An Impedance-Based Complexity Metric for Unmanned Aircraft System Traffic Scenario Classification

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This paper introduces an impedance-based metric to capture the complexity of a given unmanned aircraft system traffic scenario. The metric accounts for both the number of aircraft and the traffic flow pattern. The work presented here extends an earlier approach that introduced another scenario complexity metric based on the number of potential conflicts weighted by the conflict resolution cost associated. Complexity measurements for randomly-generated scenarios were produced through high-fidelity fast-time simulations and treated as baseline. Then the impedance based metric was evaluated, for the same scenarios, without the need for an actual flight simulation and a conflict resolution method. The results show that the impedance-based metric has a strong correlation to the baseline data and performs marginally better than the weighted conflict-based complexity metric introduced in the earlier work. The metric computation generates impedance maps which are useful for identifying high complexity regions in a scenario, where flight plan changes might be necessitated. This metric can therefore be used, in conjunction with other complexity metrics, to inform adequate traffic management strategies and classify a traffic scenario as acceptable, unacceptable or acceptable with changes made to flight plans that pass through the high complexity regions. The metric can also be used as a guidance metric for strategic conflict management methods.

I. Introduction

The airspace of the future is expected to support Unmanned Aircraft Systems (UAS) aircraft operations that are orders of magnitude higher than conventional aviation traffic the National Airspace System (NAS) handles today [1–3]. An important question is if there is a traffic density at which the airspace becomes too complex to operate. This paper presents an approach to estimate the complexity of a given UAS traffic scenario with an associated traffic density.

The availability of airspace to meet traffic demand in a safe and efficient manner is central to airspace operations both today and in the future with increasing number of unmanned and manned vehicles sharing the airspace with commercial air traffic. Measures of airspace complexity are used by air traffic management to schedule flights and resolve conflicts. New measures of airspace complexity are needed to make traffic flow decisions as controller workload limitations are enhanced or removed in certain parts of the airspace by increased automation.

In conventional aviation, air traffic complexity is evaluated from controller and pilot workload[4–7]. Monitor Alert Parameter (MAP)[8], the maximum number of aircraft an Air Traffic Control (ATC) controller can simultaneously handle, is an example. Another example is Dynamic Density (DD)[9, 10], a weighted summation of factors that affect the air traffic complexity. The complexity metrics are defined based on an assumption of a structured airspace and Air Traffic Management (ATM) that includes controller displays, sectors and airways[11–13]. Fast-time and real-time simulation methods [14] are then used to evaluate a given traffic scenario.

Intrinsic metrics have also been developed to estimate complexity in a sector independent of controller workload. Delahaye et. al. [15, 16] proposed a geometrical approach based on the properties of relative positions and relative speeds of aircraft in a sector to obtain time histories of traffic divergence, convergence, and sensitivity. They also developed entropy based velocity vector field methods [16, 17] to compute complexity maps for given traffic scenario snapshots.

Future UAS traffic and its management would differ from conventional traffic in several ways. First, the high number of proposed operations suggests a need to shift from a human to an automated controller, negating the use of cognitive

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measures. Second, future operations may be free flight by nature i.e. using a predefined on-board conflict resolution model, they may prefer responsibility for determining their course independent of a global plan or system[2, 18]. Furthermore, a good and quick approximation of UAS traffic complexity, without the need for a full-scale simulation, would support a real-time assessment of traffic scenarios[19], re-planning of flight routes and schedules to alleviate traffic bottlenecks, and mitigation of operation risk. A set of different complexity metrics can together also help classification of traffic scenarios for traffic management studies.

This paper extends an earlier approach by Xue [20] that introduced a scenario complexity metric based on the number of potential conflicts weighted by the associated conflict resolution cost. In this work, an impedance-based complexity metric is proposed. When the number of conflicts is high, a scenario is expected to be complex. However, it may not necessarily be so if those conflicts are isolated. The pattern of traffic flow also contributes to the complexity of the scenario, if the aircraft begin to impede the conflict resolutions of others in the airspace. The proposed impedance metric therefore accounts both for the number of conflicts and the free space available around aircraft in conflict. Furthermore, it simplifies the complexity computation process. First, the metric is tuned for a given type of aircraft and conflict resolution method, using high-fidelity simulation data as baseline. Then the impedance for new scenarios can be computed assuming the aircraft as point masses, without having to simulate the vehicle dynamics or actual conflict resolution maneuvers for each of the scenarios.

A high-fidelity fast-time simulator, Fe^3 [21], was used to simulate over a thousand randomly generated scenarios and measure the baseline for complexity. The impedance metric was then evaluated separately for the same scenarios and compared against the baseline data and the metric from previous study. The results showed that the correlation between the proposed impedance metric is better than the previous metric. It also produces impedance maps showing regions of high complexity which provides better spatial information for managing air traffic.

The rest of the paper is organized in the following way. The test scenario description, and the metric and its evaluation in detail are presented in Section II. Detailed results and discussion are presented in Section III. Summary of the paper, as well as identification of directions for further research is presented in Section IV.

II. Methodology

In this paper, the focus is on estimating the complexity of operations in a two-dimensional horizontal portion of airspace that has no constraints such as controlled airspace, temporary flight restrictions, geo-fences or terrain. In the next two sections, the test scenarios and the evaluation of the impedance metric are described in detail.

A. Test Scenarios

The test scenario generation remains the same as used in [20]. To evaluate the complexity metrics, random scenarios with a large variety of complexities were generated. Then the metric referred to as "number of resolution maneuvers" was evaluated in the Fe^3 [21] simulator. The high-fidelity simulator uses dynamic models of aircraft and a pairwise conflict resolution method that employs a combination of speed and direction changes to simulate the trajectories and encounters of aircraft typical to a real scenario. The aircraft are therefore actually diverting during close encounters instead of a prescribed course change. Using the simulation-generated measurements as the baseline for the complexity of the scenario, the proposed complexity metric, Impedance (I), was then analyzed and compared using statistical methods. Note, the number of conflict resolution maneuvers measures the resolution moves issued during the simulation. Since the time step size in Fe^3 is 0.5 seconds, the number of conflict resolution maneuvers also reflects the resolution duration.

For the generated scenarios, several criteria were used to ensure high traffic intensity and comparability in scenarios. First, a 1.3x1.3 nautical mile region was defined (shown as the red box in Fig. 1), and all flights were required to go through the predefined region with origin and destination outside of the region. Second, at most one turning point was allowed other than the origin and destination in a flight plan. Third, all flights were set to depart within a five-minute window. Lastly, this study focused on low-altitude small UAS traffic. Hence, the target ground speeds of all flights were set in the range of 5 meters per second to 20 meters per second. Fig. 1 shows a sample scenario with 30 vehicles, where the circle, cross, and diamond markers represent origins, destinations, and mid-points, respectively.

In [20], the number of aircraft in these scenarios was varied from 5 to 50 (or in density from 3 to 30 vehicles/nmi^2). Fig. 2 shows the percentage of scenarios with and without conflicts during the process of generating scenarios. When the traffic density increases, the likelihood of having conflicts increases and reaches 100 % at approximately 15

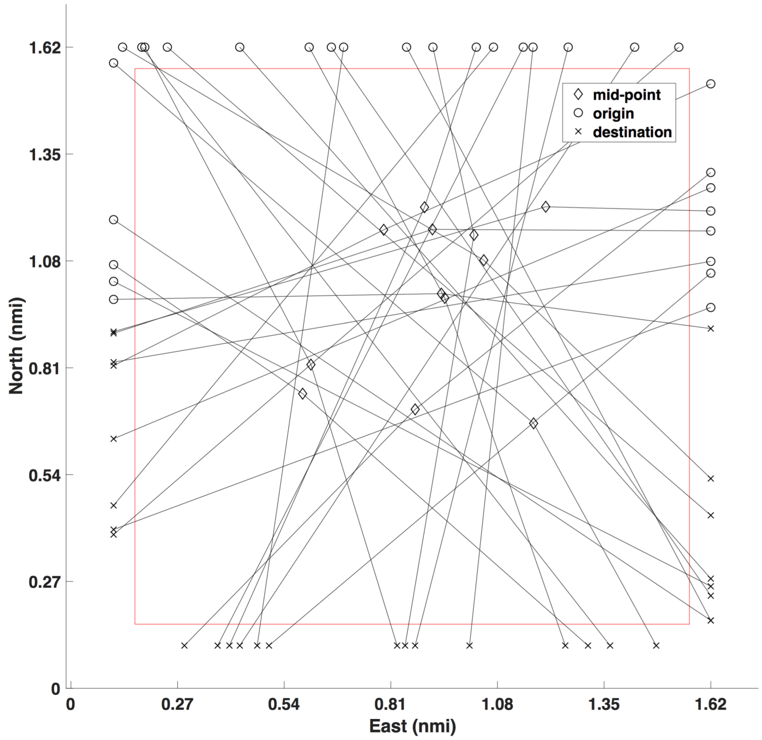

Fig. 1 A Sample Scenario with 30 flights

vehicles/nmi^2. Additionally, scenarios with aircraft densities from 50 to 100 were also generated in increments of 2. Consequently, a total of 1045 scenarios were created and used. From 5 to 50, 20 scenarios were generated at each level of density and from 52 to 100, 5 scenarios were generated at every alternate level of density. Scenarios without conflicts are defined as having zero scenario complexity based on the proposed metric. Therefore, only the scenarios with potential conflicts are used in experiments.

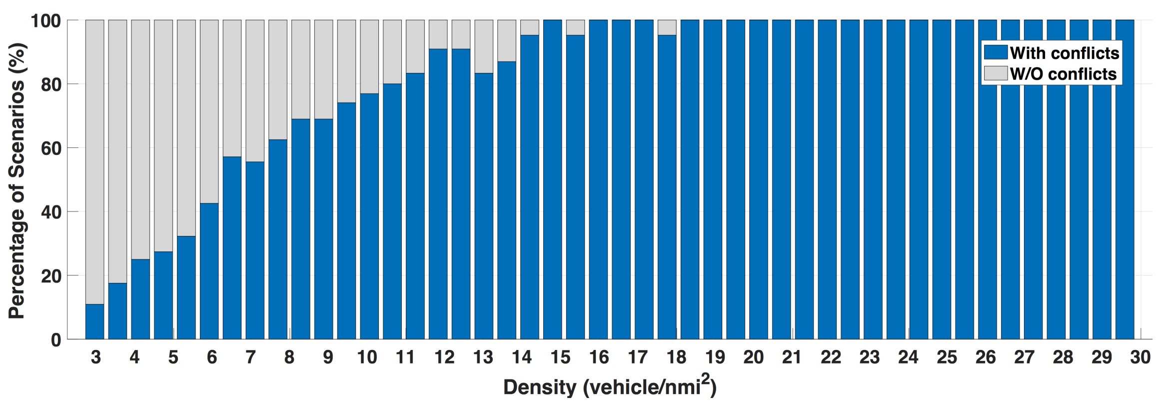

Fig. 2 Likelihood of Conflicts at Different Density Levels

B. The Impedance Metric and Its Evaluation

To evaluate the complexity of a scenario, first a notion of conflict is defined. Two aircraft are assumed to be in conflict at a given time if they are within a distance $h_{sep} = k.D_{wc}$ of each other, where D_{wc} is the well-clear distance (arbitrarily chosen at 50 feet or 15.24 meters) and k is a rational number (≥ 1) multiplication factor. h_{sep} is referred to as *Conflict Distance* in this paper. This approach is used to calibrate the Impedance evaluation to the region of influence of the conflict resolution method that would have been used in an actual traffic simulation.

For a given scenario, the Impedance metric is computed as follows:

Let R be the pre-defined region of interest in two-dimensional Euclidean space, i.e. R $\in \mathbb{R}^2$. Grid the region into square cells C_{xy} with a side length l, where x is the row number and y is the column number. Each cell has n adjacent cells C_{axy}, where $n \in [3, 5, 8]$ depending on the location of the cell (corner, edge, interior) in the grid. The letter a is used to denote adjacent. At each instant of time t_i in the entire duration of the scenario, compute the aircraft occupancy graph/map O_{t_i} =[O_{xy,t_i}], where O_{xy,t_i} is the number of aircraft in a cell at that time. Also, at each t_i, compute the aircraft conflict graph/map $C_{t_i,c}$ =[$C_{xy,t_i,c}$], the set of all cells that have at least one conflict in them. For each $C_{xy,t_i,c}$, let m of the adjacent cells $C_{axy,t_i,c}$ have at least one aircraft in them over the next dt seconds. This can be obtained for each adjacent cell by summing its occupancy, O_{xy,t_j} for $t_j \in [t_i + 1, t_i + dt]$.

The *Impedance of a Cell* in space (location xy) at time t_i, $I_{xy,t_i} = m/n$. Thus at each time instant t_i, there is a colored grid/map produced, called the *Impedance Map* I_{t_i} =[I_{xy,t_i}], where the color of a cell indicates its impedance $I_{xy,t_i} \in [0, 1]$. Now, to get a single snapshot of the region, the time slices need to be collapsed over the entire period of the scenario. This produces the *Impedance graph/map of the Scenario* I_{xy}. An example is shown in Fig. 3. This can be done by either taking the time mean or a percentile value of each cell's impedance. To understand the severity of impedance in each cell over the entire scenario, in this study, the p^{th} percentile value of $I_{xy,t}$ is used to collapse the graphs in time. Finally, to get a single impedance number for the whole scenario, both the space and time dimensions need to be collapsed. To do this, compute the percentage of cells in the time collapsed map with $I_{xy} \geq P$, where P is the chosen impedance threshold. This gives the *Impedance*, I for the entire scenario.

For example, suppose choosing the 99^{th} percentile value for time collapse and an impedance threshold, P = 20%, results in an impedance value of 0.3 for a scenario. This can be interpreted as - 30% of the region has conflicts that are impeded by nearby aircraft in one-fifth (20%) of the vicinity, 1% of the time. In other words, conflicts in almost one-third of the region are impeded in the scenario.

The metric computation uses two parameters: the conflict distance parameter k and the time window parameter dt. A set of traffic scenario complexities evaluated in a high-fidelity simulator like Fe^3, with a given conflict resolution model, is used to tune the impedance metric parameters to achieve the maximum correlation. Then, the tuned parameters can be used to evaluate the complexity for any new scenario (comprising the same type of aircraft and the same conflict resolution model) without the need for high-fidelity simulations. The metric captures the effect of aircraft dynamics and resolution models in its parameters. For example, an aircraft with low maneuverability will need more space and the conflict resolution method will have a high conflict distance when evaluating the baseline data in Fe^3. That in turn means the Impedance metric tuned for that type of aircraft and conflict resolution method will have a different value of k and dt where it is most correlated with the baseline data. In other words, the tuning of the Impedance metric parameters is tied to the type of aircraft and conflict resolution method that will be used in the real scenarios.

C. Assumptions

In addition to the scenario assumptions stated earlier, the chosen values of different parameters are defined as follows:

- The cell edge length $l = 100m$ ($0.054nmi$).
- For each scenario, impedance is computed by varying the k value between 1 and 5, to ensure that the conflict distance is less than the cell edge length.
- The time window dt is varied between 3 seconds and 17 seconds with 2-second increments. Since each aircraft flies at a speed between 5 to 20 meters per second, an aircraft will leave a cell anytime between the next time step to 20 seconds at most. Hence, time window values are chosen between those numbers, ignoring the smallest and largest values. On average it will take about 5 seconds to reach an adjacent cell.
- The percentile number p = 99.9. This is done to capture the worst impedances observed at every cell over the entire duration of the scenario.
- The impedance threshold P is varied from 10% to 80%. In other words, if 10% impedance is considered bad, having a third aircraft in the vicinity is considered bad and every moderate to bad cell will contribute to the scenario complexity. This is typically what might be considered bad in a realistic scenario today. On the other hand, if only 80% or more impedance is considered bad, only the worst of the bad cells will contribute. This could be the case for a highly futuristic scenario where multi-aircraft conflicts are operationally acceptable.
- Since this study focuses on scenario intrinsic complexity, uncertainties on wind, communication, navigation, and surveillance were not included in the simulations.

After the impedance metric for each scenario is evaluated, the Pearson method is used to compute the correlation

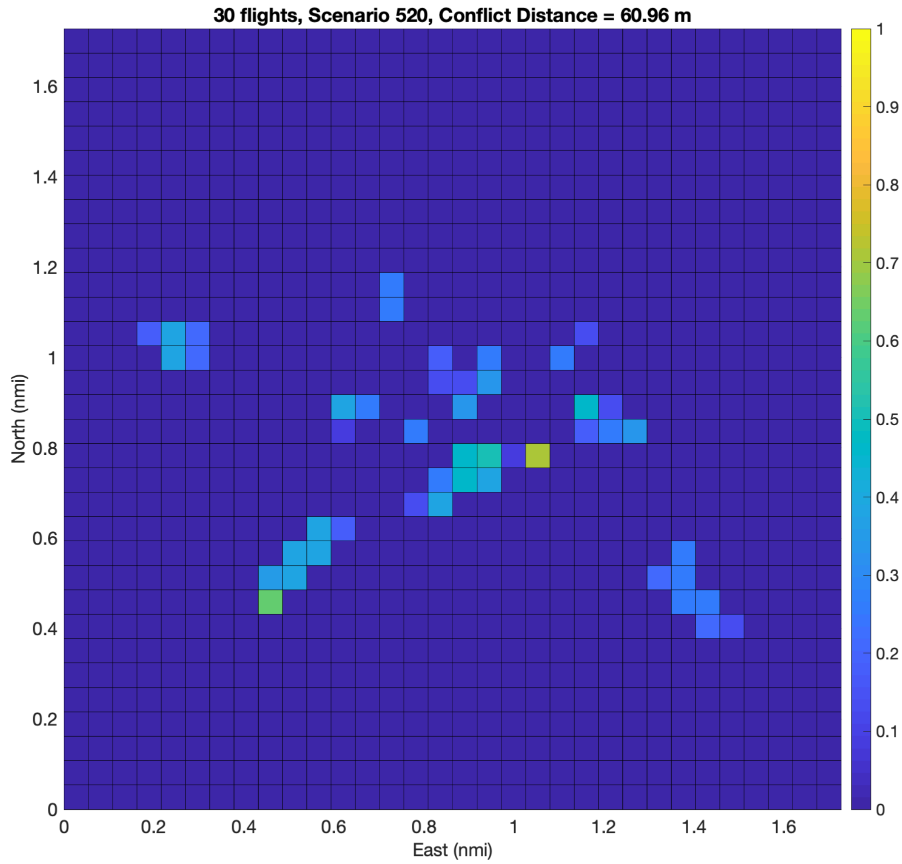

Fig. 3 The Impedance Map of the Sample Scenario with 30 flights at conflict distance, h_{sep} = $60.96m$, for a time window, dt = 5 sec

between the impedance measures and the number of resolution maneuvers (baseline) for each scenario. This varies as a function of the chosen k, P and dt values and is discussed under results. Furthermore, since the Pearson method is designed for checking linear correlations, a maximal correlation method[22] is also used to capture any non-linear association, and the Alternative Conditional Expections (ACE) method implemented in Matlab is used to compute such maximal correlations.

III. Results

Impedance maps were generated for each scenario at different conflict distances and time windows. For any given time window, two common trends were observed. For a fixed conflict distance, h_{sep}, as the traffic density was increased, the spread and value of the impedance increased (the cells became yellower/brighter) (Fig. 4). For a fixed traffic density, as the conflict distance was increased, again the spread and value of impedance increased (Fig. 5). However, the effect was less pronounced. This indicates that the metric is more sensitive to the traffic density than the conflict distance.

For computing the final impedance number for each scenario, the cell impedance threshold was varied from 10% to 80%. This was repeated at different conflict distances. For each time window, to determine the best combination of conflict distance and cell impedance threshold, correlations were computed between the impedance numbers and the baseline data. In general, as the conflict distance was increased, the peak correlation was observed at higher impedance thresholds. It was found that a conflict distance, h_{sep} of 75 feet and a threshold, P of 10% had the best correlation coefficient when compared with the number of resolution maneuvers from the actual simulation, irrespective of the time

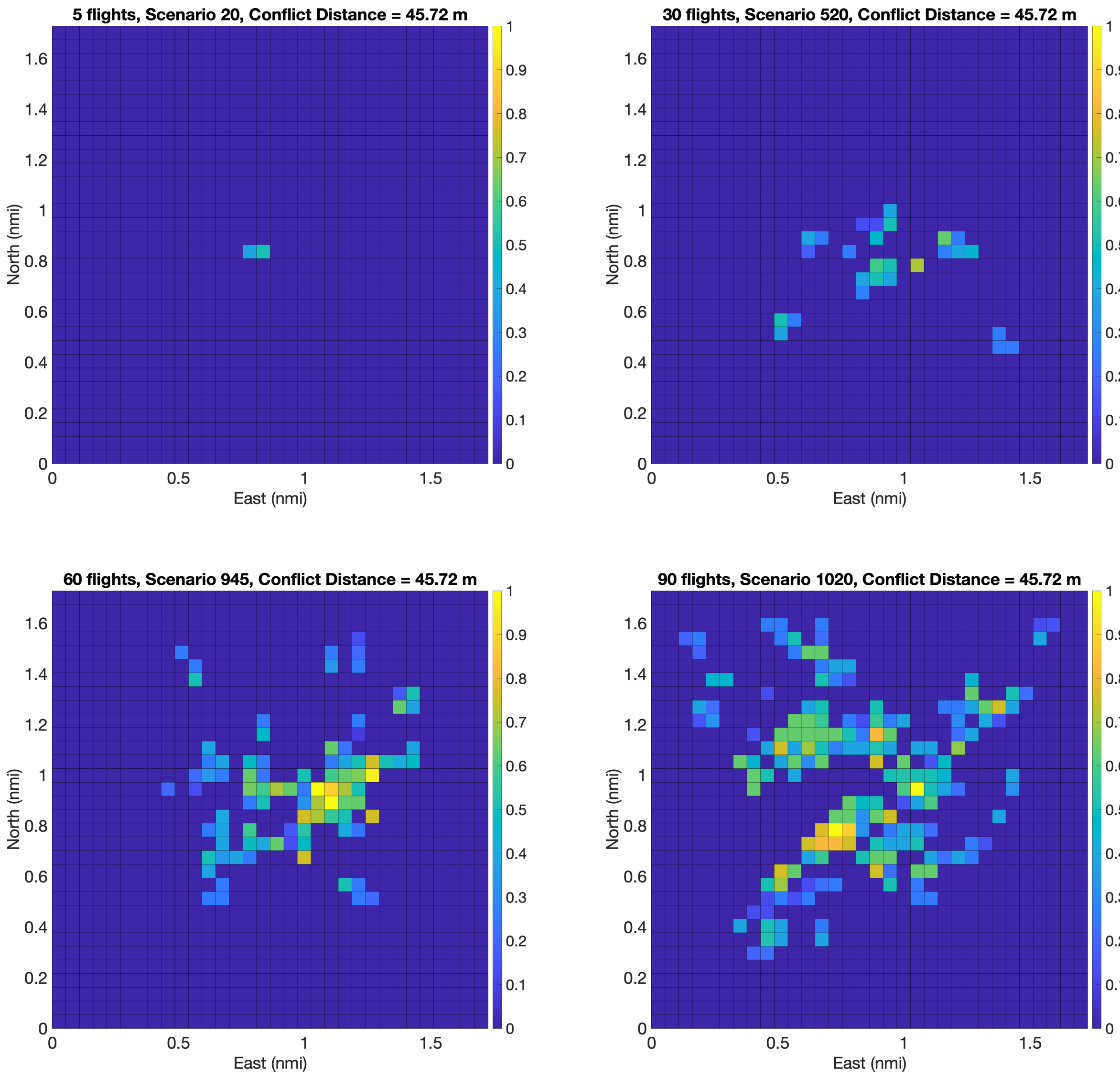

Fig. 4 Impedance maps with varying traffic density and fixed conflict distance, $h_{sep} = 45.72m$ for a time window, dt = 9 sec

window. As the time window was increased, the correlation improved up to a time window of 9 seconds, and then deteriorated. The best Pearson correlation observed was 0.9207 for the 9-second time window (Fig. 6). The correlation obtained for the same using the ACE method was 0.9325. The corresponding best correlation coefficients for the weighted conflict complexity metric from our earlier work were 0.9 and 0.913, respectively[20]. The impedance metric therefore performed better.

A. Discussion

The impedance metric serves two purposes. First, the space and time collapsed impedance of a scenario provides a single complexity number in the usual sense of measuring airspace complexity. It captures the impact of both number of conflicts, and the relative spatial distribution of aircraft in conflict with respect to other aircraft in vicinity, which could impede the performance of the conflict resolution strategy. Second purpose is the impedance map, which provides

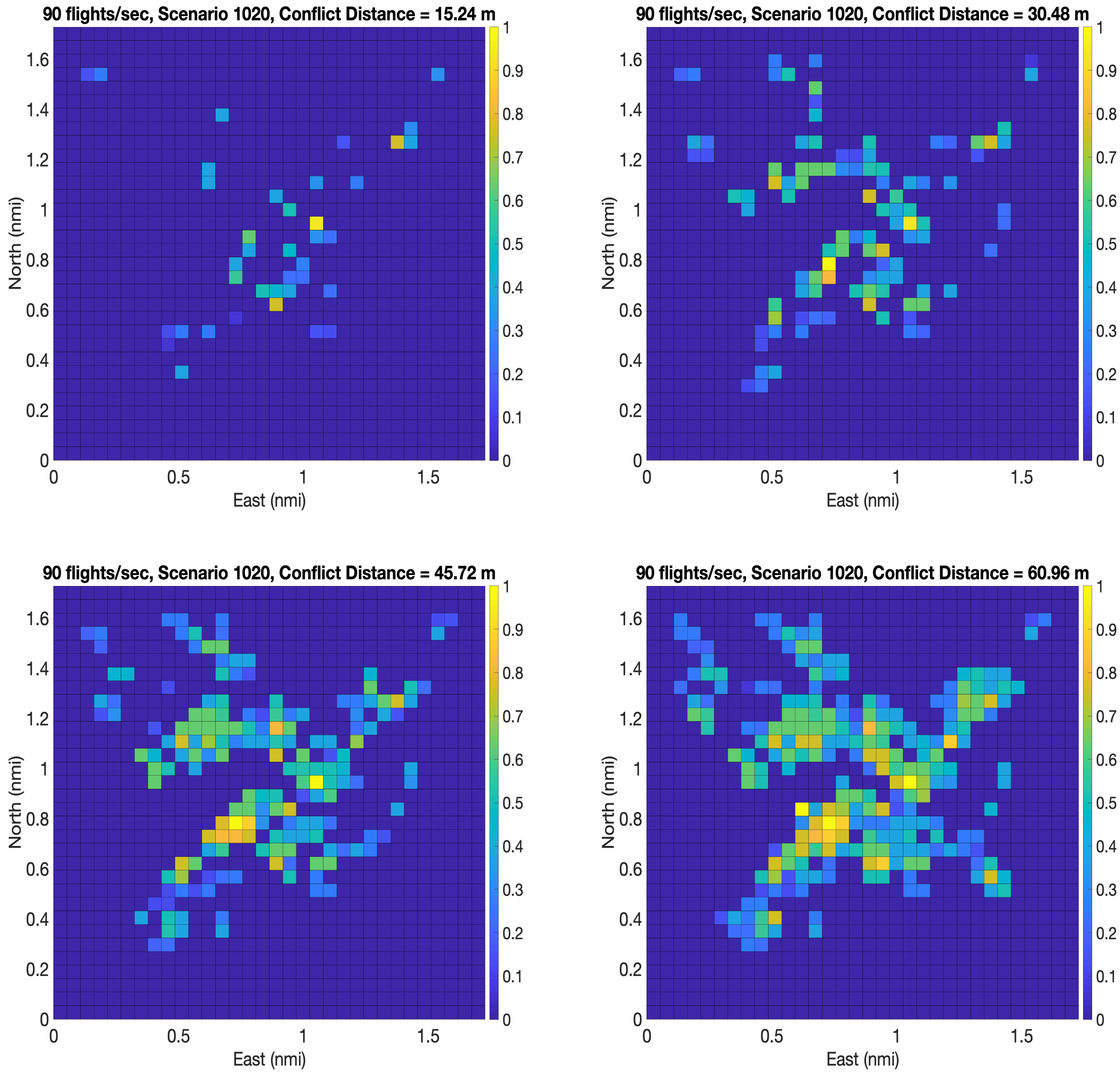

Fig. 5 Impedance maps with varying conflict distance, h_{sep} and fixed traffic density for a time window, dt = 9 sec

visual information to identify the hot spots: regions with limited conflict resolution capability in the scenario. This is useful in not only flagging a scenario as too complex but also pin-pointing where the problem is. Consequently, more informed air traffic management decisions can be taken. Suppose an arbiter runs a scenario and the impedance is above a threshold, then the maps show her where the hot spots are, and she could either deny the whole scenario, or just the flights which go through that area, or provide a reroute to flights going through hot spots, and so on.

IV. Conclusions

In this paper, an impedance-based metric was introduced to represent the complexity of a given unmanned aircraft system traffic scenario. There were 1045 scenarios analyzed, and their impedance metric was computed and compared against the baseline data produced from high-fidelity simulation. The metric was evaluated for varying conflict distances and traffic scenarios. It was found that the proposed metric had a high correlation of 0.92 (Pearson) and 0.9325(ACE)

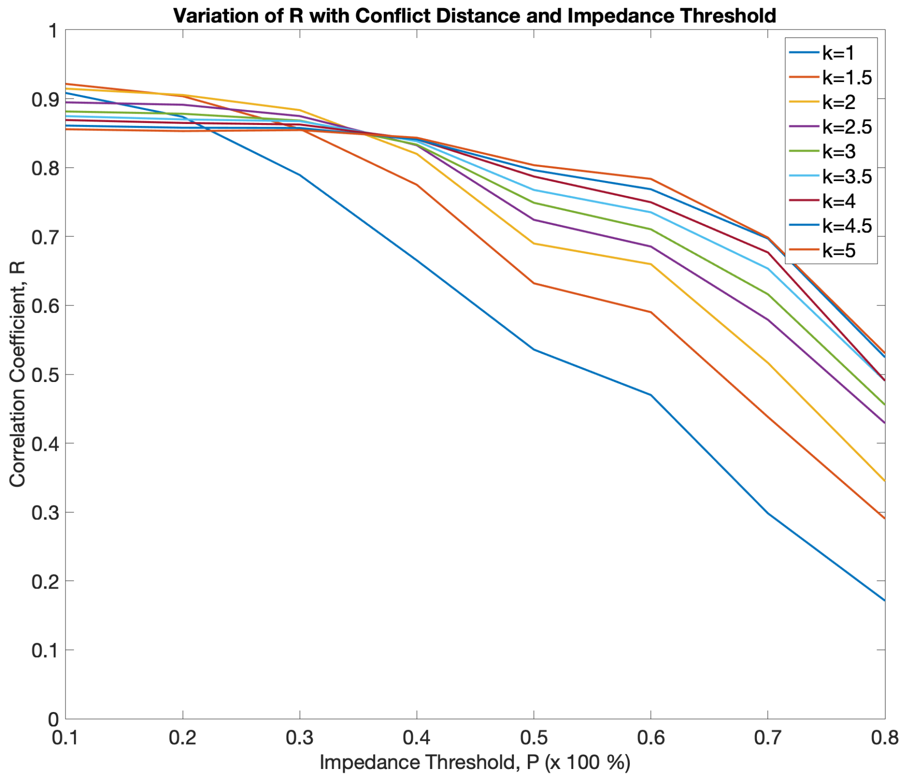

Fig. 6 Correlation between Impedance and Number of Resolution Maneuvers (baseline) as a function of conflict distance and impedance threshold at dt = 9 sec

with the baseline data.

Additionally, the metric provides a way to account for both the number of aircraft and the traffic flow pattern. The impedance maps produced as part of the impedance computation process identified areas of concern in a given scenario. Such information may be helpful for developing traffic management strategies such as adjusting and re-planning only flights that pass through the most impeded areas.

The air traffic services in a UAM environment may be provided by one or more operators. Each operator needs real-time tools to assess the safety and efficiency of operations and make adjustments to changing traffic demands. The impedance metric provides a tool to identify hot spots, regions with limited conflict resolution capability, in the airspace operations. It can therefore also be used to assess if and how the hot spots vary with uncertainties like sudden changes in demand, wind speed variations and low visibility. Similarly, it could be used to reallocate demand to maintain safety.

The results presented in this paper investigated the top 0.1% impedances in each cell for a scenario. In other words, the metric is only studying the worst 1 minute for every 1000 minutes in an area. Other levels of impedance can be explored further and tested against the baseline. Also, for this analysis, a fixed grid cell edge length was assumed. Grids with varying edge lengths could also be explored.

Finally, this work extends our earlier work that introduced a weighted conflict-based scenario complexity metric. The impedance metric performed marginally better than the weighted conflict metric. This is part of an extended effort to develop complexity metrics that can be computed in real time without the need for scenario simulation. This therefore can be used for jointly classifying a scenario as acceptable, unacceptable or acceptable with changes made to flight plans that pass through high complexity regions and then applying necessary air traffic management strategies.

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