DYNAMIC EVENT TREE FRAMEWORK TO ASSESS COLLISION RISK BETWEEN VARIOUS AIRCRAFT TYPES

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Abstract

The air transportation system provides an extremely safe mode of transportation. Maintaining adequate separation ensures safety but limits capacity of the airspace. In addition to the expected growth in commercial flights, the number and diversity of other aircraft (e.g., unmanned aerial vehicles, UAVs) will also increase significantly. Various types of UAVs have a wide range of specifications and performance characteristics (e.g., cruise speed and maximum operating altitude) that can differ significantly from manned aircraft. They may also have different collision avoidance technologies that rely on various sensors (e.g., optical, thermal, or laser) to detect and avoid nearby aircraft. While accommodating the variety of aircraft types in an airspace, collision risk should remain less than a specified target level of safety. This paper develops a case study for collision risk of an airspace with different aircraft types and collision avoidance capabilities using a proposed dynamic event tree framework. Sensitivity analysis is conducted on the parameters used in the case study.

Introduction

The air transportation system provides an extremely safe mode of transportation. As traffic demand grows and as new aircraft types with different collision avoidance capabilities are introduced, the system must continue to maintain a high target level of safety.

Air transportation passenger traffic in the U.S. is forecasted to increase by 2.5 percent annually for the next 25 years [1]. In addition to the growth in commercial flights, there will be increasing demand in unmanned aircraft systems (UAS) as well as commercial spacecraft eager to access the National Airspace System (NAS). The U.S. Department of Transportation expects that public agencies, including the Department of Defense, will operate more than 50,000 UASs by 2030 [2]. Wieland [3] estimates a demand of over 25,000 UAS flights per day above 2,000 feet above ground level.

Not only the number of aircraft, but also the diversity of aircraft will increase. Unmanned aerial vehicles have a wide range of specifications and performance characteristics (e.g., cruise speed and maximum operating altitude) that can differ significantly from manned aircraft. They may also have different collision avoidance technologies that rely on various sensors (e.g., optical, thermal, or laser) to detect and avoid nearby aircraft. Furthermore, they conduct numerous types of missions that can result in different flying patterns. Examples include monitoring air quality, weather data collection, and tactical fighting of wildfires.

To accommodate the various aircraft types, the collision risk of the airspace should remain less than a specified target level of safety. A number of analyses have been conducted to evaluate collision risk for UAS in terms of technology, concept of operations, algorithms, and so forth (e.g., [4], [5]). Most papers focus on evaluating how successfully the collision avoidance technology can detect and avoid a collision with a manned aircraft. This paper develops a similar case study for collision risk between a manned aircraft and a remotely piloted vehicle using a proposed dynamic event tree (DET) framework. An advantage of the DET framework is that it is easy to adapt to collision scenarios between different types of aircraft, such as UAS-UAS collisions. The framework also considers component failures in the analysis. Sensitivity analysis on the model parameters including component failure probabilities, maximum detection range of the sensors, and collision geometries are conducted.

This paper is organized as follows: The proposed dynamic event tree framework for collision risk is described in the next section. Then, a case study for collision risk between aircraft equipped with various types of collision avoidance capabilities is illustrated in terms of airspace concept of operation and conflict detection. Results and sensitivity analysis on the parameters are presented.

Dynamic Event Tree Framework

Dynamic event trees (DET) were used in previous collision risk studies as an extension of standard event trees to include branching probabilities that vary as a function in time ([6], [7]). Reference [8] generalized the methods in [6] and [7], proposing a general DET framework to model mid-air collision scenarios.

The proposed DET framework consists of three levels, a high-level dynamic event tree, a generic sub-tree, and supporting fault trees (Figure 1). The high-level tree (top of Figure 1) models multiple phases of conflict detection and resolution (CD&R) systems that operate in a sequence to prevent a collision. The generic sub-tree (middle) models a sequence of events that should occur for the collision risk to be successfully resolved within each phase – for example, working physical components, successful detection of the conflict, identification of resolution maneuvers, and correct pilot behavior. The sub-tree is also structured as a dynamic event tree to model time-varying transition probabilities. Lastly, fault trees (bottom) model the component-based failure logic of the systems. Each CD&R system can be supported by several components, some of which can support multiple CD&R systems. That is, there may be component dependencies between the systems.

Several assumptions are made within the framework:

- Each component fails randomly according to a component-dependent fixed rate.
- All components are statistically independent of each other.
- All components are unrepairable.
- Each CD&R system has a random time to successfully detect a conflict and propose a resolution maneuver, according to some probability distribution function.
- The time for the flight crew or remote operator to correctly respond to a proposed resolution maneuver is random, according to some probability distribution function.

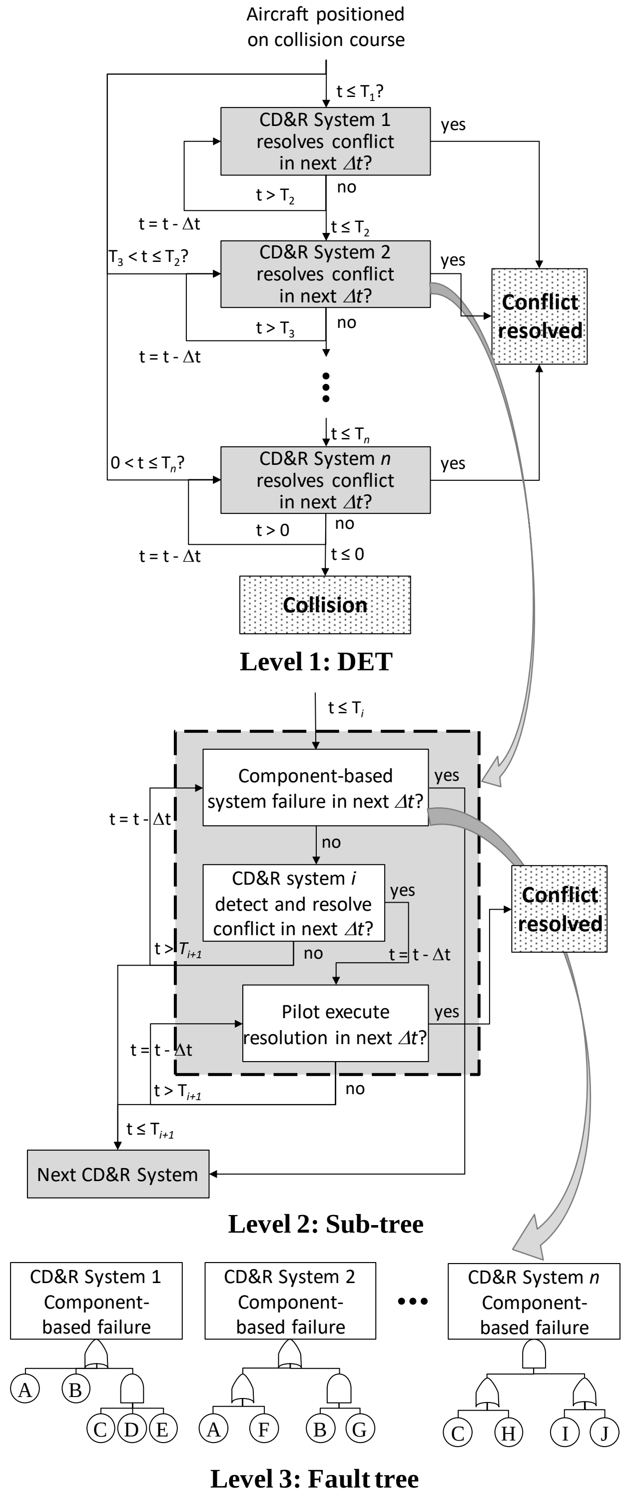

Figure 1. General Framework of Dynamic Event Tree [8]

In Figure 1, the initiating event is a situation in which two aircraft are on a collision course with each other. Time *t* is defined as the time remaining to the collision. This value is decremented by a small amount Δt in an iterative manner until either a collision occurs (at $t = 0$) or is avoided. Note that t, as defined here, *decreases in time*. Each CD&R system attempts to detect and resolve the conflict until either the conflict is resolved or t reaches a designated time point T_i, at which point the next CD&R system takes over from the previous one.

In order to evaluate the DET framework, we use a method described in [8] which uses a binary decision diagram based algorithm for reliability analysis of phased-mission systems (PMS-BDD) [9], adapted to dynamic event trees.

Case Study

In this section, we give a case study of collision risk between a manned aircraft and a remotely-piloted unmanned aircraft, where the two aircraft have different types of collision avoidance systems. The case study is developed in a future NAS environment under a proposed Autonomous Flight Management (AFM) concept [10].

Autonomous Flight Management (AFM)

In order to handle increasing aircraft demand, additional automation will be needed in future NAS operations. One proposed concept is the Autonomous Flight Management (AFM) concept [10]. AFM distributes the responsibility of maintaining safe separation to operators in the air. The AFM concept is used as part of the case study for collision risk in this paper.

Based on [10], an aircraft operating in the AFM concept has three safety layers that sequentially operate to prevent a mid-air collision. These systems are a strategic intent-based (SI) CD&R system, a tactical intent-based (TI) system, and a tactical state-based (TS) system. The first two safety layers (SI and TI) are implemented via an Airborne Separation Assistance System (ASAS), which is a software automation system onboard the aircraft that performs conflict detection, resolution, and prevention functions. Both systems use state and intent information of other aircraft to suggest resolutions. The final safety layer is the Traffic Collision Avoidance System (TCAS), which uses state information of the two aircraft to avoid an imminent collision. The three systems are assumed to operate in the following respective time intervals: Between 8 min and 3 min prior to a collision, between 3 min and 1 min prior to a collision, and within 1 min prior to a collision. Times for each CD&R system to activate are chosen to provide an acceptable trade-off between the benefits of alerting as early as possible and the costs of false alarms [11].

CD&R for UAS

We consider the hypothetical introduction of unmanned aircraft systems (UAS) into the AFM framework. In the future NAS, various types of UAS may have different conflict detection and resolution systems onboard. Unlike manned (commercial) aircraft, UAS may not be equipped with all three CD&R systems due to cost, weight, capacity, or power restrictions.

Table 1 provides a summary of example sensors for UAS in terms of type, information that can be obtained, detection range, and weather conditions in which a sensor operates ([12], [13], [14]). Mode A/C transponders, Automatic Dependent Surveillance-Broadcast (ADS-B) and Traffic Alert and Collision Avoidance System (TCAS) are cooperative sensors because they transmit their position information either by interrogation or on their own. The other sensors are non-cooperative sensors. An aircraft equipped only with a non-cooperative sensor can acquire information of other nearby flights, but the other flights do not have position information of that aircraft. Radar and LIDAR systems locate nearby aircraft by deploying energy, e.g., emitting an electronic pulse, while electro-optical (EO) systems and acoustic systems sense aircraft passively (e.g., by listening to sound made by aircraft). Active non-cooperative sensors require more energy so are typically bigger and heavier. Passive non-cooperative sensors are smaller and lighter, but they do not provide range information directly.

Table 1. Summary of example sensor technologies for UAS

Sensor	Type	Information acquired	Detection Range	Weather Condition
Mode A/C Transponder	Cooperative	Range, Altitude	160 km	VMC / IMC
ADS-B	Cooperative	Position, Altitude, Velocity	240 km	VMC / IMC

TCAS	Cooperative	Range, Altitude	160 km	VMC / IMC
Radar	Non-Cooperative (Active)	Range, Bearing	35 km	VMC / IMC
LIDAR	Non-Cooperative (Active)	Range	3 km	VMC / IMC
Electro-Optical (EO) system	Non-Cooperative (Passive)	Azimuth, Elevation	20 km	VMC
Acoustic system	Non-Cooperative (Passive)	Azimuth, Elevation	10 km	VMC

Note: VMC-Visual Meteorological Conditions, IMC-Instrument Meteorological Conditions

In the case study, the manned aircraft is assumed to be AFM-equipped with three safety levels. But the unmanned aircraft is assumed to have only one safety layer, namely a non-cooperative radar to acquire position information of other aircraft. The timings of these safety layers are illustrated in Figure 2. The time interval of the UAS safety phase (T_4) depends on the sensor range, speed of the aircraft, and conflict geometries.

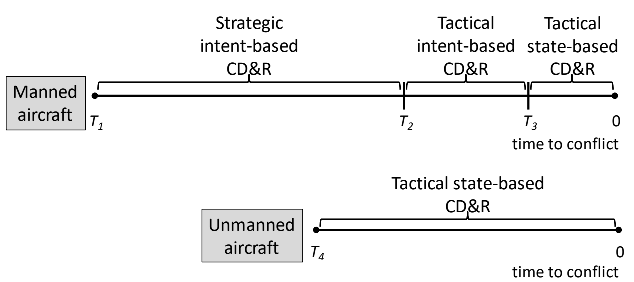

Figure 2. CD&R phases for the case study

An assumed concept of operation of the CD&R system on the unmanned aircraft is as follows: The onboard radar provides relative position information of nearby aircraft. An onboard CD&R processor detects potential conflicts using this information and determines appropriate resolutions. Resolutions are transmitted to a remote pilot via a command and control link. The pilot of the UAS is informed of suggested resolutions aurally through a speaker and visually through a display. The pilot chooses a resolution and gives a command to the UAS to execute the resolution to avoid the predicted conflict.

The unmanned aircraft is also assumed to have a Mode A/C cooperative transponder. This is assumed since the CD&R systems on the manned aircraft require position information of the unmanned aircraft, which the cooperative sensor provides either directly or through ground systems.

Fault Trees for CD&R Systems

In order for the CD&R systems to operate, several sub-systems/components must be working. A fault tree for each CD&R system is given to show the failure logic between components and the CD&R functionality. These fault trees are based on the AFM concept in [10] for the manned aircraft combined with the assumed concept of operation for the CD&R system on the unmanned aircraft. (The fault trees for a pair of manned aircraft in AFM flight would be different.)

Figure 3 shows the failure logic of the strategic-intent-based (SI) system on the manned aircraft. The SI system can fail either due to the failure of components supporting the system or due to a surveillance failure. On the left side of the figure, the SI system is supported by a processor that runs the conflict detection and resolution algorithm and a display that visually provides conflict information and resolution to the pilot. The failure considered here is a physical failure of the processor. The system can also fail algorithmically (i.e., failure to detect a conflict due to uncertainties in surveillance information), and this is considered later in the paper.

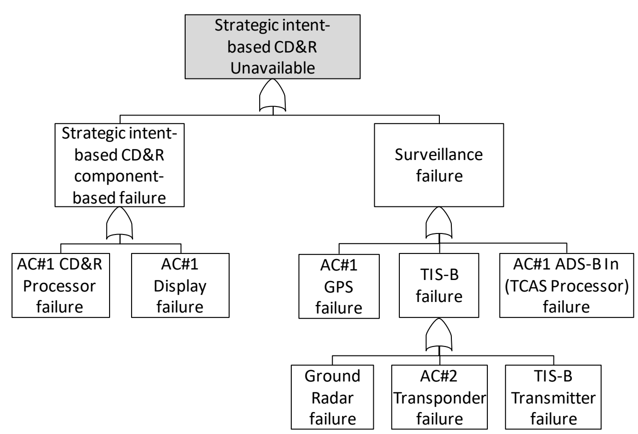

Figure 3. Supporting fault tree for strategic intent-based CD&R system (manned aircraft)

On the right side of the figure, a surveillance failure occurs when the manned aircraft cannot locate either itself or the other aircraft. The manned aircraft's own location comes from a Global Positioning System (GPS) that is assumed to collect position, velocity, and heading information (from the Global Navigation Satellite System, GNSS) and altitude information from the altimeter. It passes this information to the CD&R processor. To acquire the location of the other aircraft,

According to [10], ADS-B is the primary source of surveillance information for the manned aircraft. However, since the unmanned aircraft is assumed *not* to have an ADS-B system, the Traffic Information Service Broadcast (TIS-B) system is used to acquire the location of the unmanned aircraft. In the AFM concept, TIS-B is a ground-based backup system that provides surveillance information of non-ADS-B equipped aircraft. Ground radar locates the unmanned aircraft by interrogating its transponder. A transmitter sends the surveillance information to the manned aircraft in the form of an ADS-B Out message. The ADS-B In system on the aircraft receives the message and provides surveillance information to the CD&R systems and/or flight crew. The ADS-B In function is currently implemented in the TCAS processor on most commercial aircraft [15].

The tactical intent-based (TI) system begins to operate 3 minutes prior to a potential collision. Figure 4 shows the failure logic of the TI system, which is similar to the logic of the SI system. Failures of supporting components or a loss of location of any aircraft can lead to failure of the TI system. The TI system uses the same source for surveillance information as the SI system does, which is the ground-based TIS-B system. A key difference is that the TI system uses two means to alert the pilot of conflict detection and resolution – namely, a display and speaker.

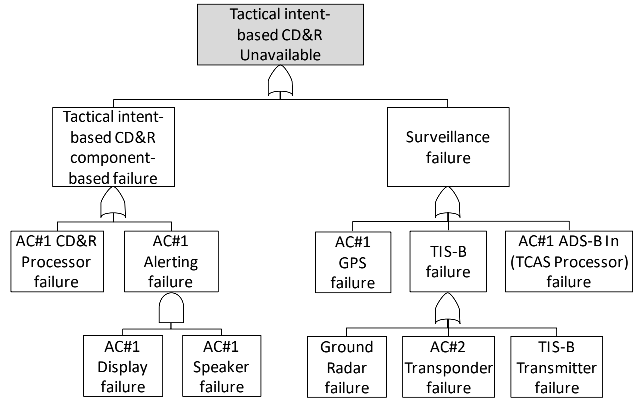

Figure 4. Supporting fault tree for tactical intent-based CD&R system (manned)

The tactical state-based (TS) system is the last CD&R system for the manned aircraft to avoid a midair collision, assumed to be TCAS here. According to [16], TCAS has a requirement to provide reliable surveillance out to 14 nautical miles (nmi). In this paper, 1 minute is chosen as the activation time of TCAS, which is enough to account for a closing speed up to 840 knots in a head-on collision. Unlike the previous CD&R systems, TCAS obtains surveillance information by direct interrogation of the transponder on the other aircraft [16]. Thus TCAS can fail if the transponder on the target aircraft fails. TCAS can also fail if the transponder on the own aircraft fails. According to [16], the TCAS processor is connected to the Mode S transponder and is not available if the transponder fails. In addition, the TCAS display and speaker support TCAS to perform its function as depicted in Figure 5.

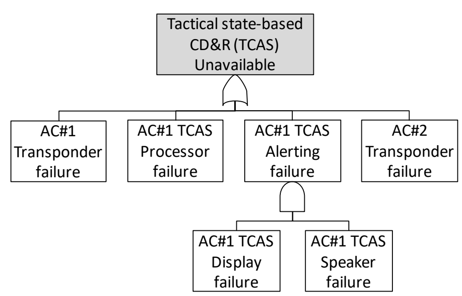

Figure 5. Supporting fault tree for tactical state-based CD&R system (TCAS, manned)

Figure 6 shows the fault tree supporting the CD&R system for the unmanned aircraft. Similar to the CD&R systems for the manned aircraft, the CD&R system for the unmanned aircraft is assumed to be configured with a processor, means of alerting (visual and aural), and sensors that provide state information of the other aircraft. An additional component is a command and control link through which the remote pilot receives resolutions and can direct the aircraft.

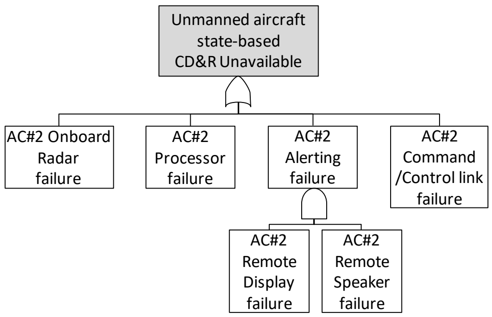

Figure 6. Supporting fault tree for tactical state-based CD&R system (unmanned)

Table 2 summarizes components that support the CD&R systems for both aircraft and their failure rates. Some of the values are assumed, and others are obtained from the literature.

Table 2. Parameters in fault trees for CD&R systems

Component	Failure Rate (/hr)	Description
CD&R Processor	6.25E-5 [17]	- Running CD&R logic using information from ADS-B In, GPS, etc.
Display	6.25E-5 [17]	- Providing traffic/conflict information and resolution trajectory to flight crew
Speaker	6.25E-5 (assumed)	- Providing aural alert to draw flight crew attention to conflicts
GPS	5.0E-5 [18]	- Providing position/velocity, altitude, heading, and air-ground status information
Transponder	8.33E-5 [17]	- Mode C / Mode S transponder including antennas - Providing aircraft state information as response of interrogation
TIS-B transmitter	1.0E-4 [18]	- Providing traffic information from ground to air
Ground radar	2.0E-5 [17]	- Secondary surveillance radar - Gathering traffic information
TCAS Processor / ADS-B In	6.25E-5 [17]	- Antennas included - Transmitting interrogation to / receiving replies from other aircraft - Running TCAS logic - Receiving ADS-B messages from other aircraft or ground facilities - Providing information to flight crew display and to CD&R processor
TCAS Display	6.25E-5 [17]	- Providing traffic/conflict information and resolution trajectory to flight crew
TCAS Speaker	6.25E-5 (assumed)	- Providing aural alert to draw flight crew attention to conflicts
Onboard radar	1.0E-4 (assumed)	- Gathering traffic information
Command/ Control link	1.0E-4 (assumed)	- Providing ability to communicate between aircraft and remote pilot - Providing ability for remote pilot to control aircraft

Algorithm Performance

In order for a conflict to be resolved, three steps need to be completed: 1) an algorithm of the CD&R system detects the conflict, 2) an algorithm of the CD&R system provides appropriate resolutions for the pilot to avoid a conflict, and 3) the pilot correctly executes the provided resolution.

Various studies have been conducted to develop autonomous CD&R algorithms. This paper uses an analytic conflict-detection method from [19] which gives the probability that a loss of separation ($\leq$ 5 nmi) occurs when the system predicts a loss of separation. Level flight is assumed. Trajectory prediction errors are assumed to be normally distributed with a constant root mean square (rms) for the lateral position prediction error and a linearly growing rms in time for the longitudinal position prediction error. The resulting probability for an actual loss of separation is a function of the time prior to the predicted loss of separation. It is also a function of other parameters such as speed of aircraft, size of the conflict zone, and the path-crossing angle. Figure 7 shows sample loss of separation probabilities for different path-crossing angles based on an implementation of the algorithm in [19] (using 5 nmi as a conflict radius).

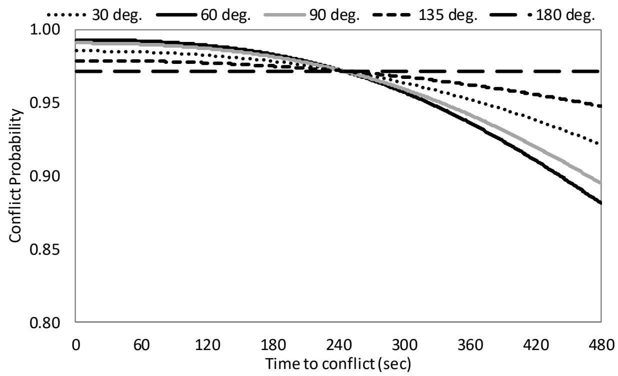

Figure 7. Loss of separation probabilities for different path-crossing angles

As a technical note, we need to convert values in Figure 7 to probabilities used in the DET model. The values in Figure 7 are *cumulative* probabilities, whereas the model uses probabilities associated with detecting conflicts in the next Δt seconds (see level-2 sub-tree in Figure 1). This can be obtained by converting the cumulative probability to an associated hazard rate function. For example, for a 90° path-crossing angle, at 480 seconds prior to a collision, the probability in Figure 7 is about 0.9. This is interpreted as the cumulative probability of detecting the conflict some time prior to a collision. The associated hazard rate is $-[\ln(1 - 0.9)] / 480 \approx 0.0048$ / sec, meaning there is roughly a 0.0048 probability of detecting the conflict each second. Over 480 seconds, the probability of detecting the conflict yields the desired value of 0.9. Over an interval of Δt seconds, the probability of detecting the conflict is $1\text{-}\exp(-0.0048\Delta t)$ which is about $0.0048\Delta t$, assuming Δt is small.

This analysis assumes that the values in Figure 7 can be interpreted as the probability of detecting a conflict, given that a collision will occur. The model in [19] gives something slightly different – the probability that a collision will occur given a conflict is detected. By Bayes' theorem, these are approximately the same, so long as the probability of detecting a collision is roughly the same as the probability of a collision (i.e., the detection algorithm is not biased high or low in terms of identifying collisions).

In this paper, it is assumed that the CD&R systems always generates an appropriate resolution once the conflict is detected.

In order to determine the probabilities for the pilot to correctly execute a resolution provided by the CD&R system, we use results from [20], which assessed the performance of commercial pilots in human-in-the-loop simulation experiments. In this study, pilot response delays in a self-separation concept were measured when interacting with automated separation assurance tools on board. A CD&R tool was set to provide two different alerting levels depending on the time to a predicted conflict. One alerting mechanism was a display with a chime sound and the other was a display with an aural warning. Average response delays to the two different alerting levels were 32.4 and 20.6 seconds, which are assumed as the pilot response delays for SI and TI respectively in this paper. Assuming exponential distributions for the response times, we convert these values to pilot response rates for the first two CD&R phases, similar to the previous discussion of Figure 7. The pilot execution rate for the last CD&R phase is based on [16], where pilots are expected to respond to a TCAS Resolution Advisory in 5 seconds.

Several assumptions for the performance of the CD&R system on the unmanned aircraft are also made. It is assumed that the CD&R system on the unmanned aircraft successfully detects and resolves a conflict with a probability (or rate) that is 30% that of the manned aircraft. This is a time-varying value (e.g., see the conflict detection rate in Table 3). The performance of the remote pilot (i.e., the random time to execute a resolution) is assumed to be the same as for the first CD&R phase of the manned aircraft.

The activation time for the CD&R system of the unmanned aircraft is based on the detection range of the onboard sensors, the geometry of the conflict, and the speed of the two aircraft. Table 2 shows a summary of the parameters for algorithm performance at time t prior to a conflict, given a 90° path-crossing angle.

Table 3. Parameters of CD&R system function and pilot behavior

Aircraft	CD&R Phase	Time to Collision (min)	Conflict Detection Rate (/hr)	Pilot Execution Rate (/hr)
Manned	Strategic intent-based CD&R	8	17	111
		7.5	19	
		7	22	
		6.5	25	

		6	28	
		5.5	33	
		5	38	
		4.5	45	
		4	54	
		3.5	65	
	Tactical intent-based CD&R	3	80	175
		2.5	100	
		2	130	
		1.5	179	
	Tactical state-based CD&R	1	276	720
		0.5	560	
Unmanned	Tactical state-based CD&R	2.5	30	111
		2	39	
		1.5	54	
		1.0	83	
		0.5	168	

Application of DET Framework

The proposed DET framework models collision risk from the perspective of one aircraft. But the collision avoidance maneuver can be conducted by either aircraft. Only one aircraft needs to execute an avoidance maneuver. If both aircraft are independent in terms of physical components supporting the CD&R systems, it is possible to independently apply the framework to each aircraft. Then, the overall collision probability is the product of the two collision probabilities from each aircraft (i.e., a collision occurs if both aircraft fail to detect and avoid the other).

The evaluation steps using the methodology described in [8] are as follows: i) Create up to 2^n DETs (where n is the number of CD&R systems on a given aircraft) to reflect the sequence of events that can occur when a given combination of CD&R systems are functional. Compute the conditional probability o_j that a collision occurs for each DET. ii) Create a fault tree for each DET generated in the previous step, combining fault trees and/or success trees for each CD&R system. iii) Apply the PMS-BDD method in [9] to the combined fault trees to give a weighted probability q_j of each DET being used. iv) Compute the overall collision probability as a weighted sum of the conditional collision probabilities ($\Sigma_j\, q_j * o_j$).

Result & Sensitivity Analysis

This section provides numerical results and sensitivity analyses of the case study for collision risk between a manned and remotely-piloted unmanned aircraft. The activation time for the CD&R system on the unmanned aircraft varies depending on the speed of the aircraft and path-crossing angles between the aircraft (Table 4). All other parameters needed for the DET framework are explained in the previous section. The case study assumes level flight.

Table 4. Activation times for CD&R system on unmanned aircraft by path-crossing angle

Angle btw flight paths	30°	60°	90°	135°	180°
Activation time (min)	4.25	3.25	2.60	2.12	1.98

Figure 8 shows the resulting collision probabilities as a function of the path-crossing angle. These are *conditional* collision probabilities, under the assumption that two aircraft are on a collision course in the first place. As might be expected, the collision probability increases for larger path-crossing angles, since the closing speed increases, thus decreasing the time available to avoid a collision (180° represents a head-on scenario). But the collision risk is not completely monotonic. The collision risk decreases slightly at first and then increases. This is because there is a competing effect where the conflict detection algorithm in [19] is more accurate for path-crossing angles between 45° and 90° (at least for the parameters used in this example), so the collision risk improves even though the time to avoid a collision decreases.

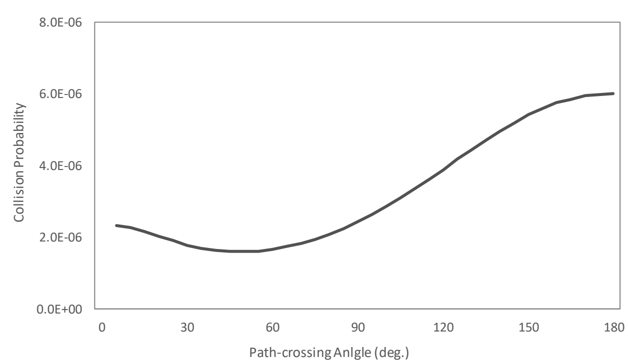

Figure 8. Collision probabilities of case study

Figure 9 shows the contribution of failure modes on the manned aircraft for the case study. Algorithm and pilot failures indicate the contribution of cases where all CD&R systems are available, but the algorithm fails to detect the conflict or the pilot does not respond in time. Component-based failures show the contribution of cases where all CD&R systems are unavailable due to component failures. Component-based failures are a major cause of collision risk; however, the relative contribution decreases for larger path-crossing angles. This is because the detection algorithm is less successful for larger path-crossing angles (less time to avoid a collision). For the unmanned aircraft, the algorithm/pilot failure is always the most contributing mode of failure (not shown in the figure).

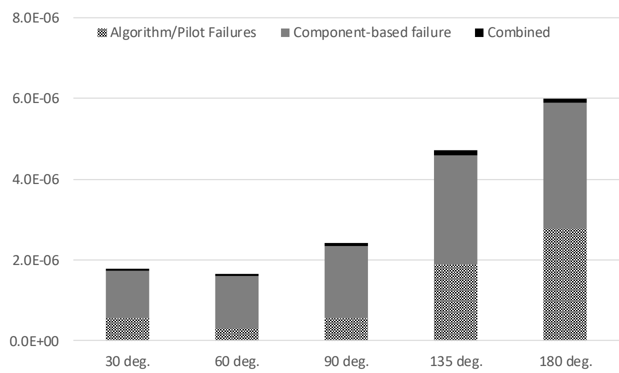

Figure 9. Collision probabilities of case study by failure modes

Figure 10 shows a sensitivity analysis of the failure probabilities of the components supporting the CD&R systems. Note that the first two elements are measured with the scale on the top axis, while the other elements are measured with the scale on the bottom axis. The value associated with each component is the relative change (improvement) in collision risk given a 10% reduction in the failure probability of the given component. For example, the transponder of the unmanned aircraft has a sensitivity of 0.044. This means that if the failure rate of the transponder is reduced by 10%, the collision risk would improve by 4.4%. The transponder on the unmanned aircraft is the most significant component followed by the TCAS processor on the manned aircraft. This is because all CD&R systems on the manned aircraft rely on the transponder to locate the unmanned aircraft.

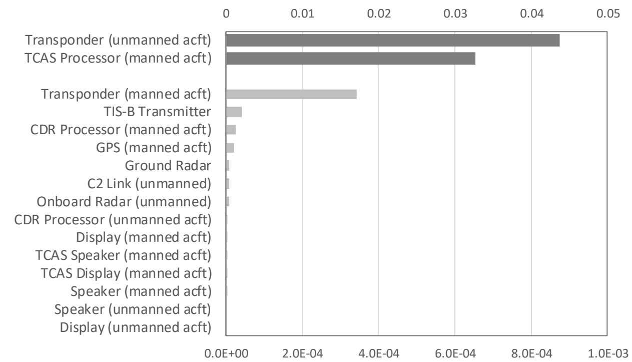

Figure 10. Sensitivity analysis of components

Figure 11 presents a sensitivity analysis of the onboard radar detection range. Obviously, a longer detection range provides a better (i.e., reduced) collision risk. The values of sensitivity are the relative decrease in collision risk given a 10% increase of the onboard radar detection range on the unmanned aircraft. The sensitivity value of 0.09, for example, means that the collision risk is decreased by 9% with a 10% increase in detection range. The improvement in collision risk varies with the path-crossing angle. The improvement gets larger as the path-crossing angle increases to 90°, then it becomes less with larger path-crossing angles. The figure also shows sensitivities with a 10% *decrease* of the radar detection range.

An interesting observation is that the impact of an increased detection range for a 30° path-crossing angle is smaller than that for a 90° path-crossing angle. With a slower closure rate (i.e., at smaller path-crossing angles), an increased range gives more time to avoid a conflict. (Conversely, in a head-on case, increasing the detection range provides only a little more time.) However, the risk reduction also depends on the conflict detection rate itself, which varies depending on the path-crossing angle. As an example, suppose that 10 seconds and 8 seconds of additional time are available to avoid a conflict for the 30° and 90° cases, respectively. Conflict detection probabilities per second are assumed about 0.01 and 0.02 for the two cases, respectively. Then, the total relative reduction in collision risk for the 30° case is about 9.6% ($\approx 1 - (1 - 0.01)^{10}$), while the relative reduction for the 90° case is about 14.9% (($\approx 1 - (1 - 0.02)^{8}$)). Even though fewer seconds are added in the 90° case, those seconds make more of a difference. (Note that the example is made for illustrative purposes.)

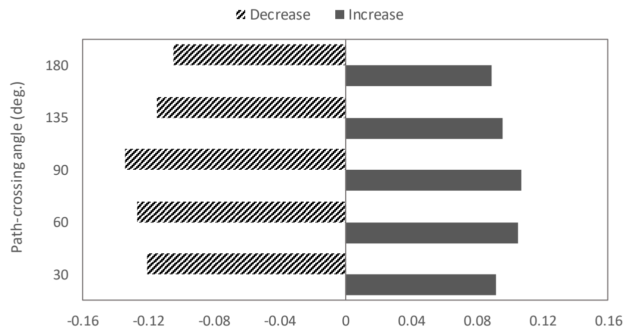

Figure 11. Sensitivity analysis of onboard radar detection range

Next, sensitivity analysis is conducted on the performance of the CD&R algorithms, specifically the trajectory prediction errors assumed in the algorithms (Figure 12). In this analysis, trajectory prediction errors for the unmanned aircraft are adjusted, while the uncertainty for the manned aircraft remains fixed. Similar to the previous sensitivity results, the value of the sensitivity is a relative change in collision risk given a change in trajectory prediction errors (e.g., errors on both along-track and cross-track dimensions change by 10%). A sensitivity value of 1, for example, means that the collision risk increases by 100% (twice as many collisions), while a value of -0.4 indicates a 40% reduction in collision risk. The impact of the trajectory prediction uncertainty is larger when two aircraft fly with a small path-crossing angle (e.g., less than 30°) or a large path-crossing angle (e.g., greater than 130°). That is, the conflict detection algorithm is more vulnerable to the uncertainty near the two extremes (i.e., 0° and 180°). Increasing the uncertainty on trajectory prediction affects the collision risk slightly more than decreasing the uncertainty.

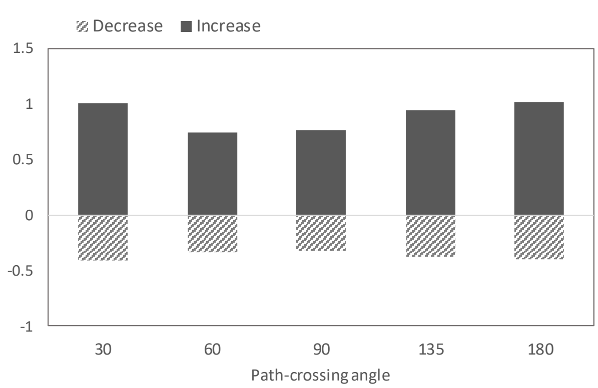

Figure 12. Sensitivity analysis of CD&R algorithms performance

Discussion on Dependency between CD&R Systems

In the case study, the manned aircraft and the unmanned aircraft are independent in terms of physical components supporting the CD&R systems, thus an independent framework to each aircraft is applied. In reality, there can be dependencies between the two aircraft, since there may be common elements that appear in the fault trees of CD&R systems on both aircraft. As an example, suppose that the UAS also has a TCAS-like system with a Mode S transponder (instead of a Mode A/C transponder) in addition to the onboard radar. The TCAS-like system on the unmanned aircraft performs the same function of the current TCAS system on the manned aircraft (i.e., direct interrogation of the transponder on the other aircraft). Similar to the current TCAS system, the assumed TCAS-like system for the unmanned aircraft requires working transponders on both aircraft, while the onboard radar is available as a backup surveillance (Figure 13). The other components that support the CD&R system of the unmanned aircraft are the same as illustrated in Figure 6. Dependency between the two aircraft must be considered in this example, since the transponders on both aircraft appear in the fault trees of both aircraft (Figures 3-5).

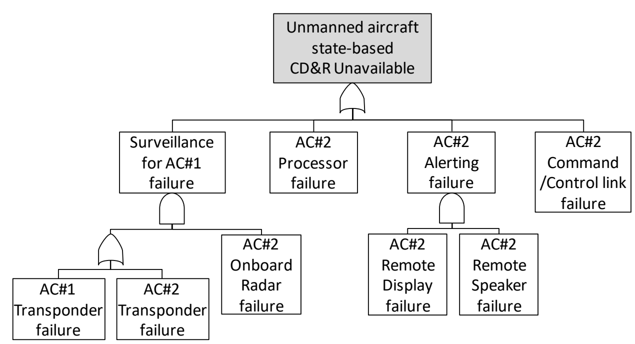

Figure 13. Supporting fault tree for tactical state-based CD&R system (unmanned TCAS-like)

In order to consider dependencies between CD&R systems on both aircraft on a collision course, it is necessary to combine the two DET frameworks that are modeled from each aircraft's perspective. Figure 14 along with Figure 2 illustrates the combination of two DET frameworks into one DET framework in terms of phase-time durations. As shown in Fiure 2, the manned aircraft has three CD&R phases, each of which operates in [T_1, T_2), [T_2, T_3), [T_3, 0] respectively, and the unmanned aircraft has one

CD&R phase that starts at time T_4 prior to the predicted conflict. If T_4 is between T_1 and T_2 – i.e., the CD&R system of the unmanned aircraft is activated during the first phase for the manned aircraft – then this first phase is divided into two phases for the joint DET framework, [T_1, T_4) and [T_4, T_2). The combined framework has four phases in total. In the first phase, only the strategic intent-based system of the manned aircraft is operating. In the remaining three phases, both aircraft have CD&R systems operating in some combination. In the example, T_4 is assumed to be between T_1 and T_2. But this is not always the case. The number of phases, the time horizons of the phases, and the CD&R systems that are operating in each phase depend on the activation times, the detection range of sensors, aircraft speeds, and collision geometries. Once the two DET frameworks are integrated, the evaluation steps of the combined DET framework are the same as explained previously.

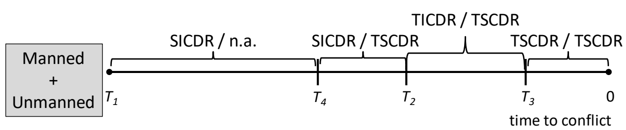

Figure 14. Combining two DET frameworks

An example analysis of dependent CD&R systems is conducted for an unmanned aircraft equipped with an onboard radar and a TCAS-like system with a Mode S transponder (as shown in Figure 13). The TCAS-like system on the unmanned aircraft is assumed to perform conflict detection with various levels of accuracy. Successful conflict detection probabilities of the system are varied ranging from 30% to 80% that of the manned aircraft. The performance level of 30% is the same level considered in the original case study. The detection range is assumed to be 35 km, as before.

Figure 15 illustrates the relative change in collision risk for the different combinations of sensors and conflict detection performance levels, compared to the original case study. For example, for the case of 'TCAS-like + Onboard radar (50%)' at a 180° path-crossing angle, the value of 0.4, means that the collision risk is improved by 40% compared to the case study. Obviously, better conflict detection performance yields reduced collision risk. In terms of path-crossing angle, the collision risk improves with smaller path-crossing angles since more time is available to avoid a collision. With the same algorithm performance level (30% scenario), the TCAS-like system can change the collision risk by 15%. The effect is small because the components additionally required for the TCAS-like system on the unmanned aircraft (i.e., transponders) are common elements that already support the CD&R systems on the manned aircraft. Thus, the improvement is not as high as might be expected, even though the unmanned aircraft has two different sources for surveillance information in parallel.

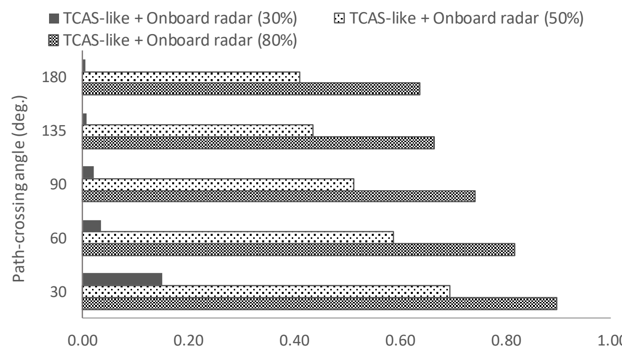

Figure 15. Sensitivity analysis of CD&R system on unmanned aircraft

Conclusions

This paper presented an application of a dynamic event tree framework to evaluate collision risk between aircraft equipped with different collision avoidance capabilities. A case study was developed for collision risk between a manned aircraft and a remotely piloted unmanned aircraft, both flying under Autonomous Flight Rules (AFR). For the manned aircraft, parameters of the conflict detection and resolution (CD&R) systems, were studied. Fault trees were constructed to model failure relationships between physical components of each CD&R system. Time varying conflict-detection probabilities were estimated based on an algorithm from [19]. For unmanned aircraft, various types of sensor technologies were surveyed in terms of type, information acquired, and detection range. A way to apply the DET framework considering dependency between aircraft on a collision course was also discussed.

Results from the case study showed that collision risk increases with greater path-crossing angles, since the closing speed between aircraft increases reducing the available time to avoid a collision. Sensitivity analysis indicated that the transponder on the unmanned aircraft is the most significant component. The maximum detection range of the onboard radar also affects collision risk, especially when two aircraft are approaching with an acute path-crossing angle.

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