Optimizing Lateral Airway Offset for Collision Risk Mitigation Using Differential Evolution

Sameer Alam, Md. Murad Hossain, Fareed Al-Alawi, and Fathi Al-Thawadi

A majority of aircraft are now using Global Navigation Satellite System (GNSS) for navigation. This has led to an effect of reducing the magnitude of lateral deviations from the route center line and, consequently, increasing the probability of a collision, should a loss of vertical separation between aircraft on the same route occur. The International Civil Aviation Organization (ICAO) has introduced Strategic Lateral Offset Procedures (SLOP) that allow suitably equipped aircrafts to fly with 1nmi or 2nmi lateral offset to the right of airway centerline in oceanic airspace. Very few aircraft, however, are using the SLOP procedure because of the lack of understanding of its safety benefits and implementation issues in identifying correct lateral offset that can reduce the collision risk. This paper proposes an Evolutionary Computation framework using Differential Evolution process to identify optimal lateral offsets for each airway in a given airspace such that it reduces the overall collision risk. Airway specific lateral offsets are then correlated with airway-traffic features using Multiple Regression models to identify which features can explain the optimal lateral offset. The proposed approach establishes a generic mapping that can suggest optimal lateral offsets for a given airspace based on airway-traffic features to mitigate collision risk. The proposed methodology is applied to Collision Risk assessment of one-day traffic data (710 flights) in Bahrain Upper Airspace (FL290-FL410)

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to estimate optimal lateral offset that resulted in significant reduction of collision risk. Further, the number of flights and crossings on an airway were identified as key features affecting optimal lateral offset.

INTRODUCTION

Most modern airliners are now equipped with sophisticated navigation equipment that allows them to fly accurately on airway centerlines of the planned route. Global Navigation Satellite Systems (GNSS) such as the US’s GPS, the EU’s Galileo, Russia’s GLONASS, and China’s Compass provide position accuracy of 10 meters or better [ICAO, 2005]. Space-based augmentation systems, such as Wide Area Augmentation System (WAAS), improve GNSS accuracy to 3 meters [Hofmann-Wellenhof, B. et al., 2007]. This performance improvement has had the unintended consequence of increasing the probability of loss of vertical separation incidents, which, in turn, increases the risk of collisions [ICAO, 2007].

With large numbers of aircraft flying in the Reduced Vertical Separation Minimum (RVSM) airspace (29,000 ft to 41,000 ft, inclusive) the probability of loss of separation with other aircrafts flying on same routes nominally separated by 1000 ft vertical on adjacent flight levels can be very high [ICAO, 2008]. Two aircraft can have loss of vertical separation due to normal height deviations (Altimeter System Errors) or from large height deviations (level burst, wake turbulence, TCAS resolution, coordination failure, etc.) [ICAO, 2002]. The mid-air collision between an Embraer Legacy and a 737-800 over Brazil in 2006 [Almeida, I.M. et al., 2002] due to the Embraer Legacy aircraft’s assigned altitude deviation is such an example. Both aircrafts were flying, accurately on airway centerline, in opposite directions at the same altitude leading to collision. Given SESAR’s target of improving safety by a factor of 10 by year 2020 [EUROCONTROL, 2008], there is a need of innovative approaches in the manner that we manage our airspace and traffic flow to mitigate collision risk [Fowler, D. et al., 2007].

ICAO in PANS ATM Doc 4444 [ICAO, 2007] has proposed Strategic Lateral Offset Procedures (SLOP) in oceanic and remote airspace which allow aircrafts to fly with 1 nmi or 2 nmi lateral offset to the right of airway centerline on a suitably equipped aircraft (automatic offset tracking by flight management system [FMS]). SLOP provides an additional safety margin and mitigates the risk of traffic conflict when non-nominal events (normal or large height deviations) occur [ICAO, 2007]. SLOP procedure, however, has not resulted in the desired reduction in airspace collision risk for two main reasons:

- Limited implementation: SLOP is implemented in oceanic airspace only and few aircraft use this procedure. The North Atlantic Planning Group has recently expressed concern that not enough
Aircraft appear to be flying the offset procedure in the North Atlantic, thus negating, in part, the safety benefits [ICAO: North Atlantic Systems Planning Group]. Data collected by UK National Air Traffic Services (NATS), which provide ATC services in the eastern part of North Atlantic, show that less than 10% of aircraft are using the SLOP procedure due to lack of understanding of its safety benefits [Werfelman, L., 2010].

- Use of fixed offset in SLOP: The underlying idea behind SLOP was that a random application of the procedure would dramatically reduce the risk of loss of separation events. The key to this dramatic reduction in risk is the randomness of offset application. To create this randomness, aircraft operator procedures must not specify any one of the three offset options (centerline, 1 nmi, and 2 nmi). Most of the aircraft that fly SLOP elect to use fixed offset of 1 nmi, thereby defeating the underlying idea.

Further, no review has been undertaken of the implications of such offsets, and there exists minimal advice to pilots and guidelines to safety planners/ATC supervisors on such offset procedures and safety benefits [Rawlings, R., 2008].

Since the use of offsets could influence system safety there is a need to develop criteria enabling the identification of where and how offsets can be safely used, including any limitations that must be applied. Also, defining operational procedures and requirements for their application is needed to ensure that such offsets can be safely used.

Thus, the key research questions in this paper are: Instead of having a fixed lateral offset, can we achieve an airway specific lateral offset that can reduce the overall airspace collision risk. In other words, ways in which local level optimization can be achieved while managing the system level performance. Secondly, which airway and traffic features affects the optimal lateral offset value. This understanding may provide valuable insight into lateral airway offset decisions by safety planners and airline operators to mitigate collision risk in continental airspaces.

The large search space (possible solutions, i.e. lateral offset values for each airway in a continuous range) and interaction of collision risk model with airway and traffic features make traditional search methods unsuitable for this kind of problem [Alam, S. et al., 1997]. Nature-inspired techniques such as evolutionary computation [Fogel, D. and Michalewicz, Z., 1997] have emerged as an important tool to address complex problems effectively in the air transportation domain, in which traditional methodologies and approaches are infeasible.

In this paper we propose an evolutionary framework in which we use differential evolution [Storn, R. and Price, K.V., 1997], a population-based search approach, as lateral offset optimizer, air traffic simulator ATOMS [Alam, S. et al., 2008] as the simulator for a given traffic scenario, ICAO Collision Risk Model [ICAO 2008] as an evaluator of
collision risk, and multiple regression model as an identifier of correlation between airway-traffic features and optimal lateral offset.

This paper is structured as follows: we first present the proposed approach in an abstract manner. We then highlight the impact of lateral navigation precision on collision risk followed by some background on collision risk model, SLOP and differential evolution. We then outline the methodology, where we further detail the evolutionary framework to evolve optimal lateral offset for each airway. Experimental design is then presented along with different parameter settings using in collision risk model as well as differential evolution process. Results are then presented and summarized followed by discussions and some future directions for this work.

PROPOSED APPROACH

Figure 1 illustrates, in an abstract manner, the proposed approach. As shown, we assume that for a given traffic data, airspace and time period, its collision risk is assessed to be above a certain threshold (No Offset scenario). Applying fixed lateral offset of 1 nmi or 2 nmi
to the right of airway centerline may reduce collision risk (Fixed Offset scenario). Our approach is to design a framework that not only estimates the optimal lateral offset for each airway in the given airspace such that the overall collision is reduced, but also identifies the airway and traffic features that effect the offset value to predict the optimal lateral offset values without the need for an optimization process. This approach is important because any optimization process for such a large number of possibilities is inherently an expensive process (computation time and resources) and would be impractical to run frequently.

NAVIGATION PRECISION AND COLLISION RISK

RVSM safety assessment shows that the precision of lateral navigation is an important factor with regard to vertical collision risk [ICAO, 2010]. A general assumption is that 50% of the flying time is being made with GNSS navigation and the remaining 50% with VOR/DME navigation, while an extended use of GNSS navigation should have a risk increasing effect. For example, an increase of the GNSS flight time proportion to 75% would cause the estimate of the technical vertical risk to increase by a factor of approximately 1.5 nm [ICAO, 2010]. Therefore, the risk mitigating effects of lateral offset are significant.

Further, there is no practical difference between two aircraft colliding on a “fixed” airway and two aircraft colliding that are coincidently flying the same random route. Also, there is no difference between two aircraft colliding on a fixed airway or two aircraft colliding over the same random waypoint contained in each of their random routes. In each instance, the collision might be avoided if one, or both, aircraft is flying an offset.

BACKGROUND

Vertical Collision Risk

A mid-air collision between two aircraft nominally separated by 1,000 ft could occur only if either one or both aircraft were to deviate vertically from their assigned flight level such that the vertical separation between the aircraft is lost. There are two main reasons why an aircraft may not be at its assigned flight level: normal height deviations and large height deviations.

Normal height deviations arise because of typical assigned altitude deviation (AAD) and altimetry system errors (ASE), whereas large height deviations occur because of operational issues such as a level burst or TCAS alert. The focus of this paper is on normal height that occurs for purely technical reasons. Technical vertical risk is computed, using a mathematical model, using historic flight data
and takes into account, among several factors, the accuracy of navigation, the airway structure, the aircraft population, and the total flying time within the region.

**Strategic Lateral Offset Procedure (SLOP)**

SLOP are ICAO approved procedures [ICAO: PANS ATM, 2007] that allow aircraft to fly on a parallel track to the right of the center line relative to the direction of flight to mitigate the vertical overlap probability due to increased navigation accuracy and wake turbulence encounters in oceanic and remote airspace. As illustrated in Figure 2, the SLOP allows crews the discretion to fly either on the airway centerline or conversely offset to the right by maximum of 1 nmi or 2 nmi depending upon the spacing between route center lines (30 nmi or more) in oceanic or remote airspace.

The decision to apply a strategic lateral offset shall be the responsibility of the flight crew. The flight crew shall apply strategic lateral offsets only in airspace where such offsets have been authorized by the appropriate ATS authority and when the aircraft flight management system (FMS) is equipped with automatic offset tracking capability.

**Differential Evolution**

Differential evolution [Storn, R. and Price, K.V., 1997] is a stochastic, population-based optimization algorithm belonging to the class of evolutionary computation algorithms. Differential evolution algorithms are highly effective in optimizing real valued parameter (lateral

![Figure 2](image-url)  
**Figure 2.** Lateral offset and resulting safety buffer between two aircrafts with vertical position errors on a 1000 feet separation.
offset values in our case) and real valued function (minimize collision risk in our case). They are also highly effective in finding approximate solutions to global optimization problems (airspace collision risk in our case) [Price, K. et al., 2005].

**PROBLEM FORMULATION**

The problem formulation consists of two stages. First is the optimization stage, where the optimal lateral offset for each airway is determined such that overall airspace collision risk is minimized; the second is the correlation stage, where for a given optimal lateral offset of an airway, correlation, if any, with that airway and traffic features is identified such that the optimal lateral offset can be estimated. This is formulated as follows:

**Optimization Stage**

Given an airspace $Z$ with $J$ airways and traffic data $D_i$ where $i=1$ to $m$ where $m$ is the number of aircrafts flying through airspace $Z$, determine the lateral offset in the direction of traffic (right to the airway centerline) to maximum of $K$ NM in decimal latitude interval for each airway $N'$ such that it minimize the overall collision risk of the airspace $Z$. The Optimization function is expressed as follows:

$$\min f(CR)_z \text{ s.t. } g(N_z \rightarrow N'_z) \text{ where } N'_Z \in [0,K]$$

(1)

**Correlation Stage**

This stage determines the best set of parameters (airway and traffic features), such that the model predicts experimental value $y^*$ (lateral offset) of the dependent variable $y$ as accurately as possible. We also determine whether our model itself is adequate to fit the observed experimental data and check whether all terms in our model are significant. The function is expressed as follows:

$$y^* = b_0 + b_1x_1 + b_2x_2 + \cdots + b_nx_n$$

(2)

s.t

$$\text{Min } f(r_j) = y^*_j - y_j$$

(3)

Where $y$ is dependent variable (predicted by a regression model), $y^*$ is dependent variable (experimental value), $b_0$ is intercept (constant), $x_i(i=1,2,\ldots,n)$ is the $i$th independent variable from total set of $p$ variables, $b_i(i=1,2,\ldots,n)$ is the $i$th coefficient corresponding to estimated value and $j = 1, 2, \ldots, n$ are data points.
METHODOLOGY

Evolutionary Framework

The proposed methodology to evolve optimal lateral offsets for each airway in a given airspace such that it minimizes the overall collision risk is illustrated in Figure 3. There are two set of processes in the methodology illustrated with two different shaded schemes. The process components depicted in white color are of Air Traffic Simulation which evaluates a given traffic data for collision risk in airspace with lateral offset applied. The process components depicted in blue color are of Evolutionary Computation which involves Differential Evolution to evolve optimal lateral offset values using evolutionary operators.

In Evolutionary Computation process part, we first establish upper and lower bound for airway offset (in nmi). We then randomly initialize (within these bounds) a population of solutions representing a set of vector where the size of each vector is equal to number of airways i.e. each vector comprises of offset values for each airway in a given airspace. These vectors undergo mutation and recombination to generate two vectors which we call target vector and trial vector. These two vectors compete with each other with their set of offset values in the air traffic simulator. The vector which minimizes the collision risk for a given traffic data is admitted to the next generation and the process continues until maximum generation is reached. At this stage the best performing solutions (vectors) are selected from the final population.

Figure 3. Optimal Offset evolution methodology using air traffic simulator, differential evolution and collision risk model.
Biological Representation of Airway Offsets

The solution vectors are encoded into a genetic data structure (chromosome) to facilitate exchange and crossover of information in the evolutionary process of optimization. Each population of solution consists of several chromosomes, depending upon the population size, as illustrated in Figure 4.

Each chromosome represents a set of lateral offset values that would be applied to its each airway. For example, if there are n airways, then there will be n offset values in a given chromosome, one for each airway.

Airway Structure and Lateral Offset

We have chosen maximum lateral offset as 4 nmi right to the airway center line. We propose this value for continental airspace based on airway structure, illustrated in Figure 5, in radar control environment. This offset may be widened if midpoint between two NAVAIDS is more 51 nmi.

Figure 4. Chromosome design with offset values for each airway in the given traffic scenario.

Figure 5. Airway structure with 4 nmi spacing from airway centerline if distance between two VOR is less than 51 nmi.
The Differential Evolution Process

Given function $F$ to optimize with $D$ real parameters, first select the size of the population $N$ (it must be at least 4). The parameter vectors have the form:

$$x_i, G = [x_{1,i,G}; x_{2,i,G}; \ldots; x_{D,i,G}] i = 1, 2, \ldots, N.$$  \hspace{1cm} (4)

where $G$ is the generation number.

In the initialization phase we define upper and lower bounds for each parameter such that:

$$x^L_j \leq x_{j,i,1} \leq x^U_j$$ \hspace{1cm} (5)

The lower bound is set to 0.0 nmi; i.e., the centerline. The upper bound is 4.0 nmi, i.e., maximum proposed offset value in continental airspace. We then randomly select the initial parameter values uniformly on the intervals, $[x^L_j, x^U_j]$. After initialization each of the $N$ parameter vectors undergoes mutation, recombination, and selection.

In the mutation phase, which expands the search space, for a given parameter vector $x_{i,G}$ we randomly select three vectors $x_{r1,G}, x_{r2,G}$ and $x_{r3,G}$ such that the indices $i, r1, r2, \text{and} r3$ are distinct. We then add the weighted difference of two of the vectors to the third

$$v_{i,G+1} = x_{r1,G} + F(x_{r2,G} - x_{r3,G})$$ \hspace{1cm} (6)

The mutation factor $F$ is a constant from $[0,2]$. $v_{i,G+1}$ is called the donor vector.

Recombination incorporates successful solutions from the previous generation. The trial vector $u_{i,G+1}$ is developed from the elements of the target vector, $x_{i,G}$ and the elements of the donor vector, $v_{i,G+1}$. Elements of the donor vector enter the trial vector with probability $CR$.

$$u_{j,i,G+1} = \begin{cases} v_{j,i,G+1} \text{ if } \text{rand}_{j,i} \leq CR \text{ or } j = I_{rand} \\ x_{j,i,G} \text{ if } \text{rand}_{j,i} > CR \text{ and } j \neq I_{rand} \end{cases}$$ \hspace{1cm} (7)

$\text{rand}_{j,i} \sim U[0,1]$, $I_{rand}$ is a random integer from $[1,2,\ldots,D]$ and $I_{rand}$ ensures that $v_{i,G+1} \neq x_{i,G}$.

In Selection, the target vector $x_{i,G}$ is compared with the trial vector $u_{i,G+1}$ and the one with the lowest function value (Collision Risk) is admitted to the next generation.

$$x_{i,G+1} = \begin{cases} u_{i,G+1} \text{ if } f(u_{i,G+1}) \leq f(x_{i,G}) \\ x_{i,G} \text{ otherwise} \end{cases} \hspace{1cm} i = 1, 2, \ldots, N$$ \hspace{1cm} (8)

Mutation, recombination, and selection continue until some stopping criterion is reached (number of generations). The best individual is selected from the final population. This represents the optimal lateral
offset values for the airways that minimize the overall airspace collision risk.

**Airway Traffic Features**

In this paper, we have focused on upper airspace region (also known as RVSM airspace) for its significance in airspace collision risk assessment. Each flight level, which is vertically separated by 1000 ft, is treated as a unique airway. Even bidirectional routes are treated as unique (one for each side).

Based on our previous research in collision risk assessment [Alam, S. et al. 2013a; Alam, S. et al., 2013b, Alam, S. et al, 2012], we have identified following airway and traffic features as of interest in exploring correlation with the optimal lateral offset:

- **Airway distance (nmi):** great circle distance (nmi) from entry waypoint to exit waypoint including intermediate waypoints for a given airway.
- **Number of aircraft:** number of flights that fly on a given airway (each way independent).
- **Intermediate waypoints:** number of waypoints on a given airway between its entry and exit waypoint.
- **Average flying time (minutes):** average flying time of all the aircrafts on a given airway.
- **Airway crossings:** number of other airways that crosses a given airway. Bidirectional routes are counted as two crossings.

**Regression Analysis**

The objective of regression analysis is to predict some criterion variable better. The multiple regression model determines the best set of parameters \( b(b_0, b_1, b_2, \ldots b_p) \) in the model \( y_j = b_0 + b_1x_{1j} + b_2x_{2j} + \cdots + b_px_{pj} \) by minimizing the error sum of squares. These coefficients allow us to calculate predicted value of the dependent variable \( y \) (optimal lateral offset).

To make specific predictions using the model, we substitute the five airways and traffic features scores into the equation and then come up with the predicted lateral offset value. The difference in the predicted offset and the actual offset is called as residual error \( r_j \), which is the difference between the observed value \( y^* \) of the dependent variable for the jth experimental data point and corresponding value \( y^* \) given by the above regression model.

If there is an obvious correlation between the residuals and the independent variable \( x \) (say, residuals systematically increase with increasing \( x \)), it means that the chosen model may not be adequate to fit the experiment. A plot of residuals is very helpful in detecting such a correlation.
**EXPERIMENTAL DESIGN**

We first estimate the baseline collision risk for the given air traffic data. We then estimated collision risk with 1 nmi offset and 2 nmi to the right of airways for the given traffic data. Evolutionary framework was then employed with differential evolution to find optimal offset values for each airway along with associated airway-traffic features. Multiple Regression model is applied to come up with equation that can predict the optimal offset value given airway-traffic features.

**Airspace**

For the experiments we used one day’s traffic data (710 flights) from Bahrain airspace. The traffic data used were of Bahrain Upper Airspace, i.e. RVSM with flight level 290 to FL4190, inclusive. Thus, there were 13 flight levels. As we treated each airway uniquely (even bi-directional ones), in total there were 94 airways in the Bahrain airspace. Figure 6 illustrates the Bahrain airspace, which

![Bahrain RVSM airspace and airway structure used in the experiment.](image)
is characterized by three well-identified crossing meshes as seen in the figure.

**Lateral Overlap Probability**

For the Bahrain region it is assumed that 75% of flights are using GNSS, and 25% of flights are using VOR/DME for navigation. Following the RVSM global system performance specification, the standard deviation for VOR/DME navigation is taken as 0.3 nmi and a standard deviation of 0.06123 nmi will be used for the GNSS. i.e. $\sigma_{VOR/DME} = 0.3$ nmi and $\sigma_{GNSS} = 0.06123$ nmi.

**Collision Risk Model**

ICAO collision risk model [ICAO, 2008] is used to compute vertical collision risk. ICAO collision risk model is different than the basic Reich collision risk model because of the complexity and variability of the traffic patterns in most continental radar controlled airspace it accounts for. The model has three main parameters: the probability of vertical overlap, the frequency of horizontal overlap events per flight hour, and the weighted average of kinematic factors. The latter is the combined parameters dependent on the geometry of the proximate pairs.

**Differential Evolution (DE) Parameters**

For DE process the number of generations is set to 100, and the population size (individual solutions) is set to 30. This implies that for the traffic scenario there are 30 independent set of airways offset (in nautical miles) with the bound of 0 nmi to 4 nmi with 0.1 nmi for 710 flights, and the evaluation is repeated 100 times.

For the evolutionary process, the DE mutation parameter $F$ is set to 0.25. To find a proper crossover rate, we have performed experiments with different crossover rates. Figure 7 shows the best fitness value after the final generation for different crossover rate ranging from 0.05 to 1.0. From Figure 7, we found that the best fitness value is lowest for a crossover rate of 0.65. As a result, the crossover rate for the DE is set to 0.65 for subsequent analysis.

All experiments were run independently on the National Super Computing Facility with a cluster based on Intel Sandy Bridge 8-core processors (2.6 GHz) and 160 TBytes of main memory.

**Air Traffic Simulation**

For air traffic scenario simulation we have used Air Traffic Operations & Management Simulator (ATOMS). ATOMS is a high fidelity,
4D, point-mass model based, 5 degrees of freedom air traffic simulator developed by the lead author. The collision risk model is integrated into ATOMS such that every flight pair is evaluated, in each discrete time interval, for collision risk. Thus, ATOMS is used as the evaluation objective function for traffic scenarios: every time it is called with a scenario, it computes the collision risk and other parameters.

RESULTS AND ANALYSIS

The collision risk per flight hour for baseline traffic without any offset is $2.951 \times 10^{-7}$, with 1 nmi offset to the right is $3.01 \times 10^{-7}$, and 2 nmi offset to the right is $2.94 \times 10^{-7}$. We then present the how the evolution progressed over 100 generations. As shown in Figure 8, the evolutionary process manages to drive the population of initial solutions towards optimal solution (minimize the overall collision risk). Initially, the average collision risk, with randomly initialized lateral offset values in the interval of [0.0-4.0] nmi for each airway, was $2.06 \times 10^{-7}$ collisions per flight hour and the best solution in that population had the fitness value of $2.02 \times 10^{-7}$ collisions per flight hour.

By the hundredth generation, the upper limit on number of generation, the DE process appears to have converged, and the best solution has the average fitness for different run are reported in Table 1.

Table 1 illustrates the effectiveness of the DE process in evolving solutions (lateral offsets) for individual airways such that the overall collision risk of a given airspace and traffic data is minimized.

Table 2 tabulates the evolved lateral offset values, in the best individual of the final population, for 94 airways in the Bahrain airspace. The table also shows the airway and traffic features.
Figure 8. Convergence of differential evolution process over 100 generations.
(distance, intermediate waypoints, number of crossings, number of flights, average flying time). We then present the frequency chart for the offset values in the range of [0.0, 4.0] for the best individual of the evolved population after 100 generation. Figure 9 shows the number of occurrences of offset values for each value on the range discretized by 0.1 nmi.

Figure 10 shows that for 94 airways, the DE process has come up to an even distribution of offset values in the given intervals. This implies that evenly distributed lateral offset values result in minimizing collision risk in an airspace.

We then present results from multiple regression analysis. Table 3 presents the analysis of variance (ANOVA) analysis that provides the breakdown of the total variation of the dependent variable (lateral offset) into the explained and unexplained portions. SS regression is the variation explained by the regression line, which in our case is 9.8%, of which the number of flights (6.04%) and number of crossings (1.8%) are the main contributors. Out of 94 airways the model was able to predict in only five cases. The F-statistic is calculated using the ratio of the mean square (MS) regression; the positive F value in Table 2 indicates a positive correlation with the lateral offset value.

Table 4 presents the summary of regression statistics; the multiple correlation coefficient is 0.269646557. This indicates that the correlation among the independent and dependent variables is positive. This statistic, which ranges from −1 to +1, does not indicate the statistical significance of this correlation. The coefficient of determination, $R^2$, is 0.072709266. This means that close to 7.2% of the variation in the dependent variable (optimal lateral offset) is explained by the independent variables (airway-traffic features).

The standard error of the regression is 1.188 nmi, which is an estimate of the variation of the observed optimal lateral offset, in nmi, above the regression line.

The results of the estimated regression line include the estimated coefficients, the standard error of the coefficients, the calculated
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Continued
t-statistic, the corresponding p-value, and the bounds of 95% confidence intervals.

As shown in Table 5, the independent variables that are statistically significant in explaining the optimal lateral offset values are the
Figure 9. Number of offset occurrences in each discrete lateral offset interval in the [0,4] nmi range.

Figure 10. Consolidated frequency of offset values in the 0-1, 1-2, 2-3 and 3-4 nmi intervals.

Table 3. Analysis of Variance

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<tr>
<th>Source</th>
<th>Degrees of Freedom</th>
<th>Seq Sum of Squares</th>
<th>Adj Mean Square</th>
<th>F-Value</th>
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<td>Distance (nm)</td>
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<td>Intermediate Waypoints</td>
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<td>0.3</td>
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<td><strong>Error</strong></td>
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Proof Only

Table 4. Summary of Regression Statistics

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Table 5. Regression Coefficients

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<td>Constant</td>
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<td>Distance (nmi)</td>
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<tr>
<td>Intermediate Waypoints</td>
<td>−0.1331</td>
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<tr>
<td>Crossings</td>
<td>0.0222</td>
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<tr>
<td>Number of Flights</td>
<td>−0.01259</td>
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<tr>
<td>Average Flying Time</td>
<td>−0.0059</td>
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</table>

number of crossings and number of flights, as indicated by (a) calculated t-statistics that exceed the critical values, and (b) the calculated p-values that are less than the significance level of 5%. Thus, the regression equation is given by:

\[
\text{Evolved Offset (nmi)} = 1.809 + 0.00161 \text{ Distance (nmi)} \\
- 0.1331 \text{ Intermediate Waypoints} \\
+ 0.0222 \text{ Crossings} - 0.01259 \text{ Number of Flights} \\
- 0.0059 \text{ Average Flying Time}
\]

We then plotted the residual plots for number of crossings and number of flights as shown in Figures 11 and 12, respectively. As there is no obvious correlation between the residuals and the independent variable lateral offset (residuals do not systematically increase with increasing

![Crossings Residual Plot](crossings_residual_plot.png)

Figure 11. Error residual plot for number of airway crossings.
crossings and number of flights), it indicates that the chosen model may be adequate to fit the experiment.

CONCLUSIONS

The proposed evolutionary framework using differential evolution successfully evolved optimal lateral airway offsets such that the overall collision risk was minimized. An interesting observation was that evolved lateral offsets were evenly distributed in the respective lateral latitude bands. There was a weak correlation between airway and traffic features with only 7.2% of the variation in the dependent variable (optimal lateral offset) that can be explained by the independent variables. The number of flights and airway crossings were two features that correlated with optimal lateral offset with their error residual plots indicating usefulness of the model.

Applying airway specific optimal lateral offset in airspace may achieve the desired reduction in collision risk. Further, identifying airway and traffic features that effect the lateral offset may give airline safety and ATC managers an insight into how to manage traffic flow in their respective airspace.

In a high density radar controlled environment, however, lateral offsets may not significantly reduce the system safety as crossing traffic generates the dominant risk. In many parts of the Middle East region the route spacing is at or close to the minimum that can be supported by the navigation performance requirement. In our future work, we would investigate how the application of lateral offsets in such situations may increase the risk associated with the passing traffic on the neighboring track and how to mitigate it.

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of NCI Intersect Super Computing facilities to run the experiments. The content of this work does not necessarily reflect the official position of MIDRMA and/or ICAO.

ACRONYMS

AAD  assigned altitude deviation
ANOVA analysis of variance
ASE altimetry system errors
ATOMS Air Traffic Operations and Management Simulator
CR collision risk
DE differential evolution
FMS flight management system
GNSS Global Navigation Satellite System
ICAO International Civil Aviation Organization
MS mean square
NATS National Air Traffic Services
RVSM Reduced Vertical Separation Minimum
SLOP Strategic Lateral Offset Procedures
TAV target vector
TRV trial vector
VOR/DME Very High Frequency Omnidirectional Radar/Distance Measuring Equipment
WAAS Wide Area Augmentation system

REFERENCES

EUROCONTROL (2008), “ATC - SESAR 2020 Concept Mid-Term Validation (MTV) Episode 3.”
ICAO: A unified framework for collision risk modelling in support of the manual on airspace planning methodology with further applications (2008), circ 319-an/181, Canada.


ICAO: Implementation of Strategic Lateral Offset Procedures in the AFI Region (2010), AFI Planning and Implementatin Regional Group, APIRG/17 – WP/44.


Rawlings, R. (2008), The application of Offset Tracks in European Airspace, HindSight (6), EUROCONTROL.


BIOGRAPHIES

Sameer Alam received his Ph.D. in Computer Science from the University of New South Wales (UNSW) in 2008. He is a Lecturer in Aviation at the UNSW, Australian Defence Force Academy Campus in Canberra. His research interests are in Nature Inspired Computation and Multi-Objective Optimization applied to air transportation domain, focusing on safety, capacity, and environmental issues. He has been CI/Co-CI for EUROCONTROL’s Innovative Research project, AirServices Australia’s aviation emission project and the ICAO MIDRMA collision risk modelling project. He has published more than 40 peer reviewed research articles and won four best paper awards in premier ATM conferences (IEEE DASC 2010, ATM R&D 2011, ICRAT 2014 and ATM R&D 2015).

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**Fathi Al-Thawadi** is the Head of Aeronautical and Airport Operations, Civil Aviation Affairs, Bahrain. He received his diploma in air traffic control from Gulf Civil Aviation College Doha, Qatar, in 1983 and his M.S. in computing from the University of Glamorgan, UK in 2000. He was the Project Manager for Airport Operation Systems from 2003 to 2005. He is a member of the Middle East Regional Monitoring Agency (MIDRMA - ICAO), EUROCONTROL (Control Flow Management Unit – CFMU) and Arab Civil Aviation Commission.