Analysis of Conflict Resolution Methods for Manned and Unmanned Aviation Using Fast-Time Simulations

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***Abstract*—In the coming years, aviation will have to cope with an increase in the number of aircraft, and of drones purchased in the open market. The human intervention of Air Traffic Management (ATM) will be overburden with guaranteeing flight safety with hundreds of manned aircraft and Unmanned Aerial Vehicles (UAVs) operating simultaneously. Conflict Resolution (CR) models are under research, aiming at relieving the workload of ATM services and to enable UAVs to fly safely in the civil airspace. However, these are tested using different simulation tools and scenarios, making it impossible for a direct comparison. This paper compared the performance of commonly used CR methods under the same conditions both for manned and unmanned aviation. Disparities with previously conducted research using different scenarios show the importance of creating a standardized simulation library. Additionally, under the traffic scenarios considered, velocity obstacles (VO) based methods obtained a better performance safety-wise.**

***Keywords*—Conflict Detection and Resolution (CD&R), Air Traffic Management (ATM), U-Space, Self-Separation, Velocity Obstacles (VO), BlueSky ATM Simulator**

I. Introduction

Recent studies show that Europe had 11 million flights in 2018 and may expect an average annual growth rate of 2.0% between 2019 and 2025 [1]. Such numbers raise concerns regarding safety in high traffic densities. Air Traffic Management (ATM) is responsible for detecting and avoiding possible conflicts in all phases and informing the crew of a possible avoidance maneuver. However, ATM support is limited to the number of air traffic controllers (ATCO). Increasing this number is not an easy task, due to the necessary extensive personnel training, and the financial costs involved. One of the solutions aimed at reducing the need for ATCOs are automated CD&R mechanisms. These are capable of informing the crew of both conflict risks and proper resolution maneuvers without direct ATM involvement.

Moreover, the aviation field must prepare for the introduction of large numbers of mass-market drones. These must be capable of conflict detection and resolution (CD&R) without human intervention. The Federal Aviation Administration (FAA) ruled that an Unmanned Aerial Vehicle (UAV) must have Sense & Avoid capability in order to be allowed in the civil airspace [2]. Additionally, the International Civil Aviation Organization (ICAO) requires UAV CD&R models to be capable of detection and avoidance in both static and non-static environments. Only after meeting this requirement, will civil-UAVs be allowed to fly beyond the operator's visual line-of-sight [3].

The last comparison and discussion of CD&R methods for manned aviation was in 2000 by Kuchar [4]. Since then, several newly improved models have been developed, including a new branch of CD&R models directed at unmanned aviation. Fast-time simulations are commonly used to test these models. Unfortunately, no standard exists on how to produce the simulation scenarios. Final results are often not comparable as they are highly dependent on these scenarios. Such makes it difficult to determine the best potential method and to define a single standardized approach. More recently, Jenie [5] proposed a CD&R classification aimed at unmanned vehicles. Nevertheless, no analysis has yet been done regarding the behaviour of CD&R models for high traffic densities of unmanned vehicles. Without the latter, we cannot defined how CD&R models should develop towards guaranteeing safety in the future of aviation.

The goal of this paper is to identify which CR characteristics favor conflict resolution by directly comparing CR models within the same conditions. Fast-time simulations are performed using open-source, multi-agent ATM simulation BlueSky [6]. Note that the results obtained are dependent on this tool and the chosen scenarios. The CD&R models are used for both manned and unmanned aviation, as it is also relevant to examine the differences between the two. Unmanned aviation offers certain degrees of freedom: possibility of hovering and turning directions faster, which could potentially enhance the performance of a CR model.

II. Minimum Separation

Generally, an intrusion occurs when minimum separation is lost. While a loss of separation (LOS) does not always represent a future collision, it means that two aircraft are closer than the accepted safety distance. Conflict avoidance systems thus aim at preventing entering another aircraft's area of minimum safe separation. When a loss of separation is predicted to occur in the future, this is called a conflict. Once a conflict is detected, the aircraft is deviated towards a deconflicting path.

The value of the minimum safe separation may depend on the density of air traffic and the region of the airspace. However, most CD&R studies use ICAO's [7] definition of 5 NM horizontal separation and 1000 ft vertical separation. For unmanned aviation, there's no pre-defined standard separation distance; although 50 m is a value commonly used in research [8].

In Fig. 1, distance R represents the radius of the protected zone (PZ). The distance at the closest point of approach (CPA) represents how close the aircraft are expected to get. If it is predicted that aircraft will, in the future, be at a distance $d_{CPA} < R_{PZ}$, a conflict has been detected. CR models must then act to modify the aircraft's movement as to avoid LOS.

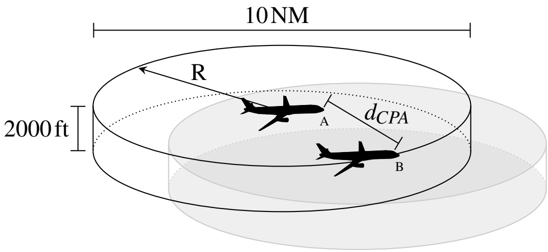

Figure 1. ICAO's self separation: 5 NM horizontal separation and 1000 ft vertical separation. Loss of separation has occurred.

III. Conflict Detection

A state-based conflict detection will be considered. This assumes linear propagation of the current state of all involved aircraft. Based on this approach, the time to CPA is equal to:

$$t_{CPA} = -\frac{\vec{d}_{rel} \cdot \vec{v}_{rel}}{v_{rel}^2}, \tag{1}$$

and the distance between aircraft at CPA is:

$$d_{CPA} = \sqrt{d_{rel}^2 - t_{CPA}^2 \cdot v_{rel}^2}. \tag{2}$$

The previous equations will be used to calculate distance to threats at CPA. Although, some conflict detection models opt for calculating distance at CPA through the discretization of a 4D path, this detection model has the advantage of enabling the distance to be calculated independently of the existence of nodes.

IV. Conflict Resolution

Four commonly used conflict resolution models were chosen for direct comparison. Description of these methods and comparison regarding planning, control, coordination, and conflict resolution are discussed hereinafter.

A. Velocity Obstacle (VO) Theory [9], [10]

Velocity obstacle representation is defined as the set of all velocity vectors of a moving agent which will result in a collision with a moving obstacle at some future point in time.

Fig. 2 illustrates a traffic situation in which the ownship aircraft is in conflict with an intruder. Initially, the collision cone (CC) is defined by lines tangential to the intruder's PZ. The ownship and intruder are in conflict since the relative velocity is inside the CC. By adding the intruder's velocity, the CC is translated forming the intruder's VO. This VO represents the set of velocities, for the ownship, which results in a loss of separation with the intruder. R represents the radius of the PZ. $P_{Ownship}(t_0)$ and $P_{Intruder}(t_0)$ denote the ownship's and the intruder's initial position, respectively. $P_{Intruder}(t_c)$ identifies the intruder's position at the moment of collision.

Two commonly used conflict resolution methods based on VO will be compared:

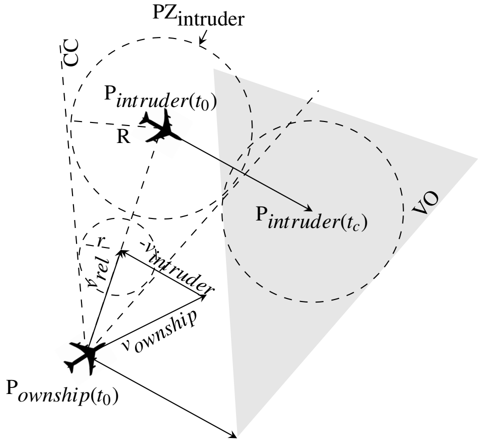

Figure 2. Representation of a velocity obstacle.

1) *Artificial Potential Field* [11], [12], where the destination is an attractive force and other aircraft act as a repulsive force, forcing the ownship aircraft away from their minimum separation area. Aircraft simultaneously push and are pushed away from other aircraft.
This model has the advantage of simplicity; the resulting calculations are computationally light, and, as resolution "force field" vectors can be summed for each conflict pair, it can resolve multiple conflicts simultaneously in two and three dimensions. The disadvantage is that heading changes are solely based on this repulsive force, and can even oppose the initial desired path when the ownship aircraft is surrounded by multiple aircraft.
The CR algorithm used to test this implementation is the Modified Voltage Potential (MVP), described by Hoekstra [11], for which the geometric resolution is displayed in Fig. 3.

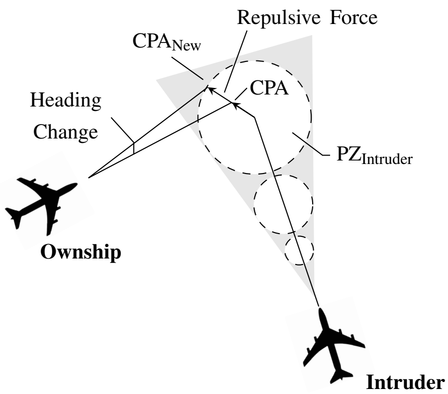

Figure 3. MVP resolution. Adapted from Hoekstra [11].

2) *Geometric Space Solution* [13], [14] uses a geometric determination of heading and velocity values that will prevent the ownship aircraft from entering an intruder's PZ. Possible conflict and conflict-free areas are computed by calculating future positions of one or more intruders. The CR algorithm used to test this implementation is the Space Solution Diagram (SSD) described by Dam [13]. As seen in Fig. 4, all heading and speed combinations are represented within two circles; the inner and outer circle

represent the aircraft's minimum and maximum velocity, respectively. The heading and speed combinations which would result in a loss of separation with intruders are represented in grey. Any heading and speed combination outside of this area is a deconflicting maneuver.
The main advantage of this method is the possibility of avoiding conflicts in advance. Additionally, the spatial representation of heading and speed result in a complete overview of the possible deconflicting maneuvers. However, this large spatial representation requires significant computational resources which may cause the SSD model to be slower than models like the MVP, for example.

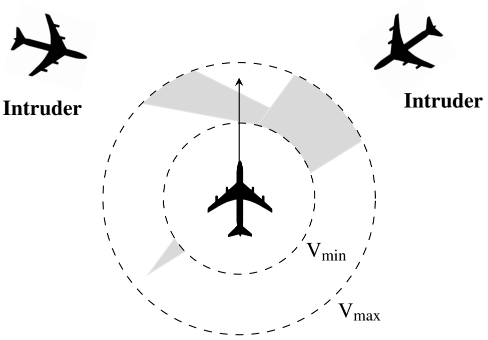

Figure 4. SSD resolution. Adapted from Dam [13].

B. *Coordinated Resolution [15], [16]*

A coordinated resolution resolves conflicts based on cooperative communication between aircraft, which share their intent until a global deconflicting solution is found. In each iteration, each aircraft broadcasts a deconflicting intention, which is received by neighbouring aircraft. These iterations will continue until all deconflicting maneuvers result in a non-conflict situation. As each aircraft proposes a maneuver according to their preference policy, the objective of this method is for the final solution to be the best globally possible for all. Additionally, there is no uncertainty regarding intruder's movements as these share their future intention.

Naturally, there is a risk that aircraft will communicate indefinitely without reaching an agreement, mostly due to neither aircraft wishing to significantly alter their direction. Consequently, either a clear aircraft priority, respected by all intervening aircraft, or a break condition must be added to the communication cycle. Priority can be based on factors such as aircraft's current speed, proximity to destination, rules of the air (RoTA), or even type of operation. Additionally, the rate of communications must be in accordance with real physical limitations. The communication frequency of the network is often limited and aircraft may be unable to exchange data at a high frequency. Therefore, the number of iterations should also be limited to match a realistic case-scenario.

The method herein used is similar to Yang [15], where each aircraft sends its deconflicting policy to intruders until all broadcast policies result in a global deconflicting situation (see Fig. 5). A break condition is applied in order to prevent an infinite loop.

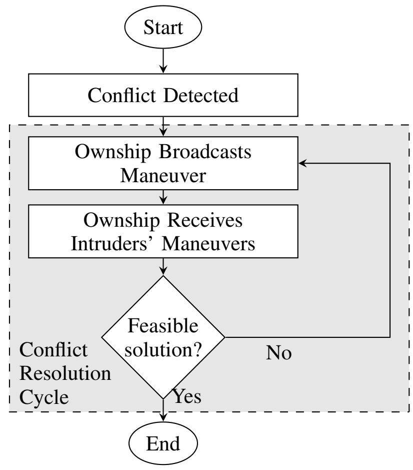

Figure 5. Iterations of a coordinated solution. Adapted from Yang [15].

In the simulated *coordinated* CR method, each aircraft will proposed to others a heading and/or speed change in order to avoid conflict. Preference over heading or speed is based on the aircraft's own policy. These changes will, preferably, not alter the flight path significantly. In order to limit the number of computational calculations, a break condition is applied to the cycle.

C. *Centralized Cost Solution [17], [12]*

This solution favours deconflicting maneuvers with a low cost. Most implementations of this strategy are based on the Ant Colony method. All aircraft have a pre-planned trajectory; however, this must be recalculated once a conflict is detected. Aircraft pick the trajectory with the lower cost from a set of limited possibilities, which may be defined by spatial nodes or possible heading/speed changes. The cost is based on the preferences for each aircraft; this may be lower fuel consumption, safety, flight path or time optimization. The cost definition herein used is adapted from Hao [17]:

$$\begin{cases} F = w_l \Delta P_L + w_v \Delta V + w_d D_{th} + \delta P \\ w_l + w_v + w_d = 1 \end{cases} , \tag{3}$$

where ΔP_L represents the variation of the total length of the path, ΔV the change in velocity, and D_{th} the distance to threats. Lastly, penalty value P is used to add an extra cost to trajectories which cross an intruder's PZ, as to make these more expensive and, therefore, less desirable. The value of the weight coefficient denotes their importance. If, for example, a lower fuel consumption is favoured over distance to threats, then w_l and w_v should be given higher values, as to make an increment in flight path or speed variation significantly expensive. Note that other properties could be added to the cost equation as desired. When summed, the weight coefficients are equal to one.

The advantage of this method is that a preference can be made either over performance or security. It may even be considered that crossing a PZ over a small period of time is better than increasing flight path or adopting a significant change in speed. The disadvantage is that aircraft are limited to the discrete solutions. And the more existent paths, the

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more computationally heavy this model is, possibly making it inadequate for a real-scenario.

In the simulated *cost* CR method, a discrete set of possible heading/speed changes is considered as possible new paths. This set is computed based on increasing the absolute value of the aircraft's heading, together with speed variations within the aircraft's performance range. The cost for each trajectory is calculated, and the least costly one is selected as the new path.

D. Properties of the Resolution Models

Table I describes the main properties of the chosen CR models. These are all tactical, i.e. a mid-range action (several minutes) that changes a small part of the flight path. Indeed, most current models work on a range of minutes prior to expected collision. Only the *Cost* model is centralized; information regarding traffic is received from a common station. All others receive information from the traffic itself. While the *coordinated* model focus on explicit intent communication with other aircraft, in *MVP* and *SSD* each aircraft chooses its conflict resolution without sharing. *MVP* resolves pairwise conflicts, i.e. each maneuver resolves a conflict with one intruder, whereas *SSD* decides upon a conflicting maneuver which resolves conflict with all aircraft simultaneously.

TABLE I. PROPERTIES OF THE CR MODELS USED IN SIMULATION.

	CR Models			
Planning	Tactical			
Control	Decentralized			Centralized
Coordination	Implicit		Explicit	**Cost**
Conflict Resolution	Pairwise	Global	**Coord**	
	MVP	**SSD**		

V. EXPERIMENT: CONFLICT RESOLUTION

A. Apparatus and Aircraft Models

Open Air Traffic Simulator BlueSky [6] was used. This tool has an Airborne Separation Assurance System (ASAS) to which different CD&R implementations can be added; therefore, allowing for all CD&R to be tested under the same scenarios and conditions. Simulations scenarios are based on the work of Sunil [18]. These scenarios do not follow a standard as such does not exist. The results obtained should be directly associated with using this specific tool and scenarios. A different tool and/or scenario may produce different results.

Boeing 747-400 and a DJI Mavic Pro quadcopter were used for manned and unmanned aviation, respectively. The objective was to choose aircraft with a significant speed range in order for protection of the flight envelope to limit speed variation by the CR models as least as possible. Characteristics of both are displayed in Table II. The data for the B747-400 aircraft comes from BADA [19]. For the DJI Mavic Pro model, speed and mass were retrieved from the manufactures data. Although exact turn rate and acceleration/braking values are not available, common values were assumed.

B. Independent Variables

Four independent variable are included in this experiment: traffic density, maneuvering space, CR strategies and look-ahead time.

TABLE II. PERFORMANCE DATA FOR BOEING 747-400 AND DJI MAVIC PRO USED WITH BLUESKY SIMULATIONS.

	Boeing 747-400	**DJI Mavic Pro**
Speed [kts]	450–500	−35–35
Mach [-]	0.784–0.871	–
Mass [kg]	285.700	0.734
Turn Rate [°/s]	1.53–1.70	max: 15
Load Factor in Turns	1.22	–
Acceleration/Breaking [kts/s]	1.0	1.0

Traffic density varies from low to high as per Table III. Density values were defined based on current expectations. In 2017, the Netherlands had a maximum traffic density of 32 aircraft per 10 000 NM^2 in the upper airspace [18]. Given traffic increase expectations [1], Netherlands may then expect up to 45 aircraft per 10 000 NM^2 by 2025. Regarding unmanned aviation, drones may take over light weight deliveries. For the urban area of Paris, this represents over 1 M drones per 10 000 NM^2 by 2035 [20]. However, these values are significantly heavy computationally. Consequently, lower densities, compatible with the BlueSky tool, were picked. The obtained results can be used as an initial indication of which CR characteristics may have better results with the higher estimated densities.

TABLE III. TRAFFIC VOLUME USED IN SIMULATION.

		Traffic Density [$ac/10000\,\mathrm{NM}^2$]	Instantaneous Aircraft	Spawned Aircraft
Manned Aviation	Low	32	648	3070
	Medium	37	768	3640
	High	45	911	4317
Unmanned Aviation	Low	12000	1080	4629
	Medium	13856	1247	5345
	High	16000	1440	6172

A look-ahead time of 5 minutes is used for conflict detection. This threshold is used with time to CPA. Note that the look-ahead distance will be bigger for manned aviation, as manned aircraft will cross a longer path in 5 minutes.

VI. EXPERIMENTAL DESIGN AND PROCEDURE

All aircraft will flight at the same flight level. However, aircraft are still spawned at a lower altitude and climb into cruising level, as to prevent very short term conflicts between just spawned aircraft and pre-existing cruising traffic. Unmanned aircraft are expected to climb almost vertically. A path pre-defined through waypoints then follows. Once aircraft finish their path, they are deleted as they descend below cruising flight level. Logging is restricted to the cruise phase of the flight. The path is linear, with aircraft having a constant heading varying from 0° to 360°. The total flight distance is uniformly distributed between a pre-defined minimum and maximum value based on the minimum flight time and the average True Air Speed (TAS). TAS values also range between TAS_{min} and TAS_{max}, dependent on the model of the aircraft. Note that no wind was considered.

Spawn area is a square with a side length defined according to average TAS and flight time. The spawn locations (origins) and destinations of each aircraft are placed on the edge of this area, intercalated with a spacing equivalent to the minimum separation distance plus a 10% margin, as to avoid conflicts between spawn aircraft and aircraft arriving at their destination.

An aircraft is removed from the simulation once it reaches final destination or in case it leaves the simulation area. Considering that aircraft may temporary leave the main square simulation area in case a conflicting maneuver so demands, a second squared area is considered: the experiment area. As a result, aircraft in a conflict situation close to their origin or destination are not deleted incorrectly from the simulation.

Each scenario consists of a build-up period for the necessary traffic volume to be created, followed by logging time, during which traffic volume is held constant, and a down period, allowing for aircraft created during the logging period to finish their flights. The experiment is repeated multiple times with different origin-destination combinations. More details are displayed in Table IV.

TABLE IV. PROPERTIES OF THE SCENARIOS USED IN SIMULATION.

	Manned Aviation	**Unmanned Aviation**
Scenario Duration [h]	3	
Number of Repetitions [-]	3	
Min Flight Time [h]	0.5	
Experiment Duration [h]	1h45m (45m - 2h30m)	
Simulation Area [NM^2]	202500	900
Experiment Area [NM^2]	405000	1800
Min Flight Distance [NM]	200	15
Max Flight Distance [NM]	250	20
Radius PZ Horizontal [NM]	5	0.027
Radius PZ Vertical [ft]	1000	65
Flight Level [ft]	36000	300

A. Dependent Measures

Two different categories are used to compare the simulated conflict resolution methods: *safety* and *efficiency*.

Safety is defined in terms of the number and duration of conflicts and LOSs. Naturally, fewer conflict and LOSs are expected to be safer. Additionally, LOSs differ in severity according to how close aircraft get to each other:

$$LoS_{sev} = \frac{R - d_{CPA}}{R}. \quad (4)$$

A low separation severity is preferred.

Efficiency is evaluated in terms of distance travelled and duration of flight. An off-CD&R situation has a better performance in terms of flight distance and time, as the flight path will be a straight line. CR models move aircraft out of their intended trajectory in order to avoid conflicts/LOSs; therefore, making the path longer. However, a CR model which results in considerable path deviations, significantly increasing the path travelled and/or the duration of the flight is considered inefficient. Additionally, for manned aviation, the work done (W) associated with fuel consumption can be calculated by:

$$W = \int_{path} \vec{T} \cdot d\vec{s}, \quad (5)$$

where $\vec{T}$ and $d\vec{s}$ represent the thrust vector and the displacement vector along the path, respectively.

VII. EXPERIMENT: RESULTS

The effect of the independent variables on the dependant measures is presented, in order to assess the effect of each conflict resolution model. Box-and-whisker plots are used to visualize the sample distribution over the several simulation repetitions. For clarity, outliers are not displayed.

A. Safety

Fig. 6 displays the number of conflicts per aircraft. The increase of number of conflicts is due to secondary conflicts created by the resolution maneuvers. The number increases with the traffic density; with more aircraft it is progressively more difficult to avoid LoSs without triggering secondary conflicts. In average, VO based models (*MVP* and *SSD*), display the less number of secondary conflicts for both manned and unmanned aviation.

Fig. 7 shows the amount of time spent in a situation of conflict. Based on this information and Fig. 6, the number of conflicts is not directly correlated with the amount of time in conflict. Although, the *MVP* model has a higher number of conflicts than *SSD*, for example, it has a lower time in conflict.

Fig. 8 identifies the number of LoSs. *MVP* has the lowest number of LoSs on all examined traffic densities.

Fig. 9 displays the intrusion severity per CR model; *MVP* is better at maximizing the distance at CPA. Results are comparable for the other models. There is no direct correlation between intrusion severity and the traffic density.

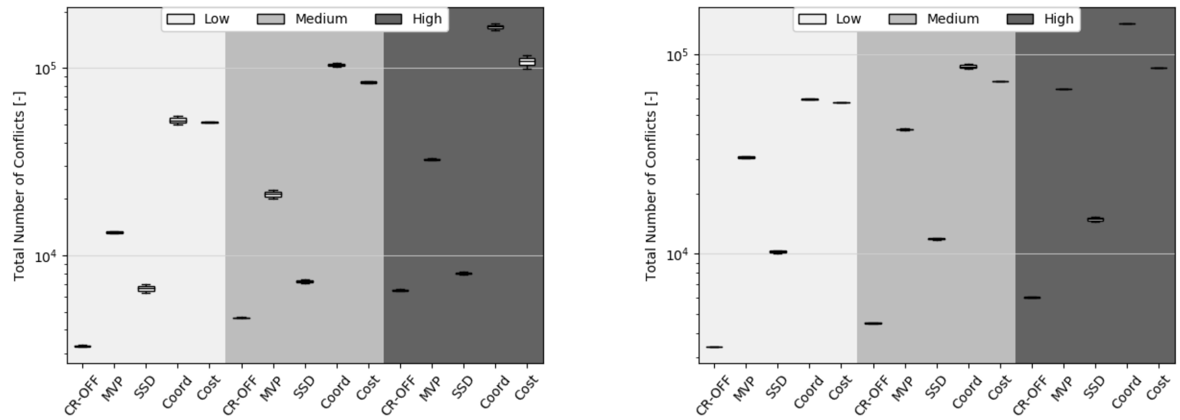
B. Efficiency

According to Fig. 10, the *MVP* model results in the smallest path deviation. In other models, as aircraft perform longer deconflicting maneuvers, these take longer to reach their destination. As seen in Fig. 11, CR models may increase flight time when the models decrease the speed of the aircraft as a deconflicting maneuver. *MVP* also has the smallest time deviation.

Fig. 12 identifies the extra work done performed by manned aviation. These values are comparable with the extra flight distance (see Fig. 10). The increase in work performed is a direct consequence of increasing the flight path due to conflict resolution maneuvers. *MVP* has the smallest path deviation and, therefore, the smallest work increase. Note that the total work presented shouldn't be used as exact values but as an estimation which may be used for comparison.

VIII. DISCUSSION

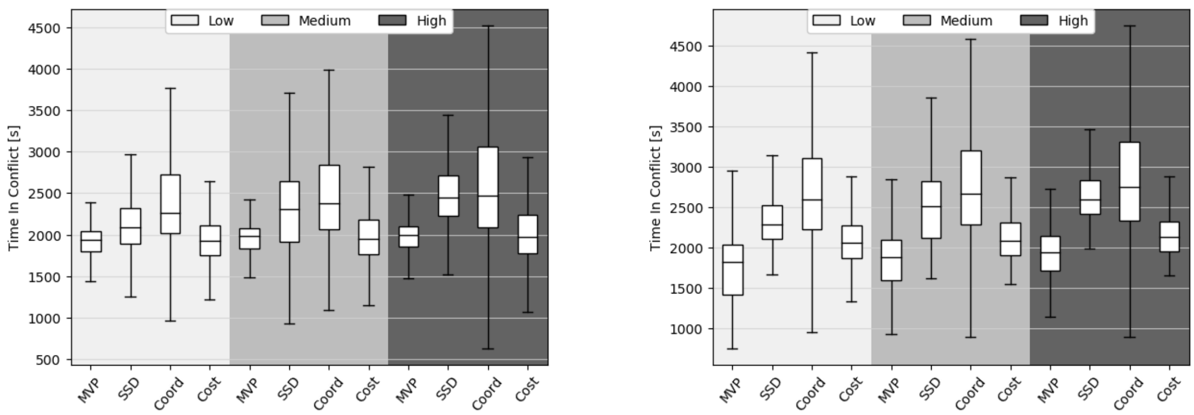
The conclusions of this work are dependent on the tools and traffic scenarios considered. The objective was to obtain a direct comparison between commonly used CD&R models. In absolute terms, the obtained results showed some disparity between results obtained by previous research under different simulation conditions. For Piedade [21], who used BlueSky for manned aviation with different scenarios and smaller traffic densities (from $9\,\mathrm{ac}/10000\,\mathrm{NM}^2$ to $27\,\mathrm{ac}/10000\,\mathrm{NM}^2$), *MVP* showed fewer LoSs than *SSD*. Regarding the *coordinated* model, Yang [15] was able to guarantee safe separation of 48 UAVs in a space of $22\,\mathrm{NM}^2$. Finally, for the *cost* model, Hao [17] showed no LoSs for 5 manned aircraft in a $54\,\mathrm{NM}^2$ scenario. These results should also be taken into account when considering the performance of these models. However, they are almost impossible to compare with the work herein given the differences in scenarios and traffic densities. This shows the



(a) Manned aviation.

(b) Unmanned aviation.

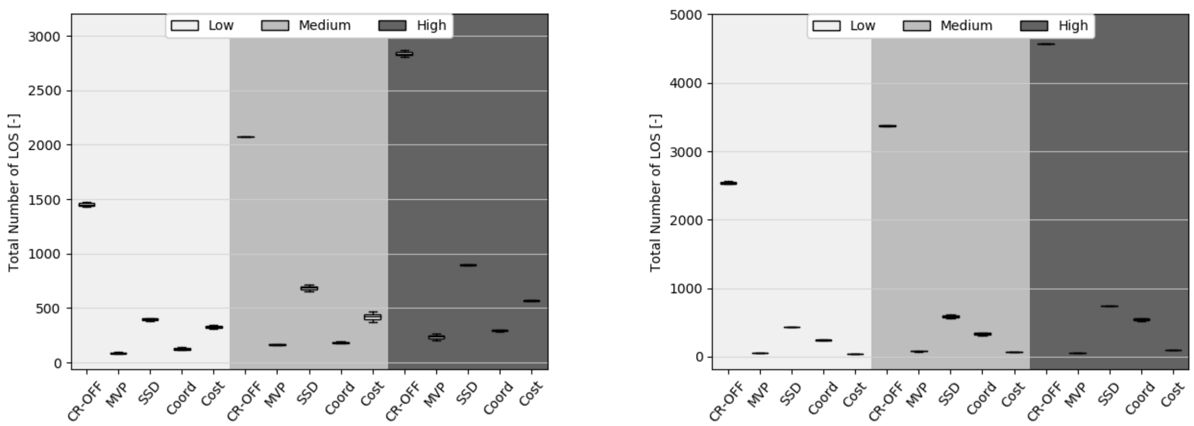
Figure 6. Number of conflicts per CD&R model.



(a) Manned aviation.

(b) Unmanned aviation.

Figure 7. Time in conflict per CD&R model.



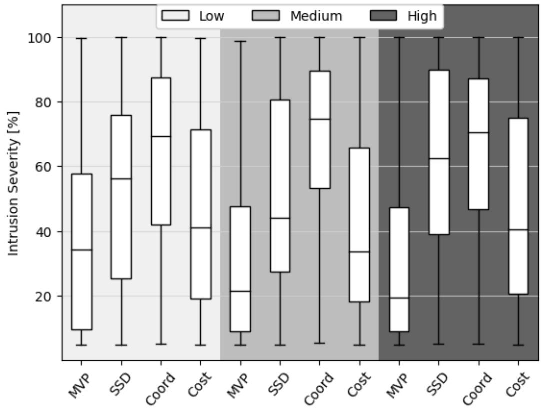
(a) Manned aviation.

(b) Unmanned aviation.

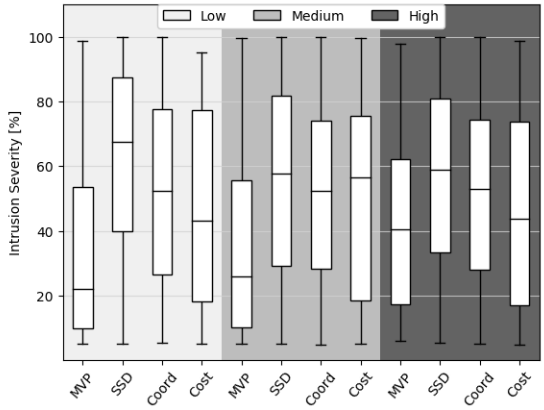
Figure 8. Number of losses of separation per CD&R model.

importance of developing a standardized simulation library, so CD&R models can be fairly tested under the same conditions.

Experimental results displayed no significant disparity in terms of which type of CD&R model performs better between a manned and an unmanned environment. Additionally, the differences in unmanned over manned aviation heavily favours the performance of the models. For the characteristics of the experiment performed, VO based methods showed better results overall, in particular the *MVP* model. Having minimum

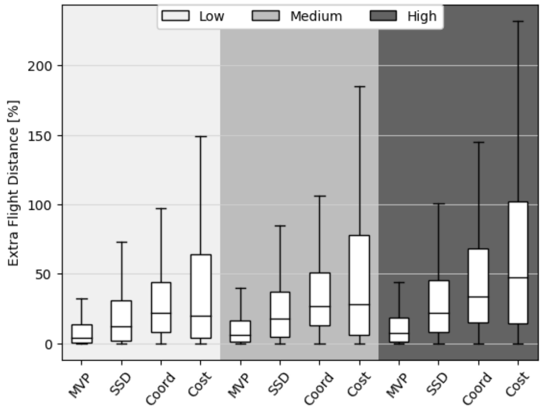


(a) Manned aviation.

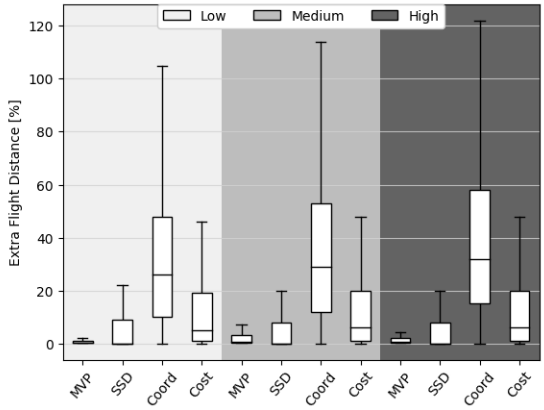


(b) Unmanned aviation.

Figure 9. Intrusion severity rate per CD&R model.

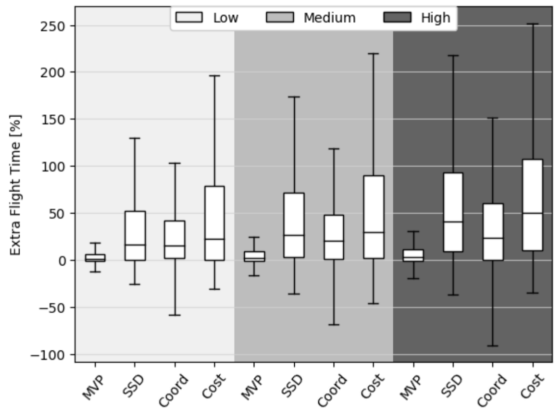


(a) Manned aviation.

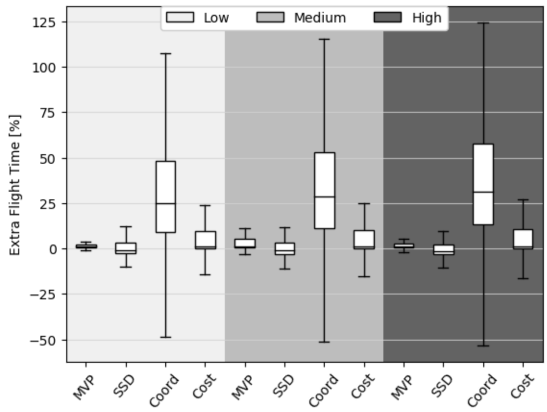


(b) Unmanned aviation.

Figure 10. Extra flight distance per CD&R model.



(a) Manned aviation.



(b) Unmanned aviation.

Figure 11. Extra flight time per CD&R model.

path deviations for CR, as executed by the *MVP*, reduced the effect of resolution maneuvers on flight efficiency while still guaranteeing minimal LoSs. At high densities, tactical conflict resolutions can trigger conflict chain reactions due to the scarcity of airspace [22]. Other CR models which do not compute the 'shortest-path' resolution from the nominal path, as is the case with *MVP*, will potentially create a higher chain reaction as these require a bigger portion of the airspace. However, results may vary considerably depending on the designed experiment and, therefore, the best CR characteristics

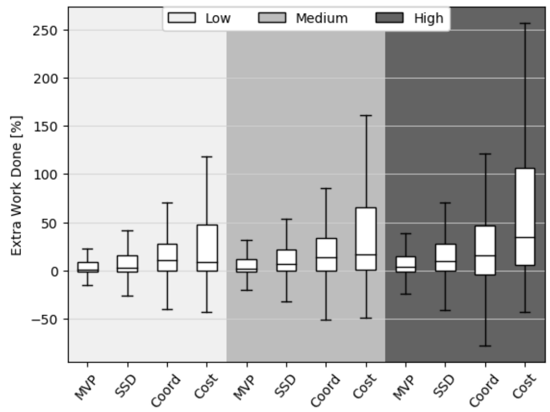


Figure 12. Extra work done per CD&R model for manned aviation.

should be named per environment conditions.

In the future, it is advised to perform simulations for unmanned aviation with higher traffic densities, in order to better establish the behaviour of CR models in the presence of secondary conflicts. Additionally, different minimum separation distances should be tested. As currently there is no standard, it is of importance to analyse the overall safety of different values.

IX. Conclusion

Several commonly used CD&R models were tested using multi-agent ATM simulation BlueSky [6] and traffic scenarios developed by Sunil [18] both for manned and unmanned aviation. Velocity obstacles based methods showed better performance safety-wise.

The discrepancy between the results here presented and previous research shows the importance of creating a standardized simulation library under which CD&R models can be fairly compared. CD&R models aim at relieving the workload of ATM services and assuring safe integration of UAVs into the civil airspace. However, a better notion of how current models behave for specific traffic scenarios is essential in order to determine a way forward for improvement.

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