Using Agent-Based Modeling to Determine Collision Risk in Complex TMA Environments

The Turn-On-ILS-Final Safety Case

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Abstract—In this paper we present an agent-based concept to assess aircraft collision risk (CR) for modern instrument flight procedures, focusing on the intermediate and final approach. The aircraft’s, ATC and CNS systems’ behavior are modelled as agents—acting stochastically by means of a Monte-Carlo simulation engine—to represent a statistically realistic environment. We first draw an overall picture of current CR estimation techniques focusing on blundering aircraft as a major hazard during approach. Then we present the ANP-based CR calculation and the agent-based simulation of nominal trajectories in detail, covering virtually all other hazards. By applying the model to various approach traffic configurations, we could demonstrate the potential for detailed insight into CR drivers. Therefore, various acceleration techniques were evaluated (mathematical parameter reduction, parallelization, sampling heuristics). We could improve the implementation so as to apply the model to the ‘classic’ safety case of blundering during parallel ILS approaches as defined by ICAO SOIR and the ‘novel’ safety case of turning onto the final approach track from radar vectors at reasonable computing times. The results indicate that ‘classic’ CR values are reproducible from published assumptions and that only a few, well-justifiable and thus verifiable model extensions are required to successfully assess ‘novel’ safety cases. As such, the presented model may revive CR considerations for modern procedure design in complex TMA environments.

Collision Risk Modeling; Agent-Based Modeling; Independent Parallel Approach Procedure; Blundering; Target Level of Safety.

I. INTRODUCTION

The continuously growing traffic demand [1, 2, 3] in civil aviation forces the ATM system to utilize existing airport infrastructure and surrounding airspace at its best. Increasing traffic volumes impose additional approach and departure capacities concentrating at the runway or runway system. In turn, this may lead to higher workloads for both air traffic controllers (ATCO) and pilots as the highly efficient use of pre-set sequencing and spacing constraints become crucial and environmental issues such as noise abatement are taken into consideration. While introducing important measures to minimize aircraft emissions and maximize throughput, the current high safety standards in aviation must not be compromised, but instead, pushed further in order to numerically compensate the projected traffic growth.

The performance-based navigation concept (PBN, ICAO 2008 [4]), which is based on the RNP/RNAV philosophy, is a promising innovation. The European SESAR2020 project PJ01-03 focuses particularly on dynamic and enhanced routes and airspace by, for example, investigating PBN for parallel approaches. PBN allows for a more flexible route design, e.g., circumnavigating densely populated or other noise-sensitive areas during intermediate and even final approach by introducing procedure legs such as “turn to fix” or “radius to fix.” Since these new procedures will have to demonstrate equivalent safety standards compared to conventional procedures, in the course of this paper we first present these reference values through an analysis of conventional procedures and published safety cases.

Depending on the airport runway operation mode (segregated or mixed), individual requirements have been established by ICAO to assure safe operations. However, these safety measures are somehow “static” and do not foresee specific adjustments to local conditions because no explicit cause-to-risk correlations exist in current guidance material except for the final approach segment [5]. To overcome this lack of cause-and-effect reasoning, the present project investigates pairwise aircraft collision risk modeling (CRM) while also explicitly taking controllers and flight crews into account, modelled mathematically as so-called agents. The case study assumes radar vectoring towards the final ILS approach, laterally intercepting the localizer (LOC) and subsequently the glide slope (G/S) until the aircraft has crossed the runway threshold.

The following four sections summarize and present (in section II) the results of a literature review regarding current regulations and the scientific state-of-the-art knowledge in the field of assessing operational safety during independent parallel approach procedures. We make conclusions about input parameters of the model and summarize CRM Acceptance Criteria as
the output of the model. In section III, we specify how the fast-
time model is integrated into the overall architecture and explain how the agents are modeled. In section IV, we transfer the spec-
ification into software in order to calculate safety and capacity metrics (i.e., probability of separation infringements and the nui-
sance breakour rates as detailed in section II.D) for various sce-
narios depicting traffic, runway/airspace layout and agent be-
havior (i.e., procedures and hazards as detailed in section V.A).
In section V, we discuss the model verification concept and the results gained.

II. STATE-OF-THE-ART IN SAFETY ASSESSMENT FOCUSING ON THE APPROACH SEGMENT

A. Independent Parallel Approach, Safety

The FAA began research in the field of independent ap-
proaches to parallel runways as early as the 1960s. Since then, the MITRE Corporation in particular has progressed in developing and conducting simulations aiming at reducing runway sep-
Aration requirements [6, 7]. Besides developing technology like
high update rate radars (down to 1 Hz), the FAA also started
three major research programs: The Multiple Parallel Approach
Program (MPAP, [8]), the Precision Runway Monitoring
(PRM) Demonstration Program [9] and the Converging

For the purposes of the MPAP and CASTWG, the FAA cre-
ated a fast-time model called Airspace Simulation and Analysis
for TERPS (ASAT). An ASAT study is split into the two stages of
real-time, human-in-the-loop and fast-time computer-only simula-
tion. Otherwise hard-to-reach human factors (reaction times, workload, etc.) and aircraft behavior data (e.g., roll rate, climb rate, airspeed, etc.) is acquired in the first stage. This em-
pirical data is statistically fitted and transferred into continuous
probability density functions (PDF). By means of Monte-Carlo
simulation, this data is recombined with additional data from
technical specifications (e.g., radar errors) while a vast amount
of simulation runs helps to increase statistical significance and
sharpen the confidence interval [10].

Along MPAP, which was started in the late 1980s [8], ASAT has been used to investigate simultaneous parallel approach sce-
narios with dual, triple and even quadruple runway configura-
tions within the US. Rare blunder situations (see section II.C)
were the main interest due to the considerable impact on safety.
Therefore, the blunder occurrence probability (or blunder rate)
was the central hazard for collision risk with aircraft operating on the adjacent approach track when no evasive actions were
taken. To efficiently collect the most relevant data, we focus on
such blunder-evader constellations solely within the project’s
real-time experiments [10].

B. Intercept of the Final Approach

Published studies regarding the final approach segment al-
ways assume that separation requirements will be met during the intercept maneuver even though workload is considerably high and accepted as relevant during this flight segment. Important
changes in the aircraft guidance mode are also necessary for safe
operations. As the aircraft’s headings converge, violations of
separation standards could (in theory) occur suddenly and with-
out meaningful precursor events, e.g., in case of a late or incor-
correct turn anticipation by the flight crew or degraded/misconfig-
ured aircraft guidance systems.

The literature, however, does not yield any safety or human
factor considerations concerning these potential issues [6, 7, 9, 10, 11, 12]. Therefore, we can only take note of the fact that
conservative procedure design usually foresees a vertical buffer,
e.g., by displaced runway thresholds, thereby safeguarding the
intercept against these and any other connected issues.

C. The Blunder Hazard

In the scope of independent parallel approaches, so-called
“blunder” events require special attention [6]. A blunder de-
cribes an unexpected deviation of an aircraft from its intended
flight path (e.g., the final approach track) that does not result
from ubiquitous navigational errors or could otherwise be at-
tributed to the total system error in general, but from human er-
or malfunctions in technical equipment. The extent of the
initial deviation from the desired track forms the blunder angle.
Immediately after detection of such abnormal behavior, ATC
will issue a correction advisory to the crew. If the evasive air-
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Figure 1 - Schematic runway configuration and approach layout as it is
considered in the CRM application

considering the pre-set NTZ width. This is not at all compliant to modern concepts (e.g., the PBN philosophy [4]), indicating a necessity for further research.

The NTZ dimensions are the result of a geometric construction of the flight paths of a worst-case blunder and an adjacent operating aircraft executing an evasive maneuver, which effectively dictate the minimum distance at the closest point of approach (CPA) for an aircraft pair. The case of dual blunders lies outside of this rationale and is therefore not part of this construction but rather a very rare though potentially risk-intensive corner-case.

D. Acceptance Criteria

Obviously, safety acceptance, especially of TMA procedures, competes with both acceptable system capacity and also with emission abatement. Consequently, the relationship between a given CR and its implication on runway throughput is crucial for both the regulator and the operator. Therefore, we define different measures that allow for an assessment of safety versus capacity.

1) Safety

In case of a blunder event, the risk of a collision is determined by calculating the probability of two aircraft coming into physical contact. In general, this is the case if the slant range between the aircraft falls below a threshold defined by the aircraft’s physical dimensions. This “conflict risk” approach was generalized and adopted by FAA/MITRE and subsequently ICAO, and it is defined as a threshold of 500 ft as the ‘hit’ distance regardless of the orientation in 3D space.

In ICAO’s safety regulation, the Target Level of Safety (TLS) concept aims at defining, by means of mathematical proof, a maximum tolerable occurrence rate for hazardous events while concentrating on though not being limited to the accident category induced by a physical contact. For independent parallel approaches regulation does not allow for more than 1 violation of the 500 ft slant-range criterion in 56 million approaches, equaling a “conflict” rate of 1.8×10⁻⁸ per approach [14]. Assuming a final approach segment length of 10 NM and an average approach speed of 150 KIAS, the time per approach is 4 minutes, resulting in a “conflict” frequency of roughly 2.7×10⁻⁷ per flight hour.

It is therefore important to stress that this value does not equal an accident-type TLS; historical incident data proves that only a small portion of slant-range violations indeed led to an accident, whereas the majority fell into the severe incident category according ICAO Annex 13 [15]. Therefore, it is necessary to consult recent safety publications such as SESAR [16] for comparison and interpretation.

2) Capacity

During parallel approaches, a blunder should induce a breakout maneuver of an aircraft operating on the adjacent approach track following the published missed approach procedure. This scheme enforces safety at a minimal cost of capacity. Since aircraft are subjected to navigational tolerances, NTZ alerts may be triggered by aircraft deviating from but autonomously returning to their approach track. Nevertheless, the (automatically triggered) NTZ alert requires ATC to ‘break’ the adjacent aircraft ‘out’ of the approach. This is called a nuisance breakout in the sense of a false positive alert (see scenario A in Figure 2). The frequency of such events is called nuisance breakout rate (NBR) and forms a (lost) capacity measure.

Fixing a general NBR target, however, is unrealistic since it depends on many factors, e.g., on the traffic mix and the given runway spacing. To give indications about NBR estimates, we find in Massimini [7] that the NBR estimated is considerably below 5 % of all approaches. In McCartor and Ladecky [12], aircraft performing an RNP 0.3 (non-precision) approach are observed to cause similar nuisance breakouts 2-4% of the time.
III. CRM MODEL ARCHITECTURE

A. Overview

The configuration of our integrated agent-based traffic simulation and collision risk estimation model, which studies though is not limited to the safety case of independent parallel approach operations (see Figure 3), comprises of multiple interacting modules that are repeatedly triggered following a Monte-Carlo parameter variation scheme. Previous work in development and application of the model is described in [17, 18, 19, 20, 21].

For the safety case focused on in this paper, the following CRM parts were customized: The independent parallel approach configuration including all associated parameters (green colors in Figure 3), the definition and calculation of relevant metrics (blue) and customizations to the visualization. After a short introduction to the core model (traffic simulation, collision risk quantification, parameter variation, orange), these customizations are covered in detail, followed by geometric construction of the infrastructure and scenario definition descriptions.

B. CRM - Agent-Based Traffic Simulation

The main idea of an agent-based model is creating software entities which closely resemble real-world entities in terms of knowledge (information base), behavior (rules of deciding and acting) and communication (sensing the environment, interacting with other agents) without ‘cheating’ for the sake of efficient modeling or computing. The main benefit is emergent behavior, where a multiplicity of well-modeled software agents exhibit the same features as their real-world counterparts without the need for explicit modeling of complex traits. Although getting the behavior ‘right’ is often troublesome, the major benefit is that the model is generative, meaning it is able to predict patterns outside the evident behavior specification which can be (and often are) ‘wrong’ but which may provide valuable insight into unforeseeable hazards; this is particularly relevant in the aviation domain.

The following software agents are part of the model:

<table>
<thead>
<tr>
<th>aircraft body</th>
<th>point mass model with basic aerodynamic behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>autopilot</td>
<td>controlling only pitch, roll and power based on current set-points</td>
</tr>
<tr>
<td>flight guidance</td>
<td>waypoint navigation, path planning, providing autopilot with inputs</td>
</tr>
<tr>
<td>pilot</td>
<td>reacting to ATC, providing delayed and possibly flawed inputs to flight guidance</td>
</tr>
<tr>
<td>radar</td>
<td>registering aircraft positions with or without update rate and interpolation, subjected to accuracy constraints</td>
</tr>
<tr>
<td>voice-com</td>
<td>blocking channel message transducer with speaking time approximation</td>
</tr>
<tr>
<td>controller</td>
<td>with modules resembling various strategies of tactical air traffic control, receiving radar, interacting with pilots through voice-com</td>
</tr>
</tbody>
</table>

Except for the aircraft and flight guidance agents, all other work is purely event-driven (e.g., radar pattern detected, reaction / reading time passed). The emergent behavior is the timed sequence of events shaping the synchronous aircraft movements, whereby the concept explicitly addresses the missing cause-to-effect relations as elaborated in section I.

C. Agent Action Sequence for the Blunder Event

The agent logic is best understood following an assumed blunder-evader constellation as depicted in Figure 2. Agent entities will be underlined in this sub-section.

Initially, both aircraft are following their specific approach track. Upon blunder initiation, the blundering aircraft’s flight guidance reverts to vectoring mode with a new heading given by the blunder angle and the initial approach track. It is reached by modeling a constant bank rate of $\Phi = 10^\circ/s$ by the autopilot either until reaching the bank limitation $\Phi_{\text{max}} = 25^\circ$ [5] (for clean configuration) or the standard procedure turn rate of $\Psi = \ldots$

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1 Ant colonies on their quest for food, based only on the description of one archetypical ant are a classic early example of agent-based models.
$3°/s$. The final turn radius $r$ and the required bank $\Phi$ for a procedure turn observing the bank limitation are calculated as follows:

$$r = \frac{v^2}{g \cdot \tan \Phi}$$ (1)

$$\Phi = \min \left( \tan \left( \frac{v \cdot \psi}{g} \right), 25° \right)$$ (2)

During the period of ‘rolling up,’ the aircraft will follow an EULER spiral (clothoid). The on-following curve with constant bank and speed is circular. It is correctly terminated by the autopilot with the appropriate ramp-down of the roll, resulting in a clothoid transition towards the anticipated blunder heading.

While performing the described maneuver, the blunder position is radar-detected and passed on to the controller, upholding all performance assumptions (e.g., delay, resolution). Upon such ‘evident’ NTZ penetration, the corresponding software module inside the controller agent will trigger the ‘alert.’ The behavior is pre-defined: The break out of the (previously paired) aircraft on the adjacent approach track, again by means of vectoring, optionally adds a vertical guidance and requests the blunder aircraft to immediately return to its initial approach track.

For the ‘classic’ ICAO SOIR blunder scenario, all reaction and communication times are subsumed by ICAO’s original assumption of 8 s. This incorporates the controller’s reaction time to the NTZ alert, voice-com and the pilot’s reaction time until aircraft compliance with the advisory. Following ICAO’s assumptions, we only assume 8 s total reaction time from NTZ alert to aircraft reaction and procedure turns (i.e., no manual aircraft handling assumed).

By the more sophisticated design of our simulation system mostly overridden for this study, the controller reaction time would be built from a blocking resource model resembling the top-level task items of scanning the radar screen, conflict inspection, decision-making [22] and advisory transmission (including interruptible read-back and compliance monitoring). The advisory transmission would require a free voice-com channel and the utterance would be accounted for according to ACT-R [23] with syllable and word pause times, etc. Finally, the pilot reaction time will be modeled with a PDF evaluated in a previous human-in-the-loop study [21].

Using knowledge about human factors, the total reaction time could be estimated as: (1) controller reaction, (2) voice-com on free channel, (3) pilot reaction, (4) pilot input to the aircraft. Let (1) be almost immediate due to the uniqueness of the alert and the pre-defined actions, except for the necessity to look up the evader call sign at the radar screen (GOMS complex information look-up, 1200 ms [24]), (2) can be calculated by the syllable/word count of the advisory according to ICAO phraseology and phonetics and metrics from ACT-R [23], e.g.

\textit{air-line\_1\_2\_3\_turn\_left\_hea-ding\_4\_5\_6\_im-me-diate.}

15 syllables + 10 word gaps + initiation + comprehension $15*50 \text{ ms} + 10*100 \text{ ms} + 150 \text{ ms} + 180 \text{ ms} = 2,080 \text{ ms}$

With 1,540 ms and 0 to 2,000 ms on average (depending on the input strategy), (3) and (4) can be adopted from Vogel, Thiel and Fricke [21], where a pure human factors estimate is presented as well. In total, we can account for 5 to 7 s (4,820 to 6,820 ms on average) of the 8 s assumption without taking the radar update rate into account; this then appears roughly valid considering that much time can be saved by observing the controller’s acute voicing in hazardous situations and early cue words in ICAO phraseology.

Once configured by the pilot, the evader autopilot will initiate the same aircraft turn maneuver as described in the beginning of this sub-section.

In parallel, a second controller who is simultaneously monitoring the blunder’s approach track will initiate a comparable advisory to the blundering aircraft, whose pilot would subsequently start implementing the corrective maneuver (‘normal’ blunder) or fail to react (‘worst case’ blunder).

D. Aircraft Navigation Performance

With respect to the defined navigation aids, all trajectories produced by the traffic simulation are ideal and incorporate all of the features of the agents’ decision-making including timing, which we call microscopic because of the fine-grained dependencies between agents (e.g., milliseconds of reaction time deciding upon which aircraft is being served first by ATC).

In addition, all flight movements are known to exhibit a navigational error consisting of path definition, navigation system and flight technical errors. We handle these errors on a macroscopic level. By analyzing large radar data sets and filtering flights navigating autonomously on flight guidance systems only (no manual control, no active ATC advisories) and statistically fitting (often heavily tailed) PDF, all micro-effects stemming from weather (e.g., turbulent wind), control system dynamics, etc. can be summed up into one distribution (independently per axis of the trajectory-fixed coordinate system; i.e., cross-track, along-track, vertical-track tolerance - XTT, ATT, VTT). We refer to these PDF of navigational accuracy as actual navigation performance (ANP) equivalent, but it is not limited to the term used in PBN [25, 26].

E. Monte-Carlo Evaluation and Numeric Complexity

We utilize pseudo-random variables in order to efficiently and reproducibly assess the influence of arbitrarily distributed stochastic parameters present in the form of aircraft pairing, navigation tolerances (ANP), radar accuracy and reaction times.

 Normally, to determine a risk of less than $10^8$ collisions per approach (due to blundering) with an accuracy of 5%, the simulation needs to span far more than 10 quadrillion approaches according to the Bernoulli Law of Large Numbers, as quantified by Chebyshev’s inequality in equation (3). Here, the simulation is considered a Bernoulli experiment (collision yes/no) which is repeated $n$ times, in which a collision is recorded $n_1$ times. The
type-I error probability is set to $1 - P = 0.05$ and the probability estimation tolerance is set to $\varepsilon = 10^{-8}$ per aircraft pairing. These values represent a general engineering confidence interval which certainly may be debatable for life critical applications.

$$P\left(\frac{\bar{r}}{n} - p < \varepsilon\right) \geq 1 - \frac{1}{4\varepsilon^2 n} \quad n \geq 5 \cdot 10^{16}$$

The computational effort can, however, be reduced by focusing on approach “points of interest.” Assuming a blunder rate of 1/24,000 leads to 500 billion approaches to simulate. In contrast to this theoretic approximation, FAA conducted studies where a similar simulation was run 100,000 times [9].

The slant range between blunder-evader aircraft pairs is therefore continuously traced. If it falls below a given threshold, a TCV is recorded. Finally, the probability of a TCV based on its number of occurrence $N_{TCV}$ and the total number of simulated events $N_{Events}$ is calculated as follows:

$$P(TCV) = \frac{N_{TCV}}{2 \cdot N_{Events}} \cdot P(Blunder)$$

The widely accepted assumption of a fixed blunder probability $P(Blunder)$ helps to increase computational efficiency. The blunder-evader results are collated with inherently safe normal operations as a post-processing step.

The NBR is also calculated analytically during post-processing using the NTZ penetration probability and the physical runway layout. Both approach tracks’ NBR are calculated separately by geometrically integrating the cross-track ANP distribution function along the extended runway centerline, as shown in equation (5). Figure 4 illustrates this process. Yellow-grey areas under the Normal Distribution function depict NTZ penetration probabilities at single points as the integral of the cross-track deviation. The length of the final approach track along the NTZ boundary is denoted as $l$. The overall NBR is the counter-probability of the event that “on neither approach track, a nuisance breakout occurs.” All NBR values depend on the current navigation accuracy.

$$P_{NTZ} = 1 - \int_0^l \left(1 - p_{NTZ}(x)\right) dx$$

$$= 1 - \exp\left(\int_0^l \ln\left(1 - p_{NTZ}(x)\right) dx\right)$$

$$P_{NB} = 1 - \left(1 - P_{NTZ,left}\right) \cdot \left(1 - P_{NTZ,right}\right)$$

B. Geometric Design, Stochastic Variables

For the targeted safety case, airport, final approach configuration and runways are assumed to operate in single mode (approaches only) with guidance and surveillance equipment compliant to ICAO SOIR Mode 1 specifications [14].

A standard ILS final approach begins with intercepting the LOC. Then a straight horizontal flight segment is followed for at least 2 NM, allowing the aircraft to establish and stabilize laterally before vertically intercepting the G/S and to begin its further descent until touchdown.

Aircraft approaching the same or the adjacent runway must maintain radar separation (3 NM laterally or 1,000 ft vertically) at all times even though they are considered ‘independent.’ The angle between intercept vector and final approach course must not exceed 30° [14]. The model, however, allows for certain violations, thus reflecting navigational, control and human error.

The actual LOC intercept point is subject to uncertainties (aircraft/pilot behavior) and variations resulting from sequencing in a vectored onto ILS environment. These, however, are not reported in the paper and will be modeled by an appropriate PDF.
Surveillance system requirements depend on the actual runway spacing: Between 3,400 ft and 4,300 ft (centerline to centerline), ICAO requires a radar update rate of every 2.5 seconds. The azimuthal accuracy of the recorded aircraft positions shall match a Normal Distribution with $\sigma = 0.06^\circ$. Beyond 4,300 ft runway spacing, an update rate of only 5 seconds as well as an azimuthal accuracy of $\sigma = 0.3^\circ$ is required.

Aircraft speeds are also stochastically modeled. While historical investigations by ICAO assume an unrealistic constant speed of 150 KIAS, our model is able to handle various distributions. Besides a static value, aircraft speeds may also be subjected to a Normal Distribution $N(\mu, \sigma^2)$ or follow the ICAO approach category scheme [5].

Finally, blunder parameters are stochastic variables as well. These are the distribution of blunder occurrence along the approach track, the blunder angle and the worst-case blunder rate.

C. Implementation of the Turn-Onto-Final Safety Case

For each simulation run, blunder-evader pairs are positioned on the parallel approach tracks. First, the distance from threshold for the blundering aircraft is chosen randomly. Subsequently, based on the provided ANP function, cross- and vertical-track deviations are determined, assuring the necessary initial adherence to the NOZ before the actual blunder event. Additional stochastic parameters are speed, blunder angle and vertical blunder behavior (leveling-off due to lost G/S signal versus upholding the current rate of descent).

Now, a deterministic blunder trajectory is generated. The crossing point with the adjacent approach track is calculated and forms the midpoint of the evader placing area, which extends, plus/minus, half of the required in-trail separation, thereby covering precisely the location of the most threatened aircraft for the independent parallel approach configuration. The assigned evader placement follows a uniform distribution. Once placed, the evader is shifted back in time in order to let blunder and evader enter the simulation at the same time.

After having assigned the initial positions and all aircraft parameters, the simulation continues as described in section III.C and stops as soon as the closest point of approach (CPA) has been passed. For the minimum distance, the TCV is evaluated.

D. The Turn-Onto-Final Safety Case

The ‘novel’ safety case now covers the LOC intercept. Here, a blundering aircraft represents a missed or weak intercept (e.g., as a result of human error such as flight guidance mode confusion). The model basically handles such events identically to those on final approach. While blunders on final approach ‘perform’ the blunder maneuver, the modification of ‘missing’ the turn leads to an equivalent situation during turn-onto-final. In contrast to the baseline scenario however, there is no NTZ provided at this point [14]. Therefore, no controller interventions will be considered (as there is no NTZ penetration) even though in reality a controller may certainly detect this hot spot and act accordingly. Therefore, the current agent behavior represents a conservative (worst-case) safety consideration.

E. Model Limitations

We currently assume that human actions are purely event driven. The controller will initiate corrective commands only after receiving a NTZ alert. The pilot agent only consequentially intervenes after receiving a command. However, in reality, the controller will most likely detect deviations during the approach well prior NTZ alert and issue appropriate commands. Additionally, pilots may also be able to detect deviations and undertake corrective maneuvers without ATCO recall. The model therefore is rather conservative at this point. Furthermore, the distribution functions used to represent navigation tolerances presume a Brownian motion and thereby widely neglect flight mechanics. This theoretically allows an aircraft to suddenly change attitude in space between two simulation steps. At the same time, the employed ANP functions are considered to be independent while deviations from the flight path may not. ANP functions were deduced from recorded real flight paths and are therefore environment specific. Data contains environmental effects like winds, which will often be specific for the location, and the time the data was recorded. Therefore, reference data should contain a very large range of all external effects. Alternatively, locally fitted ANP functions should be developed.

V. Model Verification & Discussion

A. Model Verification Using the ‘Classic’ ICAO Scenario

The fast-time model show that results are comparable to those of previous studies by ICAO. This is depicted in the following by running two exemplary use cases. While for intercept maneuvers there is no comparable study available, we configured the final approach blunder and nuisance breakout modules of the model to be comparable with historical studies. Hence, we expect to get similar results.

Parameter settings are mostly taken from the ICAO SOIR document [14]:

- Aircraft speed: 150 knots
- Blunder angle/rate: 30° / 1/2,000
- Worst-case blunder rate: 1/100
- XTT: 150 ft at 10 NM from threshold (1-sigma)
- Reaction and communication delay: 8 s
- Radar azimuthal resolution (1-sigma): 0.3° / 0.06° (for 4,300 ft / 3,400 ft runway spacing)
- Radar update period: 5s / 2.5s (for 4,300 ft / 3,400 ft runway spacing)
- Slant Range (test criterion for TCV counts): 500 ft
- Width of NTZ: 2,000 ft

Since not all the required parameters could be retrieved from publications, we made the following assumptions:

- Aligned (no displaced) thresholds
• XTT linearly increasing with threshold distance [23]
• Vertical-track-tolerance as in Anderson [23]
• Radar antenna located in the geometric center of all (four) runway thresholds
• Evader (missed approach) climb gradient: 2.5%

Using these settings, multiple simulations were conducted. For each run, the random number generator is initialized with an individual seed. Figure 5 visualizes the development of resulting probability over an increasing number of simulated blunder events. Results stabilize at a probability of around $7.0 \cdot 10^{-8}$ TCV per approach, which is quite close to the ICAO result of $1.78 \cdot 10^{-8}$ (one TCV per 56 million approaches).

B. Discussing Monte-Carlo Runs and Thresholds

As discussed above, the expected runtime of the simulation depends on the expected probability of ‘positive’ observations (i.e., test criteria violations or collisions). Running multiple simulations over a wide range of blunder events shows that results stabilize at around 3 million events, as depicted in Figure 5. Especially the highly volatile left part of the graph depicts that 100,000 simulation runs on which the historical ICAO probability are based [14] are far too small for reliable results. Furthermore, it is important to recall that the probability value for a TCV, as given by ICAO, does not represent an accident-type of TLS since historical incident data proves that only a small minority of slant-range violations indeed led to accidents, whereas the majority fell into the severe incident category of ICAO Annex 13 [25]. Therefore, it is necessary to consult recent safety publications such as by Thiel, Seiß, Vogel and Fricke [26] for comparison and interpretation. The document offers a transcription of a singular TLS value into seven incident/accident severity categories and correctly connects safety with reliability by declaring a “Maximum Tolerable Frequency of Occurrence” (MTFoO).

REFERENCES


