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Taxonomy of Conflict Detection and Resolution Approaches for Unmanned Aerial Vehicle in an Integrated Airspace

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Abstract—**This paper proposes a taxonomy of Conflict Detection and Resolution (CD&R) approaches for Unmanned Aerial Vehicles (UAV) operation in an integrated airspace. Possible approaches for UAVs are surveyed and broken down based on their types of surveillance, coordination, maneuver, and autonomy. The factors are combined back selectively, with regard to their feasibility for operation in an integrated airspace, into several 'generic approaches' that form the CD&R taxonomy. These generic approaches are then attributed to a number of available method in the literature to determined their position in the overall CD&R scheme. The attribution shows that many proposed methods are actually unsuitable for operation in an integrated airspace. Furthermore, some part of the taxonomy does not have an adequate representative in the literature, suggesting the need to concentrate UAV CD&R research more in those particular parts. Finally, a multi-layered CD&R architecture is built from the taxonomy, implementing the concept of defense-in-depth to ensure UAVs safe operation in an integrated civil airspace.**

Index Terms—**Unmanned Aerial Vehicle, Conflict Detection and Resolution, Collision Avoidance, Airspace Integration.**

I. INTRODUCTION

PROSPECTIVE civil applications of Unmanned Aerial Vehicles (UAVs) have motivated many to commercially fly them in the civil airspace [1]. One of the biggest concerns for these flights is ensuring their safety in the integrated airspace, which includes avoiding conflicts and collisions amongst themselves, as well as with the existing manned air traffic. A vast variation of approaches [2]–[59], in both hardware and software concepts, have been proposed to handle that particular problem. These approaches are defined as Conflict Detection and Resolution (CD&R) systems.

Although many of these CD&R studies show promising results, the huge variety of approaches available adversely raises confusion on the integrated airspace management. Considering the rapidly increasing number of developers and users, a large variety of CD&R approaches is inevitable and therefore it is difficult for an authority to enforce a single standardized approach. Furthermore, the worthiness of each of the approaches to support an operation in an integrated airspace is still questionable since UAV CD&R systems are rarely demonstrated handling heterogeneous environments, where vehicles have different preferences in resolving conflicts and interacting with each other. This is one of the reasons why civil-UAVs are yet to be allowed to fly beyond the operator line-of-sight (BLOS). [60], [61]

Perhaps what is lacking here is a versatile general architecture that defines the implementation of the variation of UAV CD&R in an integrated airspace. For comparison, manned-flight has managed to establish a standardized multi-layered CD&R architecture, commonly presented as 'layers of safety' [62] as shown in Figure 1. This architecture implements a defense-in-depth concept, that is, rather than having a single complex CD&R system to handle all types of conflicts, it incorporates several simpler subsystems where each of them are assigned to handle one particular type of conflict. Hence, the safety is managed from the procedural layer that eliminates unnecessary encounters simply by scheduling, up to avoiding any close-encounter obstacles in the 'See and Avoid' layer using the pilot's discretion.

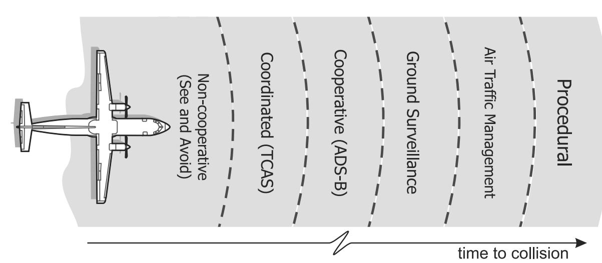

Fig. 1: Multi-layered architecture of Manned-flight CD&R (Layers of Safety)

Taking example from the manned-flight, UAVs can also incorporate a multi-layered architecture that combines several approaches in a complementary manner. Adopting such architecture would also enable UAVs to act and respond as manned aircraft do, a key requirement in safely integrating into a non-segregated airspace [61]. The multi-layered architecture can also be viewed as a fail-safe system that will not directly leave a UAV vulnerable whenever a failure occurs. It is possible to realize this architecture by exploiting the large creativity of CD&R approaches available in the literature. A categorization of these approaches is therefore needed to identify redundancy

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in the available methods, as well as to identify areas that is not covered yet.

This paper, therefore, proposes a taxonomy of CD&R approaches aiming to define their positions in the overall safety management of UAV operations in an integrated airspace. The available approaches in the literature are broken down to create a taxonomy based on the type of (1) surveillance, (2) coordination, (3) maneuver, and (4) autonomy. The factors are then combined back, selectively with regard to their feasibility for operation in an integrated airspace, into several *generic approaches*. These can be attributed to each available CD&R approach in the literature to determine whether it is complementary or interchangeable with another. An example of an exhaustive multi-layered architecture based on the taxonomy is also proposed, along with the general implementation for UAV operation in an integrated airspace.

This paper is an extension of the work originally reported in [63] by the same authors. The current paper contributes to this study by providing an improved categorization of the existing UAV CD&R methods in a comprehensive taxonomy with bigger literature to identify important future avenues of research in UAV CD&R systems.

The research in this paper is presented as follows. After the introduction, Section II will present an inventory of CD&R approaches, based on the four factors explained before. Section III presents the taxonomy of UAV CD&R, consisting generic approaches which are derived through a process of method combination and selective elimination. The availability of these generic approaches in the literature is also tabulated. In Section IV, an example of a multi-layered architecture for UAV CD&R is presented, along with a general implementation of the architecture. Section V concludes the paper and provides suggestions for future work.

II. Inventory of Approaches for UAV Conflict Detection and Resolution System

The three factors that distinguish the layers of safety in the manned-flight CD&R are the type of surveillance, coordination, and maneuver, as shown in Figure 2. These three are the factors that directly affect the airspace management: surveillance and coordination require cooperation from other vehicles as well as the local authorities, while the length of maneuvers can affect the traffic globally. Hence, each of the manned-flight safety layers can be viewed as a generic approach that combines those three factors. For example, the Traffic Warning and Collision Avoidance System (TCAS) can be seen as a combination of *distributed dependent surveillance, explicit coordination, and escape maneuver*. Other types of CD&R categorizations can also be found in literature, such as in [64]. However, they focus more on the internal algorithms.

The UAV CD&R approaches in literature can also be broken down and viewed as combinations of those three factors. An additional factor of 'autonomy' is added in the taxonomy, differentiating whether an (human) operator is involved or not in the approach execution.

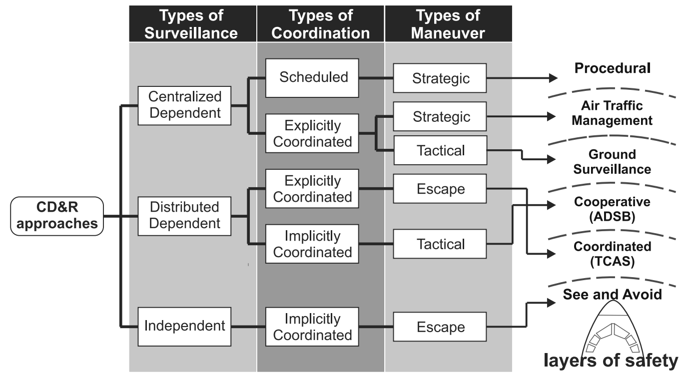


Fig. 2: Taxonomy of CD&R approaches in manned flight

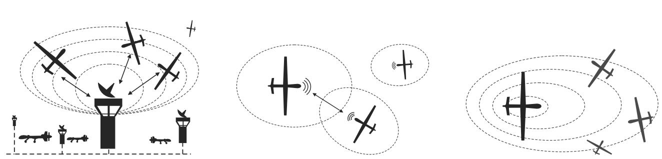
A. Types of Airspace Surveillance

Airspace surveillance is the detection step in the CD&R process. Here, three types of surveillance can be distinguished, as they are presented in Figure 3.

- **Sur**$_1$: Centralized-dependent surveillance,
- **Sur**$_2$: Distributed-dependent surveillance, and
- **Sur**$_3$: Independent surveillance.

A centralized-dependent-surveillance system obtains data from a common station, or a station-network, and can be available even before the flight is conducted, e.g., a map of static obstacles. In manned-flight, this part is included in the first three safety layers. An aircraft can retrieve data about the traffic, terrain, and weather in the area from ground centers such as the Air Traffic Control (ATC) or the Aviation Weather Center (AWC). UAV operators might also employ this data to plan each flight and reduce any unnecessary conflicts. An example of this practice is demonstrated in [13] and [65]. In contrast to manned-flight, centralized-surveillance for UAVs might only be suitable before flight, since most UAVs, being small and manufactured with non-metal materials, are difficult to detect using conventional RADAR on ground.

A distributed-dependent-surveillance system obtains data from the traffic itself. This surveillance method, therefore, requires every vehicle to cooperatively broadcast their flight data. In manned-flight, this practice is conducted in the Cooperative and Coordinated layers, by using the Automatic Dependent Surveillance Broadcast (ADS-B) [66] system, and the TCAS, respectively. Applications for UAVs, which is also known as collaborative sensing, such as presented in [30] and [26]. CD&R approaches that does not mention a particular surveillance method are considered to be using a distributed dependent surveillance system.



(a) (b) (c)

Fig. 3: Airspace Surveillance for UAVs: (a) Centralized-dependent, (b) Distributed-dependent, and (c) Independent

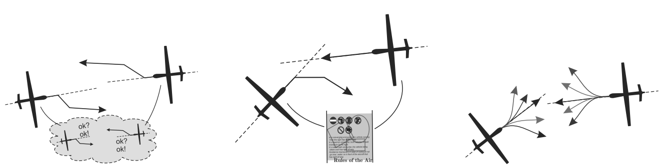
The third method of surveillance obtains airspace data independently using an on-board sensor system. In manned-flight, this type of surveillance is only present through (human) visual confirmation, used in the last layer of safety, the 'see and avoid' procedure [67]. While this type is the primordial system for avoidance in manned-flight, in the UAV domain it dominates most of the research. On-board sensors are the most popular way to provide surveillance, or sensing, in UAV studies, which includes cameras (visual light and infra-red) [31], acoustic sensors [58], acoustic-vector sensors [68], and even miniaturized versions of active-sensors like the laser-range-finder [44] or RADAR [69].

B. Types of Coordination

In order to simplify the resolution, many studies assume some level of coordination between vehicles. This research differentiates the levels into three types of coordination, as listed below, and as depicted in Figure 4. The scheduled coordination, in the Procedural layer shown in the Figure 2, is omitted from the list since it can be viewed as an implicit (rule-based) coordination.

- $\mathbf{Coo}_1$: Explicitly coordinated avoidance,
- $\mathbf{Coo}_2$: Implicitly coordinated avoidance, and
- $\mathbf{Coo}_3$: Uncoordinated avoidance.

Avoidance is said to be explicitly coordinated if an explicit communication exists among the involved vehicles. Hence, a specific resolution, often using a common algorithm, can be produced for each conflicting vehicle. Combination with a ground station is a common practice in manned-flight, such as the TCAS, which gives a pair of aircraft a confirmed advisory to avoid conflict. In the UAV domain, the ACAS Xu [50], a part of the next generation of TCAS, shows an example of this coordination. This paper also includes methods that only avoid static obstacles, as an explicitly-coordinated avoidance.



(a) (b) (c)

Fig. 4: Types of Coordination: (a) Explicitly Coordinated, (b) Implicitly Coordinated, and (c) Uncoordinated

An avoidance is implicitly coordinated if each involved vehicle maneuvers according to a common set of rules or strategies. This ensures a level of coordination without a direct communication for resolution. Being partially limited by the rules, the vehicles can simplify the resolution by limiting the maneuver choice, or by setting up priorities based on vehicle types. An example of this type of coordination in manned-flight is the use of right-of-way rules in the 'see and avoid' procedure [67]. The 'Free-flight' concept introduced in [6], [10], [25], [70], also employs an implicitly coordinated method for avoidance. The work in [19] and [53] presents an example of this type of coordination for UAV applications. This paper also includes methods that only avoid obstacle with known adn constant trajectory, as an implicitly-coordinated avoidance.

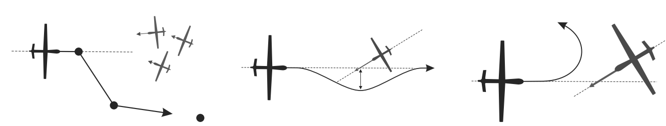
When the avoidance is uncoordinated, each involved vehicle has its own preference for resolution based on the conflict situation, and therefore can create a complex situation. The ownship in this case can assume that the obstacle is rogue and may conduct unexpected maneuvers. This makes the resolution calculation more difficult since it has to take into account every possible movement and collision risks induced by an obstacle. In manned flight, this avoidance is not implemented unless it is an emergency, which highly depend on the pilot judgment. In UAVs, some examples exist for an agile UAV, such as presented in [17]. Some work, such as in [3], applies this type by using a predefined set of actions for an aggressive sure-escape, avoiding the entire portion of the risk at once.

C. Types of Avoidance Maneuver

As airborne vehicles, UAVs are able to perform many kinds of maneuvers in the 3-Dimensional space. This research differentiates between three types of maneuvers, as presented in Figure 5.

- $\mathbf{Man}_1$: Strategic maneuver,
- $\mathbf{Man}_2$: Tactical maneuver, and
- $\mathbf{Man}_3$: Escape maneuver.

A strategic maneuver is a long-range action that changes the initial flight-path significantly, in the attempt to avoid unnecessary encounters. The maneuver commonly generates several new waypoints, which can be both in vertical and horizontal direction. The flight-planning in both manned and unmanned flight [13], [22], is included in this type of maneuver.



(a) (b) (c)

Fig. 5: Types of Maneuver: (a) Strategic maneuver, (b) Tactical maneuver, and (c) Escape maneuver

A tactical maneuver is a mid-range action that changes a small part of the flight path while aiming to keep the deviation as small as possible. This type of maneuver focuses on ensuring a certain separation threshold during an encounter with other vehicles. An example of this method in manned-flight is the Airborne Separation Assurance System (ASAS), such as presented in [40]. Most of the advanced methods for UAVs are using this maneuver to limit the path deviation as small as possible by using, for instance, geometric guidance [42] or optimization of a cost function [43]. Several papers mention this type of maneuver as a deconflict maneuver [53], [71].

The last approach is to escape any potential collision all together with a maneuver that solely brings the vehicle to safety. This escape maneuver should be aggressive and conducted immediately, commonly using an open-loop command, driven by the maximum performance limit of the vehicle. In manned-flight, this type of maneuver is applied in the 'see and avoid' layer, in the way that they ignore any optimization, and focus only on safety. The way the TCAS and the ACAS X [50] works where a maneuver is conducted in a relatively short distance, is also included as an escape maneuver. In UAV domain, several examples use this maneuver type, including the work in [28] and in [34].

D. Types of Autonomy

Based on the type of autonomy, a UAV can conduct avoidance based in two different ways:

- $\mathbf{Aut}_1$: Manually, or
- $\mathbf{Aut}_2$: Autonomously

In this research, these are differentiated more on the involvement of a human operator in the final decision for avoidance, and not on the calculation process. For instance, if a conflict situation is processed on-board, but then the results is send for the ground operator to decide, it is still considered to be manual avoidance. Manual avoidance is preferable by most of the current regulations, which limits UAV operation to within line-of-sight of the operator [60].

Beyond the line-of-sight (BLOS), however, the effectiveness of manual avoidance is greatly reduced, as the situational awareness of the operator becomes low [19]. The final decision for avoidance, hence, should be given to the on-board autonomous system. Currently, even though many studies proposed various autonomous methods, such as in [56], this is not applicable in a commercial manned-flight due to safety reasons. In the UAV domain, on the other hand, research has been focused mostly on the autonomous avoidance ability.

III. Taxonomy of Conflict Detection and Resolution Approaches for UAV

By direct combination from the approach inventory in the previous section, there can be 54 possible generic approaches to form the taxonomy, resulting from 3 types-of-surveillance $\times 3$ types-of-coordination $\times 3$ types-of-maneuver $\times 2$ types-of-autonomy. Several of these combinations, however, might not be suitable for a UAV flight in an integrated airspace, and therefore can be removed from the final structure of the taxonomy. This section presents the taxonomy by first elaborating the characteristics of prospective UAV flights in the integrated airspace.

A. UAV Flight in the Future Integrated Airspace

The taxonomy is built under the assumption that UAVs are already integrated in the airspace system, as depicted in Figure 6. Each of these prospective UAVs is listed in Table I, along with the references.

Observing the future integrated airspace prospectives, a few characteristics can be defined, along with the improbability in implementing some combinations of the CD&R methods. The superscripts following each improbable combination are codes used for building the taxonomy in the next subsections.

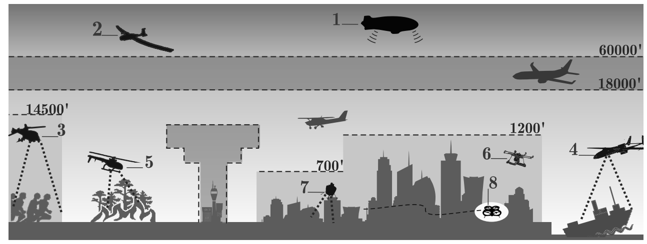


Fig. 6: Prospective use of UAVs in Civil Airspace, adapted from [1]. The UAV numbers refer to Table I.

TABLE I: Prospective UAVs operation in the civil airspace [1]

Mission	Operational Weight	Cruising Altitude
1. Telecommunication [1], [72], [73]	± 20 ton	20 km
2. High-Altitude Imagery [1], [74]	± 800 kg	18 km
3. Border Patrol [1], [75]	< 25 kg	< 6 km
4. Maritime Surveillance [1], [76]	< 20 kg	< 6 km
5. Environmental Sensing [1], [77]	< 25 kg	< 6 km
6. Media and Traffic Reporting [1], [78]	< 10 kg	<1.5 km
7. Law Enforcement [1], [79]	< 25 kg	< 120 m
8. Delivery Service [80]	<25 kg	< 120 m

1) Detectability: Observing Table I, most of the prospective UAV examples are small vehicles that are below 25 kilograms, operating at low altitude, and manufactured mostly using non-metal materials. Consequently, they are hard to detect by a centralized surveillance system such as a conventional radar. Therefore, any centralized surveillance in the future might only be able to support UAVs before their flight, as a center for traffic, terrain, or weather information. This is the implementation of a strategic maneuver coupled with an implicit-coordination, which happens manually before flight. Hence, the improbable combinations caused by this characteristics are: $[\mathbf{Sur}_1 + \mathbf{Coo}_1]^{(1a)}$, $[\mathbf{Sur}_1 + \mathbf{Coo}_3]^{(1b)}$, $[\mathbf{Sur}_1 + \mathbf{Man}_2]^{(1c)}$, $[\mathbf{Sur}_1 + \mathbf{Man}_3]^{(1d)}$, and $[\mathbf{Sur}_1 + \mathbf{Aut}_2]^{(1e)}$.

2) Cooperation: As shown in Figure 6, there can exist different types of UAV carrying out various missions in the same part of the airspace. To ensure safety while embracing this heterogeneity, the authorities might require each UAV to cooperatively broadcast its states to the surrounding vehicles, hence utilizing a distributed-dependent surveillance. This surveillance, however, is not reliable for a strategical maneuver, since the broadcast range is limited. Furthermore, the update rate of the broadcast system is commonly inadequate for a close distance escape maneuver, e.g., the ADS-B only broadcast once per second. Therefore, the improbable combinations caused by this characteristic are: $[\mathbf{Sur}_2 + \mathbf{Man}_1]^{(2a)}$, and $[\mathbf{Sur}_2 + \mathbf{Man}_3]^{(2b)}$.

3) Sense and Avoid: Currently, all examples of UAVs listed in Table I utilize an on-board sensor system to independently (hence, independent-surveillance) provide the required data in high sampling rate. The data is then used to generate an avoidance maneuver, which completes the process commonly known as Sense and Avoid. This is likely to be preserved in the future integrated airspace as a last resort maneuver to resolve conflicts when other methods fail. Sense and Avoid, however, can only be a tactical or an escape maneuver, due to the relatively short detection range of its surveillance system. This range limitation also warrants an autonomous system to provide a fast response in avoidance. Hence, the improbable combinations caused by this characteristics are: [$\mathbf{Sur}_3$ + $\mathbf{Man}_1$]$^{(3a)}$, and [$\mathbf{Sur}_3$ + $\mathbf{Aut}_1$]$^{(3b)}$.

4) Coordination: The heterogeneity of the future integrated airspace will also trigger the heterogeneity of CD&R protocols. Therefore, enforcing an explicit-coordination among these UAVs is inherently difficult regardless of the surveillance and maneuver methods. Hence, the authorities might only impose some sort of implicit-coordination such as a right-of-way rules [67]. The possibility of rogue obstacles in the airspace, however, would still require the UAVs to also consider an uncoordinated avoidance scheme. Therefore, the improbable combinations caused by the heterogeneity are: [$\mathbf{Coo}_1$ + $\mathbf{Sur}_1$]$^{(4a)}$, [$\mathbf{Coo}_1$ + $\mathbf{Sur}_2$]$^{(4b)}$, [$\mathbf{Coo}_1$ + $\mathbf{Sur}_3$]$^{(4c)}$, [$\mathbf{Coo}_1$ + $\mathbf{Man}_1$]$^{(4d)}$, [$\mathbf{Coo}_1$ + $\mathbf{Man}_2$]$^{(4e)}$, and [$\mathbf{Coo}_1$ + $\mathbf{Man}_3$]$^{(4f)}$.

5) Autonomy: Perhaps only the Media and Traffic reporting mission, from the list in Table I, has the UAV operating within the line-of-sight of the operator. All other missions are conducted beyond the line-of-sight (BLOS), which reduce the operator ability to manually mitigate conflicts due to the lack of situational awareness [19]. Therefore, autonomous operation is needed for the BLOS escape maneuver. Hence, this characteristic makes the [$\mathbf{Aut}_1$ + $\mathbf{Man}_3$]$^{(5a)}$ combination improbable.

B. Combination Process of CD&R Methods

The combining process is conducted in succession, instead of using direct permutation the four methods, to remove way any infeasible combination early, as shown in Figure 7. This paper selects a combination order that starts from the type of surveillance and ends with the type of autonomy, based on the factors' influences to the airspace authorities, air-traffic, and operators.

In every step, each combination is reviewed against the integrated airspace characteristic, as explained and coded in the previous subsection. If a combination is suitable, the process is continued until all four methods are combined as one 'generic approach'. When a combination is improbable, it is marked with an improbability flag. The combination process is still continued for this case, since, while it is difficult, it is not entirely impossible. Only when a particular combination generates more than one flag, then the process is discontinued, as it is shown in Figure 7. Note that some combinations can raise more than one flag at once, e.g., $\mathbf{Sur}_1\mathbf{Coo}_1$.

Ultimately, nine combinations emerge as generic approaches that do not raise any improbability flags throughout the process. These nine are the final approaches of the proposed taxonomy for the UAV CD&R. Although some of them already are popular with a lot supporting studies, other flagged combinations are rendered as less probable to be applied in the future integrated airspace. This is discussed more in the next subsection.

C. Approaches Availability

Table II listed a total of 64 previous studies on a CD&R system, along with each of their method combination attribution. The matches and mismatches of the CD&R approaches in the literature with the proposed taxonomy are also shown, where the rows of the nine generic approaches in the taxonomy are shadowed. This table omits combinations that are both flagged and does not have representative in the literature. It should be noted that the classification of approaches is strictly based on the demonstration shown in each reference, either by simulations or by real experiments.

Evidently, the high number of mismatches indicates that most research on CD&R are not ready to facilitate UAV integration into the airspace. The lack of representative methods on some parts of the taxonomy suggests that the research needs to change its focus to the parts that handle the characteristics of the future integrated airspace.

The first three rows of Table II consist of the combination of centralized-dependent surveillance ($\mathbf{Sur}_1$) and the explicit coordination ($\mathbf{Coo}_1$). This combination, however, is immediately marked with two improbability flags, considering the detectability and the coordination of UAVs. These improbabilities do not apply in manned-flight, which is predominance in these first three rows.

The $\mathbf{Sur}_1\mathbf{Coo}_2\mathbf{Man}_1\mathbf{Aut}_1$ combination, the first generic approach of the taxonomy, is very similar to the Procedural layer of manned-flight (see Figure 1). Hence, the CD&R examples include methods for flight traffic management, which is not yet being considered in UAV domains. Local path planning studies, such as in [9] and [32] ($\mathbf{Sur}_1\mathbf{Coo}_2\mathbf{Man}_1\mathbf{Aut}_2$), can actually fill this particular position if they are modified to a global path planning, which is conducted before each flights.

Many examples match the second and the third generic approach in the taxonomy ($\mathbf{Sur}_2\mathbf{Coo}_2\mathbf{Man}_2\mathbf{Aut}_1$ and $\mathbf{Sur}_2\mathbf{Coo}_2\mathbf{Man}_2\mathbf{Aut}_2$). These two approaches are popular since most studies are focused on developing the best avoidance method in terms of fuel or time efficiency, which is a trait specifically owned by the tactical maneuver ($\mathbf{Man}_2$). The assumption of distributed-dependent surveillance ($\mathbf{Sur}_2$), furthermore, reduces the possible uncertainties in the surveillance system and allows the studies to focus more on maneuver optimization. An example of this is presented in [53] that uses the Velocity Obstacle method to generate a deconflicting path with a minimum Closest Point of Approach.

In contrast, the fourth and fifth generic approach ($\mathbf{Sur}_2\mathbf{Coo}_3\mathbf{Man}_2\mathbf{Aut}_1$ and $\mathbf{Sur}_2\mathbf{Coo}_3\mathbf{Man}_2\mathbf{Aut}_2$) do not have any representative method at all. The only difference from the previous two approaches is that the avoidance here is uncoordinated ($\mathbf{Coo}_3$). One reason for the lack of representative is the contradiction fact: although the UAVs cooperatively broadcasting their states with a distributed-dependent surveillance ($\mathbf{Sur}_2$), the avoidance conducted is rogue without some sort of coordination. Therefore, while suitable for a UAV operation in an integrated airspace, these two particular approaches are actually improbable to be implemented.

The combination of independent surveillance ($\mathbf{Sur}_3$) and autonomous final decision ($\mathbf{Aut}_2$) dominates the UAV avoid-

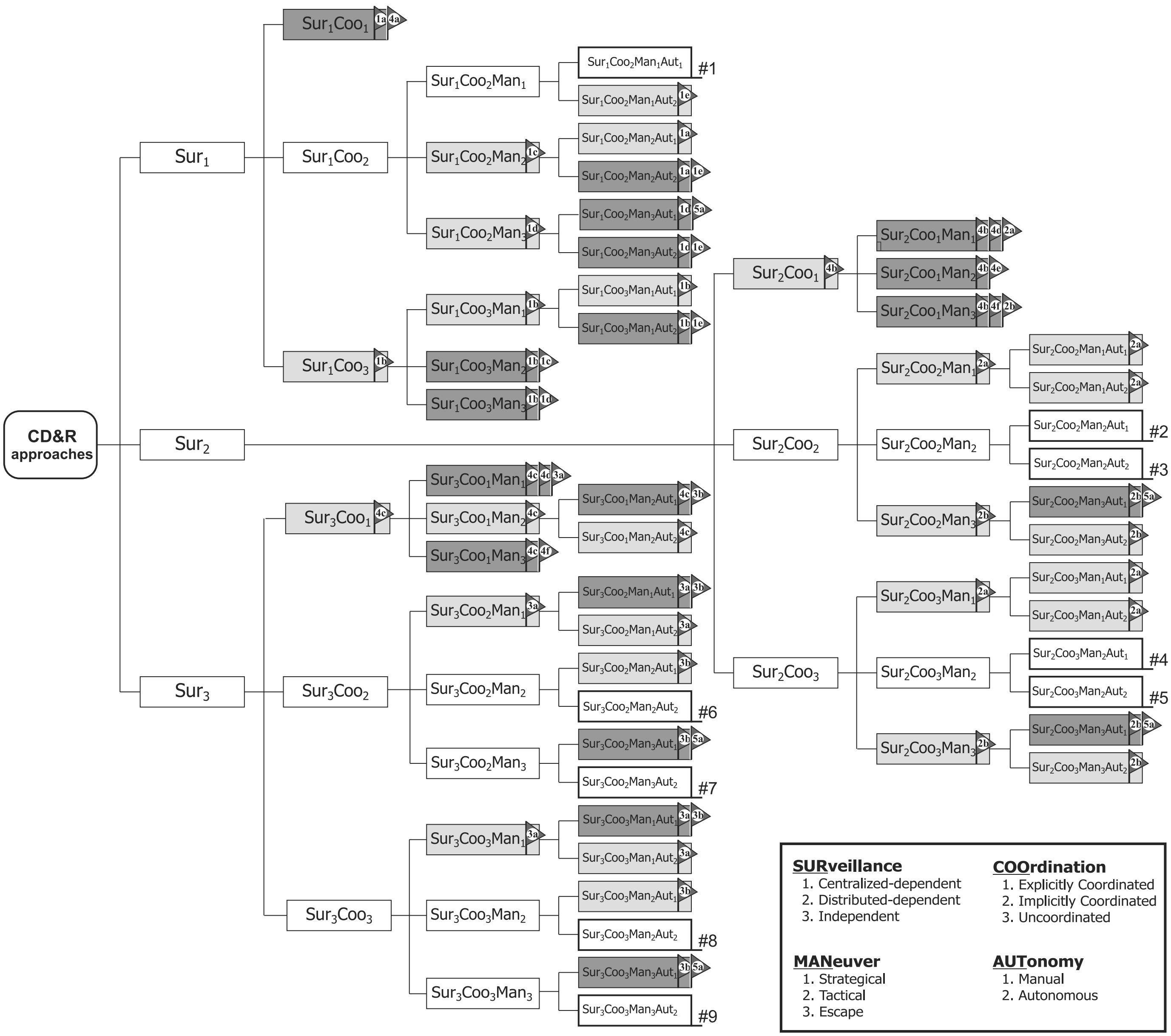


Fig. 7: Derivation of the CD&R approaches Taxonomy for UAVs flight. The flag's number refer to the improbable combination code (see section III.A). The combinations that do not raise any flag until the end are numbered form #1 to #9.

ance research. However, many of those studies fall into neither of the remaining generic approaches, since they demonstrate avoidance only between homogeneous vehicles or static obstacles, and therefore regarded as applying an explicitly coordinated avoidance ($\mathbf{Coo}_1$). The work in [3], [82], and [33], on the other hand, are considered improbable since they relies on manual operation, which is difficult to be applied in a BLOS operation.

From the remaining generic approaches in the taxonomy, the sixth combination have the most examples, where the other three almost have none. Here the popularity of a tactical maneuver ($\mathbf{Man}_2$) is still apply, but with a more advance algorithm that compensates errors in an independent surveillance system ($\mathbf{Sur}_3$).

Although examples for the seventh and ninth approach in the taxonomy $Sur_3Coo_2Man_3Aut_2$ and $Sur_3Coo_3Man_3Aut_2$) are not found in the surveyed literature, many studies actually use the open-loop input concept to autonomously generate an escape maneuver. These studies, however, only involve static obstacles and hence they are included as an explicit coordinated avoidance, resided in the row of $\mathbf{Sur}_3\mathbf{Coo}_1\mathbf{Man}_3\mathbf{Aut}_2$. Another case is the work in [17], with its Emergency Escape Maneuver, that comes close to the seventh and ninth approaches. However, it is only demonstrated under the support of a centralized dependent surveillance $\mathbf{Sur}_1$ from the ground.

Most of CD&R studies, apparently avoid the coupling between an independent surveillance and an uncoordinated avoidance ($\mathbf{Coo}_3$) that is featured in the eighth and ninth approach of the taxonomy. The main reason is because the combination would double the amount of uncertainties com-

TABLE II: Existing and/or suitable combinations of methods for UAVs in an integrated airspace. Combinations that are included in the proposed taxonomy are highlighted and numbered (see figure 7)

Combination				Flags	Examples	No.
$\mathbf{Sur}_1$	$\mathbf{Coo}_1$	$\mathbf{Man}_1$	$\mathbf{Aut}_1$	≥ 2	Prandini‡ [4], Nikolos† [13], Visintini‡ [21], Borrelli [22], and Vela‡ [35]	
$\mathbf{Sur}_1$	$\mathbf{Coo}_1$	$\mathbf{Man}_2$	$\mathbf{Aut}_1$	≥ 2	Mao‡ [25], and Treleaven‡ [29]	
$\mathbf{Sur}_1$	$\mathbf{Coo}_1$	$\mathbf{Man}_2$	$\mathbf{Aut}_2$	≥ 2	Huang‡ [56]	
$\mathbf{Sur}_1$	$\mathbf{Coo}_2$	$\mathbf{Man}_1$	$\mathbf{Aut}_1$	0	-	**#1**
$\mathbf{Sur}_1$	$\mathbf{Coo}_2$	$\mathbf{Man}_1$	$\mathbf{Aut}_2$	1	Beard [9], and Duan [32]	
$\mathbf{Sur}_1$	$\mathbf{Coo}_3$	$\mathbf{Man}_3$	$\mathbf{Aut}_2$	≥ 2	Teo [17]	
$\mathbf{Sur}_2$	$\mathbf{Coo}_1$	$\mathbf{Man}_2$	$\mathbf{Aut}_1$	≥ 2	Mao‡ [25], and Velasco‡ [59]	
$\mathbf{Sur}_2$	$\mathbf{Coo}_1$	$\mathbf{Man}_2$	$\mathbf{Aut}_2$	≥ 2	Richards [14], Sislak‡ [37], Chipalkatty‡ [46], and Hurley† [51]	
$\mathbf{Sur}_2$	$\mathbf{Coo}_2$	$\mathbf{Man}_1$	$\mathbf{Aut}_2$	1	Beard [9], Duan† [32], and Devasia‡ [38]	
$\mathbf{Sur}_2$	$\mathbf{Coo}_2$	$\mathbf{Man}_2$	$\mathbf{Aut}_1$	0	Hoekstra‡ [10], Hoekstra‡ [5], Peng‡ [36], Lupu‡ [39], Ellerbroek‡ [40], and Ellerbroek‡ [52]	**#2**
$\mathbf{Sur}_2$	$\mathbf{Coo}_2$	$\mathbf{Man}_2$	$\mathbf{Aut}_2$	0	Bicchi‡ [6], Tomlin‡ [7], Mao‡ [8], Pallottino‡ [11], Paielli [15], Richards [18], Christodoulou‡ [23], Park [30], Mujumdar [42], and Jenie [53]	**#3**
$\mathbf{Sur}_2$	$\mathbf{Coo}_2$	$\mathbf{Man}_3$	$\mathbf{Aut}_1$	2	LeTallec [19], Zeitlin [26], and Kochenderfer‡ [50]	
$\mathbf{Sur}_2$	$\mathbf{Coo}_3$	$\mathbf{Man}_2$	$\mathbf{Aut}_1$	0	-	**#4**
$\mathbf{Sur}_2$	$\mathbf{Coo}_3$	$\mathbf{Man}_2$	$\mathbf{Aut}_2$	0	-	**#5**
$\mathbf{Sur}_2$	$\mathbf{Coo}_3$	$\mathbf{Man}_3$	$\mathbf{Aut}_1$	2	Winder [3]	
$\mathbf{Sur}_3$	$\mathbf{Coo}_1$	$\mathbf{Man}_1$	$\mathbf{Aut}_2$	≥ 3	Kelly† [24], Langelaan† [27], Obermeyer† [48], and Chowdhary† [47]	
$\mathbf{Sur}_3$	$\mathbf{Coo}_1$	$\mathbf{Man}_2$	$\mathbf{Aut}_2$	1	Netter† [81], Nikolos† [13], Yang† [16], McGee† [20], Patel† [43], Hrabar† [44], and Jung† [54]	
$\mathbf{Sur}_3$	$\mathbf{Coo}_1$	$\mathbf{Man}_3$	$\mathbf{Aut}_2$	≥ 2	Beyeler† [34], Bouabdallah† [28], deCroon† [41], deCroon† [49], and Muller† [58]	
$\mathbf{Sur}_3$	$\mathbf{Coo}_2$	$\mathbf{Man}_2$	$\mathbf{Aut}_2$	0	Kitamura [2], Fasano [31], Prevost [45], Klaus [55], and Schmitt [57]	**#6**
$\mathbf{Sur}_3$	$\mathbf{Coo}_2$	$\mathbf{Man}_3$	$\mathbf{Aut}_1$	2	Lam† [82], and Lam† [33]	
$\mathbf{Sur}_3$	$\mathbf{Coo}_2$	$\mathbf{Man}_3$	$\mathbf{Aut}_2$	0	-	**#7**
$\mathbf{Sur}_3$	$\mathbf{Coo}_3$	$\mathbf{Man}_2$	$\mathbf{Aut}_2$	0	Rathbun [12]	**#8**
$\mathbf{Sur}_3$	$\mathbf{Coo}_3$	$\mathbf{Man}_3$	$\mathbf{Aut}_2$	0	-	**#9**

† Indoor application, against static obstacles.
‡ Manned-flight applications

pared to if those factors are used separately. The example in [12], in this case, stands out from the literature as being the only example of the $\mathbf{Sur}_3\mathbf{Coo}_3$ combination.

IV. A Multi-layered Architecture

Figure 8 presents an example of a multi-layered architecture for a UAV CD&R system when operating in an integrated airspace, along with the comparison with the one of manned-flight. The new architecture is built using six generic approaches taken from the proposed taxonomy. The arrangement and general implementation are discussed in the following subsections.

A. Generic Approaches Arrangement

As presented in Figure 1, the order of layers in the manned-flight CD&R architecture corresponds to each approach's distance thresholds, which depends on the range of the surveillance and the total length of the maneuver. This particular order is also used in the elaboration of the types of surveillance and maneuver (see Section II), which makes the numbering of generic approaches in the taxonomy are already in order.

By those arrangement, six generic approaches are taken from the taxonomy to build a multi-layered architecture as shown in Figure 8. The fourth and fifth approach are left out, due to the improbability reason explained in Section II.C. The eighth approach ($\mathbf{Sur}_3\mathbf{Coo}_3\mathbf{Man}_2\mathbf{Aut}_2$) is also removed, since applying its tactical maneuver after the use of escape in the seventh approach would be pointless.

Figure 8 compares the proposed UAV CD&R architecture with the one of manned-flight. Each of the proposed layers can be designated with a name that represent its most standout characteristics, i.e., (1) the Procedural, (2) the Manual, (3) the Cooperative, (4) the Non-cooperative, (5) the Escape, and (6) the Emergency layer.

B. General Implementation

The implementation of the multi-layered architecture depends closely on the type of mission. In one particular mission some layers might become less necessary, while in others they might be important. This subsection presents a general implementation in a mission where it is possible to deploy all six layers.

First, before a flight is even conducted, the UAV operator seeks approval for the mission flight-plan and collect traffic data. This activity is represented by the Procedural Layer ($\mathbf{Sur}_1\mathbf{Coo}_2\mathbf{Man}_1\mathbf{Aut}_1$). The aim is to avoid unnecessary conflict with other traffic, static obstacles, or bad weather. This is done with a centralized surveillance such as an Air Traffic Control (ATC) station.

In the transition airspace after departure, the UAV relies first on its dependent surveillance system, which can be either the ADS-B, or FLARM. The system detects other vehicles early enough to send the updated traffic data to the ground,

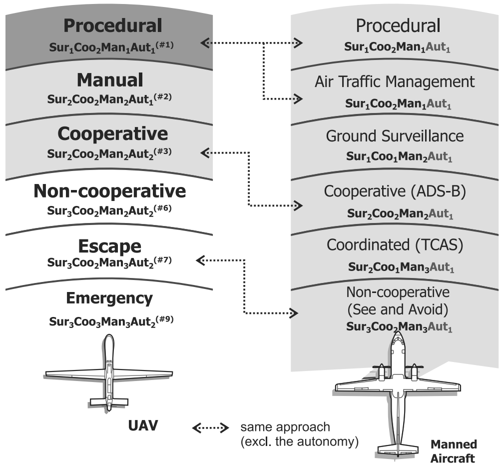


Fig. 8: Example of a multi-layered CD&R architecture for UAVs, presented as layers of safety comparable with the manned-flight's [62]

and conducts a tactical maneuver manually, i.e., the Manual layer ($\mathbf{Sur}_2\mathbf{Coo}_2\mathbf{Man}_2\mathbf{Aut}_1$). The implicit-coordination in this layer can be a simple rule like, for example, not to bother the existing traffic (first-come-first-served). These first two layers (Procedural and Manual) apply also in the landing phase.

In the en-route phase, which is mostly BLOS, the UAV can switch to the Cooperative Layer ($\mathbf{Sur}_2\mathbf{Coo}_2\mathbf{Man}_2\mathbf{Aut}_2$). The avoidance in this layer uses a shorter tactical range and is conducted autonomously. Implicit rules, such as an adaptation of the manned-flight Visual Flight Rules (VFR) [67], are applied to simplify the resolution. At this point, all conflicts with normal manned-aircraft are resolved.

The Non-cooperative Layer ($\mathbf{Sur}_3\mathbf{Coo}_2\mathbf{Man}_2\mathbf{Aut}_2$) intends to avoid obstacles that are not detected using previous distributed-dependent surveillance. On-board sensors, such as camera, can be used to generate an autonomous tactical maneuver. In this layer, every conflict with normal aircraft, manned or unmanned, is resolved.

The Escape Layer ($\mathbf{Sur}_3\mathbf{Coo}_2\mathbf{Man}_3\mathbf{Aut}_2$) aims to avoid any remaining non-cooperative obstacles that are hard to detect within sufficient range for a tactical maneuver, and are possibly not cooperative. To escape to a safety zone as soon as possible, the ownship's maneuverability should be the deciding factor in determining the layer threshold. The implicit-rules in avoiding, however, are still obeyed by the ownship, expecting that the obstacles do not intentionally make the conflicts .

Due to various unexpected situations, penetrations through all the five previous layers are still possible. For example, a cooperative UAV that has failure in its control system, rogue objects without any means of avoiidance, or even a hostile UAV aiming to take the ownship down. In these situations, the Emergency layer ($\mathbf{Sur}_3\mathbf{Coo}_3\mathbf{Man}_3\mathbf{Aut}_2$) is implemented, where the UAV can disregards the rule and conduct necessary maneuver using its maximum capability to ensure safety.

V. Conclusion

The paper has proposed a taxonomy of Conflict Detection and Resolution (CD&R) approaches for Unmanned Aerial Vehicles (UAV), which consist of generic approaches that have been reviewed with regard to their feasibility for operation in an integrated airspace. The taxonomy has then been used to attribute a total of 64 proposed CD&R methods in literature, in order to determine their positions in an overall CD&R function of UAVs. This attribution has shown that many of the available methods fall outside the taxonomy, and suggests the need to concentrate the CD&R research more to parts where representative methods are lacking.

An example of an exhaustive multi-layered architecture for UAV CD&R systems has also been elaborated in this paper, consisting of six layers of generic approaches taken from the proposed taxonomy. Although its general implementation has been discussed, the multi-layered architecture is still lacking physical thresholds between the layers, such as distances or time-to-collision. Improvement is warranted for future works, nevertheless, it has been shown that the proposed taxonomy and architecture can be a guideline for the authorities, operators, and developers, to facilitate the UAV integration into the civil airspace.

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