Agent-Based Simulation of Off-Nominal Conditions During a Spiral Descent (NextGen Vehicle NRA)

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The goal of this study is to provide quantitative simulation-based models corresponding to representative off-nominal conditions that pose credible hazards specific to new types of vehicles operating under new operational procedures within the Next Generation air Transportation System (NextGen). These models are aimed at complementing a comprehensive, but relatively high-level and mostly qualitative hazard assessment of the new vehicles operating within NextGen, by illuminating a path toward more detailed and quantitative safety analysis which will be helpful in the design of new vehicles and their operational procedures, and in developing recommendations for any appropriate new standards and regulatory guidance.

Nomenclature

\[ \begin{align*}
  z & \text{ Altitude} \\
  \psi & \text{ Heading} \\
  \phi & \text{ Bank angle} \\
  \gamma & \text{ Flight path angle} \\
  V_I & \text{ Inertial speed} \\
  V & \text{ True airspeed} \\
  V_C & \text{ Calibrated airspeed} \\
  n & \text{ Load factor} \\
  R & \text{ Turn Radius} \\
  R_{\text{min}} & \text{ Minimum allowed turn radius} \\
  W & \text{ Wind vector velocity} \\
  W_N, W_E, W_D & \text{ Wind velocity components in the NED frame} \\
  \hat{W} & \text{ Measured wind velocity} \\
  \alpha & \text{ Wind direction in the NE plane} \\
  \kappa & \text{ Amplification factor for wind speed} \\
  \tau & \text{ Pilot’s response time delay} \\
  P_E & \text{ Probability of event E’s occurrence} \\
  N(\mu, \sigma) & \text{ Normal distribution}
\end{align*} \]

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I. Introduction

The National Airspace System (NAS) is a very complex and dynamic system comprised of numerous airports, airspace, air traffic control and other resources. A varying degree of human and automated processes have roles in the operation of the NAS, both in flying and controlling the individual aircraft as well as planning and managing traffic flows to ensure an acceptable level of safety and efficiency. The NAS is also subject to an operational environment that is itself dynamic and any operational scheduled plan may suddenly be altered with little or no decision lead time as a result of changing weather, varying human performance, system degradation, or other factors.

This research is part of a comprehensive effort to investigate the impact that novel vehicle concepts and procedures may have on NextGen, an evolving concept which is focused on accommodating with acceptable safety the expected increase in both air-traffic volume and peaked demand, while also providing more consistent compliance with the business plan goals of individual operators. The introduction of novel-concept vehicles and procedures (e.g., continuous descent) within the airspace system poses interesting challenges in terms of assessing safety risk from system degradation during “nominal” operations as well as in the event of an error or a malfunction occurring at a subsystem level (e.g., human error or loss of communication or surveillance capabilities).

The Joint Planning and Development Office (JPDO), a multi-agency organization chartered in order to plan and coordinate the transformation of the NAS into a Next Generation Air Transportation System capable of efficiently supporting the expected growth in traffic while ensuring safe and environmentally friendly operations, is proposing many operational and technological changes to the air transportation system to satisfy the increased demand. This paper reports out some of the findings from the NASA NRA titled Advanced Vehicle Concepts and Implications for NextGen funded by the National Aeronautics and Space Administration (NASA) Airspace Systems Program and aimed at developing a framework by which the impact of changes to the system, in this case new vehicle concepts, can be assessed.

The specific scenario investigated in this study examines a Cruise Efficient Short Takeoff and Landing (CESTOL) aircraft in a helix approach, which is under evaluation as a potential noise-abatement maneuver. This scenario considers the impact of realistic steady state wind conditions on the ability of the flight crew to revert to manual control. Pilot intervention may be a result of wind conditions which exceed the limitations of the Flight Management System (FMS), a generator or electrical failure in which equipment providing input to the FMS is lost, a failure of navigational inputs to the FMS, or a degraded state of the FMS itself. The constantly changing relative wind to which the aircraft is exposed during the helical descent makes maintaining a planned trajectory of a spiral approach under manual control a challenge to the pilots. This is exacerbated by the CESTOL aircraft’s low wing loading relative to the one of conventional jet transports, which makes it more susceptible to wind disturbances. The flight crew’s and vehicle’s ability to maintain adequate control to accomplish a safe landing, and maintain adequate separation from other traffic flows are assessed. Specifically, attention is given to the assessment of the likelihood of a hazardous drift of the helix trajectory towards a neighboring path of vehicles operating from adjacent runways and airspace.

II. Analytical Approach

The complex dynamics and level of interactions taking place within such an environment such as the National Airspace System (NAS) makes it difficult to capture the behavior of every single entity (e.g., pilots, air traffic controllers, etc.) using classical approaches (e.g., differential equations or centralized control architectures). To this end, the agent-based paradigm has risen as a result of a shift in attention from individual systems and entities, to their, inherent interactions and the environment in which they operate. Many systems intrinsically are or have further evolved into large and complex architectures of interoperable parts and players, examples of which can be found in many domains, from complex ecosystems\textsuperscript{2} or virtual societies\textsuperscript{2,3} to the global economy\textsuperscript{4,5} or airlines’ economic strategy\textsuperscript{6} to the system-of-systems concept. Some
characteristics of these types of networks are the presence of open boundaries evolving in time, internal heterogeneity and high quantitative dimensionality. As a consequence, unified or centralized approaches may not be appropriate, as they are better suited to describe closed and well structured systems. As an alternative, agent-based techniques exploit the idea of distribution by focusing on the system constituents and their behavioral rules at the microscopic level, thus allowing the network’s dynamics and the components’ integration to emerge at the macroscopic level. Improved system-level robustness, adaptability, and self-organization are some of the resulting features that make agents appealing to engineering integration and management of complex infrastructures. In order to accomplish its objective, an agent interacts with other agents and the environment by exhibiting a host of qualities such as reactivity, proactiveness, sociability, learning, in-time evolution, and others. Interactions and heterogeneity within a system generate the need for communication protocols and schemes to optimally resolve conflicts and/or enhance inter-agent coordination, for which various solutions have been proposed in the literature.

In the context of NAS, its modeling is characterized by the interaction of various heterogeneous entities, e.g., aircraft, control towers, or various personnel, spatially distributed. Besides the intrinsic complexity of such a system, an interesting point being raised at the simulation phase is the difference in time scale among the various entities: a physics-based calculation may require a fine time step to guarantee adequate accuracy, while a discrete-in-time event will need to be updated less frequently. As observed by Lee et al., this issue of different time granularity works against the possibility of asynchronous simulation and forces synchronization, especially in the presence of stochastic events for which event time is not known a priori. As an alternative, in order to guarantee consistency of results, asynchronous simulation with partial resynchronization is suggested, where information and data updates are predicted and occur when necessary. Disruptions or unforeseen events can cause a series of cascading effects which call for time critical decisions. However, decisions may be hard to agree upon when many competing players are involved. An attempt at modeling such circumstances is provided in, where the agent-based model IMPACT (Intelligent agent-based Model for Policy Analysis of Collaborative Traffic flow management) was employed to simulate the decision-making process involving airlines and traffic control authorities in response to weather-based schedule changes. Harper et al. have also conducted similar studies with a focus on the human element in the context of decision making. Pilots, airline dispatchers and traffic controllers are all modeled using the same agent structure, made up of three units: air traffic situation assessor, collaborative decision making element, and plan executor, respectively in charge of collecting and processing current data, resolving traffic issues, and performing plan changes. The SAMPLE (Situation Assessment Model of Pilot-in-the-Loop Evaluation) agent-based architecture for modeling human behavior has been integrated in the FACET (Future Air Traffic Management Concepts Evaluation Tool) environment and principled negotiation has been employed as a means to provide coordination and resolve conflicts between aircraft, where a solution is sought by providing communal advantages for all the interested parties. The goal of the study was to establish the need, if any, for negotiation in a complex environment where responsibilities and decisions were decentralized and distributed among the parties, as would be needed for the implementation of the free-flight concept.

A. CESTOL Aircraft

CESTOL vehicles are designed to takeoff in a relatively short distance, climb quickly, cruise optimally, and land in a relatively short distance. The capability to operate from shorter runways than the current fleet of similarly sized aircraft would provide operators increased ability to operate from currently underutilized runways and airports. This in turn may help alleviate congestion at the larger airports either by diverting traffic or by decoupling operations.

The CESTOL vehicle (Figure 1) under consideration in this research project is sized for 100 passengers, designed to operate from runways as short as 3000 ft, and cruise at Mach 0.78, over a range of 600 to 2000 nautical miles (depending on operation in STOL or conventional takeoff and landing mode). To achieve the 3000 ft landing, this CESTOL design relies on low wing loading (66 lb/ft$^2$ versus 129 lb/ft$^2$ for the Boeing 737-800), advanced airfoil design (e.g., high-speed slotted wing and mission compliant adaptive wing), and a steep approach ($5.5^\circ$ versus the standard $3^\circ$ glideslope).
B. Spiral and Helical Descents

Spiral, or helical, descents are being evaluated as noise abatement procedures and as a means for alleviating high-density airspace surrounding the airport. This type of approach may contain speed restrictions, crossing height restrictions, or lateral constraints linked to airport configuration. Concerns with these types of descents are associated with maintaining trajectory both vertically and laterally, and with the impact of wind conditions, equipment limitations and failures, and crew situational awareness in a high workload environment. Illustrated in Figure 2 is the redesigned arrival and departure routes for four airports in the New York metroplex, including the spiral arrivals. This airspace redesign assumes all traffic is capable of RNP 0.3, vectoring is minimized with adequate metering, and slower traffic is segregated from nominal flows.

The spiral descents were originally envisioned as noise abatement maneuvers, were designed with constant bank angle (decreasing radius) assuming no wind, and were located over the airport to minimize the impact on surrounding communities. They were moved off the airport to allow for missed approaches and avoid interference with other traffic. The bank angle was allowed to vary while the radius was set to a fixed value to better accommodate engine-out conditions and other failures. Consideration is now being given to specify only the exit criteria to allow the flight crew and FMS more flexibility.

Assuming a constant-radius spiral (or helix) the CESTOL aircraft enters the 1.5 nm radius spiral at 10000 ft above the airport elevation, at 180 kts, and with a 25° bank angle, and exits the spiral at 1000 ft above the airport elevation, at 110 kts, and with than a ∼4° bank, at 1.5 to 3 nm from the runway threshold (Figure 3). The extra 1.5 nm or 3 nm to the runway threshold is to allow for stabilization on the glidepath as well as on the localizer. Aircraft are expected to be in full landing configuration by the time they exit the helix.

C. Modeling environment and assumptions

The agent-based simulation approach has demonstrated its efficacy and easy implementation in modeling diverse complex systems, and has been herein adopted to conduct an initial assessment of the safety of the novel helix landing procedure in the context of CESTOL. The landing procedure has been developed using the freeware multi-agent simulation environment NETLOGO\textsuperscript{12,13} (version 3D Preview 5) from the Northwestern University.

The following specific scenario was taken into consideration: a CESTOL aircraft plans to descend with a flight path angle of \( -5.5^\circ \) and a calibrated airspeed which decreases linearly with altitude. In the case of spiral descent, the turn radius is a function of load factor, flight path angle, and magnitude of the vehicle's ground speed is treated as dependent performance parameter, whereas it is treated as a requirement and kept constant for an helical descent. Two extreme possible situations can be identified in terms of safety for
the surrounding air traffic. In the first case, the flight management system is assumed to be fully functional and capable of compensating for any external disturbance (e.g., wind) for the aircraft to land safely and as expected along its designated flight path. In the second situation, a failure in the flight management system forces the pilot to perform the landing procedure manually, hence his/her qualifications, training, recent experience, level of fatigue, and overall ability to compensate for disturbances may become critical in terms of safely landing the aircraft consistently and reliably without creating an unstabilized approach or causing a conflict with other traffic. This second scenario is at the basis of the study conducted herein on plausible hazard scenarios for the CESTOL helical-landing procedure.

The main assumptions feeding into the agent-based simulation environment developed for this research study consist of the following:

1. Interaction with other approaches: only the probability of the intrusion into the airspace designated for the neighboring approaches is estimated (no interactions are considered, such as evasive maneuvers by the aircraft whose airspace is invaded).

2. Aircraft model: it is solely based on kinematics rules, where the vehicle’s state vector includes only its inertial position, flight path angle $\gamma$, bank angle $\phi$, and heading $\psi$.

3. The trajectory is divided in three segments:

   - Helical trajectory at $\gamma = -5.5$, constant turn radius $R = 1.5$ nm, and linear $V_c$ profile ($V_c = 180$ kts, $\phi = 25^o$ at 10000 ft, $V_c = 110$ kts, $\phi \approx 4^o$ at 1000 ft); furthermore, the vehicle will exit at the established altitude regardless of its position and orientation with respect to the runway;
   - Stabilization/transit phase: $\gamma$ around $-1^o$ with path decided by pilot’s based on vehicle’s location when exiting the helix;
   - Conventional landing where the flight path angle $\gamma$ is not to drop below $-3^o$.

4. The aircraft is subject to the following performance constraints:

   - The load factor $n = \cos(\gamma)/\cos(\phi)$ is not to exceed the limit of 1.15 during the helix;
   - During the transition phase, the bank angle $\gamma$ is not to exceed $\pm 20^o$ and the turn radius $R$ must be greater than or equal to $1.5 R_{min}$. 

Figure 2. Decoupled arrival and departure routes for four New York metroplex airports
5. Modeling of the wind velocity $W$: the time-invariant wind profile is assumed to depend only on the altitude $z$. At each simulation, a representative profile is constructed using a weighted sum of measured wind data, i.e., $W = \Sigma_j c_j W_j$. The time-varying nature of the wind can be modeled assuming distinct random weights $c_j$ for each of the vehicles.

6. Pilot’s compensation: in order to account for the time delay ($\tau$) in the pilot’s response, the true airspeed $V$ at any given altitude $z$ is adjusted to compensate for the wind velocity $W$ measured at the altitude $z - \tau \sin(\gamma) V_j$. During the spiraling phase, the flight path angle $\gamma$ is never allowed to drop below $-6.5^\circ$ due to the wind effect, as it is assumed that the pilot would become aware of such a steep descent and would respond more promptly. Finally, for the results presented in this research study, no compensation of cumulative velocity drift has been included. At low altitudes, however, it may be hypothesized that visual cues may become available to the pilots to alert them of large incurring drifts in the trajectory.

### III. Results

In order to assess the risk level associated with vehicle-separation violation in the presence of an helix landing, two sources of uncertainty have been modeled and their effects investigated. The first one consists of the wind forecast error, modeled via rescaling and rotation of nominal wind profiles according to Gaussian distributions $N(\mu, \sigma)$. Illustrated in Figure 4 is the nominal wind velocity profile used as baseline for this study, and obtained through linear interpolation of measurement data. The information on the wind velocity $W = [W_N, W_E, W_D]^T$ has been expressed with respect to a North-East-Down (NED) reference frame with its local-north direction parallel to the runway, with additional assumption that $W_D$ is equal to zero. The second source of error relates to the pilot’s response time delay $\tau$, which was characterized by means of a lognormal distribution $L(\mu_L, \sigma_L)$.

The airport environment considered herein is composed of two parallel runways, one of which is utilized for conventional landings, whereas the other is dedicated to those vehicles performing helix approaches. The probability $P_{violation}$ that two approaching/landing airplanes will violate the minimum-separation safety requirement can be expressed as follows:

$$P_{violation} = P_{FMS\ failure} \times P_{helix\ drift} \times P_{other\ aircraft}$$

(1)
where $P_{\text{FMS failure}}$ is the probability of a FMS failure, $P_{\text{helix drift}}$ is the probability that the spiraling descending aircraft will drift away from its nominal course, and $P_{\text{other aircraft}}$ is the probability that another airplane will be in its vicinity. Given the layout of the landing site, depicted in Figure III, attention was given to the term $P_{\text{helix drift}}$ within Eq. (1), i.e., the probability that a vehicle on a drift helix will invade the airspace reserved to other incoming aircraft by crossing the centerline in between the two runways. The

![Figure 4. Nominal wind profile.](image)

![Figure 5. Planar layout of the landing site.](image)

hazard scenarios for CESTOL aircraft have been investigated by means of a Monte Carlo representation of the disturbances associated with the wind conditions and pilot reactions to the wind conditions themselves in the presence of a degraded FMS, where both sources of uncertainty were treated as independent random inputs. The wind nominal profile of Figure 4 has been randomized for each vehicle by assuming a wind intensity’s amplification factor $\kappa \sim N(\mu = 1, \sigma = 0.1)$, and a forecast error on the wind direction sampled through $N(\mu = 0, \sigma = 5^\circ)$. As regards the pilot’s response, the time delay $\tau \sim L(\mu_L = 10\text{ sec}, \sigma_L = 10\text{ sec})$, with a constraint on its maximum allowed sampled value set equal to 20 sec to avoid unrealistic lags. Depicted in Figure 6 is a screenshot of the simulation environment highlighting both conventional and helical landing procedures. All aircraft enter their respective landing approach at the same location, but each of them experiences a different wind which ultimately leads to a different response from the pilot and, in the case of helical descents, to a unique stabilization trajectory. Shown in Figures 7-9 are the results for three wind scenarios, namely south-west, cross and tail wind. It can be observed that even in the presence of mild winds with intensity on the order of $\sim 20$ kts, significant drift of the helix may occur, as in the case of the cross-wind scenario. In case of wind and aircraft speed of the same order of magnitude, a very quick response from the pilot is needed to contain the helix drift, which may otherwise lead to impractical landing scenarios. Accumulated drift without pilot intervention, however, may become unrealistic as the pilot will eventually realize to be off course. Since the model did not include any logics to compensate for cumulative effects, the aforementioned scenarios were discarded in the post-processing of the simulation results. Of course, the amount of “invasion” of the adjacent air space will also depend on the position at which an aircraft enters and exits the helix. Even relaxing the exit condition by allowing the aircraft to abandon the helix at an altitude other than 1000 ft in favor of a better alignment with the runway may help the pilot better assess his/her position through visual cues and thus control the drift more successfully. In some of the investigated scenarios, the effect of wind exhibited rather minor sensitivity with respect to the response delay. This was the case for tail as well as head wind in which conditions the flight path angle was the aircraft’s parameter.
Figure 6. Conventional and helical landing trajectories in the presence of wind varying conditions.

affected the most.
Figure 7. Separation violation hazard in the presence of a south-west wind.
Figure 8. Separation violation hazard in the presence of a cross wind.
Figure 9. Separation violation hazard in the presence of a tail wind.
IV. Conclusion

Helical landing scenarios for CESTOL aircraft were considered and modeled to assess the hazards induced by trajectory drift and consequent invasion of the air space dedicated to other incoming traffic. The investigation was conducted using agent-based simulation approach, since it provides a suitable framework to investigate combined effects occurring at different levels associated with the complex dynamic system NextGen, the air-traffic procedures, and the vehicle characteristics.

Results have shown that the combination of cross and head winds provide the most adverse scenario for airspace invasion and inter-vehicle separation violation since it may lead to very high probabilities of drifting away from the expected trajectory even in the presence of moderate wind velocities. Of course, a risky scenario may be exacerbated further depending on the corrections applied by the pilots and their timing.

As part of future research steps, the model provides results which can be used to fine-tune the air traffic procedures to avoid or mitigate potential hazards (e.g., increased flexibility in terms of exiting the helix, or permitting some path deviation inside the helix so that a correct position may be easily attained upon leaving the helical trajectory). Missed approaches and go-around scenarios shall also be included within the simulation together with a more thorough mapping between the model logics and realistic pilot responses. Finally, additional players and sources of uncertainty and failure such as air traffic controllers and communication protocols shall be captured within the framework, thus exploiting further the modeling capabilities of agent-based approaches. In particular, the interactions among the aircrafts from several neighboring approach segments will be considered (for example, the possibility of evasive maneuvers if the possibility of space separation violation is detected).

References