A FLIGHT TRAJECTORY MODEL FOR A PC-BASED AIRSPACE ANALYSIS TOOL

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ABSTRACT

This paper documents a method for rapid generation of aircraft flight trajectories. Rapid generation of flight trajectories is important for simulation models of air traffic that involve large numbers of aircraft, especially if complex interdependencies exist between flights and short simulation run times are required. Among the many aircraft trajectory models that have been developed, one generally observes a tradeoff between modeling detail provided by the model and its computational speed. Models that provide detailed trajectories typically require simulation run times on the order of one second per trajectory. Faster models often trade modeling detail for greater simulation speed. The model presented here was developed for applications that require simulation speeds on the order of one thousand trajectories per second and modeling detail to simulate typical flight operations in airspace close to major airports known as Terminal Radar Approach Control (TRACON) airspace. The computational speed of the model results from a discrete event simulation approach. It generates continuous speed and altitude profiles based on a small set of 31 trajectory parameters that are defined for each aircraft type based on aircraft performance data. The model provides detailed flight trajectories by synchronizing the discrete events that define model trajectories with significant events of typical flight operations and methodically adjusting the size of variable simulation time steps. The time steps, chosen in accordance with common piloting procedures and flight events, are categorized in ten flight phases. This paper introduces the concept of flight phases to group flight events and their associated trajectory parameters and presents a discrete-event flight trajectory model that is based on aircraft performance and centered on piloting procedures.

INTRODUCTION

The Federal Aviation Administration's (FAA's) Operational Evolution Plan (OEP) for the National Airspace System (NAS) addresses the challenge of managing safe and expeditious flight for an increasing quantity of air traffic. In the OEP, the FAA promotes several strategies for increasing airport arrival and departure rates as well as reducing passenger delays, including: (1) deployment of new aircraft navigation technologies, and (2) redesign of the TRACON airspace. Airspace redesign can involve changing the shapes and volumes of airspaces assigned to air traffic controllers, the number and location of air routes and navigation fixes, or the techniques used by controllers to sequence and separate air traffic. Increased deployment and use of Area Navigation (RNAV) procedures should lead to more diversified navigation routes and to improved utilization of available airspace.

Computer simulations of air traffic are a major source of quantified estimates of system benefits that can arise from TRACON airspace redesign and modern navigation techniques. A practical and usable model of TRACON operations requires sufficient modeling detail to allow evaluations of the impact of alternative route designs and navigational procedures while limiting simulation run times. The complex sequencing and separation interactions between multiple aircraft generally produce a large space of potential solutions to the Air Traffic Control (ATC) decision problem. Furthermore, allowing for variability in aircraft operational or navigational performance may necessitate repeated searches for desired solutions as flights progress. Consequently, rapid generation of flight trajectories is essential in order to maintain adequate simulation run times.

A flight trajectory model has been developed using the programming language Simulation Language with Extensibility (SLX)[1] as part of an airspace analysis tool for air traffic throughput and delay studies. It provides basic timing and distance information as typically required for airspace redesign benefit analyses. Design objectives of the PC-based trajectory model include adequate modeling detail of flight trajectories in the terminal area, relative ease of use, adaptability to specific modeling needs, and fast simulation speeds

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required to model complex interdependencies of large numbers of flight operations.

The modeling approach presented in this paper evaluates basic piloting procedures to define a small set of trajectory model parameters. The model parameters are grouped according to typical phases of flight. The paper identifies the flight phases that are considered intrinsic to fixed-wing flight and describes their application to classify significant flight events for use in expeditious discrete event simulations of flight trajectories using simulation time steps of variable length.

TRAJECTORY MODEL CONCEPTS

The conceptual model presented here views a flight trajectory as an estimate of the anticipated behavior of an aircraft in space and time based on: (1) characteristic flight performance of the aircraft; (2) typical piloting procedures; and, (3) planned navigation route of flight. The following paragraphs outline key aircraft performance considerations as well as how basic concepts regarding piloting procedures and navigation requirements are implemented in the model.

Aircraft Performance

The aircraft type largely determines the main features of a flight trajectory. Performance data provided by the aircraft manufacturer generally include characteristic speeds and climb/descent gradients. The data are often presented as functions of aircraft gross weight and atmospheric conditions and establish envelopes for safe flight. While takeoff and landing speeds typically have narrow envelopes, the wider range of possible climb, cruise, and descent speeds generally requires interpretation of the manufacturer's performance information when adapting the data for modeling purposes. Furthermore, climb and descent speeds as actually flown are dependent not only upon aircraft performance, they may also be limited by flight procedures preferred by the pilot or by speed restrictions imposed by ATC.

The EUROCONTROL Experimental Centre has published aircraft performance data for 71 basic types of aircraft.[2] This Base of Aircraft Data (BADA) was derived from ATC surveillance radar data of actual flight operations acquired for seasonal atmospheric conditions during the summer and winter months and analyzed in terms of a Total Energy Model. It provides characteristic aircraft performance data including typical climb and descent speeds and vertical speeds (climb rates) as well as cruise speeds for operations within the ATC environment. The aircraft climb and descent performance of the model presented here is based on BADA climb and descent data. Other parameters such as takeoff and landing speeds, aircraft acceleration and deceleration as well as cruise speeds are primarily based on Total Airport and Airspace Modeller (TAAM) aircraft performance data.[3]

Piloting Procedures

While aircraft performance envelopes generally provide wide ranges of operational options to the pilot, established operational procedures often call for operations that are characterized by a few typical engine power settings and a small set of key aircraft operational speeds. In addition to providing key aircraft operational speeds, piloting procedures can offer general timing information detailing when speed transitions are typically initiated. The model presented here is designed to facilitate implementation of typical piloting procedures and their impact on flight profiles of commercial flight operations. In addition to aircraft operational considerations, key procedural speeds often take into consideration general ATC requirements. For example, general speed restrictions apply to flight at altitudes below 10000 feet mean sea level (MSL) and a speed limit of 250 knots indicated airspeed (KIAS) constrains the speed profiles of flight trajectories of higher-performing aircraft. The trajectory model therefore allows specification of 10000 feet MSL as a target altitude in the definitions of flight phases of higher-performing aircraft types.

Navigation

Navigation information is input to the model via flight plan data. For each flight, a single line of formatted text specifies aircraft data, scheduling information, and other flight plan information including the origin and destination airports, as well as the route of flight. The route is defined by a sequence of navigation fixes that typically include charted radio navigational aids, airway intersections, radials and distances relative to a fix, or latitude and longitude information of a waypoint. Altitude and runway information for the departure and destination airports as well as latitudes and longitudes of the navigation fixes that define the route are obtained from databases provided by the National Flight Data Center (NFDC). Based on Great Circle navigation, the trajectory model then generates a 4D flight trajectory for the full route of a flight specifying latitude, longitude, altitude and time and other pertinent data of the flight at each defined point along the route. Trajectory points include the discrete events associated with an aircraft's departure, navigation fix crossing, and arrival at the destination airport, as well as the events related to aircraft operational procedures. Aircraft operational procedures are grouped by the phase of flight they occur in and are discussed below.

FLIGHT PHASES

The challenge of developing an expeditious flight trajectory model includes the definition of relevant time steps that allow definition of a small set of flight parameters while maintaining flexibility to model flight trajectories of adequate fidelity, especially in TRACON airspace.

The model presented here attempts to link the step size of time increments to significant flight events that occur relatively infrequently over the course of a typical flight and generally coincide with changes in an aircraft's general state of motion. Changes in an aircraft's general state of motion, in turn, often follow adjustments of engine power settings or pilot control inputs commonly prompted by established piloting procedures. The model describes these changes within the framework of ten flight phases that are defined to group and capture discrete flight events related to changes in characteristic aircraft performance and typical piloting procedures. Gradual changes between significant flight phase events due to, for instance, variations in atmospheric conditions during climb or descent, are captured by an averaged parameter value that is used to model the flight trajectory within a flight phase. The model therefore assumes linear changes of flight parameters between flight-phase events. Furthermore, all aircraft accelerations and decelerations are assumed executed at a constant rate.

Most flight phases defined here involve one speed transition: a new target airspeed is established at the beginning of a phase and maintained throughout the remainder of a phase. The other flight phases involve no speed transition or two speed transitions. It is noteworthy to point out that even though piloting procedures are modeled by sequentially establishing a number of discrete indicated airspeeds throughout the various phases of flight, the actual, or true airspeed (TAS) of the model aircraft generally changes realistically as altitude is gained in a climb or altitude is lost during descent. For example, during a climb at constant indicated airspeed, the true airspeed continually increases as the aircraft gains altitude. This increase is a result of changes in atmospheric conditions which give rise to greater divergence between indications of the airspeed indicator and the true airspeed of the aircraft. While the airspeed indicator is calibrated to indicate true airspeed at MSL and in standard atmospheric conditions, its indications remain below the true airspeed of the aircraft at a rate of approximately 1.5 to 2 percent per 1000 feet of altitude. During a constant indicated airspeed climb, the increase in true airspeed is typically sustained by gradually reducing the aircraft's pitch attitude, thus reducing the climb gradient as altitude increases. These changes are captured by the flight parameters defined for each phase of flight.

A total of 31 flight parameters are defined for each aircraft type including accelerations, speeds, altitudes, as well as climb and descent gradients. All aircraft accelerations are expressed in units of KIAS per minute, climb and descent airspeeds in KIAS, most cruise airspeeds in Mach number, and altitudes are specified in feet above ground level (AGL) as well as feet MSL where appropriate. Model parameter units were chosen to closely match the units of key speeds and target altitudes that typically define piloting procedures of transport category aircraft.

The current version of the model does not include effects due to wind and the progress of a flight is modeled to depend solely on its true airspeed. The model calculates flight progress distances and time by converting all indicated airspeeds to true airspeeds depending on the actual altitude of the aircraft.

The following paragraphs motivate and outline the ten flight phases that were chosen to constitute a flight in the model presented here and specify the selected model flight parameters. While fixed-wing aircraft are generally assumed to sequentially complete all flight phases, the model allows for variations within certain phases to accommodate higher and lower performing aircraft types or flight at atypical cruising altitudes. To simplify the discussion of the flight phases, an aircraft of type B737-300 is assumed where parameter values are given. A notional illustration of the flight phases is given in Figure 1.

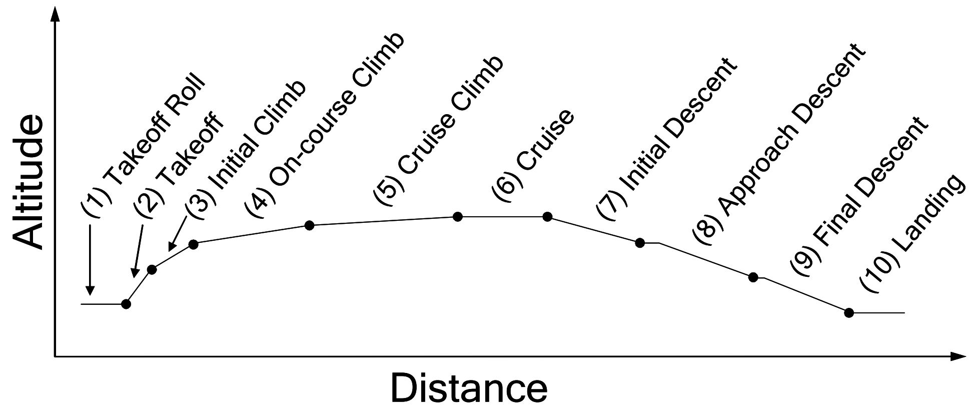

Figure 1. A Notional Altitude Profile Illustrating the Ten Flight Phases of a Model Flight Trajectory

Flight Phase 1: Takeoff Roll

The objective of the takeoff roll phase of an aircraft is to accelerate sufficiently such that the wings generate adequate lift to safely support the weight of the aircraft when it becomes airborne. The speed at which the aircraft can become airborne is called rotation speed. The beginning of this phase generally coincides with the pilot's application of engine takeoff power. The resulting forward thrust and acceleration of the aircraft is maintained until rotation speed is achieved which defines the end of the takeoff roll flight phase of the model. Rotation is the process of changing the orientation in space, called attitude, of the aircraft's longitudinal axis from a level attitude to a nose-high takeoff attitude. The parameters that are chosen to describe this phase are the aircraft's takeoff roll acceleration and rotation speed.

Flight Phase 2: Takeoff

As the pilot establishes aircraft takeoff attitude during rotation, the lift produced by the wings increases and supports the weight of the aircraft. The resulting increase in aerodynamic drag leads to a significantly reduced takeoff acceleration. When the aircraft is airborne and a positive climb gradient has been established, the landing gear is raised. After acceleration to initial climb airspeed, the subsequent climb generally assures obstacle clearance by providing efficient gain in altitude for the distance flown by the aircraft. The takeoff flight phase of the model is concluded when the aircraft has climbed sufficiently and reached a "safe" altitude above ground level where obstacle clearance considerations are no longer a factor.

The takeoff phase consists of two parts. The first part is characterized by the aircraft's acceleration to initial climb airspeed. The second part describes a climb at constant indicated airspeed. Takeoff acceleration, initial climb speed, climb gradient, and obstacle clearance altitude are the parameters defined to model the takeoff phase of flight.

Flight Phase 3: Initial Climb

When obstacle clearance considerations are no longer a concern, engine power is generally reduced from takeoff thrust to climb thrust in order to minimize the time the engines are subjected to the increased stresses of takeoff power settings. The model maintains initial climb airspeed throughout the initial climb phase. Maintaining initial climb airspeed while engine power is reduced to climb thrust typically requires a reduction in the flight path's climb gradient. The initial climb flight phase in the model is completed when the aircraft climbs through a target altitude typically measured AGL. The initial climb gradient and target altitude are the only parameters used to model the initial climb flight phase.

Flight Phase 4: On-Course Climb

By the time the aircraft climbs through its target altitude, ATC has often issued instructions that allow the flight to proceed "on course" according to the route for which aircraft was cleared. The objective of this phase of flight, called on-course climb phase, generally is first to accelerate to a speed where wing flaps that may have been used for takeoff can safely be retracted and then to continue acceleration to an airspeed that entails a more expeditious climb. Acceleration to on-course climb airspeed is effected by reducing the aircraft's climb gradient and raising of wing flaps which results in reduced aerodynamic drag of the aircraft. Flight at on-course climb airspeed typically establishes an efficient gain in altitude of the aircraft for the time flown. Speed restrictions generally apply to flight in the airspace below 10000 feet altitude above MSL, often limiting the on-course climb speed to 250 KIAS. In most cases, the on-course climb flight phase is completed when aircraft reach 10000 feet MSL and speed restrictions no longer apply.

This phase consists of two parts. The first part describes the aircraft's acceleration to on-course climb airspeed. The second part represents a climb at constant indicated airspeed. The parameters chosen to model the on-course climb phase are on-course climb acceleration, airspeed, climb gradient, and altitude.

Flight Phase 5: Cruise Climb

As general airspeed restrictions no longer apply at altitudes of 10000 feet MSL and above, piloting procedures often call for acceleration to cruise climb airspeed. As the climb power setting typically remains unchanged, acceleration to cruise climb airspeed is achieved by reducing the climb gradient. Maintaining a constant indicated cruise climb airspeed requires continual reduction of the aircraft's climb gradient throughout the climb. While the indicated airspeed is kept constant, the actual, or true airspeed increases as altitude is gained. The increase in true airspeed is reflected in a rising Mach number that approximately represents the ratio of the aircraft's true airspeed to the speed of sound at the given altitude of the aircraft. Once the Mach number matches a desired Mach number for cruise climb, the climb is typically continued using a constant Mach number at or below the cruise Mach number throughout the remainder of the climb. The model's cruise climb flight phase is completed when the aircraft reaches cruise altitude. Because cruise altitude is specified in a flight's flight plan, it is input to the trajectory model and not a parameter of the model.

This phase may consist of up to three parts. The first part is characterized by the aircraft's acceleration to cruise climb airspeed. The second part describes a climb at constant indicated airspeed. If the cruise altitude specified in the flight plan is above the altitude associated with the pilot's transitioning to Mach number as speed reference, the third part of the phase describes the climb from transition altitude up to cruise level. Parameters that are used to model the cruise climb flight phase are cruise climb acceleration, airspeed, gradient, and cruise Mach number.

Flight Phase 6: Cruise

When the aircraft reaches cruise altitude, leveling off and continued flight at cruise altitude typically involves adjusting engine power to maintain a desired cruise airspeed. The model cruise flight phase ends when the aircraft approaches the top-of-descent point located a distance from the destination airport that allows a descent to the destination airport at a specified descent gradient.

This phase consists of two parts. Depending on the aircraft type and the cruise altitude specified for the flight, the first part may characterize the aircraft's acceleration to cruise airspeed. The second part describes cruise flight at cruise airspeed (or Mach number). Parameters employed to model flight during the cruise phase are cruise acceleration and airspeed.

Flight Phase 7: Initial Descent

After reducing power to idle power, the first part of the initial descent phase is often flown at a descent Mach number that matches or is similar to the cruise Mach number. As altitude decreases and airspeed indications approach the desired initial descent airspeed, the initial descent is continued with reference to the airspeed indicator at constant initial descent airspeed. The initial descent phase is modeled to end when an altitude of 10000 feet MSL is reached.

This phase may consist of up to three parts. If the cruise altitude specified in the flight plan is above the altitude associated with the transitioning to Mach number as speed reference, the first part of the phase describes the descent from cruise altitude to transition altitude. The second part typically characterizes a deceleration to initial descent indicated airspeed followed by the third part, a descent at constant indicated airspeed The parameters used to model the initial descent flight phase are cruise Mach number, initial descent deceleration, airspeed, gradient and altitude.

Flight Phase 8: Approach Descent

The first part of the approach descent flight phase typically commences with slowing the aircraft to approach descent speed, an indicated airspeed of 250 knots or less, before the descent is continued to altitudes below 10000 feet MSL. Approach planning often calls for continued descent to a target altitude and slowing of the aircraft to a target airspeed before it is safe to extend the wing flaps. Target altitude and airspeed are typically associated with intercepting approach navigational aids such as the localizer of an Instrument Landing System (ILS) at a target distance from the approach end of the landing runway of the destination airport. While sequencing aircraft for approach, ATC often assigns aircraft heading and speed changes that lengthen the distance flown to the destination airport. The approach gradient used in the model is determined accordingly and is not chosen to be a model parameter. The approach descent flight phase is completed when the flight reaches a target distance from the airport.

This phase consists of two parts. The first part is characterized by the aircraft's deceleration to approach descent airspeed. The second part describes a descent at constant indicated airspeed. The parameters for this phase of the model are approach descent deceleration and airspeed as well as target speed, altitude, and distance.

Flight Phase 9: Final Descent

As the flight continues inbound, a momentary leveling off at target altitude and wing flap extension often provides the required deceleration of the aircraft to final approach descent airspeed. This airspeed and level flight are maintained until a typical three-degree descent gradient is intercepted. At this point, the lowering of the landing gear and successive wing flap extensions generally result in gradual slowing of the aircraft to landing airspeed. The final descent flight phase in the model is completed when the aircraft touches down for landing at landing airspeed.

This phase consists of three parts. The first part characterizes the aircraft's deceleration to final approach descent airspeed. The second part describes flight at constant indicated airspeed until the aircraft intercepts the final approach descent gradient. The third part represents the final descent to the runway while gradually decelerating to landing speed. The parameters chosen to model the final descent flight phase are final descent deceleration, airspeed, gradient, and landing airspeed.

Flight Phase 10: Landing

The landing phase often involves rapid deceleration on the runway initially by engaging engine thrust reversers followed by application of wheel breaking. The model landing flight phase is completed when the aircraft decelerates to taxi speed. Landing deceleration is a model parameter as well as the airspeed associated with taxiing off the runway.

MODEL IMPLEMENTATION

The trajectory model was implemented using the programming language SLX.[1] First, required modeling input such as geographic airport and air navigational data as well as the air traffic data are read into memory, then model flights are implemented as instances of an active object of object class "Flight" whose actions include the scheduling and execution of the ten flight phases described above. For a "basic" flight with departure and destination airports but no additional route elements such as navigational fixes in the traffic data file, the resulting model trajectory is characterized by up to 20 discrete flight events or trajectory points. The number of trajectory points results from the number of flight phase parts that were used to model the flight. In addition to latitude, longitude, altitude and time of an aircraft completing each flight phase or part of a flight phase, the current implementation of the model provides other pertinent flight information such as accumulated distance and time flown, indicated and true airspeeds of the aircraft, and the course of the flight relative to true north. When navigational route elements are specified in a flight's navigation route, the model generates similar trajectory information at a crossing of each route element. Depending on the number of elements of a flight's route, the model typically characterizes a domestic flight by about 30 to 50 discrete flight events. While the methodical selection and definition of flight phase events ensures adequate model fidelity in TRACON airspace, the relatively small number of events facilitates rapid generation of flight trajectories.

The trajectory model has been employed to estimate operational benefits of additional departure routes at a major US airport. In this study, multi-queue departure sequencing and separation algorithms require repeated generation of flight trajectories. Using the powerful mechanisms SLX provides for describing parallel processes, these algorithms are implemented to generate separate trajectory modeling processes. The following example illustrates a typical sequence of executions of the trajectory modeler to determine departure times of aircraft departing consecutively from the same runway. Minimum departure separation distances required by FAA Order 7110.65 establish aircraft separation standards and protect trailing aircraft against encountering the turbulence of the wake vortices that remain behind the leading aircraft. If, for example, wake vortex separation requires that a trailing aircraft does not become airborne until a separation distance of five nautical miles is established with the preceding aircraft, the following executions of the trajectory model would determine the earliest time the trailing aircraft can be released for takeoff. First, the point along the flight trajectory at which the trailing aircraft will become airborne is obtained from parallel execution of the trajectory modeler and extraction of the distance associated with completion of the takeoff roll flight phase. The elapsed time is recorded for the point at which the aircraft becomes airborne. Second, a waypoint is inserted in the route of the preceding aircraft at the required separation distance beyond the distance where the trailing aircraft will become airborne. The trajectory of the preceding flight is then modeled and the actual simulation time it crosses the additional waypoint is noted. The earliest time the trailing aircraft can be released for takeoff is then determined as the simulation time the preceding aircraft crosses the added waypoint minus the time it takes the trailing aircraft to complete its takeoff roll. In this example, generation of two model trajectories provided the earliest departure time to ensure aircraft separation at the moment when the trailing aircraft becomes airborne. More complex separation requirements typically demand generation of greater numbers of model trajectories. SLX provides highly optimized algorithms for event management that allow exceptionally fast execution of simulation models. A typical simulation run of the departure route model was found to generate about 50000 trajectories requiring a run time of about 1 minute under Windows2000 on a Dell OptiPlex GX110 PC with a 1 GHz Pentium 4 processor.

The current version of the trajectory model does not evaluate the effects of prevailing winds on aircraft trajectories. A next step in the development of the model could be the implementation of mechanisms for aircraft performance randomization. Future work may include extension of the model to handle the altitude restrictions typically imposed by ATC in TRACON airspace to temporarily restrict aircraft from climbing above or descending below a specified altitude.

SUMMARY

An aircraft flight trajectory model was developed for application in airspace design studies. This PC-based model provides the modeling detail and flexibility required for modeling flight operations in terminal airspace, while achieving simulation speeds that allow for representing the complex interdependencies of large numbers of flight operations.

Simulation speed of the model is achieved by defining simulation time advances in steps of variable length. Adequate model fidelity is ensured by linking the step size of simulation time increments to significant flight events. This model employs the concept of ten flight phases that serve as a framework to capture characteristic aircraft performance and typical piloting procedures in terms of 31 modeling parameters for each aircraft type. The model uses standard databases of the infrastructure of the NAS as well as flight plan data to generate continuous speed and altitude profiles of 4D flight trajectories.

The trajectory model has been implemented in the simulation programming language SLX and applied to estimate operational benefits of airspace design changes.

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