the next fix on the route.

Step 6: The global route and the local trajectory is displayed in the cockpit display units.

Step 7: The GRP updates the flight plan at regular intervals or when manually initiated and the updated route is transmitted to the ground depending on the equipment.

Step 8: The flight planner is deactivated when the flight enters the arrival terminal airspace and coordinates with the ATC to land.

Figure 12 shows the implementation of the flight planner for dynamic re-planning. In the figure the flight route is modified as different sectors are loaded with traffic. Thus the flight planner offers a simple and organized solution approach for the en-route air traffic problem.

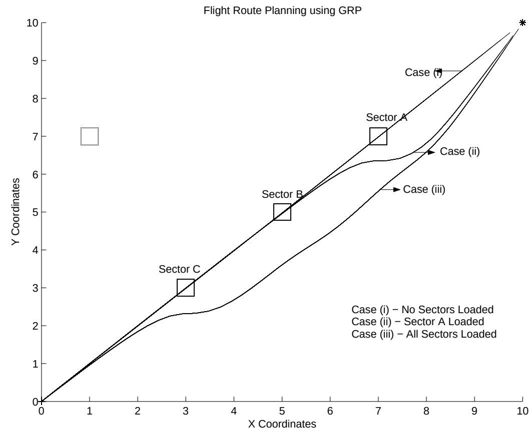

Figure 12: Implementation of the Flight Planner and Dynamic Re-planning Capability

Advantages of Potential Functions Methodology:

The potential functions methodology evolved specifically considering the air traffic management problem. The primary problem of air traffic management is collision avoidance with optimal path planning. The potential function based approach offers a convenient way to solve this problem. The potential functions methodology is a bottom up approach that begins with modeling objects. Objects form the physical environment and the attributes of the objects define the complete environment. When all the objects and their attributes are clearly defined, their interaction model explains all the dynamics of the environment. Any problem between objects defined in this environment will automatically consider the attributes and interaction model which will provide a better solution. The problem modeling and solution becomes simple in this approach as the attributes and interaction need not be modeled.

Moreover, the use of potential functions to represent objects results in a common object data format. All the objects are defined in terms of potential functions strength and location. This makes its advantageous in a distributed system where inter-exchange of information occurs between several sub-systems in the distributed system.

This paper demonstrates a low level implementation of the object oriented approach. The different objects in airspace are modeled as potential functions and the attributes defined in the form of shape and strength of the potential functions. By considering the potential function the host-centric interaction model is clearly defined as attraction and repulsion. This made the problem formulation simpler and the solution obtained is more robust and complete.

Conclusion:

Free flight has been accepted as a solution for future challenges in air traffic management. While many tools are being developed and procedures standardized for managing different issues in free flight, a research focused on object oriented modeling of airspace should be pursued.

An object oriented approach not only provides solution to all the problems but also in a simple and efficient way. It also takes into consideration all the complexity of the airspace, thus easing the evaluating parameters for complexity, and providing a solution that does not alleviate another one. This was shown through the potential functions methodology, which enables an effective representation of the airspace, and development of algorithms and tools for complete en-route air traffic solution.

While this paper limits its scope to lateral maneuvers and en-route airspace, efficient solutions exist with 3D potential functions. Future research should be directed to include maneuvers in vertical direction with speed changes. The interdependency of various factors should also be studied in detail to create a better object and interaction model that help in innovating more efficient solutions.

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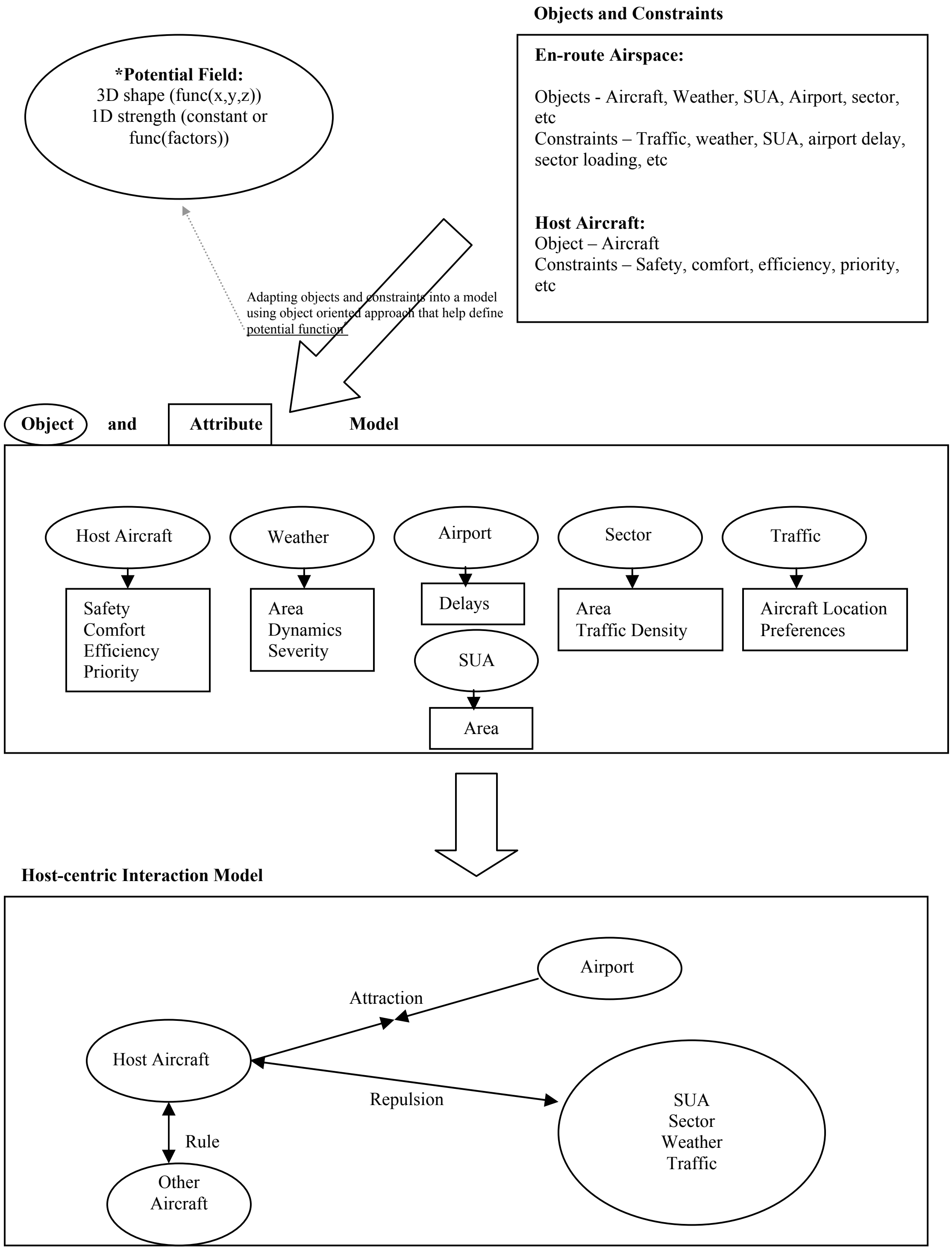
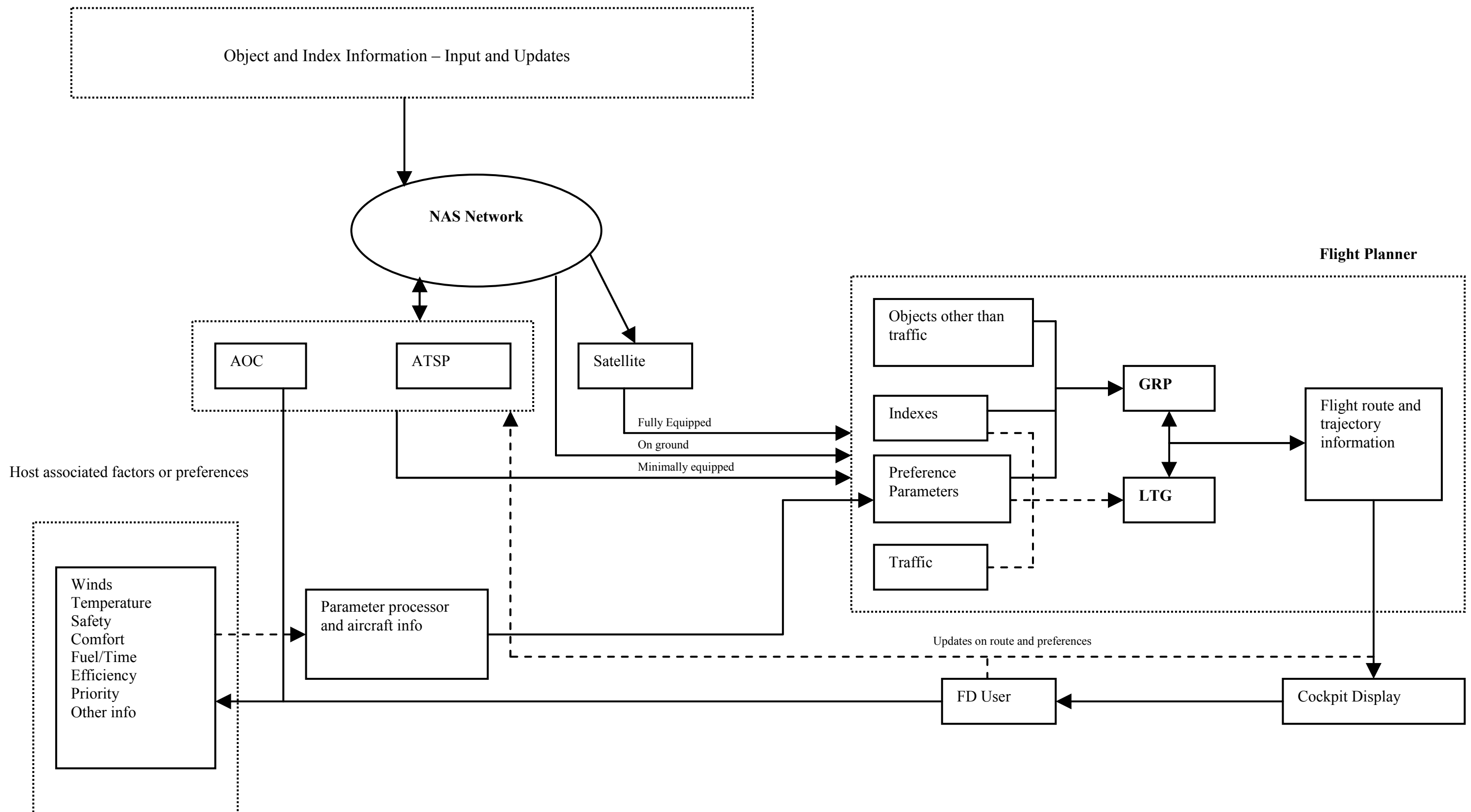
Annexes:



Annexure A: Potential Functions Methodology Scheme



Annexure B: Functional Layout of the Flight Planner