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Literature Survey of Trajectory Predictor Technology

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16. Abstract

Separation Management is a project within the Federal Aviation Administration's Next Generation Air Transportation System (NextGen) program to identify a series of automation upgrades and algorithm enhancements to improve the accuracy of the strategic en route conflict probe (CP) and the tactical conflict alert (CA). Results of this research will help to define the Computer-Human Interface (CHI) enhancements to the controller's displays and will result in defining new requirements for future En Route Automation Modernization (ERAM) releases.

The research will help determine if additional, new, or improved capabilities should be added to both the CP and CA to reduce the occurrences of false alerts and prevent the automation from missing valid alerts. Related controller tools for the Radar Controller Console (R-Side) display are being developed to provide visual cues to increase the controller's situational awareness of the predicted conflict events.

This paper focuses on the trajectory prediction (TP) subfunction of the CP process. Increasingly realistic flight models obviate the need for changes in TP software design. Evaluation of the methods presented in each paper was done using the trajectory predictor abstraction defined in FAA Action Plan 16 (AP16) as a standard.

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Executive Summary

In this survey document, hundreds of research and operational papers were reviewed to identify previous research related to the Separation Management areas of interest. For this report, only papers that discussed topics directly related to the Trajectory Predictor (TP) algorithms, operations, and implementations were considered for review. From the hundreds reviewed, a total of 282 were identified as relevant to the Separation Management research. A detailed review of the 282 documents was conducted and the results entered into a relational database specifically created for this effort. Finally, from the original 282, a subset of 20 documents, with unique approaches and directly related to TP operation, were selected for even more detailed analysis. An attempt was made to make the final 20 papers represent a cross-section of the different areas of research related to trajectory prediction, and were chosen because they described innovative solutions and proposed enhancements that have not yet been fully explored.

Evaluation of the techniques presented in each paper was done in relation to the trajectory predictor standard defined in FAA Action Plan 16 (AP16). AP16 was a collaborative effort between EuroControl and the FAA and included many organizations involved in tool and predictor development. The AP16 document was drafted to reduce duplication of effort between the organizations, with the resultant benefit of reducing time to deployment, enhancing quality of validation, and reducing overall costs. The AP16 identifies specific areas of functionality within a generic trajectory predictor defined as preparation, update, computational, and export. This subfunction definition is advantageous because it tends to simplify maintenance and enhancement.

The maturity of each paper was also determined using the Levels of Maturity (LOM) as defined by the FAA in the Technical Readiness Level (TRL) standards. The TRLs are a systematic metric used by the FAA to support the consistent comparison of research maturity. A full explanation of each LOM is described in Appendix A, Technology Readiness Levels. An overall evaluation of the LOM classification, for the 282 documents reviewed in this paper, can be found in Figure 3, Levels of Maturity Analysis.

Many of the papers presented mathematically intensive optimization techniques for flight planning and separation assurance. These were mostly focused on increasing capacity and, consequently decreasing delay. A major recurring theme, in a majority of the research papers reviewed, was distributing the workload of flight planning and separation assurance between controllers and flight crew. An emphasis on more sophisticated mathematical modeling was evident due to the increased use of the aircraft's Flight Management System (FMS) and Automatic Dependent Surveillance – Broadcast (ADS-B) capabilities to provide more accurate trajectory calculations.

Additional research is encouraged in the areas of vertical modeling, hold modeling, and the calculation of more accurate closure rates used for improving trajectory predictions and ultimately optimizing conflict detection and resolution.

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1 Introduction

1.1 Purpose

Separation Management is a project within the Federal Aviation Administration's Next Generation Air Transportation System (NextGen) Program to identify a series of automation upgrades and algorithm enhancements to improve the accuracy of the strategic en route conflict probe (CP) and the tactical conflict alert (CA). Results of this research will help to define the Computer-Human Interface (CHI) enhancements to the controller's displays and will result in defining new requirements for future Enroute Automation Modernization (ERAM) releases.

The research will help determine if additional, new, or improved capabilities should be added to both the CP and CA to reduce the occurrences of false alerts and prevent the automation from missing valid alerts. Related controller tools for the Radar Controller Console (R-Side) display are being developed to provide visual cues to increase the controller's situational awareness of the predicted conflict events.

1.2 Background

Currently the CP alerts are displayed only on the Data Controller console (D-Side) of the en route controller's display, and provide up to a 20-minute look-ahead time, identifying and alerting controllers to potential loss of minimum separation between pairs of aircraft. The CA function is currently operational only on the R-Side and provides tactical alerts using up to a three-minute look-ahead time to identify the potential loss of minimum separations.

Several research studies, as well as anecdotal reports, indicate that both the CP and CA functions generate false negatives (a.k.a. missed alerts), and false positives (a.k.a. false alerts). Untimely and false alerts diminish controller confidence in the automated Decision Support Tools functionality, and can lead to the controllers' disabling the functionality or simply disregarding the alerts.

1.3 Scope

The Separation Management project is currently looking into the following areas of research: (*Description in italics is from the Separation Management Project Description document*.)

- Reduction of false and missed alerts
  The development effort to improve the functionality of the conflict probe to reduce the number of missed alerts and false (nuisance) alerts to increase the conflict prediction accuracy and timeliness

- Improving trajectory modeling of the tools
  Consists of the incremental development activities to improve the trajectory modeling and to evaluate the potential airspace capacity changes and benefits.

- Integration of problem detection on the radar console
  The development effort to integrate the conflict probe and conflict alert functionality onto the controller's radar display.

- Implementing Flight Management Computer (FMC) route offsets
  The development effort to introduce the entry of offset clearances, and the coordination between controlling sectors for aircraft cleared on an FMC offset route.

- Implementing aircraft-to-aircraft alerts to support 3nm separation of aircraft
  The development effort to evaluate the impact of the implementation of terminal separation rules to reduce horizontal separations (e.g. 3 nm).

- Improve input of clearances and flight plan amendments
  The development effort to facilitate more frequent entry of Air Traffic Control (ATC) clearance and flight amendments.

- Alerting ground control of flight plan deviation
  The development effort to improve problem detection with enhanced alerting capabilities when an aircraft is not following the ATC automation's flight plan specification for an Area Navigation/Required Navigation Performance (RNAV/RNP) route.

In this paper, only research conducted for trajectory prediction will be examined. The trajectory predictor is the vital process that feeds all the advanced tools used for conflict detection, alerting, and resolution.

1.4 Document Organization

The organization of this document is as follows:

Section 1 contains a brief introduction regarding the motivation for this report.

Section 2 is an overview of the industry standard (generic) definition (AP16) of TP functionality.

Section 3 presents the data collection criteria, including the rationale for selecting specific documents.

Section 4 provides more specific details about each paper, and describes, in detail, the research that was conducted in the area of trajectory prediction.

Finally, Section 5 provides a quick summary of the findings along with a few recommendations for future research to improve trajectory predictor technology.

2 Trajectory Predictor Technology

The Trajectory Predictor (TP) describes the predicted path an aircraft will follow through the airspace. This trajectory can be described mathematically by a time-ordered set of aircraft state vectors. The computation is performed based on input data consisting of the current state and the future intent of the aircraft. The TP uses models for aircraft performance, meteorological conditions, and airspace adaptation data.

The TP is a function that can be utilized by a client application to support application tools within the Air Traffic Management (ATM) system. These applications will support Decision Support Tools (DST) that provide data, conflict advisories, and recommended conflict resolutions to en route ATM systems.

For a majority of the en route airspace, the minimum safe separation for aircraft is 5 nm. horizontally, and 1,000 ft vertically. Aircraft predicted to be separated by less than the 5 nm/1,000 ft minimum are brought to the attention of the controller who will intervene and take actions to keep the aircraft safely separated.

Algorithms for predicting aircraft separation can be simple or relatively complex. The complex algorithms take into consideration varying conformance bounds and add probability estimates. Warning times to the controller will vary based on the results of the algorithm calculations.

Currently many of the conflict detection predictors are based on the aircraft's maintaining a constant altitude, velocity and acceleration. More complicated software algorithms are being tested that will accurately predict conflicts for aircraft that are transitioning altitudes, and holding.

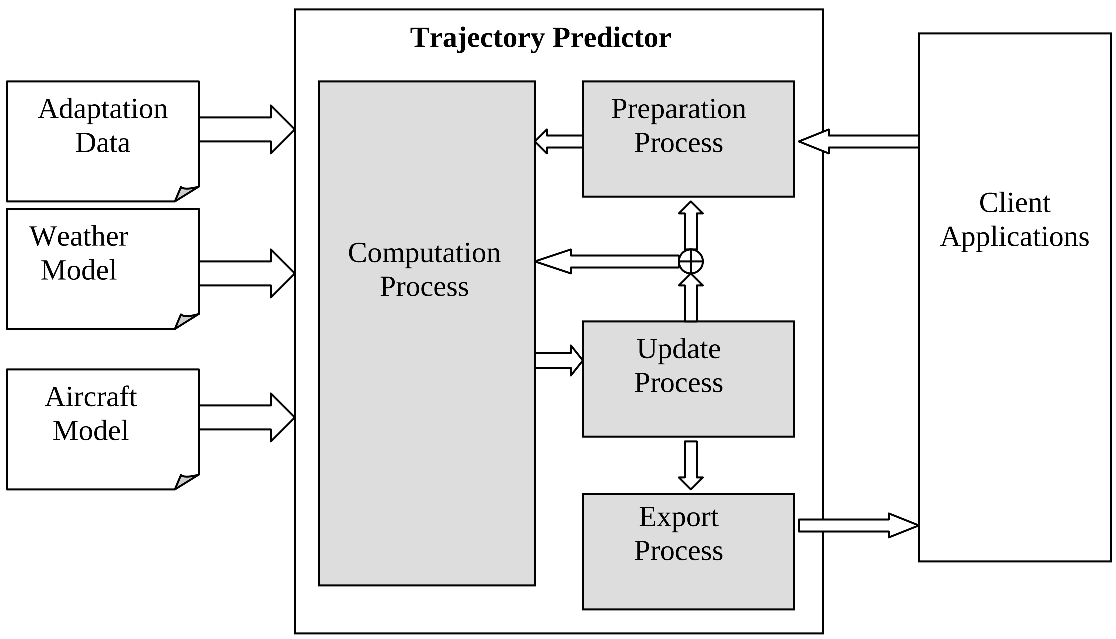

Figure 1: Trajectory Predictor – Process Flow

A diagram of the process flow within the generic TP structure, as described in EuroControl/FAA Action Plan 16 (AP16), is presented in Figure 1. The TP client application accepts data inputs from adaptation, weather, and aircraft models. The TP application is comprised of the following four component processes: Preparation, Computation, Update, and Export.

Within the TP, a Flight Object (FO) represents the system instance of a particular flight that can be shareable with other stakeholders. The Flight Object typically contains the following information for a flight:

· Initial Aircraft State - The Initial Aircraft State describes the aircraft state, as input into the TP at the time of the start of the trajectory computation.

· Flight Intent - Flight Intent is an element of the Flight Object that describes the constraints and preferences applicable to the flight.

· Aircraft Intent - Aircraft Intent is the aircraft operations plan that defines precisely how the aircraft intends to meet the constraints and preferences defined in the Flight Intent.

2.1 FAA Action Plan 16[1] Generic Trajectory Predictor Process Flow

From the Executive Summary of the AP16 document *"The primary purpose of EuroControl/FAA Action Plan 16 is to minimize duplication of effort in the many organizations involved in tool and predictor development, thereby reducing costs, reducing time to deployment, and enhancing the quality of the validation and improvement process."*

2.1.1 Preparation Process

The preparation process builds initial conditions and a Behavior Model that provides a list of the maneuvers that the aircraft intends to fly. The Behavior Model describes how the aircraft will meet the trajectory constraints within its user preferences.

State Processing

The State Processing generates the Initial Conditions for trajectory generation.

Flight Intent Processing

Flight intent processing operates on a Behavior Model, or if the Behavior Model is not defined, it will create one from the Initial Conditions and Flight Intent. The Flight Intent processing evaluates the Initial Aircraft State, both laterally and vertically, against the set of constraints defined in the Flight Intent. The output of the Flight Intent is comprised of the Initial Conditions and the complete set of constraints that must adhered to during trajectory generation.

Behavior Model Generation

The Behavior Model consists of ordered lists of maneuvers that the aircraft will perform to meet the trajectory constraints. The Behavior Model is internal to the TP and is built from the Initial Condition and Flight Intent information.

2.1.2 Computational

Within the TP client application, the computational process computes the predicted trajectory based on the predefined Behavior Model.

[1] Common TP Structure and Terminology in support of SESAR & NextGen, Eurocontrol/FAA Action Plan 16 Common Trajectory Prediction Capability, *Version 1.0, January 29, 2010*

2.1.3 Update Process

The update process monitors the conformance of the computed predicted trajectory. The update process checks to see if the computed trajectory is in conformance with the trajectory constraints specified in the Input Flight Intent. When the trajectory is out of conformance, the Update process will recompute the trajectory using the updated Behavior Model and/or Flight Intent data.

2.1.4 Export

Finally, the export process distributes the TP results to client processes. These client processes will receive predicted trajectory data, error messages associated with the data, and an updated Behavior Model when the trajectory does not match all the predefined constraints.

The export process sends its results to the output clients. These results include the current predicted trajectory, an updated Behavior Model, and any relevant error messages.

2.2 FAA Action Plan 16[2] Generic Trajectory Predictor Data Flow

2.2.1 Trajectory Prediction – Data Inputs

The Client Inputs include: (*Ref:* Figure 2)

a.) Aircraft State

The Initial Aircraft State represents the aircraft state data at the start of the trajectory computation cycle and is composed of, but not limited to, the 3D aircraft position and associated time.

b.) Flight Intent

Flight Intent is that element of the Flight Object that contains the constraints and preferences applicable to the flight. It describes aircraft, airport, and airspace constraints and operator preferences.

c.) Behavior Model

The Behavior Model contains a list of maneuvers that describes how the aircraft intends to satisfy the trajectory constraints and user preferences.

d.) Processing Strategies and Configuration Control

The Processing Strategies specifies how the predictor will conform to the constraints and preferences identified in the Flight Intent. The Configuration Control defines processing characteristics such as aircraft performance models and the functionality of the integration and export functions.

[2] Common TP Structure and Terminology in support of SESAR & NextGen, Eurocontrol/FAA Action Plan 16 Common Trajectory Prediction Capability, *Version 1.0, January 29, 2010*

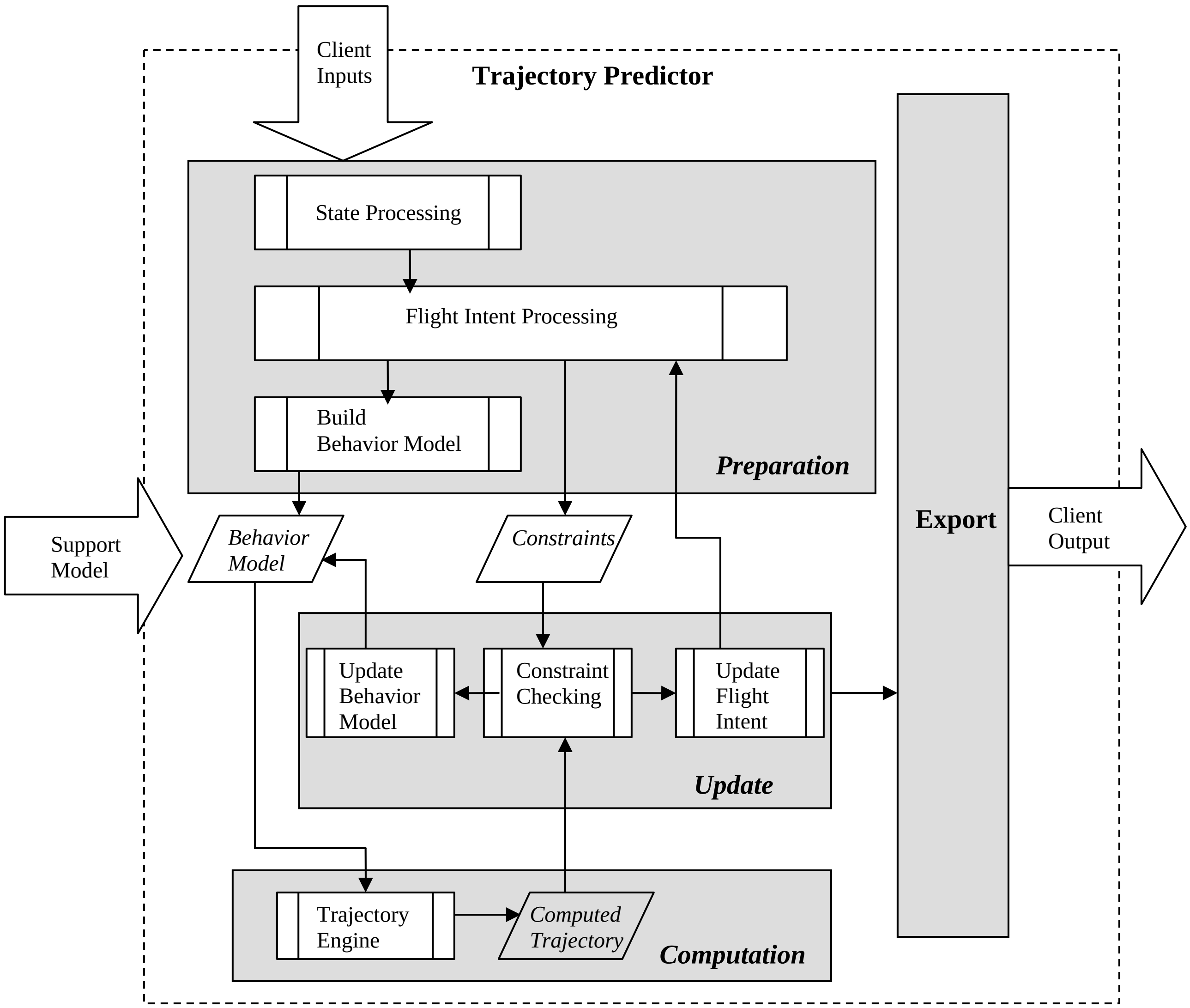

Figure 2: Trajectory Predictor – Data Flow

The Support Model Inputs include: (*Ref:* Figure 2)

a.) Adaptation Data
Describes the operational environment and includes the airspace adaptation, aircraft adaptation, and an earth model.

b.) Weather Model
Generates predicted information describing the current state of the air mass where the aircraft is operated.

c.) Aircraft Model
Describes the operational characteristics of the aircraft.

2.2.2 Trajectory Prediction – Computations

a.) Aircraft State Processing
Processing required to generate the Initial Condition supplied to the computation process.

b.) Flight Intent Processing
Processing that evaluates the Initial Condition and compares it to the set of constraints in the Input Flight Intent to identify missing components.

c.) Behavior Model Generation
The Behavior Model Generation process builds a Behavior Model from the input provided from the Initial Condition and the Flight Intent.

2.2.3 Trajectory Prediction - Outputs

The Export process provides the results of the TP processing to the TP clients. The following information is exported:

a.) Predicted Trajectory
The Predicted Trajectory predicts the future path of an aircraft through the airspace.

b.) Updated Behavior Model
If the Update Process detects non-conformance, an updated Behavior Model associated with the predicted trajectory is exported.

c.) Updated Constraints
Updated information on constraints that may have changed are output.

d.) Errors Encountered
Errors and/or warning messages encountered during the computational process are output to the TP clients.

3 Data Collection & Analysis

The documents reviewed for this survey were identified from an archive collection of the current research completed, or in progress, by FAA, MITRE, NASA Ames Research Center, EuroControl, Lockheed Martin, Boeing, and several educational institutions involved in aviation research including MIT, Embry-Riddle, and Georgia Tech.

The goal during the document selection was to review a large cross section of the current research and technology that is being developed, tested, and deployed. Priority was given to technologies that were unique, innovative, or targeted solutions for advanced air traffic systems, especially those involved in NextGen.

For this report, a questionnaire, mentioned below, was developed for compiling the results of the document reviews. The criteria for consideration into this report was that the paper identified research pertaining to the development of new technologies, or enhancements to current technology being used for the trajectory prediction of aircraft. Results from the trajectory predictor (TP) are the foundation of all DSTs and the results are needed to produce accurate and timely conflict detections, controller alerting, and recommended resolution actions. The TP functionality can be defined as:

Trajectory Modeling (Predictor)

The trajectory modeling function creates 4-dimensional (space and time) representations of an aircraft's predicted flight path based on the converted routes as derived from the flight plan, weather data, aircraft characteristics and airspace definitions, including restrictions.

For this survey, hundreds of research and operational papers were reviewed, and a subset selected that contained research directly related to the Separation Management areas of interest. The documents that did not discuss concepts in these areas were disregarded for this report. The subset selection amounted to 282 papers that included research conducted over the past 10-12 years, and most were presented at conferences sponsored by AIAA, DASC, and IEEE.

To fairly evaluate each document, a standard questionnaire was developed. A list of the documents and a set of standard questions along with check-boxes that identified several categories of interest were developed and entered into an ACCESS[3] database. The check-boxes were chosen to allow for easy tabulation of the results.

After the complete set of documents was reviewed, a finer review of the documents was made to select papers that concentrated on unique areas of Trajectory Predictor (TP) algorithms, operations, and implementations. From the original 282 documents, a sub-subset of 20 documents directly related to TP research was selected to be used for a more detail analysis in this report. The detailed results are presented in Section 4 of this document. Since it would be prohibitive for this report, to review all 282 in detail, the final 20 papers represent a cross-section of different areas of research related to trajectory prediction and were chosen because they described innovative solutions and proposed enhancements that have not yet been fully explored. There was also consideration taken to include research from several different research communities.

4 Detailed Synthesis of Research Papers

4.1 Brief Analysis of All the Papers Reviewed

This section contains the results of the document reviews conducted and presents a summary of the concepts and research conducted within the papers reviewed. The primary areas of research and a brief synopsis of the associated research, prototypes, and reports are discussed. Many of the papers support the concepts identified for analysis by the Separation Management Program initiative.

Figure 3 depicts the results of the Level of Maturity (LOM) (Ref: Appendix A) evaluation for all the 282 documents reviewed as part of this report. The majority of the research, as

[3] ACCESS - Microsoft relational database

expected, was in the area of new concept development and proof of concept. The next steps, validation of the concepts and eventual migration into operation were not as prevalent in these research papers. This was expected as most of the research papers were looking into future concepts that could, with further research, be developed and implemented to improve the TP performance.

Figure 4 summarizes the several categories that were chosen to be tabulated from the total number (282) of documents reviewed. Areas that stand out are lateral, longitudinal, and vertical profiles, all important elements of an accurate Trajectory Predictor. Also significant were flight plan and surveillance. These are the major components of the flight object that is composed of state data and aircraft intent.

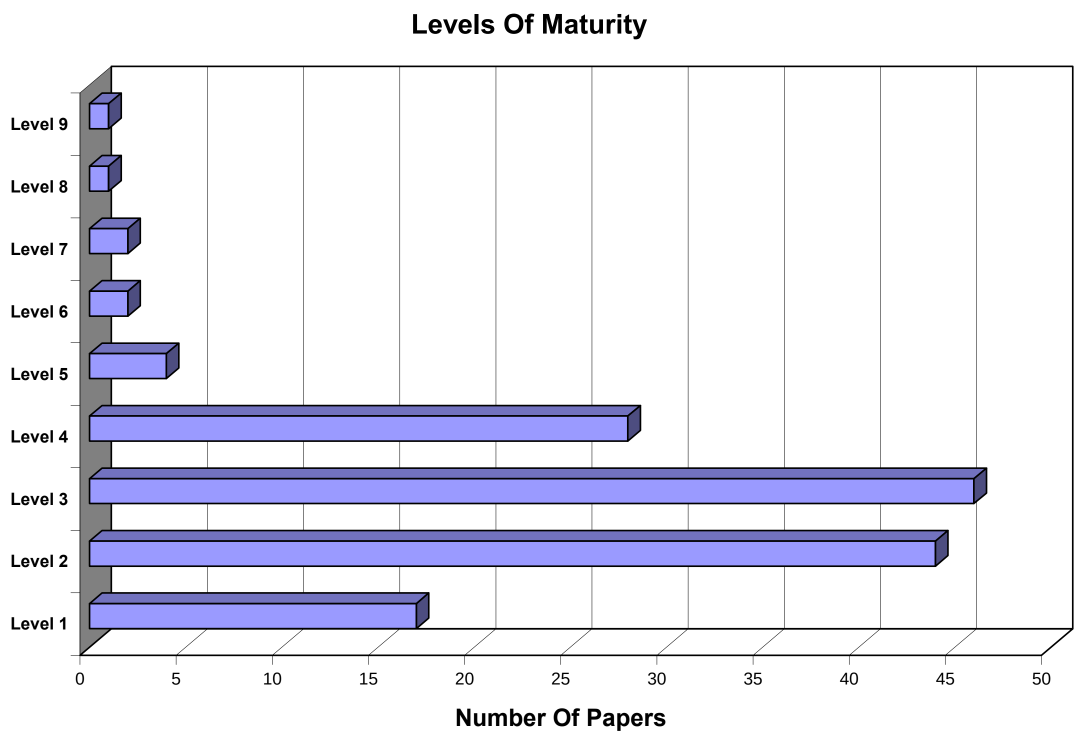

Figure 3: Levels of Maturity Analysis

Table 1 contains a list of the 20 documents chosen (from the 282 reviewed) for detailed review. The documents present innovative approaches to trajectory prediction and have explored areas not in the current HOST or ERAM releases. Some of the areas include, holding, modeling turns, vertical modeling, and mathematical flight models.

The document reviews focus on algorithms discussed and developed in the survey document set that are directly or potentially applicable to the trajectory prediction function of the air traffic management (ATM) system. As part of an ongoing effort by a joint FAA/EuroControl Common Trajectory Prediction Committee to abstract ATC functions, a virtual specification[4] for this process was developed. Details regarding this process were discussed in Section 2.

[4] Vivona, Robert A., Cate, Karen T., and Green, Steven M., *Abstraction Techniques for Capturing and Comparing Trajectory Predictor Capabilities and Requirements*. AIAA AF2008098

This abstraction serves as a model for parsing the algorithms identified as applicable to trajectory prediction in some fashion.

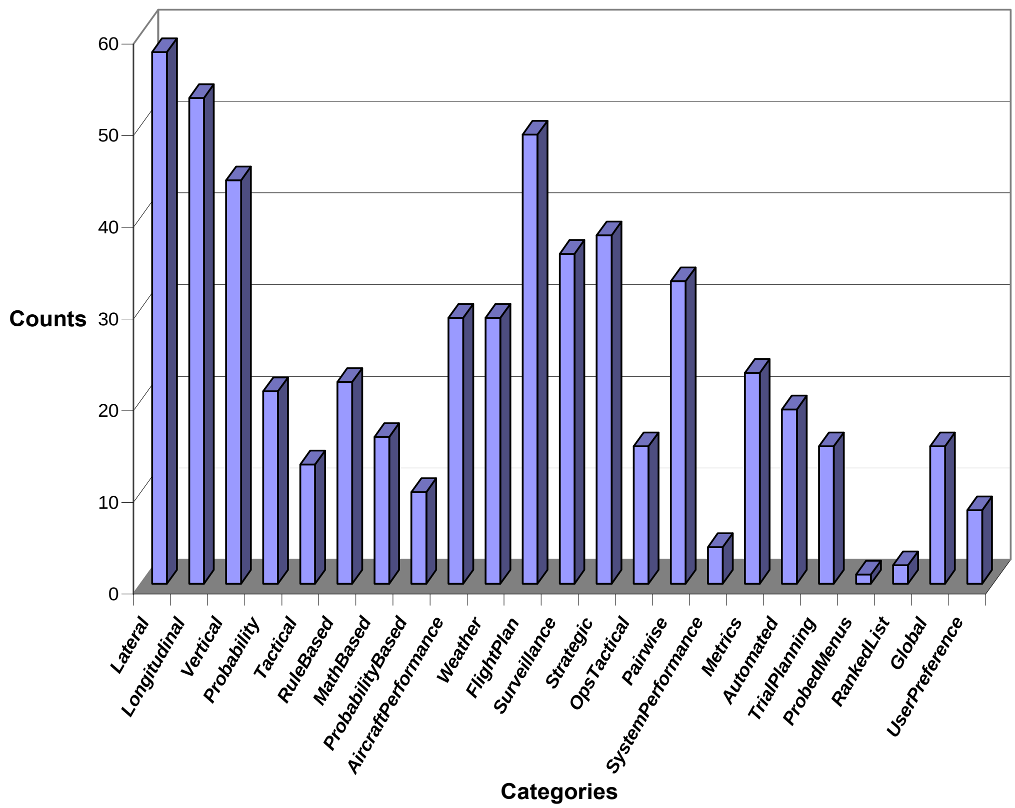

Figure 4**:** Trajectory Predictor Categories

Overview: It should be noted that rarely did the papers in this set directly reference the trajectory prediction abstraction described in Section 1. In fact only two explicitly did so. Indeed, the main theme of some of the papers analyzed may not emphasize trajectory estimation per se. For the most part, the papers described methods for estimating flight state variables. The advent of sophisticated flight systems with powerful computational capability aboard modern transport aircraft offered the opportunity for high fidelity flight path estimation, specifically with respect to kinetic flight dynamics. Additionally the broadcasting of real time meteorological data made possible the integration of atmospheric conditions into the dynamics. The significant influence of winds and their effects on flight velocity can now be included in the mechanizing equations. Additionally, the tendency toward autonomous flight rules, whereby the flight crew assumes increasingly higher responsibility for separation, has greatly influenced the inclination toward state-of-the-art flight monitoring systems.

Preliminaries: Within the set of documents chosen for discussion related to trajectory prediction, a subset use the kinetic flight equations for implementation. The aerospace community has developed a standard for the notation and that convention will be followed in this document. For an understanding of this notation, the reader should refer to Appendix C.

Table 1: - Documents Chosen for Detailed Review

	Title	**Affiliation** Research & Technology	**Org**	**Date**
1	Trajectory Computation Infrastructure Based On BADA Aircraft Performance Model	Boeing Europe, EUROCONTROL Experimental Centre	IEEE	Oct-2007
2	Preliminary Results For A Robust Trajectory Prediction Method Using Advanced Flight Data	Imperial College London	IEEE	Oct-2007
3	Objective Function For 4D Trajectory Optimization In Trajectory Based Operations	University Politechnica of Bucharest	AIAA	Aug-2009
4	A Model To 4D Descent Trajectory Guidance	Universidad de Las Palmas de Gran Canaria, Las Palmas de Gran Canaria, Spain	IEEE	Oct-2007
5	Performances And Sensitivities Of Optimal Trajectory Generation For Air Traffic Control Automation	University of Minnesota	AIAA	Aug-2009
6	3D Conflict Resolution of Multiple Aircraft via Dynamic Optimization	Carnegie Mellon University, Honeywell International	AIAA	May-2003
7	A Quaternion-based Inverse Dynamics Model For Real-time UAV Trajectory Generation	Cranfield University,	AIAA	Aug-2009
8	Improved Ground Trajectory Prediction By Multi-Aircraft Track Fusion For Air Traffic Control	Swiss Federal Institute of Technology	AIAA	Aug-2009
9	Kinematics-Based Model For Stochastic Simulation Of Aircraft Operating In The National Airspace System	U.S. DOT National Transportation Systems Center	IEEE	Oct-2007
10	An Intent Based Trajectory Prediction Algorithm for Air Traffic Control	Purdue University	AIAA	Aug-2005
11	Path Stretching and Tracking for Time-Based Aircraft Spacing at Meter Fix	Direction des Services de la Navigation Aérienne, Ecole Nationale de l'Aviation Civile and LAAS du CNRS	AIAA	Aug-2006
12	An Algorithm For Conformance Monitoring In Air Traffic Control	Purdue University	AIAA	Aug-2009
13	Target Tracking and Estimated Time of Arrival (ETA)	Stanford University, NASA	AIAA	Aug-2006
14	Flight-Mode-Based Aircraft Conflict Detection using a Residual-Mean Interacting Multiple Model Algorithm	Stanford University	AIAA	Aug-2003
15	Robust Nonlinear LASSO Control - A New Approach for Autonomous Trajectory Tracking	Ball Aerospace Australia	AIAA	Aug-2003
16	A Holding Function for Conflict Probe Applications	NASA Ames	AIAA	Aug-2004
17	Intent Inference and Strategic Path Prediction	Metron Aviation, Inc., Purdue University	AIAA	Aug-2005
18	4D Trajectories A Functional Data Perspective	Ecole Nationale de l'Aviation Civile/DTI, France	IEEE	Oct-2007
19	On-Line Trajectory Optimization for Autonomous Air Vehicles	Georgia Institute of Technology	AIAA	Aug-2003
20	Utilizing RNAV Avionics: Testing Lateral Offset Procedures	MITRE Corp., FAA, Continental Airlines	IEEE	2003

The Trajectory Prediction Subfunctions: As discussed in Section 2 above, the abstraction identifies four components for the trajectory prediction process. Of the four, this section will focus on the computation subfunction. The remaining subfunctions will be briefly discussed. In the uncommon case where some specifics are related to these remaining subfunctions, the contributions will be discussed. The brevity is necessitated by the fact that the papers reviewed do not for the most part adhere to, nor reference the abstraction.

The preparation subfunction brings together all the data necessary for the execution of the trajectory prediction. Further, it is this module that is responsible for the translation of the intent script into the mathematical code used to perform the computations.

The update module ensures compliance with the aircraft intent or flight plan and flags potential loss of separation with other trajectories. It is within the scope of this module to alter the intent script and behavior in an attempt to regain separation compliance.

The export process returns the resulting trajectory to the ground-based computer hosting the flight object. Because of the diversity of the modeling equations, different state variables will be exported to update the flight object. It should be noted that the abstraction dictates that, at a minimum, the trajectory should be comprised of four dimensions (4-D), and the geodetic coordinates of the aircraft for the duration of the prediction time frame. It will be seen that only one of the twenty papers discussed complies with this requirement. Furthermore, some of the papers do not operate in full three dimensional space.

The mathematical models under study fall into one of the following classifications:

i.) **Point-Mass models**: A large number of the set of twenty papers used point mass flight estimation models. This feature manifests the tendency toward more realistic modeling of flight, but lacks the complexity of the kinetic model in that rotational moments are ignored. The range of complexity varied greatly within this subset of papers. Point-mass models signify that aerodynamic equations are in play with the above notable exception.

ii.) **Kinematic Models:** In these models, only position and time rate of changes are modeled. The model is integrated forward with respect to time, acceleration to velocity, etc.

iii.) **Kinetic Models:** One paper in the set included moments and, therefore is classified as full, kinetic models. Although this model represents the ultimate complexity of this subset of documents, it is listed second to point-mass models due to the overwhelming number of papers that used point-mass models.

iv.) **Other Models:** Papers that do not fit into the above three categories, but are in a variety of different categories, are lumped into a separate non-specific category.

4.2 Detail Document Analysis of Selected Papers

Sequenced by decreasing orders of complexity, the trajectory estimation equations for the papers utilizing kinetic models are as follows:

4.2.1 Point-Mass Models

1. ***Trajectory Computation Infrastructure based on BADA Aircraft Performance Model*** **Eduardo Gallo, Javier Lopez-Leones, Miguel A. Vilaplana, Francisco A. Navarro of Boeing Research and Technology Europe and Angela Nuic, EuroControl Experimental Center**

Theme: The paper focuses on what it terms the Trajectory Computation Interface (TCI), which brings together aircraft performance data, weather information and flight intent information. These intent data are synthesized via an Aircraft Intent Description Language (AIDL) into instructions for propagating aircraft tracks into the future as required in trajectory prediction.

This paper was chosen for discussion first because it symbolizes the apparent direction ATM is heading. That direction is to design to software implementations to specifications. This paper is explicitly designed to the abstraction of the trajectory prediction process. Such a design philosophy facilitates updating the modules without the need to revamp the entire system. The trajectory prediction abstraction is one of those specifications.

Preparation: Introduced in this paper is the specification for the intent language, which is the intellectual product of the authors. The aircraft intent description language (AIDL) and the attendant behavior language expresses flight intent as mathematical models, an explicit subfunction of the trajectory prediction process. Aircraft intent instructions are of two types, those controlling longitudinal motion and those controlling the aircraft via modifying the aerodynamic configuration. The mechanizing math relationships are termed *laws*.

The set of laws expressing longitudinal control are the speed law (SL), optimal speed law, vertical speed law (VSL), altitude law (AL), energy law (EL) and throttle input law (TIL). The law lexicon is augmented by instructions for aerodynamic reconfiguration. This set of instructions include landing gear value (LGV), high lift value (HLV) and speed brake law (SBL). A key finding from this paper is that all flight commands can be constructed in terms of this concise aircraft data intent language. Although this finding is scientifically sound, more validation may be needed to confirm this conclusion. Together the abstraction and the AIDL could serve as a guide to modular design of the trajectory prediction process.

Computation: The trajectory equations in this mathematical flight model are the point-mass equations, which include wind effects and fuel burn (time rate of change of weight). The focus is on flight in a vertical plane using the subset of the AIDL which synthesizes this restricted motion. Therefore the two velocity components are longitudinal and vertical. The inclusion of wind acceleration in the model is unexplained as to the source of that information. Presumably, it comes from the "earth model" input source, which appears to signify meteorological and atmospheric data.

Contribution: The use of realistic flight equations provides a major innovation for this generation of ATM processing. The adherence to the abstraction for the trajectory prediction process is another positive aspect manifested in this document. Finally, the effort to standardize the aircraft intent language must be recognized as a major advancement to the technology. Together when treated as a specification, the AIDL and the trajectory prediction abstraction makes possible modular design and modification of any contributing component residing within the ATM system.

Level of Maturity: The experimentation testing the efficacy of this proposal is classified as LOM 4 (Ref: Appendix A). As a work in progress, it is expected that additional details will be added and tested in the future.

2. *Preliminary Results for a Robust Trajectory Prediction Method using Advanced Flight Data*
Marie-Dominique Dupuy, Marco Porretta of the Centre for Transport Studies, Imperial College London, London, UK

Theme: This paper models flight using a sophisticated point-mass system of equations. Likewise, there is a reference to an aircraft intent language developed by Boeing Research and Transport Europe in its COURAGE program[5]. The objective of the proposal is to obtain higher precision through the use of the aerodynamics and to standardize the intent language. Flight tests were conducted and described whose objective was to obtain a flight profile for the aircraft intent instruction set.

Preparation: Aircraft intent is implemented from the following component structures

- Hardware configuration – e.g. control surface settings
- Horizontal profile instructions – e.g. constant heading linear segment, turn type and related parameters.
- Vertical profile instructions – e.g. hold and sink and climb rates
- Speed profile – e.g. set speed, ramp speed
- Thrust profile – e.g. idle thrust

The instruction profiles were derived from analysis of recorded flight data. The BADA database provided aircraft performance restrictions.

Computation: Although there are no details forthcoming from this paper other than the inclusion of the expressions for the point-mass flight model, it is assumed that the data input from the BADA database would provide the necessary data for aircraft performance restrictions.

Contribution: Due to the similarity of the theme and content of this document with the "*Trajectory Computation Infrastructure based on BADA Aircraft Performance Model*" paper previously reviewed, the contributions attributed to that document apply to this one as well.

Level of Maturity: This effort is classified as LOM 3 (Ref: Appendix A). Proof of concept as of the publication date was through numerical validation.

3. Objective Function for 4-D Trajectory Optimization in Trajectory-Based Operations
Octavian Thor Pleter and Cristian Emil Constaninescu, University Politecnica of Bucharest and Irina Beatrice Stefanescu of the Romanian Space Agency

[5] Link to aircraft intent language developed in the COURAGE program http://www.eurocontrol.int/care-tp/gallery/content/public/docs/CARE-TP%20spec%20UPT.pdf

Theme: In concert with the direction toward the use of point-mass equations for trajectory modeling, the authors enhance the model with constraints due to aircraft performance. The integration with onboard flight monitoring systems makes this feature an integral part. The trajectory equations in this mathematical flight model assume:

- Axial rotations are zero
- Engines are parallel to fuselage
- Climb angle constant

In addition to the point-mass model described below, the theme of the paper addresses optimizing the desired trajectory under weather conditions and economic and safety constraints.

Computation: This paper derives some of the parameter values from the flight management system. Although specific implementation may differ depending on the aircraft manufacturer and model, these parameters are given by mathematical relationships emanating from constants. These relationships would be implemented in the update subfunction of the trajectory prediction abstraction thereby ensuring that the trajectory stays within constraints (Ref: 7.1 Math Model 1).

Update: The application of the above described constraints would be implemented in the trajectory update process.

Contribution: It should be noted that this paper is the only one that outputs the position in geodetic coordinates. It is probably a reasonably simple matter, however to convert the Cartesian coordinates output by other algorithms to geodetic coordinates. Using a spherical earth model, the differential equations used to generate the trajectory in geodetic coordinates are shown in Section 7.2 Math Model 2.

Level of Maturity: This paper is classified as LOM 2 (Ref: Appendix A). The paper does not discuss any effort of verification beyond the mathematical development.

4. A Model to 4-D Descent Trajectory Guidance

Jose Miguel Canino Rodriguez, Luis Gomez Deniz, Signal and Communications Dept. and Electronic Engineering Dept., Universidad de las Palmas de Gran Canaria; Jesus Garcia Herrero, Computer Science Dept., Universidad Carlos III; Juan Besada Portas, Jose Ramon Casar Cooredera, Signal, System and Radio Communication Dept., Universidad Politecnica de Madrid

The trajectory equations in this mathematical flight model make the following simplifying assumptions:

- Axial rotations are zero
- Engines are parallel to fuselage
- Climb angle is zero
- Climb angle rate is zero
- Roll rate is zero
- Pitch rate is zero

Computation: The energy share factor $\left(E_f\right)$ (Ref: Section 7.3 Math Model 3) is introduced in this paper as a multiplicative efficiency factor influencing the thrust and drag. Furthermore, the vertical Cartesian coordinate estimates the desired altitude MSL, assuming a flat earth model. Since the paper targets navigation in the terminal area, this is a reasonable simplification.

Although not specifically addressing the update subfunction of the trajectory prediction abstraction, this paper has application to the update process. After the completion of the trajectory computation, along path, cross path and vertical deviations from flight intent are analyzed to ensure operation within constraints. Accordingly, flight intent is altered as indicated in rules identified in Section 7.4, Math Model 4.

Level of Maturity: Since this proposal is being validated in the laboratory, it is classified as LOM 3 (Ref: Appendix A).

5. ***Performances and Sensitivities of Optimal Trajectory Generation for Air Traffic Control Automation***
   Di Wu and Yiyuan Zhao, University of Minnesota.

Theme: This paper addresses the sensitivity of flight segment models with respect to errors or variation in the independent variables. The flight models are point-mass defined and limited to vertical plane flight. Both open-loop and closed-loop sensitivities are discussed.

In addition to contributing a set of flight synthesis equations for trajectory estimation, this paper describes a set of constraints that may be applied by the update subfunction to detect state variables that may be in non-compliance with aircraft performance.

Computation: The flight equations used in this paper restrict flight to the vertical plane. Horizontal displacement and velocity are manifested in a single component. The only time-varying angle in the model is the angle of climb. The roll or bank angle is assumed equal to zero.

In contrast to other papers employing the point-mass equations, this set involves wind acceleration. There is, however no indication for the source of these data. Another difference from the other point-mass model discussions is that the fuel burn rate is proportional to the thrust. The operative constraints are described in Section 7.5, Math Model 5.

Contributions: The main perceived value of this effort is the role it potentially plays in determining the accuracy of flight segment models in two situations

- open-loop - reliability of the trajectory solution process

  a.) the model is inaccurate for trajectory generation
  b.) independent parameters vary

- closed-loop – assessing trajectory predictability

  a.) the actual trajectory deviates from the modeled trajectory due to flight conditions b.) actual flight conditions not in concert with assumed flight conditions in the model

For these reasons, there is a role for these methods for application in flight intent models.

Level of Maturity: This proposal is given a LOM 2 (Ref: Appendix A). No support or test results were given.

6. ***3-D Conflict Resolution of Multiple Aircraft via Dynamic Optimization***
Arvind U. Raghunathan, Vipin Gopal, Dharmashanker Subramanian, Lorenz T. Biegler and Tariq Samad, Dept. of Chemical Engineering, Carnegie Mellon University and Honeywell Laboratories.

Theme: This paper focuses on optimizing the trajectories of an entire scenario of air traffic, constraining the individual trajectories such that separation is maintained between any pair of aircraft and impingement of restricted airspace and severe weather fronts is avoided. The target for this process is during flight plan generation. The modeling equations ignore wind effects and fuel burn, but otherwise closely follow the kinetic equation set previously discussed. The trajectory models are typical of kinetic equations, but uses an unconventional expression for the drag force.

The innovation offered through this paper is the concept of disjunctive constraints (Ref: Section 7.6, Math Model 6).

Contribution: This process could possibly be utilized in the trajectory prediction update process to ensure compliance in predicted aircraft tracking, in particular if a single parameter is restricted to a given range.

Level of Maturity: This paper is classified LOM 3 (Ref: Appendix A). A proof of concept was developed using a four aircraft scenario and applying the algorithm as it was intended, namely ensuring separation from other flights and weather fronts.

7. ***A Quaternion-based Inverse Dynamics Model for Real Time UAV Trajectory Generation***
Rick G. Drury and James F. Whidborne, Cranfield University, Bedfordshire, IK

Theme: An alternative formulation for point-mass equations is the quaternion. The quaternion is an algebra complete with mathematical operations. Since the point-mass equations deal significantly with geometric rotations, the quaternion triple product offers an expedient method for the three common cascaded rotations. The quaternion triple product replaces the matrix triple product, which saves mathematical operations.

One component of a quaternion is a three dimensional vector and the other component is a scalar. A quaternion with a zero scalar component maps directly to a three dimensional vector. A quaternion multiply operation is comprised a two vector-scalar multiplications, one vector (cross) product, one scalar product and one scalar multiplication. For more details, refer to Section 7.7, Math Model 7.

Contribution: Although this is not the first application of quaternions to flight modeling, the suggestion to use this algebra for that purpose is well founded. In addition to simplifying the mathematical operations, quaternion algebra eliminates vulnerabilities of classical formulations, such as gimbal-lock singularity

Level of Maturity: The efficacy of this concept was demonstrated through simulation and is classified as LOM 3 (Ref: Appendix A).

8. ***Improved Ground Trajectory Prediction by Multi-Aircraft Track Fusion for Air Traffic Control***
Ioannis Lymperopoulos and John Lygeros, Swiss Federal Institute of Technology, Zurich, Switzerland

Theme: The paper presents a method of improving the accuracy of trajectory prediction by improving the accuracy of predicting the winds aloft. The track history of an aircraft indirectly gives an estimate of the winds aloft in the airspace in which it has just flown. Many aircraft flying through the airspace give an overall measurement of the winds in the airspace which are used to build a probabilistic horizontal wind field which in turn improves the accuracy of the trajectory predictions. The true airspeed of the aircraft is estimated using a hybrid tracking algorithm to process the radar data, an FMS model, and data from BADA for the aircraft type. The algorithms are tested through simulation. The along track errors in the trajectory predictions measure the performance of the estimates.

Preparation: The simulation requires the Rapid Update Cycle (RUC) wind data to use as the nominal wind field.

Computation: The simulation requires a zero mean, Gaussian radar measurement model sampled in time. A hybrid tracking algorithm is used to process the simulated radar data. The aircraft are flown by a simple FMS model following synthetic flight plans. The stochastic component of the wind field is calculated using an atmospheric wind model. It is assumed that the wind is invariant under rotations and that the correlation decays exponentially as horizontal distance, altitude and time difference increase. The wind vectors are estimated from the radar track data and the true airspeeds are assumed to be known (all 215.6 m/s in the simulation). The wind data is used to construct a wind field for the airspace. The wind field is modeled in the calculation of the trajectories. The trajectories are compared to the actual simulated flight paths and the along track errors (predicted versus actual) calculated.

Contributions: A new, improved method of incorporating aircraft tracking data into RUC wind forecasts is presented.

Level of Maturity: This paper is classified as LOM 3 (Ref: Appendix A).

4.2.2 Kinematics Models

Kinematics models deal only with position, heading, and speed data. The aircraft performance parameters are not considered in a kinematic model.

9. ***Kinematics Based Model for Stochastic Simulation of Aircraft Operating in the National Airspace System***
Seamus M. McGovern, Seth B. Cohen, Minh Truong; USDOT National Transportation Systems Center; Gerard Fairley, EG&G Technical Services

Theme: This paper addresses flight modeling for the purpose of simulating flight. The reason for choosing this paper for review in application to trajectory prediction is that it offers simple models for straight linear flight and turning flight segments.

Since simulation is an objective, there is a need to add perturbations to the data. To that end, the paper introduces some probability distributions previously not used, to this author's knowledge, in air traffic management. As a consequence, if these stochastic models are indeed representative of measurements or computation errors, position uncertainty can be lessened by using the parameters of these distributions.

Computation: The flight characterization is accomplished through tracking of the tangential velocity (with respect to the surface of a spherical earth model) resolved into north and east components. Independently, a vertical one-dimensional transition is modeled via a decoupled equation. The linear flight path model along the surface of the spherical earth is described in Section 7.8, Math Model 8.

Contributions: Any effort to model perturbations in trajectory estimation inherently contributes to the trajectory prediction process if the probabilistic model exhibits a significant goodness of fit. The probability distributions described in this paper are offshoots from the normal distribution and appropriate where perturbations are limited in range or skewed. Once stochastic models are shown to demonstrate high fidelity to the physical process, separation requirements could possibly be modified, hopefully resulting in reduced separation.

Level of Maturity: Since this paper has just begun to investigate these concepts, it was given LOM 1 (Ref: Appendix A).

10. An Intent Based Trajectory Prediction Algorithm for Air Traffic Control

Javier Lovera Yepes, Inseok Hwang and Mario Rotea, Purdue University

Theme:

The paper describes an Intent-Based Trajectory Prediction algorithm (IBTP) which is an extension of the IMM (Interacting Multiple Model) and the RMIMM (Residual-Mean Interacting Multiple Model) developed previously by the authors' R & D group. The algorithm combines state (position, velocity, acceleration, flight mode) estimates and intent. It selects at any given time the most likely of 13 distinct primitive intent (immediate goal) models. It is limited to the horizontal only (no vertical intent). The trajectory flight mode time sequence is generated by a Markov chain. Two Kalman filters determine whether the aircraft is flying straight or is turning and give the current position and heading of the aircraft. It compares the current aircraft heading with the headings to different future way points and calculates intent likelihoods. The flight plan, ATC regulations, weather data, time to go, and the rate of change of the intent likelihood are combined to select the intent. Simulation of routing around a weather quadrilateral shows that the IBTP is effective and better than the RMIMM and the IMM.

Preparation:

The airspace adaptation, the weather (from FIS-B), and the aircraft positions and velocities (from ADS-B) are needed as input data to the algorithm. The simulation requires the use of a six degree of freedom Boeing 737-200 flight simulator to provide flight track data, and ADS-B and FIS-B messages.

Computation:

The aircraft current state is determined by the Residual-Mean Interacting Multiple Model (RMIMM) which also detects turns which are a key factor in determining intent. The state is combined with the other input data using the path history with a fading memory, the rate of change of the intent likelihood, and the time to go to select an intent which then becomes the trajectory prediction. Monte Carlo simulation of flying around a moving convective weather cell demonstrates that the new algorithm (IBTP) out performs previous similar algorithms.

Contributions:

A new algorithm for intent inference and trajectory prediction has been presented which improves on similar previous algorithms.

Level of Maturity:

The Level of Maturity is 3 (Ref: Appendix A). The algorithm has been demonstrated in a very limited simulation with no absolute performance measurements.

11. *Path Stretching and Tracking for Time-Based Aircraft Spacing at Meter Fix*

Thierry Miquel, Direction des Services de la Navigation Aerienne, Toulouse, France

Theme:

Similar to the paper ***A Model to 4-D Descent Trajectory Guidance*** described above, this paper suggests a geometry-based path diversion for a trailing aircraft closing in on a lead aircraft following the same air route.

Preparation: The preparation module compiles the required input

- the parameters of the delay maneuver, a, T, δ
- the initial (and final) heading $\psi(0) = \psi(T)$
- horizontal position at the time of the start of the maneuver $x(0), y(0)$
- horizontal position at the time of the end of the maneuver $x(T), y(T)$
- true airspeed V
- ground track angle χ
- Meteorological data
- Horizontal wind speed W and direction ψ_w at the requisite flight level

Any behavior model would have to include this maneuver in its repertoire. The preparation would have to include synthesizing this command into the mathematical model as part of the formulation, since compensation for the wind is vital to the model. In particular, this is required so that the resultant velocity vector, as perceived on the ground can be computed.

Computation:
The true airspeed model used in this paper is described in Section 7.9, Math Model 9.

Contributions: The extended path is generated by a "fishtailing" maneuver on the part of the trailing aircraft. Given a required delay T to avoid overtaking the lead aircraft, the algorithm proceeds to perturb the trailing aircraft heading in a sinusoidal fashion (Ref: Section 7.9, Math Model 9.).

This procedure is executed under autonomous flight rules (AFR). To a ground track sensor expecting a linear constant velocity transition from waypoint to waypoint, the diversion maneuver will appear as longitudinal errors unless the intent is communicated to the ground tracking software. Therefore, any trajectory prediction computation would have to duplicate this trajectory. Failure to do so would be sensed as position error in the ground track, necessitating expanded separation requirements.

Level of Maturity: The research conducted in this paper does not extend beyond LOM 2 (Ref: Appendix A).

12. An Algorithm for Conformance Monitoring in Air Traffic Control
Chze Eng Seah, Alinda Aligawesa and Inseok Hwang, Purdue University, West Lafayette, IN.

Theme: The paper extends the work of the Purdue group on their Interacting Multiple Model (IMM) and applies it to monitoring an aircraft's conformance to its flight plan in level turns and in descents. The algorithm is tested by simulation using synthesized random trajectories, and noise models for the surveillance radar and for ADS-B tracking. The performance of the conformance monitoring algorithm is measured by the false alarm rate and by the detection time.

Computation: Computation is required for the simulation input data, the algorithms, and for the performance measures. The aircraft's state is defined by its position and velocity and by its flight mode, which is either constant velocity, level or descending, or constant level coordinated turn. Kalman filters update the aircraft states and Markov chain models update the flight modes. The differences between the measurements and their expected values, called the residuals, are thresholded to detect non-conformance. Descent conformance is checked for three different descent modes.

Contribution: An existing algorithm has been improved for monitoring aircraft conformance to a flight plan and has been tested through simulation against two standard aircraft maneuvers.

Level of Maturity: This paper is classified as LOM 3 (Ref: Appendix A).

13. Target Tracking and Estimated Time of Arrival (ETA) Prediction for Arrival Aircraft
Kaushik Roy, Benjamin Levy and Claire Tomlin, Stanford University, Palo Alto, CA

Theme: The paper gives the trajectory prediction accuracy results for algorithms applied to an arrival route flown to the runway threshold. The predictions are used to estimate the time of arrival at the runway threshold. The two principal algorithms, the Interacting

Multiple Model (IMM) and the particle filter are enhanced by using a new flight mode (straight or turning) determination algorithm. Their tracking abilities are compared and the ability of the IMM algorithm using either the existing Markov mode algorithm or the new autonomous mode algorithm to predict runway ETAs is measured. The algorithms are tested against the arrivals for Runway 12L from the PETTIT corner post at the Lambert International Airport (Saint Louis, STL). Both recorded flight tracks and simulated flight tracks are tested. The main novelty is a new way of predicting when the aircraft is going to switch from flying straight to turning and vice versa.

Preparation: Aircraft tracks are recorded for flights landing on 12L at STL. The flights are compared to the trajectory predictions for the determinations of the ETA errors. The tracks are also used to determine the regions of the turns and the headings of the straight flight path segments. The regions and the headings are input to the new flight mode determination algorithm. From the recorded tracks a nominal track for arrivals is extracted and is used, with tracking noise added to the simulation input.

Computation: The two hybrid algorithms were applied to the STL arrival data using both the observed and simulated track data, and with and without the new flight mode prediction algorithm. The new algorithm replaces the random Markov model for flight mode changes. The term hybrid is used because Kalman trackers are used to track the continuous aircraft state variables and separate methods are used to determine the discrete flight modes – straight or turning. The Kalman filter parameters change when the flight mode changes. A particle is a trajectory prediction. The particle tracking filter maintains a set of up to 100 probable trajectories which are updated every computation step, retaining the most probable. The particle algorithm is computationally intensive. The trajectory position and ETA errors were measured. The errors are highly sensitive to the nominal arrival trajectory extracted from the observed tracks.

Contribution: An improvement to the IMM algorithm has been found which shows promise of improving the trajectory accuracy. However, the algorithm has only been tested on one data set from one runway at one airport.

Level of Maturity: This paper is classified as LOM 3 (Ref: Appendix A).

14. *Flight-Mode-Based Aircraft Conflict Detection Using a Residual-Mean Interacting Multiple Model Algorithm*

Inseok Hwang, Jesse Hwang and Claire Tomlin, Dept. of Aeronautics and Astronautics, Stanford University, Palo Alto, CA

Theme: Paper presents a better way of determining whether an aircraft is flying straight at a constant velocity or is in a constant rate turn using the output of a bank of Kalman radar tracking filters. The results adjusts the Kalman filter weights for better tracking. Results demonstrated by Monte Carlo simulation. The improved aircraft state estimation is applied to the Paielli-Erzberger probability of conflict method. Extensions using the flight mode data to predict trajectories are added to the Paielli-Erzberger algorithm for turning aircraft.

Computation: The Interacting Multiple Model (IMM) has been described in previous papers. It estimates the aircraft state using a weighted use of the estimates from a bank of Kalman filters that are matched to the aircraft's flight mode. The residual means of the

Kalman filter calculations are used to select the most likely flight mode. A random distribution is added to the current state of the aircraft before applying the Paielli-Erzberger conflict probability algorithm. The algorithms are tested in a Monte Carlo simulation using synthetic aircraft tracks. Real ETMS air traffic data from the Oakland Center was also used. A protocol–based conflict resolution algorithm was applied assuming that the positions and velocities of the aircraft were known.

Contributions: A new method of determining whether an aircraft is flying straight or is turning from a bank of Kalman tracking filters is presented and the Paielli-Erzberger conflict probability 2D algorithm is extended to turns.

Level of Maturity: This paper is classified as LOM 3 (Ref: Appendix A).

4.2.3 Kinetic Model

The equations for this model include the use of aircraft performance parameters.

15. ***Robust Non-linear LASSO Control: A New Approach for Autonomous Trajectory Tracking***
David P. Boyle, Ball Aerospace Australia, Sydney, Australia and Gregory E. Chamitoff, NASA Johnson Space Center, Houston, Texas

Theme: The paper presents a new design of a flight controller. Its application is to fly an autonomous UAV following a predefined flight trajectory. It is designed to use maximum vehicle performance and to be insensitive to wind gusts and variations in the aircraft's flight parameters. The controller uses time stepping, constrained nonlinear optimization to minimize the error between the commanded acceleration and the current acceleration. The algorithm was tested in a simulation using MATLAB on a single, challenging, trajectory using a model of an existing UAV. The flight successfully followed the specified trajectory.

Preparation: To test the control algorithm in the simulation, in addition to the aircraft model, the controller needs the mass and the rotational moments of inertia of the aircraft, the constraints on the aircraft performance, the constraints required for stability and controllability, and the probability distributions of the parameters. The wind gusts were modeled by the Von-Karman gust model as specified in MIL-SPEC-F-8785C. A scalar cost function was specified for the optimization.

Computation: The computation is done in an aircraft centered XYZ coordinate system contained in a uniform gravity field. The aircraft state variables are the three velocity components, roll, pitch, and yaw angles; the roll, pitch and yaw angular rates; and the altitude. The four control variables are the ailerons, elevator, rudder, and the throttle. Because of the necessary search for the optimal solution, the controller is computationally intensive. Depending on the flight condition, the time required to process one step ranges from 10 seconds to 150 seconds. Since the step interval is 0.1 seconds more work needs to be done. The authors of the paper are working on speeding up their algorithm.

Contributions: A new robust aircraft controller suitable for UAVs that can achieve high accuracy while tracking aggressive trajectories is presented. The intensive computation required remains a problem.

Level of Maturity: This paper is classified as LOM 3 (Ref: Appendix A).

4.2.4 Other Models

This category includes all algorithms related to trajectory prediction that do not fit into the categories discussed above.

16. A Holding Function for Conflict Probe Applications

Dave McNally, NASA Ames Research Center and Joe Walton, University of California, Santa Cruz.

Theme: The author of this paper observed that there was no realistic model for aircraft maintaining a holding pattern. Consequently, the conflict probe's ability to detect potential conflicts with holding aircraft is severely compromised. That limitation was the driving force for the development of the paper.

In the interest of surveying literature to determine if there were new methods that could be and should be integrated into the trajectory prediction software, the McNally and Walton paper offers the enhancement of adding a holding status to the trajectory generator. Trajectory prediction is executed for use in the conflict probe. The lack of a reasonable model for holding aircraft has precluded prediction of aircraft position while in that posture. The geometry developed for the holding pattern allows this prediction to take place. Therefore, the geometry of the holding pattern is a candidate for improving the trajectory prediction process.

Computation: The paper describes the process whereby the detection of the parameters of the holding pattern are estimated from position estimates.

Referring to Figure 5 the parameters of the holding pattern, as defined in this paper are

- Bearing of the outbound segment ψ
- Turn radius R
- Coordinates of the holding fix ◎
- Turn direction (clockwise, right turns or counter clockwise, left turns)
- Leg length D

Once these parameters are determined, the four dimensional position of the aircraft can be predicted for the duration of the holding pattern under the assumption of constant speed and altitude.

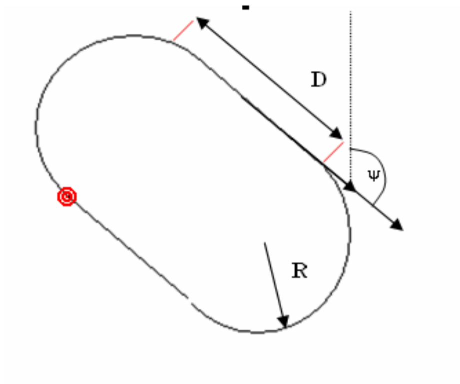

Figure 5: Geometry of a Holding Pattern

Contribution: In the current NAS System, aircraft in a holding pattern have trajectories modeled by a constant (unchanging) position for the duration of the hold instruction. For purposes of conflict detection, potentially intrusive aircraft are maintained at a required distance from this singular point. The mathematical model of a hold pattern with a truly time varying position transition is not only more realistic, but unquestionably improves the ability to prevent loss of separation.

In addition to contributing a geometric model of a holding pattern, this paper describes a method for detecting the entering into a holding pattern by an aircraft by inspection of past track reports.

Level of Maturity: The maturity classification given to this effort LOM 4 (Ref: Appendix A). The algorithm was tried out on DFW data during a rainstorm requiring the formation of a holding pattern scenario. The track data from this operation was input into software written to detect and parameterize the actual patterns.

17. Intent Inference and Strategic Path Prediction

Jimmy Krozel, Metron Aviation, Inc, Herndon, VA and Dominick Andrisani, II, Purdue University, West Lafayette, IN

Theme: The paper presents a method of inferring the intent of an aircraft by fitting an intent model to observed aircraft motion, weather, flight plan, and adaptation data. The method uses flight plans, aircraft tracking data, hazardous weather, Special Use Airspace definitions, and airspace structure (adaptation) to predict the trajectories. A large set of primitive intent models are defined – for horizontal maneuvers (16), vertical maneuvers (14), and speed maneuvers (11). The intent models are ranked according to their fit (correlation) to the current aircraft state and the airspace information. A trajectory is constructed by generating a sequence of most likely intents. The method was tested with field data from ZAU (Chicago) using pilot / controller voice recordings, ETMS track (1 minute samples) data, and NWS / NCWD weather (5 minute samples) data. The method was demonstrated to two airline pilots who gave positive critiques.

Preparation: Flight plans, airspace adaptation, convective weather, and radar track data are necessary to apply the method of building flight trajectories.

Computation: Intent inference and path prediction are solved simultaneously. First, aircraft, weather, and other state data are processed as input. A Horizontal (H), Vertical (V), and Speed (S) analysis are performed in parallel. In each of the [H,V,S] dimensions, a local correlation is computed. The local correlation correlates the state data with an intent model (in the H, V, or S dimension). Local path correlations are buffered to create a history of correlation data, called the global correlation data. Finally, all the H dimension global correlations are compared, all the V dimension global correlations are compared, and all the S dimension global correlations are compared. The best global correlation for the [H,V,S] dimensions is returned as the inferred intent. Given this inferred intent, a prediction for the aircraft is made assuming that the aircraft is flying according to the logic of the inferred intent.

The concept was evaluated at the Chicago Center (ZAU). Recorded Pilot ↔ Controller dialogue was used to validate the choices of aircraft intent.

Update: The correlation values of the alternative intents are updated as new track and weather location data is received and a new trajectory is built if necessary. In particular, a change in aircraft heading from the current intent requires a new trajectory. The calculations are repeated for the new trajectory.

Contribution: A new method of building a trajectory is presented.

Level of maturity: This paper is classified as LOM 4 (Ref: Appendix A).

18. 4-D Trajectories: A Functional Data Perspective

S. Puechmorel, ENAC Dept., Toulouse, France and D. Delahaye, DTI/R&D, Toulouse, France

Theme: This paper proposes the use of space curves described parametrically as splines for use in modeling flight segments. Since most flight legs are comprised of turns and linear segments, this model appears feasible for this application.

A method of representing an aircraft trajectory functionally is delineated. The math for optimally matching the functional version to the XYZT sampled version is derived. The trajectories are parameterized by arc length. Optimal spline fitting is used to smooth and interpolate the trajectory. No experimental data is presented.

Preparation:
A set of 4 D trajectories is necessary to convert to the spline format.

Computation: The nodes, manifest in the waypoints from the flight plan, are input to the trajectory predictor along with the estimated arrival time for the waypoints. From a predetermined degree of smoothness requirement, splines are fit connecting the waypoints, ensuring at least continuity through the nodes (zeroth order smoothing). Higher degrees of smoothing ensure velocity smoothness, etc.

No numeric data is presented. The paper walks through a series of considerations to be made in choosing a specific smoothing spline method to represent trajectories. It concludes by recommending cubic spline representation.

Contribution: Use of splines for this application has the advantage of replacing flight trajectory position samples, possibly augmented by velocity coordinates by a paucity of coefficients to the spline model. Additionally, continuity and smoothness can be controlled by requiring the flight segment nodes to join and for various orders of derivatives to exist at those nodes. The versatility of splines includes the capability of having trajectories that self-intersect, which can be of importance in terminal area maneuvering.

The use of splines is not without penalty in that more intense computation is required. However, recent and enduring technology advances have made this requirement a non-issue and the advent of sophisticated flight monitoring systems are a case in point.

Level of Maturity: The innovative nature of this paper and its contents classifies it as LOM 1-2 (Ref: Appendix A).

19. On-Line Trajectory Optimization for Autonomous Air Vehicles
Shannon Twigg, Anthony Calise and Eric Johnson, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, GA

Theme:
The paper mathematically defines an aircraft terrain following trajectory which has constant energy (kinetic + potential). The trajectory is optimized with respect to minimum time or a combination of minimum time and minimum threats where threats are defined geographically. The algorithm has been developed to be applied to autonomous air vehicles (UAVs). Previous work developed constant velocity trajectories. The constant energy trajectories make fuller use of the aircraft's capabilities. Maintaining constant energy requires the aircraft to fly faster at lower altitudes.

Preparation:
Requires the use of terrain data, threat data, and some aircraft parameters needed by the algorithm.

Computation:
A set of simultaneous differential equations are derived. The equations are solved minimizing a cost function based on flight time and threats. The flight path is the fastest one available which avoid the threats. Future work will include vehicle dynamics and maximum limits on the turn rate, angle of attack, and velocity. The trajectories generated have been tested by using a simulator at the Georgia Tech UAV (50 pounds empty weight) to fly the trajectories.

Contributions:
This work is of interest to the future of UAVs, that will be flying autonomously, with similar trajectories.

20. Utilizing RNAV Avionics: Testing Lateral Offset Procedures
Albert A. Herndon et al., MITRE Corp., Jeffrey T. Williams, FAA, Capt. William Vaughn, Continental Airlines

Theme:

The main topic of this paper is utilizing a lateral offset determined by an onboard flight monitoring system coordinated with ground control to increase airspace capacity. Such a capability, compatible with autonomous flight rules, would require an enhancement in the aircraft intent repertoire, necessitating the requisite addition to the intent lexicon.

Computation:

Any trajectory prediction process would need to add the capability to predict a trajectory in which a given flight segment includes a lateral offset instruction. Since the preparation subfunction of trajectory prediction is tasked with this requirement, any intent language is required to include this maneuver and its attendant parameters. In addition, the translation from a verbal statement to the corresponding mathematical model must be implemented.

Contribution:

The intended contribution is a potential for increased en route capacity, however, if this proposal ever becomes integrated into the air traffic control system, the logic discussed above in the computation section would need to be an integral part of the trajectory prediction process.

Level of Maturity:

The procedures described in this paper were tested in actual air traffic control en route environment with Continental Airlines and FAA air traffic control personnel participating. As such, this LOM is designated a Level 5 (Ref: Appendix A).

4.3 Synopsis of Detail Document Analysis

Clearly, the tendency for future trajectory generation and prediction is toward the more sophisticated technique of applying the physics of flight. The preponderance of flight monitoring systems in cockpits of modern transport aircraft, with its capacity for sensing and recording flight parameters, has bought this capability into the realm of possibility. Coupled with the increase in air traffic and the finite capability to control it from the ground perspective, it was inevitable that this enhancement to air traffic control would be necessary.

Despite the migration of separation responsibility from the ground to the cockpit, the need to track aircraft in all stages of flight on the ground still exists. Indeed, the ultimate decision for avoidance of conflict lies with the air traffic controller. The function of trajectory prediction as a decision support tool plays a major role in this effort.

While legacy versions of trajectory prediction primarily employed position, heading, and speed for future position and velocity of aircraft, the state of the art in trajectory modeling tracks additional state variables beyond position, velocity and acceleration for its implementation. Consequently, the requirement for more sophisticated trajectory prediction is required to keep pace with this progress. This document attempted to present proposals from the aviation community toward this end.

Table 2 presents a summary of the areas of research that was conducted in the 20 documents that were reviewed in detail.

Table 2: – Research Summary of Selected Documents

	Title	Model								
		Point-Mass	Kinetic	Kinematic	Other	Lateral Motion	Longitudinal Motion	Vertical Motion	Weather	LOM
1	Trajectory Computation Infrastructure Based On BADA Aircraft Performance Model	√					√	√	√	4
2	Preliminary Results For A Robust Trajectory Prediction Method Using Advanced Flight Data	√				√	√	√	√	3
3	Objective Function For 4D Trajectory Optimization In Trajectory Based Operations	√				√	√	√	√	2
4	A Model To 4D Descent Trajectory Guidance	√				√	√	√	√	3
5	Performances And Sensitivities Of Optimal Trajectory Generation For Air Traffic Control Automation	√				√	√	√	√	2
6	3D Conflict Resolution of Multiple Aircraft via Dynamic Optimization	√				√	√	√	√	3
7	Robust Nonlinear LASSO Control - A New Approach for Autonomous Trajectory Tracking		√			√	√	√		2
8	A Quaternion-based Inverse Dynamics Model For Real-time UAV Trajectory Generation	√				√	√	√		3
9	Improved Ground Trajectory Prediction By Multi-Aircraft Track Fusion For Air Traffic Control	√				√	√	√	√	3
10	Kinematics-Based Model For Stochastic Simulation Of Aircraft Operating In The National Airspace System			√		√	√		√	1
11	An Intent Based Trajectory Prediction Algorithm for Air Traffic Control			√		√	√		√	3
12	Path Stretching and Tracking for Time-Based Aircraft Spacing at Meter Fix			√		√	√		√	2

		Model								
		Point-Mass	**Kinetic**	**Kinematic**	**Other**	**Lateral Motion**	**Longitudinal Motion**	**Vertical Motion**	**Weather**	**LOM**
13	An Algorithm For Conformance Monitoring In Air Traffic Control			√		√	√	√		3
14	Target Tracking and Estimated Time of Arrival (ETA)			√		√	√			2
15	Flight-Mode-Based Aircraft Conflict Detection using a Residual-Mean Interacting Multiple Model Algorithm			√		√	√			3
16	A Holding Function for Conflict Probe Applications				√	√	√	√		4
17	Intent Inference and Strategic Path Prediction				√	√	√	√	√	2
18	4D Trajectories A Functional Data Perspective				√					1-2
19	On-Line Trajectory Optimization for Autonomous Air Vehicles				√	√	√			2
20	Utilizing RNAV Avionics: Testing Lateral Offset Procedures				√					-

5 Summary

Section 1, Introduction, of this document, discussed the motivation, selection method, and expected results for this report. A large cross section of research relating to trajectory prediction was examined. From this extensive research, a subset of 282 documents were chosen for this report. The documents are evidence that an extensive amount of research, by several aviation communities, has been conducted over the past decade. Also evident was the fact that there is a global resource pool mobilized to modernize the international ATC system.

In Section 2, Trajectory Predictor Technology, an overview of what has come to be the industry standard definition for a generic trajectory predictor, was described as it is presented in the AP16 report.

Section 3, Data Collection and Analysis, presents the data collection criteria for this report, including the rationale for the selection of specific documents. As anticipated, most of the research was conducted at the academic level, which is evidenced in the lower levels of maturity, as shown in Figure 3 of Section 4.1. It takes years of research, prototyping, testing, and validation for concepts to be introduced into the operational system.

In Section 4, Detailed Synthesis of Research Papers, a detailed analysis of a subset of 20 carefully chosen documents was presented. This section provides more specific details about each paper, and describes, in detail, the research that was conducted in the area of trajectory prediction. It's quite obvious that trajectory prediction has progressed well beyond simple dead reckoning. Modern computer software can easily take into consideration the performance differences among the population of aircraft when planning flights and devising conflict resolutions. The increased fidelity between flight tracking and actual flight path, resulting in reduced tracking error, creates an expectation of decreased separation standards with the potential to increase capacity, utilizing technologies like multiple parallel offset en route airways.

Mathematically intensive optimization techniques are also beginning to be suggested to provide support tools for flight planning and separation assurance. Many of the papers focused on increasing capacity and, consequently decreasing delay. This was largely seen as being made possible by using automation for descent profiles.

A major recurring theme, in a majority of the research papers reviewed, was the objective of distributing the workload of flight planning and separation assurance between controllers and flight crew. This has resulted in incentives for the upgrading of the ATC system as envisioned by NextGen. There is an emphasis on more sophisticated mathematics in the modeling equations due to the increased use of the aircraft's FMS and ADS-B capabilities, which results in more realistic calculations of the dynamics of aircraft trajectories, consequently more accuracy.

Future areas of research that would be extremely beneficial as future enhancements to ERAM are in the areas of vertical modeling, hold modeling, and more accurate model of closure rates that can be used for improving trajectory predictions and ultimately optimizing conflict detection and resolution.

6. Appendix A - Technology Readiness Levels (TRLs)

Technology Readiness Levels (TRLs), (ref: Table 3), are a systematic metric/measurement system used by the FAA that supports assessments of the maturity of a particular technology and can be used to determine a consistent comparison of maturity between different types of technology.

Table 3: – Technology Readiness Levels Definitions[6]

LOM Level	Definition	Description
1	Basic Principles Observed/Reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development.
2	Technology Concept Formulated	Once basic principles are observed, practical applications can be invented.
3	Analytical/Experimental Proof of Concept	Active research and development is initiated.
4	Component Validation in Laboratory Environment	Basic technological components are integrated to establish that they will work together.
5	Component Validation in Relevant Environnent	The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment.
6	System/subsystem Model/Prototype in a Relevant Environment	A representative model or prototype system is tested in a relevant environment.
7	System Prototype in an Operational Environment	Prototype near, or at, planned operational system.
8	Actual System Completed/Qualified through Test/Demonstration	Technology has been proven to work in its final form and under expected conditions.
9	System Proven through Successful Mission Operations	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation.

[6] *NAS System Engineering Manual, Version 3.1*

7 Appendix B - Mathematical Models

Note: Any symbol not explicitly defined in this section are defined in Appendix C.

7.1 Math Model 1

Ref: ***Objective Function for 4-D Trajectory Optimization in Trajectory-Based Operations***

In addition to the point-mass modeling equations, the following equation as used to control the roll, pitch rate and longitudinal acceleration

$$\phi = k_\phi \max\{\min[d_{xt}(t), d_{xt,sat}], -d_{xt,sat}\} - k_{TC}\Delta\psi(t)$$
$$\dot{\theta} = k_H \max\{\min[h_{sat}, \Delta h(t)], -h_{sat}\} - k_\theta[\theta(t) - \alpha(t)]$$
$$\dot{V}_c = k_{CAS}\Delta V_c(t)$$

In this context, the previously undefined symbols denote:

a. k_θ Pitch control damping (no units)

b. k_ϕ Roll control damping (meters^{-1})

c. k_H Pitch control sensitivity (meters^{-1})

d. k_{TC} Roll control sensitivity (no units)

e. k_{CAS} Calibrated air speed sensitivity (no units)

f. h_{SAT} Maximum flight level deviation (meters)

g. $d_{xt,sat}$ Maximum allowable cross track deviation (meters)

h. $\Delta V_c(t)$ Deviation from target air speed (velocity units)

i. $\Delta\psi(t)$ Deviation of heading from target heading (no units)

j. $\Delta h(t)$ Deviation from target altitude (meters)

7.2 Math Model 2

Ref: ***Objective Function for 4-D Trajectory Optimization in Trajectory-Based Operations***

In addition to the conventional transition equations, the algorithm tracks the time rate of change of longitude and latitude and integrates to current position using the following

$$\dot{\lambda}(t) = \frac{\dot{x}(t)}{R + h(t)}$$
$$\dot{\varphi}(t) = \frac{\dot{y}(t)}{[R + h(t)]\cos[\lambda(t)]}$$

7.3 Math Model 3

Ref: ***A Model to 4-D Descent Trajectory Guidance***

Total energy equation

$$\frac{T(t)-D(t)}{m(t)}\left[1-\frac{V(t)}{g}\frac{dV}{dz}(t)\right]^{-1}=\frac{T(t)-D(t)}{m(t)}E_f(t)$$

7.4 Math Model 4

Ref: ***A Model to 4-D Descent Trajectory Guidance***

- Correcting longitudinal deviation $\delta\psi$ by adjusting true air speed to compensate for the wind speed is accomplished by maintaining the intended ground speed. From the definition of the sideslip angle and in the plane of the trajectory

  $$\beta(t)=\psi(t)-\arg\left[\vec{W}(t)\right]$$

  where $\arg\left[\vec{W}(t)\right]$ is the wind direction. Then the true airspeed is adjusted to:

  $$V_{adj}(t)=V(t)+\Delta V(t)=\sqrt{V_g^2(t)+W(t)^2-2V_g(t)W(t)\cos\beta(t)}$$

- Correcting longitudinal deviation for an earlier than planned arrival at a waypoint, path extension is implemented by commanding the aircraft laterally through some arbitrary predefined deviation angle $\delta\psi$ to an intermediate waypoint at P. In this maneuver, instead of maintaining the current course, the aircraft deviates right or left through $\delta\psi$ arriving at the next waypoint via an isosceles triangle with the vertex P at the virtual waypoint subtending $\Delta\omega$ radians.

- If the result of the above adjustment (V_{adj}) to the descent rate exceeds aircraft performance or safety standards, a lateral deviation to a virtual waypoint P is attempted similar the adjusting the longitudinal deviation above. In this case, a constant correction coefficient k_R is hypothesized such that $\dot{z}_{adj}(t)=(1-k_R)\dot{z}(t)$. The resulting coordinates of P are

  $$d_1=\frac{\Delta z V_g-\dot{z}(t)\Delta_{turn}}{2V_g\left[1-\cos(\delta\psi)\right]}$$

- In Figure 6, let $d\ell$ denote the distance ahead of schedule, d_1 denote the length of the leg of the isosceles triangle, R denotes the turn radius and d denote the distance along the current course to the intended waypoint. At P, the arc length along the turn radius R is

$$d_{arc} = R\psi$$
$$R = \frac{V^2}{g \tan\phi}$$

Therefore the actual arc length is given by[7]

$$\Delta_{turn} = 2R\tan\left(\frac{\psi}{2}\right) - d_{arc} = 2R\left[\tan\left(\frac{\psi}{2}\right) - \frac{\psi}{2}\right]$$

Assuming constant speed, difference in distance in lieu of time between the intended path and deviation path must be equal, i.e. $d\ell + d = 2\left[d_1 - R\tan\left(\frac{\psi}{2}\right)\right]$. Then the required deviation distance along one leg of the isosceles triangle satisfies

$$d_1 = \frac{d\ell + \Delta_{turn}}{2(1-\cos\psi)}$$

- To correct vertical deviation δh when the actual altitude is higher than planned, an attempt is made to increase drag thereby increasing the rate of descent $\dot{z}(t) \approx \dot{h}(t)$. We seek a factor k_D such that the corrected drag D_f is proportional to the current drag D. That is $D_f = k_D D$. Mathematically, from

$$\begin{aligned}\Delta\dot{z}(t) &= \dot{z}_{t\arg}(t) - \dot{z}(t) \\ &= \frac{T - D(t) - [T - D_f(t)]}{mg} V(t) E_f(t) \\ &= \frac{D(t)(1-k_D)}{mg} V(t) E_f(t)\end{aligned}$$
$$k_D = 1 + \frac{mg\Delta\dot{z}(t)}{V(t)E_f(t)D(t)}$$
$$D_f = k_D D$$

- If the result of the above adjustment to the descent rate exceeds aircraft performance or safety standards, a lateral deviation to a virtual waypoint P is attempted similar the adjusting the longitudinal deviation above. In this case, a constant correction coefficient k_R is hypothesized such that $\dot{z}_{adj}(t) = (1-k_R)\dot{z}(t)$. The resulting coordinates of P are

$$d_1 = \frac{\Delta z V_g - \dot{z}(t)\Delta_{turn}}{2V_g[1-\cos(\delta\psi)]}$$

[7] This expression represents correction of an apparent error in the paper

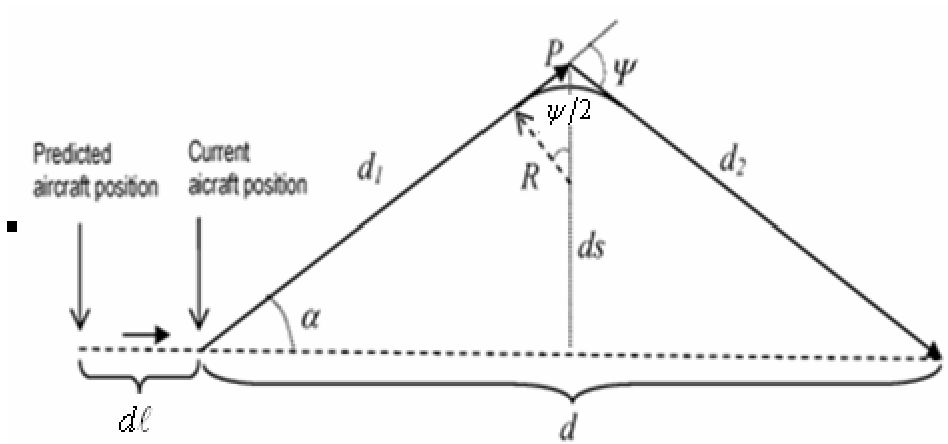

Figure 6: Lateral Deviation Path to Compensate for Longitudinal Early Arrival

(Copied from the reference document)

7.5 Math Model 5

Ref: ***Performance and Sensitivities of Optimal Trajectory Generation for Air Traffic Control Automation***

This model uses the following to restrict flight parameters to an operating range.

$$\theta(t) \in [\theta_{\min}, \theta_{\max}] = [-3^o, 8^o]$$
$$T(t) \in [T_{\min}, T_{\max}]$$
$$T(t) \in \left(0, \frac{\rho(h)}{\rho_{\text{msl}}} T_{\text{max,sl}}\right]$$
$$h(t) \in [h_{\min}, 50000]$$
$$0 < n(t) = \frac{L(t)}{W(t)} \le n_{\max} = 1.2$$
$$V^2(t) \ge = \left[1.2\sqrt{\frac{W(t)}{L(t)}}\right]^2 = \frac{1.44}{n(t)}$$
$$V(t) \le 250\text{kts}$$

7.6 Math Model 6

Ref: ***3-D Conflict Resolution of Multiple Aircraft via Dynamic Optimization***

Briefly, given two constraints e.g. $g_1(t) \ge 0, g_2(t) \ge 0$, a disjunctive constraint, defined as $g_1(t) \ge 0 \cup g_2(t) \ge 0$ can be expressed as the constraint set

$$\lambda_1(t)g_1(t)+\lambda_2(t)g_2(t)\geq 0$$
$$\lambda_1(t)+\lambda_2(t)=1$$
$$\lambda_1(t),\lambda_2(t)\geq 0$$

7.7 Math Model 7

Ref: ***A Quaternion-based Inverse Dynamics Model for Real Time UAV Trajectory Generation***

To implement a cascaded rotation, the user defines the unit skewed rotation axis vector expressed as a quaternion $u=[0,\hat{u}]$ and the rotation angle α about that axis. Thus, rotation is accomplished as

$$q_1 v \tilde{q}_1 = \left[\cos\left(\frac{\alpha}{2}\right), \hat{u}\sin\left(\frac{\alpha}{2}\right)\right][0,\vec{v}]\left[\cos\left(\frac{\alpha}{2}\right), -\hat{u}\sin\left(\frac{\alpha}{2}\right)\right]$$

Quaternion multiplication is defined as

$$q_1 q_2 = [q_{10},\vec{q}_1][q_{20},\vec{q}_2] = [q_{10}q_{20} - \vec{q}_1\cdot\vec{q}_2, q_{10}\vec{q}_2 + q_{20}\vec{q}_1 - \vec{q}_1\times\vec{q}_2]$$

Mathematical relationships for transforming matrix triple products into corresponding quaternion triple products to effect cascaded rotations are well documented.

7.8 Math Model 8

Ref: ***Kinematics Based Model for Stochastic Simulation of Aircraft Operating in the National Airspace System***

The linear flight path along the surface of the spherical earth at expanded by the current altitude is modeled as follows

$$\dot{x}(t)=V_{east}(t)=V(t)\sin[\psi(t)]+W_x(t)$$
$$\dot{y}(t)=V_{north}(t)=V(t)\cos[\psi(t)]+W_y(t)$$
$$x(t)=x(t-\Delta T)+\dot{x}(t)\Delta T$$
$$y(t)=y(t-\Delta T)+\dot{y}(t)\Delta T$$

In the above, $W_x(t),W_y(t)$ denotes the horizontal wind components at the aircraft flight level. The vertical motion is simply synthesized as

$$z(t)=z(t-\Delta T)+\dot{z}(t)\Delta T$$

The paper is unclear as to how the vertical velocity is derived.

The turning flight update requires the tracking of the bank angle. The simulation developed from the synthesizing equation assumes a constant turn rate perturbed randomly by the Johnson S_b distribution.

$$\phi(t)=\phi(t-\Delta T)+\dot{\phi}\Delta T$$

$$\Re(t)=\frac{V^2(t)}{g\tan[\phi(t)]}$$

$$\dot{\psi}(t)=\frac{V(t)}{\Re(t)}$$

$$\psi(t)=\psi(t-\Delta T)+\dot{\psi}(t)\Delta T$$

This value of $\psi(t)$ is used to compute the x-y coordinates. The symbol $\Re(t)$ is the time-varying turn radius.

7.9 Math Model 9

Ref: ***Path Stretching and Tracking for Time-Based Aircraft Spacing at Meter Fix***

This algorithm suggests a sinusoidal "fish-tailing" maneuver to lengthen the flight path in an attempt to reduce the rate of closure from the leading aircraft. Subsequent discussion addresses the solution of that expression for the optimal parameter derivation. The reader will note that the amplitude of the perturbation is a, the period is T, δ is a phase shift required to compensate for the wind velocity and that at $t=0$ and $t=T$, the original heading of the aircraft is restored. The parameters a,δ are computed from the initial and final conditions and the delay requirement T. The following equation models the "fish-tailing" maneuver.

$$\psi(t)=\psi(0)+a\left[\sin\left(\frac{2\pi t}{T}-\delta\right)+\sin\delta\right]$$

The true airspeed is converted to ground speed V_g.

$$V_g=-W\cos(\chi-\psi_w)+\sqrt{V^2-W^2\sin^2(\chi-\psi_w)}$$

$$-W\cos(\chi-\psi_w)\geq 0$$

The remaining parameters of the diversionary maneuver are computed as

$$a = J_0^{-1}\left[\frac{\sqrt{d_T^2 + (WT)^2 + 2WT\cos(\chi - \psi_w)}}{VT}\right]$$

$$d_T^2 = [x(T) - x(0)]^2 + [y(T) - y(0)]^2$$

$$\delta = \sin^{-1}\left[\frac{\theta - \psi(0)}{a}\right]$$

$$\theta = \chi + \sin^{-1}\left[\frac{W\sin(\psi_w - \chi)}{VJ_0(a)}\right]$$

The reader will note that computation of the inverse Bessel function of order zero $J_0(a)$ is required.

8: Appendix C - Flight Parameters used in Point-Mass Flight

Synthesis

The symbology for the parameters, for the most part, followed the aeronautical conventions. In order to not confuse the discussion, the following parameter definitions are described. The notation in the actual papers comprising the selected set differ from the notation defined herein.

Aircraft Parameters

- S — Wing surface area
- C_L — Coefficient of lift
- C_D — Coefficient of drag
- α_T — Inclination of thrust angle with respect to the body coordinate system
- m — Instantaneous aircraft mass
- $\dot{m}$ — Time rate of change of mass (manifested totally in fuel burn off)
- $-\dot{f}$ — Fuel burn off rate
- n — number of engines

Atmospheric Parameters

- $\rho(h)$ — Air density as function of altitude MSL
- W — Wind speed

Axial Rotational Velocity

- $\vec{\omega}^t = [p, q, r]^t$ — Rotation vector. See component definitions below
- $p = \omega_x$ — Rotational velocity of rolling axis
- $q = \omega_y$ — Rotational velocity of the pitching axis
- $r = \omega_z$ — Rotational velocity of the yawing axis

Constants

- g — Acceleration due to gravity

External Forces

- $\vec{F}^t = [X, Y, Z]^t$ — Newtonian forces
- $\vec{L}$ — Lift
- $\vec{T}$ — Thrust
- $\vec{D}$ — Drag
- $\vec{C}$ — Sideslip force

Euler Angles

- ψ Heading angle (with respect to true north)
- θ Rotation angle about y-axis, also known as pitch angle
- ϕ Rotation angle about x-axis, also known as roll or bank angle

Geodetic

- R Radius of conformal sphere modeling the earth surface
- (λ, φ, h) Geodetic coordinates, latitude, longitude altitude (ft.) MSL

Kinematic

- $\vec{x}^t = (x, y, z)^t$ Global position Cartesian coordinates.
- V True air speed
- V_c Calibrated air speed
- V_g Ground speed
- $\dot{\vec{x}}^t = [u, v, w]^t$ Velocity vector

Moment Parameters

- $\vec{\mathrm{T}}^t = [L, M, N]^t$ Moment vector. See below for definition of components
- Γ [8] Moment about the x-axis
- M Moment about the y-axis
- N Moment about the z-axis

Stability Angles

- $\alpha = \theta - \gamma$ Angle of attack
- β Sideslip angle
- γ Flight path angle

In addition, symbols used in vector parameters without the vector symbol will denote the scalar magnitude of the vector. For example, $L = \left\| \vec{L} \right\|$. Parameters evolving with time will be denoted in the usual way, e.g. $x(t)$ denoted the dependency of the *x* coordinate with respect to time. In general, dependency of the subject parameter on other parameters will be denoted by conventional parenthetical expressions. Time rate of change will be denoted through the use of the dot notation appended to the subject parameter symbol.

[8] Here we used the symbol Γ instead of the conventional L so that this parameter is not confused with lift force

9. Appendix D - Acronyms

ADS-B	Automated Dependent Surveillance – Broadcast
AFR	Autonomous Flight Rules
AIAA	American Institute of Aeronautics and Astronautics
AIDL	Aircraft Intent Description Language
ATC	Air Traffic Control
ATM	Air Traffic Management
CA	Conflict Alert
CHI	Computer-Human Interface
CP	Conflict Probe
DASC	Digital Avionics Systems Conference
DST	Decision Support Tools
ERAM	En Route Automation Modernization
FAA	Federal Aviation Administration
FMC	Flight Management Computer
FMS	Flight Monitoring System
FO	Flight Object
IEEE	Institute of Electrical & Electronics Engineers
LOM	Levels of Maturity
MIT	Massachusetts Institute of Technology
MITRE	MIT Research and Engineering
NASA	National Aeronautics and Space Administration
NextGen	Next Generation Air Traffic Control System
RNAV/RNP	Area Navigation/Required Navigational Performance
RUP	Rapid Update Cycle
TCI	Trajectory Computation Interface
TP	Trajectory Predictor
TRL	Technology Readiness Levels
UAV	Unmanned Aerial Vehicle

10. Appendix E - List of All Research Papers

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