A Tactical Conflict Resolution Method for UAVs in Geovectored Airspace

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***Abstract*—In order to enable the safe and efficient integration of Unmanned Aerial Vehicles into very low level airspace, current day research focuses on the development of new traffic services and procedures. One of these is the geovectoring protocol, which aims to reduce traffic complexity by setting limits on the allowed ground speed, course, and vertical speed. A geovector can be used to increase the capacity of an airspace by lowering the conflict rate. However, problems emerge when performing avoidance maneuvers in geovectored airspace, as the limits are ignored in this process. A powerful conflict resolution algorithm is the Modified Voltage Potential (MVP). This paper proposes an extension to the MVP algorithm, based on Velocity Obstacle theory. Making use of an alternative horizontal conflict resolution maneuver which respects the geovector, five resolution strategies are defined with different priority settings for the separate limits. The performance of these strategies is compared to pure MVP on geovector, safety, and stability measures, making use of fast-time simulations in a corridor airspace. All geovector resolution strategies show improvements on the ability to perform conflict resolution maneuvers within the geovector limits, while having marginal effects on the overall airspace safety level. It is recommended to further investigate the performance of the geovector resolution strategies for other types of airspace, to verify whether the observed reduction in conflict rate from the geovectors can be reinforced by the resolution strategies.**

I. INTRODUCTION

Rapid advancements in the technology of Unmanned Aerial Vehicles (UAVs) enable the use of this relatively new type of air traffic for various applications, such as public safety, maintenance, and parcel delivery. It is expected that roughly 7 million leisure drones and 400,000 commercial/government drones will be employed across Europe by 2050, where the majority will operate at altitudes below 150 meters [1]. Current estimates sit at over 78 thousand parcel-delivery drone and over 24 thousand food-delivery drone movements per hour for the metropolitan area of Paris by the year 2035 [2]. The safe and efficient integration of this new type of air traffic in urban areas, with high air traffic densities, is a key component of novel research on UAV airspace.

In Europe, new air traffic services and procedures are being developed for UAVs, called U-Space [3]. In order to accommodate the expected large number of UAVs, it is necessary to mitigate unsafe interactions between vehicles. Previous studies [4], [5] showed that reducing the relative velocity between vehicles lowers the conflict rate in the airspace. In order to achieve relative velocity reduction, a novel concept was proposed: the geovectoring protocol. A geovector aims to lower the conflict rate by reducing the relative velocity between aircraft. Specifically, a geovector consists of a set of limits on the allowed ground speed, course, and vertical speed of aircraft. These limits are implemented in a finite section of the airspace.

Jacobse [6] successfully implemented geovectors as a conflict prevention tool in converging traffic flows. In the experiments, conflict resolution maneuvers were always prioritized over abiding by the geovector rules. As a result, a negative correlation was observed between traffic density and the conflict rate reduction attributed to the geovectors. The increase in number of conflicts at higher traffic densities leads to an increase of geovector violations, as traffic must perform more conflict resolution maneuvers exceeding the limits.

This study aims to improve the effectiveness of the geovector rules by incorporating them into the process of conflict resolution in the horizontal plane. A conflict resolution maneuver is derived based on velocity obstacle theory. Five geovector resolution strategies are defined, with varying priority settings for the geovector constraints. The benefits of the resolution strategies are experimentally verified and compared on geovector, safety, and stability measures, for varying geovector settings. Experiments are performed using BlueSky, an open source air traffic management simulator [7].

The current paper is structured as follows. Section II introduces the most important topics from literature. The proposed method is presented in Section III, followed by a description of the experiment in Section IV. Section V presents the results from the experiments, followed by the discussion and conclusion in Sections VI and VII, respectively.

II. BACKGROUND

Sections II-A and II-B provide a brief summary of the geovectoring protocol and Conflict Detection & Resolution methods, respectively.

A. The Geovectoring Protocol

As indicated in Eq. 1, a geovector specifies minimum and maximum limits on the allowed ground speed, course, and vertical speed of aircraft. These rules are applied in a finite section of the airspace, being a function of latitude, longitude, and altitude [4].

$$\mathbf{V}_{geo} = \begin{Bmatrix} [GS_{min}, GS_{max}] \\ [\ \chi_{min}\ ,\ \chi_{max}\ ] \\ [VS_{min}, VS_{max}] \end{Bmatrix} = f(lat, lon, alt) \qquad (1)$$

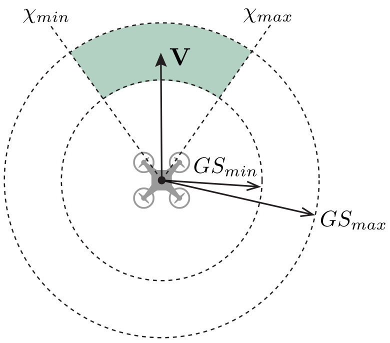

Figure 1. Illustrating the set of allowed velocity vectors (shown in green) constrained by the minimum and maximum geovector ground speed (GS) and course (χ) limits in the horizontal plane.

A geovector can be visualized in velocity vector space, showing the set of allowed velocity vectors. Fig. 1 indicates how limits are represented in the horizontal plane. For an arbitrary aircraft in a geovector area with velocity vector $\mathbf{V}$, ground speed limits (GS) can be visualized as circles centered at the point-mass representation of the aircraft, while course limits (χ) are represented by radials originating at the aircraft. The set of allowed velocities is represented by the area enclosed by the limits, colored green in Fig. 1.

B. *Conflict Detection & Resolution*

In order to prevent collisions, a safe zone is defined around each UAV which should not be entered by other UAVs. This this so called Protected Zone (PZ) is shaped like a disc with radius equal to the horizontal separation minimum (S_h) and height twice the vertical separation minimum. An *intrusion* occurs when a UAV passes through the PZ of another UAV. A *conflict* is a predicted intrusion which will happen within a certain lookahead time.

The process of Conflict Detection and Resolution (CD&R) is aimed at detecting conflicts and performing a maneuver to maintain a safe separation distance. A wide variety of methods has been developed for this purpose [8]. The present study is aimed at decentralized separation methods, each UAV will perform CD&R without involvement of centralized air traffic control. The process consists of three major steps, which are separately addressed below: detection, resolution, and recovery. The UAV performing CD&R is referred to as the *ownship*, any other UAV is called an *intruder*.

In the present study, conflicts are found by means of state-based trajectory propagation, which only relies on sharing of the current state of UAVs (position and velocity). Linear extrapolation of state-information up to the lookahead time provides linear predicted flight paths for all UAVs. If the flight path of the UAV will cross the boundary of an intruder PZ within the lookahead time, a conflict warning is issued.

In order to resolve a conflict before an intrusion occurs, an avoidance maneuver is performed. A commonly applied method for decentralized separation is the Modified Voltage Potential (MVP) [9]. The ownship computes a velocity vector change by dividing the predicted amount of PZ intrusion by the time left to perform the maneuver. The solution for the conflict is found by adding the velocity change to the initial velocity of the UAV. In case of multiple conflicts occurring at once, the ownship finds one solution by summing the velocity vector changes for each individual conflict. MVP results in the smallest possible theoretical path deviation for a conflict [10].

Finally, the solution for the conflict needs to be maintained until the UAVs have actually passed each other. The current study employs the two-criteria recovery method from [11] to determine when it is safe for the ownship to revert back to its desired velocity.

III. Method

The direction and magnitude of the velocity change vector dictated by MVP is solely determined by the geometry of the conflict. It is not ensured that geovector limits are respected in the process of conflict resolution. This section describes an alternative resolution method, which aims to solve a conflict within the constraints imposed by the geovector limits.

A. *An Alternative Conflict Resolution Maneuver*

A useful tool to visualize the set of solution velocities for a conflict is the Velocity Obstacle (VO) [12], [13]. A VO represents the set of ownship velocities yielding a conflict with the intruder. Any velocity vector outside the VO would resolve the conflict, assuming the velocity change would be instantaneous and the intruder does nothing.

The VO can be combined with the representation of a geovector shown in Fig. 1. In Fig. 2, an arbitrary conflict is depicted from the perspective of the ownship, the intruder is not shown for simplicity. The set of ownship velocity vectors allowed by the geovector is shown in green, a VO is constructed in grey. Let $\mathbf{n}_d$ represent the unit vector pointing from ownship position to intruder position. Furthermore, let $\mathbf{n}_t$ represent the unit vector parallel to the side of the VO corresponding to coordinated conflict solutions [14]. Finally, $\mathbf{V}_{int}$ represents the intruder velocity vector.

In order to solve the conflict, the ownship should apply a velocity change such that its velocity vector $\mathbf{V}_{own}$ is pushed outside the VO. As illustrated, the velocity change computed using MVP ($\Delta\mathbf{V}_{\text{MVP}}$), which is orthogonal to the relative velocity [9], pushes $\mathbf{V}_{own}$ beyond the maximum GS limit of the geovector.

Nevertheless, a subset of the allowed geovector velocities is conflict free for the example in Fig. 2. In order to ensure the conflict solution is implicitly coordinated, no resolution maneuvers should cross the span of the unit vector $\mathbf{n}_d$, as these would not end up at the closest leg of the VO. Let this set of uncoordinated velocity vectors be denoted as U and the set of allowed geovector velocities as G. Finally, let the set of coordinated conflict solutions within the geovector limits be denoted as SOL, shown in dark green in Fig. 2. The latter is defined as shown in Eq. 2.

$$SOL = G \setminus (VO \cup U) \tag{2}$$

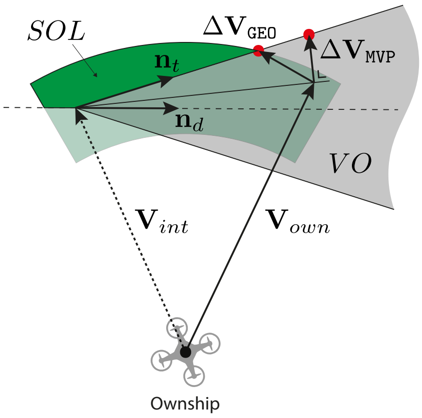

Figure 2. Illustration of the set of coordinated conflict solutions for the ownship within the geovector limits, denoted by SOL in dark green. In this example, the velocity change dictated by the MVP maneuver ($\Delta\mathbf{V}_{\texttt{MVP}}$) will lead to a violation of the geovector limits. An alternative conflict resolution maneuver can be defined within the geovector limits, denoted by $\Delta\mathbf{V}_{\texttt{GEO}}$.

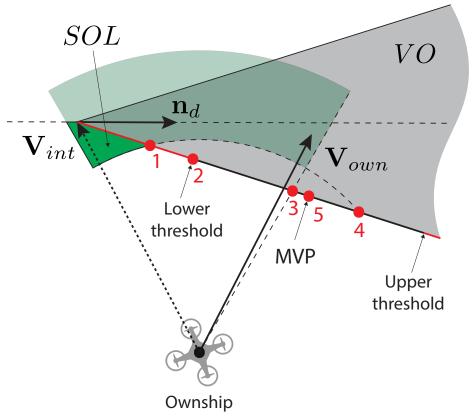

Figure 3. Categorization of alternative resolution maneuvers for geovector resolution strategies *ALL* (1), *LIM* (2), *CRS* (3), *GS* (4), and *NONE* (5). The resolution strategies are aimed at mitigating the negative effects of very large state changes corresponding to the GEO maneuver.

In case the solution set SOL is not empty, an alternative conflict resolution maneuver can be defined within the geovector limits. Let this geovector maneuver be denoted by "GEO". In order to prevent over-solving the conflict, the alternative maneuver GEO is chosen such that the ownship velocity vector ends up on the coordinated leg of the VO. Therefore, any coordinated solution for the ownship ($\mathbf{V}_{own,sol}$) can be expressed as the sum of the intruder velocity and $\mathbf{n}_t$ times a positive scalar c, as shown in Eq. 3. Here, c represents the magnitude of the relative velocity after resolution.

$$\mathbf{V}_{own,sol} = \mathbf{V}_{int} + c\mathbf{n}_t \tag{3}$$

As previously mentioned, MVP results in the smallest possible theoretical path deviation for a conflict. Therefore, the alternative resolution maneuver GEO is chosen such that the difference along the leg of the VO with the resolution vector for MVP is minimized ($||c_{\text{MVP}} - c_{\text{GEO}}||$). Applying this logic for the example conflict displayed in Fig. 2, the solution for the ownship velocity vector using the GEO maneuver is found at the intersection between the leg of the VO and the maximum ground speed limit, as shown in the figure. Note that, in case the MVP maneuver does not lead to a violation of any geovector limit in the first place, the GEO maneuver simply coincides with the MVP maneuver.

B. Five Resolution Strategies

The available solution space within the geovector can vary significantly depending on the conflict geometry. In order to prevent executing GEO maneuvers which require excessively large state changes, thresholds are installed indicating the maximum allowed deviation along the coordinated leg of the VO. Again, a comparison is made with the MVP maneuver. A minimum and maximum threshold are set at 50% and 150% of the magnitude of the relative velocity after the MVP maneuver would be performed (c_{MVP}). The effects of setting a threshold on the solution space are visualized in Fig. 3, where the parts of the leg where solutions exceed the threshold are colored red. If the GEO solution exceeds one of the thresholds, the maneuver is rejected:

$$\text{Strategy} = \begin{cases} \text{Accept}, & \text{if } \frac{1}{2}c_{\text{MVP}} \leq c_{\text{GEO}} \leq \frac{3}{2}c_{\text{MVP}} \\ \text{Reject}, & \text{otherwise} \end{cases}$$

Once the GEO maneuver satisfying all limits gets rejected, multiple alternative maneuvers can be executed. Five resolution strategies are created in the present study, the corresponding maneuvers are visualized in Fig. 3:

1) **ALL:** The ownship will still pick the GEO solution (satisfying all limits), even though it exceeds a threshold.
2) **LIM:** The solution is clipped to the threshold, such that it is not exceeded.
3) **CRS:** The ground speed limits are ignored to find an alternative maneuver within the thresholds. If not found, the resolution strategy will default to the MVP solution.
4) **GS:** The course limits are ignored to find an alternative maneuver within the thresholds. If not found, the resolution strategy will default to the MVP solution.
5) **NONE:** The MVP solution is chosen when GEO exceeds a threshold.

Finally, in case the available solution space within the geovector limits is empty, all geovector resolution strategies will default to the MVP maneuver for the pairwise conflict under consideration.

C. Total Resolution Ruleset

Using the GEO maneuver is only necessary when the MVP maneuver leads to a violation of the geovector limits. This also holds when the ownship is in conflict with multiple intruders at once. MVP finds one overall solution by summing the resolution vector for each separate intruder (conflict pair). Therefore, it is possible that the final solution does not violate any limit while the solutions for the individual conflict pairs do. In this case, the MVP solution can be accepted for every conflict pair.

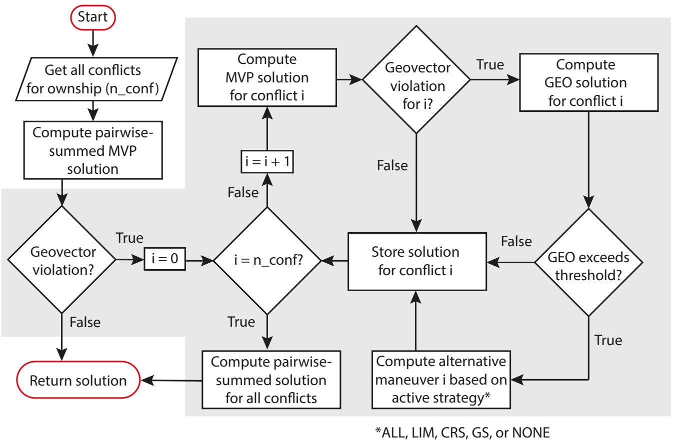

Figure 4. Conflict resolution ruleset integrating alternative maneuvers in the process of MVP. The additional ruleset taking into account the geovector limits is covered in grey.

Fig. 4 indicates the conflict resolution process performed by each UAV. The grey area represents the extra ruleset proposed in the present study. First of all, all conflicts for the ownship (conflict count = `n_conf`) are returned by the conflict detection algorithm. Using only MVP, one solution is found for all conflicts by summing the resolution vectors for each conflict pair. Subsequently, it is checked whether this pairwise-summed solution will lead to a violation of the geovector limits. If not, the solution can be returned. Otherwise, the algorithm will consider each conflict separately.

For each conflict, it is checked whether the MVP solution corresponding to that conflict pair will lead to a violation of the geovector limits. If it does not, the MVP solution will be stored for this conflict. Otherwise, the GEO maneuver is computed, satisfying all limits. It is checked whether this maneuver exceeds the threshold. If so, an alternative maneuver is determined based on the geovector resolution strategy that is applied. The alternative maneuver is stored for the current conflict. After all conflicts have been considered, one solution is found by summing the separate resolution vectors for all conflict pairs.

D. Steering Hierarchy

The conflict resolution algorithm is incorporated in the total steering ruleset using the following hierarchy:

1) **Geofence avoidance:** avoid forbidden flight areas
2) **Conflict resolution:** avoid other UAVs
3) **Autopilot:** satisfy geovector limits
4) **Autopilot:** fly to next waypoint

While performing a geofence avoidance maneuver, the UAV ignores all conflicts with other UAVs and the autopilot directions. The autopilot directions are also ignored while performing a conflict resolution maneuver to avoid another UAV. Finally, geovector rules are prioritized over the flight plan.

The current study uses a geofence avoidance method based on [15]. Assuming a geofence in the shape of a polygon, a VO can be constructed around the outermost vertices of the shape. Subsequently, a course change is applied to the side of the VO, which corresponds to the closest difference between target course (next waypoint) and avoidance course. Once the ownship has reached the corresponding vertex, it reverts back to its target course [6].

IV. EXPERIMENT DESIGN

This chapter provides a description of the design of the experiments, used to verify the effectiveness of the proposed conflict resolution ruleset in geovectored airspace.

A. Simulation Platform

Simulations were performed in the open-source Air Traffic Management Simulator ”BlueSky” [7]. The autopilot model for the UAVs has been updated to include geovector constraints and an area avoidance functionality. The proposed conflict resolution ruleset has been implemented in a seperate plug-in. The source code can be found in [16].

B. Airspace Design

A corridor airspace was used, based on [6]. The layout is shown in Fig. 5. The experiment area was shaped like a circle with a radius of 1500 m, centered on coordinate with latitude 0°N and longitude 0°E. Two geofences, shown in red in the figure, were implemented in order to create an airspace corridor through the center of the experiment area. The width and length of the corridor were set to 400 m.

The area where the experiment data was collected was also shaped like a circle, but with a radius of 1200 m. The margin between the experiment area boundary and the data logging area boundary was implemented in order to account for instantaneous conflicts when the UAVs were spawned.

The airspace was subdivided into several geovector sectors. This sector division is shown in Fig. 5. Sector 1 and 3 correspond to the converging and diverging parts of the airspace, respectively. Sector 1 extends from the corridor entry up to the boundary of the data logging area, sector 3 from the corridor exit up to the circle with radius 700 m. They were subdivided into parts A-F. Sector boundaries were defined by the bearing from the center of the experiment area relative to the true north, as indicated in the figure. Sector 2 represents the corridor section at the center of the airspace.

C. Flight Route Assignment

The flight direction for all UAVs was from south to north, through the corridor section (sector 2). UAVs were spawned randomly (with a uniform probability distribution) on the south boundary of the experiment area. They were assigned a random destination (with a uniform probability distribution) north of the experiment area. UAVs were automatically deleted when exiting the experiment area. Three sets of intermediate waypoints were defined with one waypoint at the corridor entry and one waypoint at the corridor exit: west (W1, W2), center (C1, C2), and east (E1, E2). The waypoints were spaced 100 m in the easterly direction, such that the 400 m wide

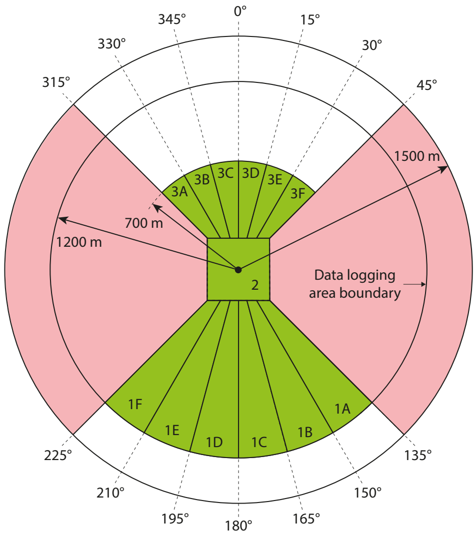

Figure 5. Layout of the airspace, showing geofences in red and geovector sectors in green.

corridor entry and exit were divided into four equal parts. Each UAV selected one waypoint set to fly through the corridor section.

D. Control Variables

The following control variables were used in the experiments:

- Lookahead time for the conflict detection module, both for other UAVs and geofences, was set to 10 s.
- Required separation minimum (S_h) between UAVs was set to 25 m.
- Flight altitude was set to 100 m.
- Each UAV was assigned a random autopilot speed (with a uniform probability distribution) on interval [7,13] m/s, which was kept constant during the entire flight.
- Traffic spawn rate was set to 720 UAVs per hour.
- Corridor width and length were both set to 400 m.
- One UAV type was used, the DJI Matrice 600, with reachable airspeeds between -18 m/s and 18 m/s.

E. Independent Variables

Two independent variables were used in the experiments:

1) **Conflict resolution strategy**: pure MVP (baseline), as well as the five geovector resolution strategies (ALL, LIM, CRS, GS, NONE). Furthermore, a case without conflict resolution was included for airspace stability measures.
2) **Geovector settings**: five combinations of GS interval and χ interval, where the interval is specified as the difference between the maximum and the minimum limit. Three combinations were identified with severe (SEV), medium (MED) and wide (WIDE) limit intervals, as well as the extremes for ground speed (EXT-GS) and course (EXT-CRS). Corresponding [min, max] limits in each of the geovector sectors can be found in Tables I and II.

- **SEV**: GS interval 1 m/s, χ interval 15°
- **EXT-GS**: GS interval 1 m/s, χ interval 45°
- **MED**: GS interval 3 m/s, χ interval 30°
- **EXT-CRS**: GS interval 5 m/s, χ interval 15°
- **WIDE**: GS interval 5 m/s, χ interval 45°

The five geovector settings allow comparison of all resolution strategies for varying limits. The seven resolution methods and five geovector settings were combined into 7x5 = 35 combinations. For each combination of independent variables, 50 experiments were performed. Per experiment, data was logged over a period of 1 hour, using a 10 minute build-up time before data logging was started.

TABLE I. [MIN, MAX] GROUND SPEED LIMITS IN ALL GEOVECTOR SECTORS FOR VARYING GROUND SPEED INTERVAL SIZES

Interval size	Ground speed limits
1 m/s	[9.5 m/s, 10.5 m/s]
3 m/s	[8.5 m/s, 11.5 m/s]
5 m/s	[7.5 m/s, 12.5 m/s]

TABLE II. [MIN, MAX] COURSE LIMITS PER GEOVECTOR SECTOR FOR VARYING COURSE INTERVALS SIZES

Sector	Course interval size 15°	30°	45°
1A, 3A	[315°, 330°]	[315°, 345°]	[315°, 0°]
1B, 3B	[330°, 345°]	[315°, 345°]	[315°, 0°]
1C, 3C	[345°, 0°]	[345°, 15°]	[315°, 0°]
1D, 3D	[0°, 15°]	[345°, 15°]	[0°, 45°]
1E, 3E	[15°, 30°]	[15°, 45°]	[0°, 45°]
1F, 3F	[30°, 45°]	[15°, 45°]	[0°, 45°]
2	[352.5°, 7.5°]	[345°, 15°]	[337.5°, 22.5°]

F. Dependent Measures

The following dependent measures were included in the study. For all measures, a resolution strategy is deemed to perform better when values are lower:

- $\%\text{manv}_{GS}$: The percentage of resolution manuevers in geovector sectors chosen outside the ground speed limits.
- $\%\text{manv}_{\chi}$: The percentage of resolution maneuvers in geovector sectors chosen outside the course limits.
- n_{conf}: The (filtered) number of conflicts per experiment run. A filter was applied on the number of conflicts to account for noise in the data coming from repetitive conflicts. A conflict for a unique UAV pair re-occurring within 15 seconds was not counted again, except if a conflict with another UAV occurred in the meantime (secondary conflicts should be counted) or if a different geovector sector was entered [17].
- n_{intru}: The number of intrusions per experiment run.
- DEP: The stability of the airspace is measured using the Domino Effect Parameter (DEP) [18], which indicates the number of secondary conflicts that emerged in the airspace. Let the number of conflicts with conflict resolution on be denoted by n_{conf}^{ON} and without conflict resolution by n_{conf}^{OFF}. For the latter, the unfiltered conflict count is used, since repetitive conflicts do not occur without conflict resolution. The Domino Effect Parameter

is computed as shown in Eq. 4. Positive values indicate a destabilizing effect of a resolution method, as performing resolution maneuvers triggers secondary conflicts. It is possible that negative values are observed as well, showing a stabilizing effect.

$$DEP = \frac{n_{conf}^{ON}}{n_{conf}^{OFF}} - 1 \tag{4}$$

G. Hypotheses

The following hypotheses were posed for the current research:

HP-1: All geovector resolution strategies reduce the percentage of conflict resolution maneuvers chosen outside the ground speed limits and course limits, compared to pure MVP.

HP-2: All geovector resolution strategies increase the overall airspace safety level compared to pure MVP.

V. Results

Data is shown in the form of box plots. Wilcoxon signed rank-tests have been performed to verify differences between the geovector resolution strategies and pure MVP [19]. Wilcoxon p-values are reported for statistically significant differences, using a significance level of $p < 0.01$.

The percentage of resolution maneuvers chosen outside the ground speed limits is shown in Fig. 6. All geovector resolution strategies resulted in a significant reduction of percentages compared to pure MVP ($p < 0.001$). Resolution strategy ALL showed the lowest values on this measure for all geovectors under consideration. Furthermore, resolution strategies LIM and GS resulted in lower percentages than methods NONE and CRS for almost all geovectors. An exception is found for geovector WIDE, where only GS appears to result in a lower percentage of ground speed violations.

Fig. 7 shows the percentage of maneuvers which were chosen outside the course limits. Again, all geovector resolution strategies show a significant reduction in values compared to pure MVP ($p < 0.001$). Percentages are lowest for resolution strategy ALL. Furthermore, it can be observed that resolution strategy CRS resulted in a smaller portion of maneuvers exceeding the course limits than NONE, LIM, and GS for geovectors with narrow ground speed interval (SEV and EXT-GS). These differences are less notable when the ground speed interval is increased. Furthermore, LIM appears to result in lower percentages than NONE and GS for geovector EXT-GS, while the opposite is observed for geovector EXT-CRS.

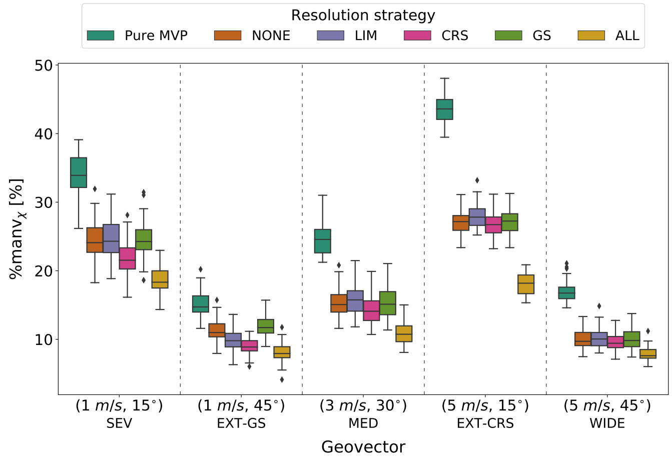

Figure 7. Percentage of resolution maneuvers chosen outside the course limits (%manv$_\chi$)

Fig. 8 shows the (filtered) total number of conflicts observed over the hour long data logging period. A positive correlation can be observed between the overall conflict count for any resolution method and the size of both ground speed and course intervals. For the combination of airspace layout and geovectors used in the experiments, ground speed limits appear to induce a greater reduction in conflict count than course limits (consider the differences between geovectors EXT-GS, MED, and EXT-CRS).

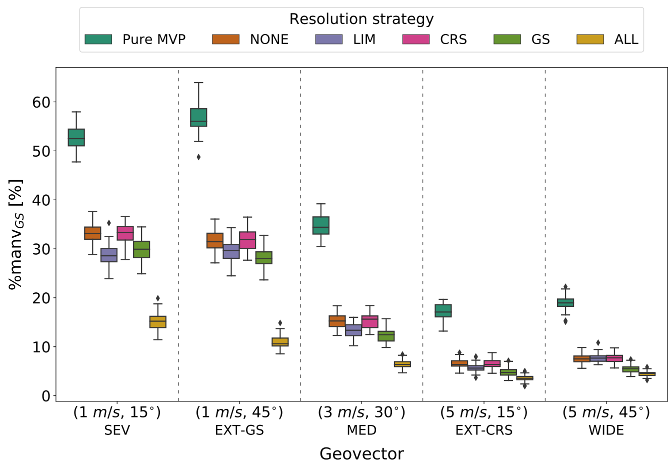

Figure 6. Percentage of resolution maneuvers chosen outside the ground speed limits (%manv$_{GS}$)

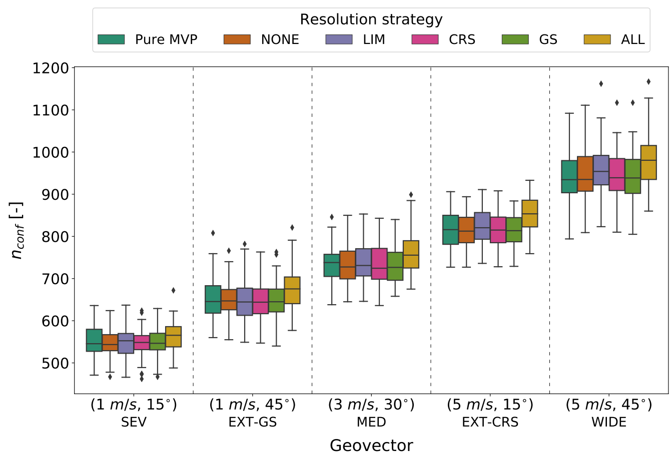

Figure 8. Number of conflicts (n_{conf}) over the logging period of 1 hour (repetitive conflicts are filtered out)

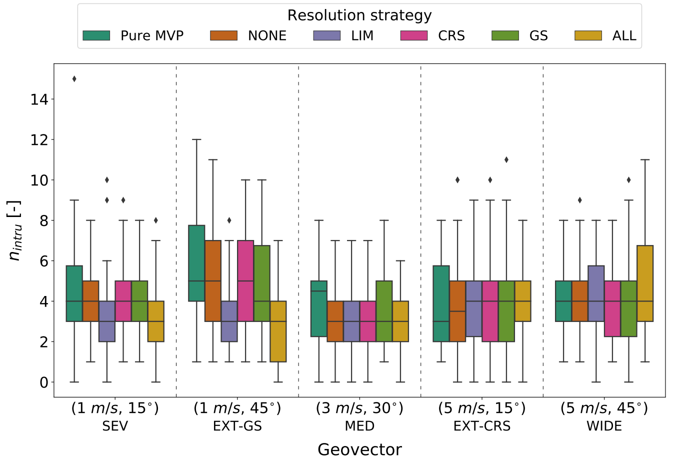

Figure 9. Number of intrusions ($\mathbf{n}_{intru}$) over the 1 hour data logging period

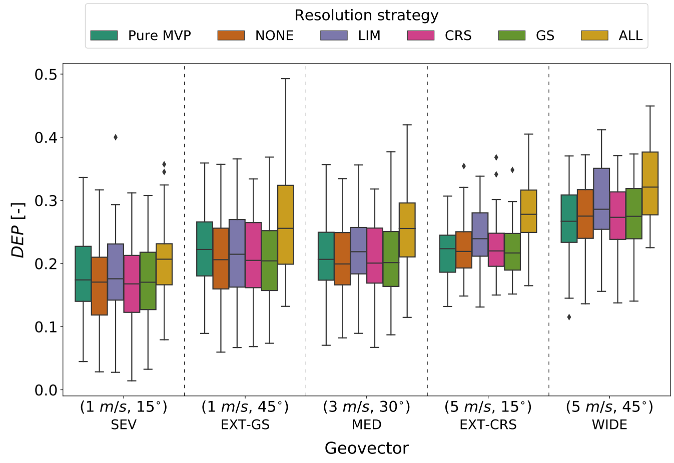

Figure 10. Domino Effect Parameter (DEP)

Considering the resolution methods for each geovector separately, statistical analysis shows a marginal but significant increase in number of conflicts for resolution strategy LIM compared to pure MVP for both geovectors with wide ground speed interval (EXT-CRS and WIDE) ($p \leq 0.002$). Furthermore, resolution strategy ALL shows a statistically significant increase in number of conflicts for all geovector settings ($p \leq 0.006$).

Fig. 9 shows the total number of intrusions observed over the data logging period. First of all, the geovector resolution strategies appear to reduce the number of intrusions, compared to pure MVP, for small ground speed interval sizes. Statistical analysis shows that resolution strategy LIM induces a significant reduction in number of intrusions compared to pure MVP for geovectors EXT-GS and MED ($p \leq 0.002$). Furthermore, resolution strategy ALL also resulted in a reduction of intrusion count for geovectors SEV, EXT-GS, and MED ($p < 0.001$). No significant differences were observed for the other data samples, when compared to pure MVP.

Finally, the Domino Effect Parameter is shown in Fig. 10. First of all, it can be observed that all resolution strategies have a destabilizing effect on the airspace, as all recorded values are positive. Compared to pure MVP, the DEP increases slightly using LIM for geovectors EXT-CRS and WIDE ($p \leq 0.002$) and using ALL for all geovector settings ($p \leq 0.006$). Nevertheless, observed effects are marginal, as the boxes in Fig. 10 mostly overlap. No geovector resolution strategy significantly reduced the DEP compared to pure MVP.

VI. DISCUSSION

The results of the experiments show interesting behavior, which was not always as expected. Two hypotheses were posed for the present research, separately assessed hereafter.

Regarding the percentage of conflict resolution maneuvers chosen outside the geovector limits, all geovector resolution strategies show a clear reduction compared to pure MVP, both for ground speed limits (Fig. 6) and course limits (Fig. 7). Hypothesis *HP-1*, which states that all geovector resolution strategies reduce the percentage of maneuvers exceeding the geovector limits, can therefore be accepted.

Hypothesis *HP-2* states that all geovector resolution strategies increase the overall airspace safety level compared to pure MVP. Fig. 9 does show a reduction in number of intrusions for geovectors with small ground speed intervals. Nonetheless, considering Fig. 8, the effect of the resolution strategy on the number of conflicts appears to be very marginal. The geovector resolution strategies did not result in a lower number of conflicts for any geovector. Considering geovectors with wide ground speed limit interval size, ALL and LIM showed a small increase compared to the pure MVP method. Furthermore, observing Fig. 10, resolution strategy ALL and LIM showed a marginal increase in measured values for the Domino Effect Parameter for geovectors with wide ground speed limit interval size. Larger state changes for conflict resolution increase the likelihood of secondary conflicts occurring, since a larger portion of the airspace is searched for new conflicts [5]. Considering all results, *HP-2* stating that all geovector resolution strategies increase the overall airspace safety level, is rejected.

Considering that the MVP maneuver represents the most optimal solution for a conflict in terms of path deviation, it can be said that the UAVs perform less efficient conflict resolution maneuvers in an effort to abide by the geovector rules. Indeed, a conflict of interests can be observed with regards to the objective of the geovector. On the one hand, a greater reduction in relative velocity brings about a greater reduction in conflict rate [4]. Nevertheless, once a conflict does emerge, choosing the most optimal solution is more beneficial in terms of preventing secondary conflicts.

Considering the bigger picture, the reduction in conflict rate caused by the geovector is not reinforced by the geovector resolution strategies, for the specific airspace design used in the present study. Nevertheless, the geovector resolution strategies show improvements regarding the ability to satisfy the geovector limitations in the process of conflict resolution, especially for geovectors with small interval sizes. Furthermore, negative effects on the overall airspace safety level appear to be marginal, compared to pure MVP. For geovectors with strict ground speed intervals, intrusions even occurred less frequently using the geovector resolution strategies. It can therefore be stated that the geovector resolution strategies achieve their intended goal: resolving conflicts while taking into account the geovector limits.

VII. CONCLUSIONS AND RECOMMENDATIONS

The present paper introduced the existing literature gap on the combination of the geovectoring protocol and conflict resolution methods. In an effort to incorporate geovector limits into the process of conflict resolution, an alternative resolution maneuver was derived based on Velocity Obstacle theory. Using this maneuver, five geovector resolution strategies were developed, which assign different priorities to the individual geovector limits. Fast-time air traffic simulations were performed to compare the proposed resolution strategies to pure MVP in high-density UAV airspace. Comparisons were made on geovector, safety, and stability measures.

The results indicate that the geovector resolution strategies show improved ability to adhere to the geovector rules while performing conflict resolution maneuvers, compared to pure MVP. Furthermore, observed effects of the geovector resolution strategies on the overall airspace safety level are marginal, indicating the strategies are feasible as conflict resolution method. This enables the use of the geovectoring protocol as a tool to structure UAV airspace, where UAVs are able to avoid each other without ignoring the geovector limits.

It is necessary to further assess the geovector resolution strategies separately, in order to better understand the behavior observed in the current study. It is also recommended to investigate the performance of the geovector resolution strategies for other airspace configurations, since the available maneuvering space for a UAV highly depends on the limits that are imposed. An important parameter to consider is the traffic spawn rate, which was held constant in this study.

Finally, the simulation of UAVs was assumed to be turbulence and wind free. Furthermore, it was assumed that the required state-information (position and velocity) for conflict detection and resoluton was noise free and instantly available to all other UAVs in the airspace. These assumptions might not closely represent reality. It is therefore recommended to further investigate the effects of these assumptions on the resolution strategies and geovectors used in the experiments.

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