OPTIMAL AIRCRAFT CONFLICT RESOLUTION IN FREE FLIGHT USING SIMULATED ANNEALING AND GENETIC ALGORITHMS

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Abstract

Limitations of the existing Air Traffic Control (ATC) systems lead to problems like congestion in airspace, delays and improper detection of conflicts between the aircraft, and their resolution. The current trend is to shift from this centralized system to an autonomous one in which the assurance of separation depends on the aircraft themselves. This concept is termed as Free Flight. In the present study we deal with the optimal resolution of conflicts between three aircraft in level flight on intersecting routes. A geometric approach has been employed to resolve the conflicts using only speed changes of the aircraft. Three objective functions are proposed to obtain the best conflict free trajectories, which penalize the aircraft for the number of speed changes and/or the extent of the speed changes. Using stochastic methods for optimization viz. Simulated Annealing (SA) and Genetic Algorithms (GA), optimal conflict avoidance speed changes have been obtained. The resulting speed change sequences for the aircraft generated using SA and GA exhibit comparable trends and values. The solutions obtained are optimal not only in the context of the magnitude of speed change but also in the number of deviations from the original speed values.

***Index Terms** : Free Flight, Conflict Resolution, Optimization, Stochastic Methods, Simulated Annealing, Genetic Algorithms*

Nomenclature

i,j	= Aircraft index
t	= Instant of time
A1,A2,A3	= Aircraft
del_u	= Specified speed change value
dev_u	= Minimum speed change deviation value
D	= Distance between two aircraft
Dmin	= Minimum separation between two aircraft
E	= State energy
F_{obj}	= Objective functions
G	= Constraint equations
k	= Boltzmann constant
ntsteps	= Stages at which each aircraft changes its speed

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p	= Probability
T	= Look-ahead time
T_e	= Temperature
U	= Speed change the aircraft undergoes to avoid conflict
V	= Initial speed of aircraft
V_A	= Velocity of aircraft subsequent to the speed change
V_{min}	= Minimum speed of the aircraft
V_{max}	= Maximum speed of the aircraft
x	= Aircraft position on the X axis
y	= Aircraft position on the Y axis
α, β	= Angles between the common intersecting tangents and the X axis
γ	= Angle between the line joining the two centers with the X axis
δ	= Angle between the line joining the two centers and one of the common tangents
ω	= Angle between the relative velocity and the X axis
θ	= Aircraft heading
ATC	= Air Traffic Control
CDR	= Conflict Detection and Resolution
GNSS	= Global Navigation Satellite Systems
ADS-B	= Automatic Dependent Surveillance-Broadcast

Introduction

Air traffic in India has registered a rapid growth in the recent years, and the international and domestic traffic is forecast to rise at an annual rate of 10.5% and 9.8%, respectively, by 2012 [1]. The Indian airspace is also quite large, covering an area of about 6 million km^2, of which nearly 40% is over oceanic areas [2]. This growth is making severe demands on the existing controlled air-space and airports leading to an increase in losses due to inefficiencies and delays.

The existing system of Air Traffic Control (ATC) is based on centralized control with limited flexibility for individual aircraft to freely choose their optimal paths. These fixed pathways minimize the potential for conflict but produce flight plans that do not minimize fuel usage or flight time, which in turn results in losses and conges-tion of airspace. One possible solution is to shift from this centralized system to an autonomous one in which the assurance of separation lies with the aircraft; giving rise to an evolutionary concept of self separation called Free Flight. Free Flight is defined as a safe and efficient flight operating capability in which the pilots have the freedom to select their path and speed in real time [3].

In Free Flight, the responsibility of conflict detection and resolution is on the pilot itself, thereby reducing the workload on the air traffic controller. The pilot of each aircraft would have to ensure proper separation from other aircraft along a chosen flight path, in addition to the responsibility for flying and navigation. This would mean autonomy for the aircraft to choose its preferred flight trajectory, with intervention in exceptional cases.

While a centralized ATC system ensures separation and conflict resolution among thousands of aircraft spread over a vast area, which involves high risk, a distributed system like this on the other hand, can be more efficient. In such a system each aircraft would need to focus only on those aircraft in its vicinity which pose a possible conflict threat [4]. A multi-aircraft system is thus formed where there is more than one aircraft that interact with each other. They share the information about their positions, veloci-ties and flight plans and upon detection of a conflict, they maneuver in such a way so as to resolve it. The bottom line in implementing this concept is the development in Con-flict Detection and Resolution (CDR) capabilities. A con-flict is an event in which two or more aircraft experience a loss of minimum separation: either lateral or vertical. Conflict detection is based on the estimation of future position of the aircraft in a fixed look-ahead time for T min, by ascertaining the possible violations of the mini-mum separation between two aircraft [5]. Conflict Reso-lution involves deciding when to initiate a resolution maneuver and in what manner to execute it. This process may consist of horizontal maneuvers, vertical maneuvers and speed changes or a combination of two or more of these maneuvers. The optimal time to initiate a maneuver can be determined by minimizing an objective function reflecting the statistically expected cost of maneuvering (or not maneuvering) an aircraft as a function of time, for example by considering a change in its velocity.

Review of Literature

Many modelling approaches for conflict detection and resolution among aircraft in Free Flight environment have been suggested in literature. Conflict detection (both de-terministic and non-deterministic) and resolution (both tactical and strategic) methodologies has been the subject of detailed investigation in surveys carried out in [6] and [7]. Aircraft are modeled in 3-D airspace in [8] and the total flight time to avoid all possible conflicts is minimized to solve the conflicts by undergoing velocity changes. Mixed-integer linear programming has been used to resolve multiple aircraft conflicts in some cases; [9] uses both velocity and heading changes by considering the path planning problem among given waypoints and [10] employs an offline planar space partition algorithm. Aircraft have been modeled as kinematic systems in [11] with bounds on their velocities and curvature. Hybrid system model and analysis techniques have been used in [12] and [13] for synthesizing conflict resolution maneuvers for aircraft. A Genetic algorithm approach for conflict resolution has previously being addressed in [14] - [16]. Potential field algorithms for separation assurance in Free Flight have been studied in [17]. A true 3-D geometric analysis to CDR has been presented in [18]. The solution is a single maneuver by the aircraft in such a way that each solution modifies only one state parameter of the aircraft. Another 3-D geometric algorithm for pair-wise non-cooperative aircraft conflict avoidance has been presented in [19]. Planar conflict resolution algorithm using particle fields for motion constraints associated with aircraft has been presented in [20]. A conflict resolution tool for the ATC is provided in [21] by taking into account the uncertainties involved in the conflict resolution process. Monte Carlo optimization method has been used as the stochastic simulator for this model. Other deterministic CDR approaches like in [22] - [24], incorporate stochastic uncertainty in their models and determine the probability of conflict. A multi-agent approach for conflict detection and cooperative conflict resolution in a 2-D autonomous Free Flight environment is suggested in [25]. Upon detection of a possible future conflict, the aircraft undergo a sequence of speed control actions to resolve the conflict. Multi-objective minimization of some loss functions for each aircraft is carried out to determine then optimal speed changes.

Case Study in Optimal Airborne Separation

In the present study, the hypothetical scenario adapted from [25] is considered, in which three aircraft (A1, A2 and A3) are flying at their preferred (optimal) speeds along straight tracks at the same altitude (FL300) in Free Flight airspace. Table-1 lists the initial coordinates, preferred airspeeds and headings of the three aircraft, where the headings are with respect to the geographic north direction.

Table-1 : Aircraft Initial Coordinates, Airspeed and Headings

Aircraft	Initial Coordinates (x,y) (nm)	Airspeed (knots)	Heading (deg)
A1	(45,0)	400	0
A2	(0,0)	480	30
A3	(150,100)	410	270

They are assumed to be equipped with Global Navigation Satellite Systems (GNSS) and Automatic Dependent Surveillance-Broadcast (ADS-B) or some other type of data link for inter-aircraft communications. These aircraft are travelling at their initial configuration speeds, which are also their optimal speeds, on paths in which they are predicted to conflict with each other in a 20 min look-ahead time. A conflict alert is declared if a separation of less than 5 nm between any two aircraft is detected along the aircrafts intended trajectories. Table-2 shows the distances between the aircraft and the violations of the separation minima (in **bold**) when the distance between each pair of aircraft falls below 5 nm in some time to come, thereby predicting a possible conflict.

Formulation of Optimal Conflict Resolution

A geometrical procedure suggested in [9] has been adopted to resolve the three aircraft conflict scenario using only speed control actions.

Geometric Methodology

The three aircraft are considered as point elements in the 2-D space along with their headings. The coordinates of any i^{th} aircraft are of the form (x_{it}, y_{it}, θ_{it}): which indicate its position and heading at any time instant t. Because the aircraft's intended flight heading does not change during conflict resolution actions, θ_{it} remains constant for that aircraft at any time instant. Each aircraft is considered to have a "reserved" disc of radius $D_{min}/2$ around itself, where D_{min} is the minimum separation between any two aircraft. The condition of non intersection of these discs is the condition of no-conflict between the aircraft. With a look-ahead time of 20 min we assume that no conflict occurs at $t = 0$.

Each i^{th} aircraft is considered to have lower and upper bounds on the speed V_i at which it is travelling initially, given as

$$V_{i,\min} \leq V_i \leq V_{i,\max} \tag{1}$$

Table-2 : Distances between the Aircraft in Time-to-Come

Time (min)	Distance (A1-A2 (nm)	Distance A2-A3 (nm)	Distance A3-A1 (nm)
0	45.00	180.28	145.00
1	41.00	167.42	135.45
2	37.00	154.56	125.91
3	33.01	141.71	116.36
4	29.02	128.85	106.82
5	25.03	116.00	97.27
6	21.06	103.15	87.73
7	17.10	90.30	78.18
8	13.17	77.45	68.64
9	9.30	64.60	59.10
10	5.64	51.77	49.55
11	**3.05**	38.94	40.01
12	**4.34**	26.16	30.48
13	7.78	13.52	20.96
14	11.59	**3.44**	11.47
15	15.50	13.10	**2.50**
16	19.46	25.73	7.95
17	23.43	38.52	17.39
18	27.41	51.34	26.91
19	31.40	64.17	36.44
20	35.39	77.02	45.98

Let us assume that the aircraft undergoes a speed change of U_{it} at some time t to avoid the conflict. Then the same lower and upper bounds on the initial speed should also apply on this new speed $V_i + U_{it}$. Hence, we get

$$V_{i,\,\min} \le V_i + U_{it} \le V_{i,\,\max} \tag{2}$$

Now consider two aircraft in collision: A_i and A_j. Let $(x_{it}, y_{it}, \theta_{it})$ and $(x_{jt}, y_{jt}, \theta_{jt})$ be their respective aircraft positions and heading at time t, and V_i and V_j be their respective initial speeds. It is assumed that θ_{it} and θ_{jt} are constant for the aircraft over all the time instances as their flight path heading does not change during the entire conflict resolution process.

After the aircraft have undergone their respective speed changes at time t we refer to Fig.1. In this the velocities V_{Ai} and V_{Aj}, of aircraft A_i and A_j respectively, represent the velocities subsequent to the conflict avoidance speed changes. The headings θ_{it} and θ_{jt} of the aircraft are measured clockwise from the geographic north direction. Their velocity vectors can be now written as

$$V_{Ai} = \left[(V_i + U_{it}) \sin\theta_{it}\,,\ (V_i + U_{it}) \cos\theta_{it}\right] \tag{3}$$

$$V_{Aj} = \left[(V_j + U_{jt}) \sin\theta_{jt}\,,\ (V_j + U_{jt}) \cos\theta_{jt}\right] \tag{4}$$

Consider Fig.2 where the circles of the two aircraft have common intersecting tangents at time t. The trajectory angles of the aircraft formed between these tangents are used to arrive at a no-conflict condition which depends on the speed changes that the aircraft will undergo to avoid the conflict. In this figure, aircraft A_i and A_j have their circles of radius $D_{min}/2$ at the centers I and J respectively.

The common intersecting tangents: POQ and ROS, which intersect each other at O, form the angles $\angle OAX$ and $\angle OBX$ with the horizontal X axis. Let these be designated by α_{ijt} and β_{ijt} respectively. The line IJ joining the two centers makes an angle $\angle OIX$ (γ_{ijt}) with the X axis. $\angle IOA$ (δ_{ijt}) is the angle between the tangent POQ and the line IJ. This angle is also equal to the angle between the tangent ROS and line IJ. By applying triangle relations we see that

$$\alpha_{ijt} = \gamma_{ijt} + \delta_{ijt} \tag{5}$$

$$\beta_{ijt} = \gamma_{ijt} - \delta_{ijt} \tag{6}$$

γ_{ijt} is obtained from

$$\gamma_{ijt} = Tan^{-1} \frac{(y_{jt} - y_{it})}{(x_{jt} - x_{it})} \tag{7}$$

and δ_{ijt} is obtained from

$$\delta_{ijt} = Sin^{-1} \frac{PJ}{OJ} = Sin^{-1} \frac{D_{\min}}{D_{ijt}} \tag{8}$$

Where D_{ijt} is the distance between the aircraft A_i and A_j at time t as given in Eqn.(9)

$$D_{ijt} = \sqrt{[(x_{jt} - x_{it})^2 + (y_{jt} - y_{it})^2]} \quad (9)$$

The Cartesian space coordinates x_{it} , y_{it} , x_{jt} and y_{jt} in Eqn.(9) represent the position of the aircraft A_i and A_j in 2-D space at any time t. The angle that the relative velocity vector $V_{Ai} - V_{Aj}$ makes with the X axis (as shown in Fig.1) is given by

$$\omega_{ijt} = Tan^{-1} \frac{[(V_i + U_{it}) \cos\theta_{it} - (V_j + U_{jt}) \cos\theta_{jt}]}{[(V_i + U_{it}) \sin\theta_{it} - (V_j + U_{jt}) \sin\theta_{jt}]} \quad (10)$$

No conflict is said to occur if the circle of aircraft A_i is either ahead or behind the shadow created by aircraft A_j in Fig.1. In other words A_i should either speed up or slow down when compared to A_j. Translating this condition in the form of a mathematical equation that relates the trajectory angles α_{ijt} and β_{ijt} between aircraft A_i and A_j with the conflict avoidance speed changes U_{it} and U_{jt} that these aircraft undergo respectively at time t, gives the no-conflict condition for the aircraft which is, that either

$$Tan\,(\omega_{ijt}) \geq Tan\,(\alpha_{ijt}) \quad (11)$$

or

$$Tan\,(\omega_{ijt}) \leq Tan\,(\beta_{ijt}) \quad (12)$$

In other terms, no conflict occurs when

$$\frac{[(V_i + U_{it}) \cos\theta_{it} - (V_j + U_{jt}) \cos\theta_{jt}]}{[(V_i + U_{it}) \sin\theta_{it} - (V_j + U_{jt}) \sin\theta_{jt}]} \geq Tan\,(\alpha_{ijt}) \quad (13)$$

or

$$\frac{[(V_i + U_{it}) \cos\theta_{it} - (V_j + U_{jt}) \cos\theta_{jt}]}{[(V_i + U_{it}) \sin\theta_{it} - (V_j + U_{jt}) \sin\theta_{jt}]} \leq Tan\,(\beta_{ijt}) \quad (14)$$

Equations (13) and (14) exhibit how the speed changes of the aircraft effectuate a change in their trajectory directions with respect to each other. In a previous study by the authors [26], the effectiveness of such speed control actions were analyzed by imposing a penalty based on separation distance and off-optimal speeds.

Problem Formulation

The task of determining the best conflict free trajectories is formulated as a multi-stage constrained optimization problem spread over t time steps in a look-ahead time of T min. If our goal is to resolve the conflicts with the least amount of total speed change for all the aircraft, then the objective function can be taken as the summation of the absolute value of speed change for each of the three aircraft at each time step, as in (15). This objective function is minimized iteratively to reach the desired goal.

$$F_{obj\,1} = \sum_{t=1}^{ntsteps} |\,U_{it}\,| \quad i = 1, 2, 3 \quad (15)$$

The speed changes (U_{it}) of the three aircraft (i = 1, 2, 3) in each of the t time steps are the design variables. The time steps *ntsteps* are the stages at which each aircraft changes its speed so as to avoid the conflict within a look-ahead time of T = 20 min. Hence, *ntsteps* = 2 and 5 signify that the aircraft change their speeds at every 10 min, and every 4 min, respectively, to avoid the conflict. The number of design variables is the product of *ntsteps* and number of aircraft.

The minimization problem is subject to the two constraint conditions for no conflict of the aircraft, Eqs.(13) and (14), and to another condition that no two aircraft come closer to each other than the minimum separation. These three constraints designated as G_1, G_2 and G_3 are specified in (16), (17) and (18) respectively.

$$G_1 \therefore Tan\,(\alpha_{ijt}) \leq \frac{[(V_i + U_{it}) \cos\theta_{it} - (V_j + U_{jt}) \cos\theta_{jt}]}{[(V_i + U_{it}) \sin\theta_{it} - (V_j + U_{jt}) \sin\theta_{jt}]} \quad (16)$$

$$G_2 \therefore Tan\,(\beta_{ijt}) \geq \frac{[(V_i + U_{it}) \cos\theta_{it} - (V_j + U_{jt}) \cos\theta_{jt}]}{[(V_i + U_{it}) \sin\theta_{it} - (V_j + U_{jt}) \sin\theta_{jt}]} \quad (17)$$

$$G_3 \therefore D_{\min} \geq \sqrt{[(x_{jt} - x_{it})^2 + (y_{jt} - y_{it})^2]} \quad (18)$$

The inequality constraints in (16) and (17) show a linear relationship between the design variables U_{it} and U_{jt} (i , j = 1 , 2 , 3 ; $i \neq j$ and t = 1 to *ntsteps*) and are modeled as 'or' constraints. The Cartesian space coordinates in (18) which earlier appear in (7) and (8) are linked to design variables U_{it} and U_{jt} through the equations (5), (6), (13) and (14). As the aircraft advance in their paths their position coordinates at time t+1 are calculated as the product of the position coordinates and their respective speeds at time t. The lower and upper bounds on the speed change of any aircraft at time t are taken as -40 kn and 40 kn [25] respectively, which form the lower and upper bounds on the design variables.

Optimization Methods

Stochastic methods based on Simulated Annealing (SA) and Genetic Algorithms (GA) were selected for optimization in the present study, due to their efficiency in tackling complex problems which have a vast search space.

Simulated Annealing [27] converges to the global optimum by simulating the process of slow cooling of molten metal to achieve the minimum energy state. The state is analogous to a solution point in the search space and the energy is analogous to the function value in a minimization problem. At each step of the simulation, a new state of the system is generated by a random selection from the neighbourhood of the current state. The new generated state will be accepted, if its energy is lesser than that of the current state. If not, it will be accepted with the probability, $p = e^{(-E/kT_e)}$, where E is the energy of the state (function value), k is the Boltzmann constant and T_e is the temperature. This step is repeated with a slow decrease of temperature to find a minimum energy state. This algorithm has been implemented in the SIMANN [28] code which was used for optimization.

Genetic Algorithms are global search and optimization procedures that are motivated by the principles of natural genetics. They start with a random population of chromosomes (solutions) and the fitness (function value) of each chromosome is evaluated. A new population is created by selecting two parent chromosomes according to their fitness; higher the fitness more the probability of selection. The parents are probabilistically crossed over with each other to form a new off spring. This off spring is then mutated with some probability and placed in the new population. The process is then repeated for this new population till the best fitness chromosomes are obtained. The GA technique, DEVOLA [29], adopted here is a real-parameter code that incorporates tournament selection and uses a single point, constant bit length crossover.

Theoretically, SA and GA are quite close to each other, and much of their difference is superficial. Both SA and GA assume that good solutions are more probably found "near" already known good solutions than by randomly selecting from the whole solution space. While the key difference between them is that GA has the feature of finding and maintaining two solutions in one single simulation run while SA creates a new solution by modifying only one solution in each step.

An exterior penalty function approach has to be employed to handle the constraints, as they cannot directly be handled in both SIMANN and DEVOLA (which only handles bound constraints). The results obtained after optimization will be presented in the sections that follow.

Results and Observations

Resulting Conflict Avoidance Speed Changes for F_{obj1}

Figure 3 and 4 show the conflict resolution speed changes obtained from SA and GA for the three aircraft for F_{obj1}; $ntsteps$ = 2 and 5 respectively. The solid lines represent the speed change sequences for the three aircraft for SA and the dotted lines for GA. Each aircraft has been designated a different marker; solid for SA and hollow for GA.

From Fig.3 it can be seen that speed change sequences obtained from SA and GA are nearly comparable to each other, with one positive and one negative speed change each for the first time step, for aircraft A1 and A2 respectively. For aircraft A3, GA generates zero speed changes while SA generates values that are infinitesimally small in magnitude. When the aircraft is made to change its speed more frequently as in Fig.4, it shows speed changes at almost every time step for all the three aircraft for SA, with speed changes for aircraft A3 being very small. Similar is the case for GA except for aircraft A2 maintaining its optimal speed with no speed changes throughout all the time steps.

A point to be noted here is that many speed changes in the suggested sequences are quite small in magnitude, but are still penalized. Hence, a second objective function which shall be minimized was formulated, as in (19), in which no penalty is added if the absolute value of the suggested speed change at any time step is less than a specified value (del_u). And whenever it exceeds del_u, the penalty is the addition of the absolute value of the speed change to itself.

$$F_{obj\,2} = \sum_{t=1}^{ntsteps} |\,U_{it}\,| + (\,|\,U_{it}\,| - del_u\,)\; i = 1,2,3 \qquad (19)$$

where

$|\,U_{it}\,| - del_u = |\,U_{it}\,|$ if $|\,U_{it}\,| > del_u$

$|\,U_{it}\,| - del_u = 0$ if $|\,U_{it}\,| \le del_u$

The objective function F_{obj2} ensures that penalty is added in proportion to the magnitude of each speed change, as long as it is higher than a specified value del_u. It is desired to reduce the magnitude of each conflict avoidance speed change through the minimization of this objective function. The value of del_u is chosen to be equal to 5 kn.

Resulting Conflict Avoidance Speed Changes for F_{obj2}

Figure 5 and 6 show the conflict resolution speed changes obtained from SA and GA for the three aircraft for F_{obj2}; *ntsteps* = 2 and 5 respectively. Fig.5 shows that the speed change trends for SA and GA for aircraft A1 and A2 overlap each other indicating that the speed changes obtained through the two techniques are equal. Similar to Fig.3 earlier, even here GA suggests zero speed changes for aircraft A3 while SA generates very small perturbations in speed changes that are in any case lesser than the value of del_u.

Figure 6 shows the similarity in speed change trends for SA and GA for aircraft A1 and A3 with the difference being in the magnitude of speed changes at some time steps; SA giving lower values for A1 and higher values for A3 than GA. Absolute speed change values lesser than del_u can be found for aircraft A1 in the fourth and fifth time steps, while those for A3 can be found in the third, fourth and fifth time steps, for both SA and GA. This means that aircraft A1 is penalized for more number of time steps than aircraft A3. For aircraft A2, both GA and SA propose zero speed change for all the time steps thereby attracting zero penalties.

However, functionally it is quite inconvenient for the aircraft to deviate from its optimal speed at every time step, even if the speed change is less than 5 kn (as seen in Fig.6 for A1 and A3). Hence a third objective function which shall be minimized was formulated, as in (20), in which a penalty factor P is imposed for any deviation from the initial configuration speed, i.e. speed at $t = 0$, which is also the optimal speed.

$$F_{obj\,3} = \sum_{t=1}^{ntsteps} P*(\,|\,U_{it}\,| - dev_u\,)\; i = 1,2,3 \qquad (20)$$

where

$|\,U_{it}\,| - dev_u = 1$ if $|\,U_{it}\,| > dev_u$

$|\,U_{it}\,| - dev_u = 0$ if $|\,U_{it}\,| \le dev_u$

Nevertheless to permit some margin for the aircraft to alter its speed, we assume safely that any speed change lesser than a minimum deviation value (dev_u) can be considered to be a zero speed change for the aircraft. This provides a facility for the aircraft to undergo a conflict avoidance speed change in some small neighbourhood of its optimal speed that has a negligible effect on its optimal speed performance. The minimization of objective function F_{obj3} ensures the least instances of deviations for the aircraft from their chosen optimal speeds while resolving the conflict. The value of P is chosen to be 1000 and that of dev_u to be 2 kn.

Resulting Conflict Avoidance Speed Changes for F_{obj3}

Figure 7 and 8 show the conflict resolution speed changes obtained from SA and GA for the three aircraft for F_{obj3}; *ntsteps* = 2 and 5 respectively. Fig.7 shows aircraft A1 and A2 being subjected to only one deviation from their optimal speed, in both SA and GA trends. The magnitudes of speed changes are in such a manner where GA gives lower values for A1 and higher values for A3 than SA. Aircraft A3 is continues on its optimal speed with no deviation in both the SA and GA trends.

Figure 8 shows that aircraft A1 deviates from its optimal speed three times in the sequence generated by SA while deviating only twice in the GA sequence. Similarly aircraft A3 deviates from its optimal speed four times in the sequence generated by SA while deviating only three times in the GA sequence. Aircraft A2 undergoes only one speed deviation in the fourth time step for SA while for GA it continues on its original optimal speed with no deviation.

Discussions and Conclusions

Having viewed the resulting conflict resolution speed changes for the three objective functions, we now look into the inference that can be drawn from the observations. The optimal conflict avoidance speed changes generated upon minimization of F_{obj1} yielded least numerical values at every time step for all the aircraft. However, many speed changes were small in magnitude but were still penalized.

Therefore F_{obj2} was devised and optimal conflict avoidance speed changes were generated in which the extent of absolute speed change from a specified value was minimized. It was then discovered that although the aircraft undergo speed changes that are smaller in magnitude than the specified minimum, they frequently deviate from the optimal speed. Hence F_{obj3} was created to achieve optimal conflict avoidance speed changes which deviate negligibly, almost zero, from the preferred optimal initial speed of the aircraft. The values obtained thereby reflect lesser instances of deviation than those obtained through the first two objective functions.

Summing up, it can be inferred that the values of the generated conflict avoidance speed changes are at their optimum, taking into account both the magnitude and the number of deviations. The process of arriving at these speed changes that are not only least in magnitude but also in the number of changes is accomplished by minimizing the objective functions progressively. These qualities are finally found to be in the speed changes obtained upon minimization of F_{obj3} amongst all the solutions that are generated.

Apart from this it can also be seen that one among the three aircraft does not undergo any speed change in each of the solutions, thereby maintaining its original optimal speed throughout the conflict resolution process. Such a conflict resolution can be termed as non-cooperative, in which the conflict resolution maneuvers are undertaken by only two aircraft while the third aircraft chooses to play no role. Another point to be noted is that the solutions generated by SA and GA are almost comparable to each other; with the only exception of GA yielding conflict resolution speed changes that deviate less number of times than those given by SA in F_{obj3} . This shows that SA and GA are both theoretically and empirically comparable to each other.

In this study, a conflict scenario involving three aircraft in a Free Flight environment is considered. A geometrical approach to successfully resolve the conflicts between the three aircraft using only speed changes is formulated. The present study contributes by devising two new objective functions to generate speed control actions that resolve the conflict by ensuring the least magnitude and the least number of speed changes. The speed changes obtained in this study deviate fewer times to lesser extent from the optimal speed of the aircraft, thereby giving the freedom to travel on their chosen trajectories.

Simulated Annealing (SA) and Genetic Algorithms (GA) are the two stochastic methods which have been used here for optimization considering their ability to tackle complex problems arising in CDR and for their robustness and ability to scan a vast search space. A Simulated Annealing (SA) algorithm, SIMANN and a real-parameter Genetic Algorithm (GA), DEVOLA, has been coupled to the objective functions to optimally find the conflict resolution speed changes which are executed by each aircraft to resolve the conflicts present among them.

It can be concluded that this study effectively resolves an existing case of aircraft conflict using speed changes by inventing new objective functions and using better stochastic optimizing techniques. To resolve the conflict, speed changes alone have been proposed in this study; as the aircrafts preferred path remains unchanged and the possible occurrence of new conflicts due to change in trajectory is avoided. The comfort of the passengers is also not compromised as they are not subjected to uneasy heading or vertical maneuvers. Nevertheless, a realistic 3-D conflict resolution approach is still possible, in which the aircraft are flying at different altitudes and undergo maneuvers such as minor altitude and/or heading changes with/without speed changes.

Future work in this area of CDR can include formulating better and efficient objective functions. Design variables must so be chosen which mainly control the aircrafts trajectory and performance. Fuel costs, acceleration costs and safety costs can also be additionally included to achieve greater coverage of all the factors which play a part in the resolution of the conflict. The optimization problem in this study can be further modeled to permit only discrete changes in the aircrafts speed. A study is currently underway in which such a scheme is being implemented and coupled to a binary-coded GA code.

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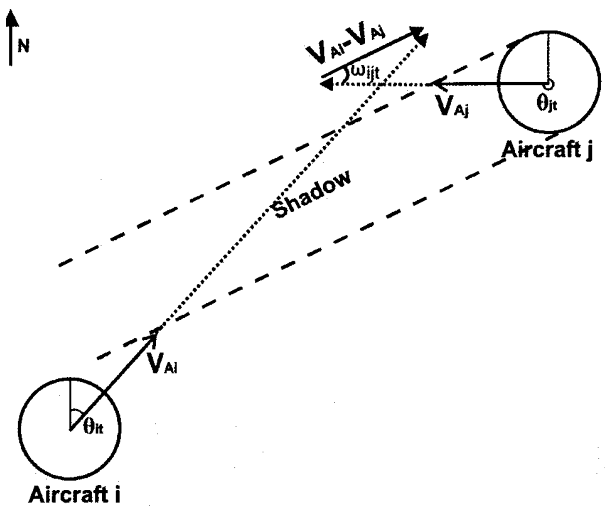

Fig.1 Intersection of the Trajectories at the Initial Configuration

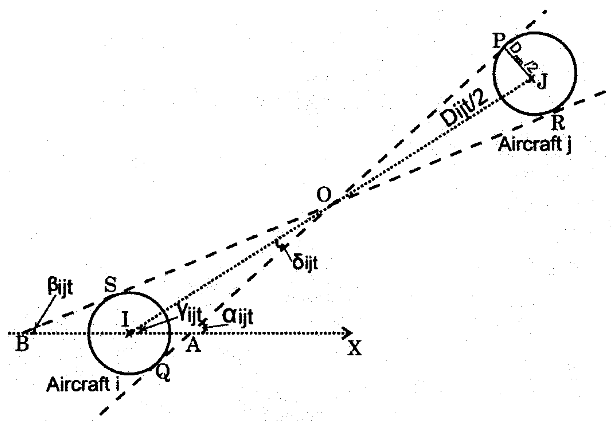

Fig.2 Interesting Tangents with the Angles Between Aircraft A_i and A_j

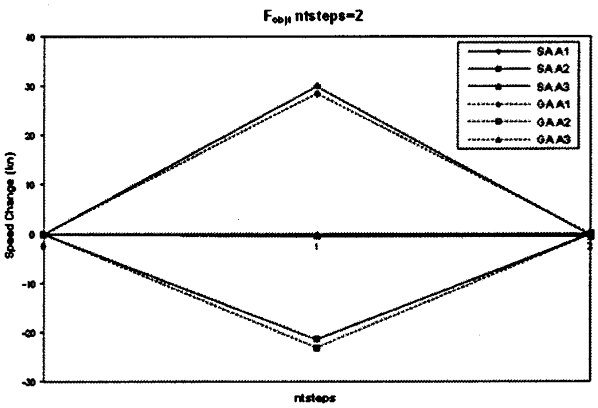

Fig.3 Conflict Avoidance Speed Changes for F_{obj1} (ntsteps = 2) for SA and GA

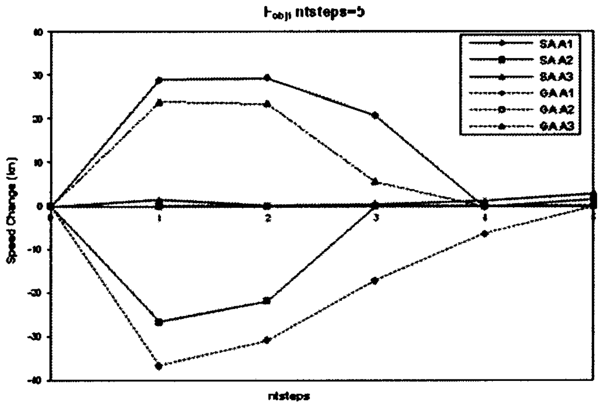

Fig.4 Conflict Avoidance Speed Changes for F_{obj1} (ntsteps = 5) for SA and GA

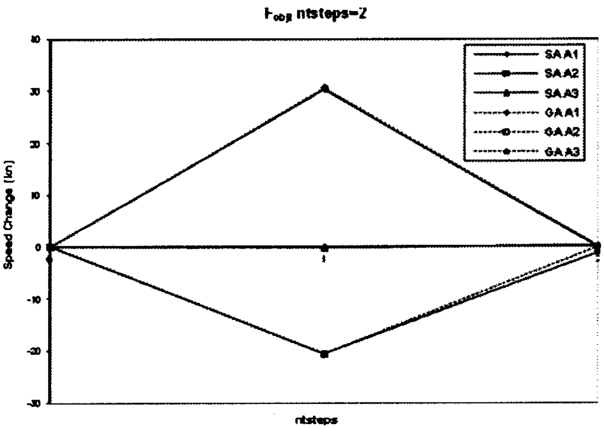

Fig.5 Conflict Avoidance Speed Changes for F_{obj2} (ntsteps = 2) from SA and GA

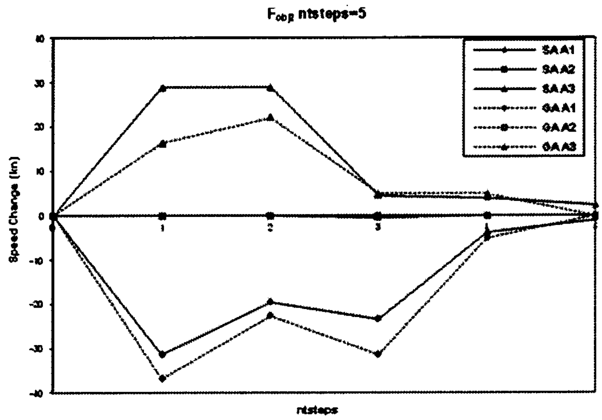

Fig.6 Conflict Avoidance Speed Changes for F_{obj2} (ntsteps = 5) from SA and GA

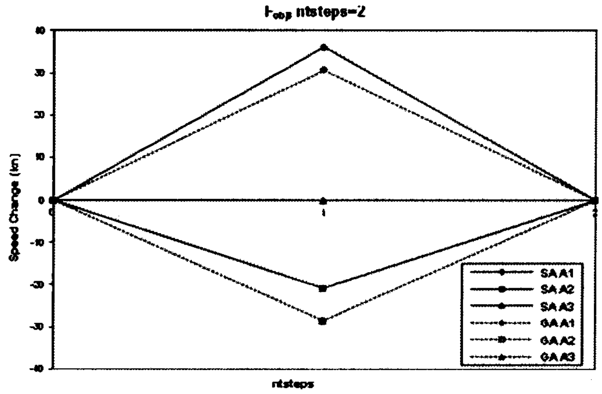

Fig.7 Conflict Avoidance Speed Changes for F_{obj3} (ntsteps = 2) from SA and GA

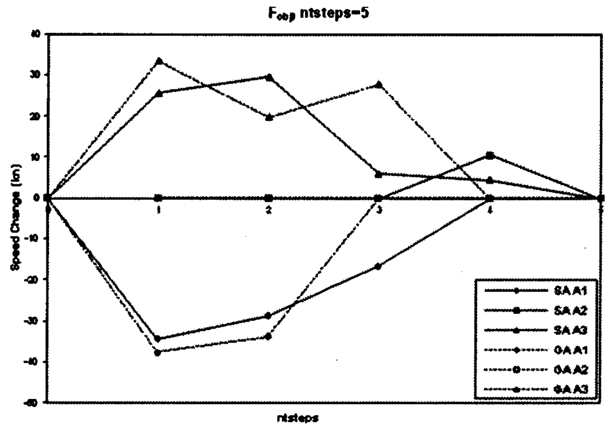

Fig.8 Conflict Avoidance Speed Changes for F_{obj3} (ntsteps = 5) from SA and GA