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Survey and Method for Determination of Trajectory Predictor Requirements

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SURVEY AND METHOD FOR DETERMINATION OF TRAJECTORY PREDICTOR REQUIREMENTS

Tamika Rentas, Steven M. Green, and Karen Cate

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ABSTRACT

A survey of air-traffic-management (ATM) researchers, representing a broad range of automation applications, is conducted to document trajectory-predictor (TP) requirements for future decision-support systems. Results indicate that the researchers are unable to articulate a basic set of trajectory-prediction requirements for their automation concepts. Survey responses show the need to establish a process to help developers determine the TP performance requirements for their concepts. Two methods for determining TP requirements are introduced. A fast-time simulation method that captures the sensitivity of a concept to the performance of its trajectory-prediction capability is discussed. A characterization method is proposed to provide quicker yet less-precise results, based on analysis and simulation to characterize the trajectory-prediction errors associated with key modeling options for a specific concept. Concept developers can then identify the relative sizes of errors associated with key modeling options, and qualitatively determine which options lead to significant errors. The characterization method is demonstrated for a case study involving future airport surface traffic-management automation. Of the top four sources of error, results indicate that error associated with accelerations to and from turn speeds is unacceptable, the error associated with the turn-path model is acceptable, and the error associated with taxi-speed estimation is of concern and needs a higher-fidelity concept simulation to obtain a more precise result.

I. INTRODUCTION

One objective of the Next-Generation Air Transportation System (NextGen) transformation is to transition to trajectory-based operations (TBO) for managing the National Airspace System (NAS; ref. 1). TBO uses four-dimensional (4-D) trajectories to manage aircraft. It will require improved trajectory-prediction capability and a seamless interface among disparate trajectory predictors (TPs) serving multiple types of airborne and ground-based automation systems (ref. 2). A key step to improving trajectory prediction is to understand the current capabilities of and future requirements for trajectory predictors. Answering the question of how to determine future TP requirements for NextGen is difficult but essential. In particular, it is important to match the requirements of the TP to the needs of the automation system it supports. If a specific TP is unable to meet the performance requirements of its client automation system, then the success of the system depends on at least one of two actions: either the TP and supporting infrastructure (e.g., source of track, intent, and wind-forecast data, etc.) must be improved, or the operational concept for the automation system must be adapted to work with the TP performance provided. It is desirable not only to establish the minimum TP requirements for the "client" automation application, but also to build a TP that meets those requirements while minimizing complexity and avoiding unnecessary effort and cost. Recent works investigating the current state of TP requirements and capabilities include a workshop with MITRE Corporation and NASA and a survey of TP requirements conducted by a team of TP experts from (but not limited to) the Eurocontrol research labs, Federal Aviation Administration (FAA), and NASA. These works are described in more detail in the “Background” section of this paper.

This paper describes two primary objectives of the work. The first is to document requirements for new TP capabilities to be developed at NASA to support the NextGen vision. Requirements are collected through interviews with automation concept developers. The interviews include questions about functional requirements such as inputs and outputs, coordinate system, and prediction horizon and nonfunctional or performance requirements such as prediction accuracy and speed of response. The goal is to determine opportunities for common TP requirements. A secondary goal is to encourage TP clients to think about requirements at the level of the predictor, not just at the higher level of the automation system. The first objective assesses what the researchers know about the TP requirements for their concepts. Based on those findings, the second objective explores methods for determining TP requirements for the goal of helping researchers define TP requirements for their automation systems of the future.

The paper begins with more details about the previous efforts that relate to this work, followed by a description of the TP requirements survey and a discussion of the survey results. The results lead into a section that explores the process for determining quantitative TP performance requirements. The method of TP error characterization is then introduced to show a direct relationship between some key TP functional and nonfunctional (performance) requirements. The purpose of this method is to identify the characteristics that must be modeled to achieve a desired TP performance level. An initial application of this analysis to surface operations is provided as an example that can be further expanded upon for surface concepts or generalized to other applications. The results will contribute toward defining prediction capabilities required for the future air transportation system as well as work plans for future TP development. This process is also expected to facilitate establishment of the definitions of quantifiable requirements and performance metrics.

II. BACKGROUND

Prior work has attempted to increase our understanding of current and future TP requirements. A common objective has been to gather and document the TP requirements and capabilities of existing automation systems, with a primary purpose of identifying opportunities for the development and shared use of common TP capabilities. Examples of common capabilities of interest include aircraft performance and pilot-procedure models, algorithms for modeling flight dynamics, and interfaces between trajectory-based automation systems that will enable the synchronization of predicted trajectories across disparate systems. Trajectory synchronization is key to the interoperability of automation systems that depend on higher levels of TP accuracy such as airborne flight management systems (FMSs) and ground-based separation-assurance systems for air traffic control.

A first attempt at capturing TP requirements is conducted in the form of a two-day workshop (December 1999) involving senior technical leads from MITRE Corporation's Center for Advanced Aviation System Development and NASA. The scope is limited to a small set of air-traffic-management (ATM) automation applications, primarily en route, including the Center/TRACON Automation System (CTAS), the User Request and Evaluation Tool (URET), and envisioned enhancements to both. The results of the workshop, captured in an annotated briefing, included a side-by-side comparison of the major TP capabilities of each application, highlighting similarities and differences. The comparison also included a summary of the major drivers behind the development of the capabilities. This exercise provided an initial understanding of the high-level similarities and differences in TP capabilities for these applications, as well as some insights regarding how to compare TP requirements and capabilities. However, the details are at too high of a level to point to significant opportunities for common capabilities. A major impediment is the lack of documentation of the salient details related to each TP (ref. 3).

The second major effort is conducted under the auspices of the United States-Europe ATM R&D Action Plan 16 (AP16) for Common Trajectory Prediction Capabilities. AP16 is a team of senior trajectory-prediction experts representing the FAA, NASA, Eurocontrol research labs, and major industry R&D organizations developing air-traffic-control and airborne (e.g., avionics and airframe) automation systems. The team conducted a broad survey requesting details on the TP requirements and capabilities (in any form) from approximately 20 research and operational organizations. The request introduced the survey and described the specific aspects of trajectory prediction for which information is needed. Key technical leads were contacted directly through a formal letter of request, email, and follow-up phone calls. After a year of effort, many organizations indicated they had nothing to offer. Of the few that did respond with relevant details, the content varied widely from one organization to another, the material was inconsistent in what was documented (little comparable overlap), and the scope of information was significantly incomplete.

Several key conclusions are generated based on feedback from these past efforts and analysis of the limited material obtained. First, documentation of this type is a systemic challenge for the community, particularly the research labs where the changes in requirements and capabilities can occur quite frequently as research progresses. Second, the focus of most automation concept/system developers seems to be limited to higher-level requirements for their automation system. Many developers have difficulty determining what their automation concept/system specifically requires from its supporting TP capabilities. Third, the wide range of approaches taken to implement TPs, for research and operational systems, makes it difficult to understand the similarities of, and true differences between, any two predictors. Two key elements are needed to achieve significant progress in the development and reuse of TP capabilities across the R&D community. First is the need for a simple and concise methodology to "standardize" documentation to achieve clear, consistent, complete, and cross-comparable TP requirements and capabilities. Second is the need for practical methods that can generate quantitative TP performance requirements that are comparable across the community.

Along the way, AP16 developed a generic TP structure to provide a common representation of TPs (ref. 4). This generic TP structure is developed in a cooperative effort to resolve conflicts in terminology and overcome the challenges of significant architecture differences among TP developers. The common structure avoids the debate of what components constitute a TP and where those components belong in a system implementation. It provides a basis for identifying common requirements, performance metrics, and validation methods. Therefore, the structure facilitates the documentation of requirements and capabilities for comparison across different TP client-automation systems.

III. TP REQUIREMENTS SURVEY

The survey is conducted through a series of interviews with leading researchers at NASA. The AP16 generic TP structure is used to organize the survey and define questions in a general way, independent of any specific architecture. Additional question details and examples are motivated by a review of internal documentation describing the TP capabilities for a few existing ground-based automation applications. Each interview begins with questions about the "client" application(s) that require TP capabilities, typically decision-support automation or a simulation. Next, the interview questions explore the needs of the client applications. In some cases, existing TP capabilities already being used are adequate to support some of the research. In other cases, new capabilities are required to support the client applications.

The questions regarding client needs are organized into four areas based on the four main TP-related processes defined in the AP16 generic TP structure: preparation, trajectory prediction, trajectory-prediction update, and the export process. The preparation process begins with the basic input to the TP, including current, estimated aircraft state, and flight plan. Based on the input, the output of the preparation process includes the input to the TP and all of the instructions required to control the integration within the trajectory-prediction process. These instructions detail the pilot intent to be modeled and how the transition between sequential flight segments is to be performed. The preparation questions ask about inputs to the TP and the integration instructions. The trajectory-prediction process calculates the trajectory using the information from the preparation process and the supporting models of the forecasted wind, temperature, and aircraft performance. The prediction part of the interview investigates the methods used to compute the trajectories. The interview then addresses the trajectory-prediction update process. These questions involve the conditions and/or frequency for which updated predications are needed, and the specific purpose for the update. Finally, the export process addresses the expected content and format of the TP output. The interview concludes with questions regarding the desired accuracy of the predicted trajectories.

The technical leads of 5 of NASA's 10 ATM research focus areas are interviewed. Each interview represented a separate research area at NASA applicable to the NextGen vision: (1) surface operations, (2) super-density operations, (3) separation assurance, (4) traffic flow management, and (5) dynamic airspace. The survey responses, which include the interview responses and information from internal documentation, are compiled, and an initial analysis is conducted to identify and resolve areas of ambiguity in the responses. Supplementary questions are generated, based on the collected responses, to address requirements that have not been considered previously. The responses from each interviewee are analyzed to determine if the responses describe a requirement for, or capability of, the TP needed to enable their concepts. Once the initial analysis is completed for all 5 interviews, results are reviewed collectively for commonalities among trajectory inputs, outputs, modeling (preparation process), and computation (prediction process) requirements.

A summary of the survey results is presented here. The goals of the applications and functions reliant on trajectory prediction are introduced for each research area. Few TP requirements for NextGen systems are collected through this survey, therefore only some common requirements among the systems and selected interview responses are presented.

A. Research Area Applications

1. Surface Operations

The surface-operations research area focuses on enabling high-density operations on the surface and immediate airspace around an airport. The approach is to develop and evaluate new concepts and algorithms for a wide variety of surface-automation applications. These applications include taxi planning and surface-traffic optimization, taxi-clearance conformance monitoring, conflict detection and resolution, collision avoidance, and the mitigation of environmental impacts. Ground-based and flight-deck solutions will be based on the prediction and monitoring of 4-D trajectories for both departure and arrival traffic on and near the surface. The 4-D trajectories will describe how the aircraft (and other vehicles) will move along the surface, including major intersection points and the arrival times for each point.

The requirements for the TP to support these applications have not yet been defined. Some general and partial requirements for the TP are provided, but this list is far from complete. The general requirements are primarily in the form of prediction-time horizon. The horizon requirement for taxi planning is 30 minutes, 5 minutes for conformance monitoring and 20 to 30 seconds for collision avoidance. While there are no TP accuracy performance requirements per se, the researcher felt that a kinetic (force-based) performance model will be required. The TP will also require actual and forecasted weather information as an input, such as rainfall and icing, along with a model of how weather conditions will affect surface-traffic movement.

2. Super-Density Operations

Super-density operations refer to the highest-density terminal operations conceived for NextGen. The research currently focuses on determining accuracy requirements and understanding the level of performance the system needs. Efforts focus on mitigating weather impact and developing scheduling improvements to understand the trade-offs in different system objectives as a function of uncertainty. Examples of these systems objectives are capacity, efficient climb/descent profile, meeting user-specified objectives, and minimizing noise and emissions.

Currently, NASA's research in super-density operations is not sufficiently mature to determine the characteristics of and requirements for supporting automation, let alone supporting TP. One anticipated requirement is the need for a prediction of the uncertainty at each point along a predicted trajectory.

3. Separation Assurance

CTAS is a decision support tool used for arrival-management and separation-assurance research by NASA. It is a set of tools that produce advisories for aircraft in the remaining airspace not covered by surface operation or super-density operations, including en-route and less-dense terminal areas. Some advisories include the earliest arrival times for aircraft entering the terminal radar approach control facilities (TRACON), an arrival metering schedule, the assignment and sequence of arrivals to a runway, trajectory modifications to meet scheduled times, conflict detection and resolution, and which aircraft will benefit from deviating from its filed flight-plan routes by using shorter, more direct, conflict-free routes.

The trajectory-prediction engine, called the trajectory synthesizer (TS), is at the core of CTAS. The TS predicts a 4-D trajectory for each aircraft from its current position to its destination, or next air-traffic-control facility, based on inputs from higher-level algorithms for route analysis and profile selection. CTAS trajectory prediction is initiated by any of the route-generation and profile-selection processes in CTAS.

Similar to surface operations, requirements for trajectory prediction are not explicitly defined for separation assurance. Following the definition of the concept, the uncertainty values of the computed trajectories must be below the vertical and lateral separation criteria of the aircraft. The prediction accuracy must be high enough to maintain the performance of the automation system. The TP must be fast enough to compute trajectories in the "required time allotted" (within the 12-second processing cycle for CTAS) and respond to controller requests in a controller-acceptable amount of time.

4. Traffic Flow Management

Traffic flow management manages traffic flows on a national and regional level. The Future Air Traffic Management Concept Evaluation Tool (FACET) is a research platform used to study traffic flow management concepts (ref. 5). FACET provides a flexible simulation environment for development and evaluation of advanced ATM concepts. It can be used to determine sector loads and complexity of the airspace. It allows rapid prototyping of new ATM concepts in the en-route airspace, including airborne self-separation, dynamic density predictions for airspace redesign and aircraft rerouting, and integrating space launch vehicles into the NAS. Each of these concepts is reliant on trajectory prediction. Currently, FACET as a tool is not being further developed, but the algorithms within FACET are being improved to make the current state of FACET more useful. Some near-term goals of the project include developing weather translation, aggregate flow models, optimization work, and airspace complexity.

5. Dynamic Airspace

Dynamic airspace applies to terminal through en-route airspace. An automation system has not been designed specifically for dynamic airspace configuration. Instead, an existing automation system with trajectory-prediction capability already developed by NASA will be used. The chosen system will be modified to calculate the maximum capacity of a given airspace. The capacity is the number of aircraft in the airspace at a given time. The system will determine ways to change airspace configurations that will allow for larger capacity.

An example of a new airspace configuration consists of tubes of airways within the airspace that will be similar to highways on the ground. Consequently, one role of the TP will be to assist in the tube design. The accuracy of the TP and the anticipated trajectory error will dictate the best size of the tubes. The predicted trajectories will also be used to determine the complexity of the given airspace. Based on the complexity of the airspace, the limit on capacity can be determined. Complexity is defined by mathematical formulas. The complexity will be calculated given the expected incoming trajectories and their uncertainty bounds. Therefore, the dynamic-airspace concept requires both the prediction of specific 4-D trajectories and the uncertainty of those predictions. Another demi-requirement resulting from these applications includes allowing the user to input error bounds into the TP for the nominal prediction.

B. Selected Interview Responses

Tables 1 and 2 summarize the responses to a functional requirement and a nonfunctional requirement question, respectively, collected during the interviews.

TABLE 1. HOW WILL TURNS BE MODELED?

Surface operations	Modeling details of the future TP are unknown.
Super-density operations	Circular-arc turns of constant radius: preferred for Required Navigation Performance routes. Model with roll and speed dynamics: Vectors.
Separation assurance	All turns are circular arcs of constant radius.
Traffic flow management	Turns are modeled as instantaneous.
Dynamic airspace	Not important. Priority: get a trajectory predictor up and running quickly to support algorithm development.

TABLE 2. HAVE ANY PERFORMANCE REQUIREMENTS BEEN DEFINED?

Surface operations	No. Trajectory must be very accurate for monitoring and conflict detection and resolution.
Super-density operations	No. Requirements are being investigated but none are currently defined.
Separation assurance	No. Trajectories need to be as accurate as possible with uncertainty below separation standards (5 nmi, 1000 ft).
Traffic flow management	No. Trajectory error is too high; any error reduction will be an improvement.
Dynamic airspace	No. Requirements will be a function of the airspace complexity or performance boundaries of the TP.

1. *Common Inputs and Outputs*

The interview responses are compared to identify common requirements, which are found in the input and output requirements listed in table 3.

TABLE 3. COMMON REQUIREMENTS FOR TRAJECTORY PREDICTION

Common Requirements
Input Initial aircraft state, Intent information, Aircraft performance model, Pilot procedure model, Airspace definition, Forecasted winds or temperature
Output Predicted 4-D trajectory, Trajectory uncertainty

IV. DISCUSSION OF SURVEY RESULTS

The objective of the survey is to document TP requirements for future automation systems, but few requirements actually resulted from the survey. For all of the research areas interviewed, requirements for future trajectory prediction have not been adequately considered. The actual responses provide information at more of a system level. As a result, the collected interview responses fit into three categories: an incomplete requirement for a future TP, an existing requirement or capability for a legacy system, or an ambiguous response that does not clearly fit into either of the previous categories, but which may be a requirement for the TP or the automation system.

An example of an incomplete requirement for a future predictor is one taken from the interview of the surface-operations research area that states that the TP must be very numerically efficient since it will have to modify and recalculate the trajectory quickly. This statement is roughly a performance requirement for the predictor, but it is missing the performance requirements for specific surface-operations functions as well as knowledge of the dependency of the surface-operations functions on TP performance. The second category of interview responses is also a result of undefined future requirements. A requirement or capability of a legacy system is often cited in the interviews when the future requirement is unknown. An example of this category of responses can be seen in the traffic-flow-management research area. The responses refer to current capabilities or requirements of FACET, the legacy system being used. Though a need for better trajectory-prediction performance for future operations as compared to current operations is apparent, the requirements for the future system in this area are still being regarded in terms of the legacy system.

A common response to a question about requirements on the expected output of the TP is a requirement to output the uncertainty of the predicted trajectories. This response fits in the third category of the interview responses, because it is unclear if the response is truly a requirement of the TP or the automation system the TP supports. Prediction errors must be defined by the client automation. A TP computes a trajectory based on inputs and set algorithms and models. From the perspective of the predictor, there is no uncertainty in its prediction since it has successfully computed the trajectory. The requirements of the operational concept will determine what is considered an error. Therefore, the function of determining the uncertainty of the prediction should be implemented outside of the TP. However, an uncertainty that can be computed by the predictor is any uncertainty in its computations. One can require a predictor to know the uncertainty in its calculations and provide that information as output from the TP. Details of the type of uncertainty the client requires will be needed to clarify if this function is a requirement for the TP or the automation system. This category of responses implies that the concept requirements are poorly defined. The client needs comprehensive requirements on the concept before being able to define the TP requirements. Otherwise, the resulting TP requirements will also be poorly defined and difficult to interpret when developing the prediction algorithms and functions.

Very few requirements are defined for the functionality or performance of the predictor in any of the research areas. Samples from the interview contained in tables 1 and 2 support this finding and highlight other significant results. Table 1 shows the responses to the question of how turning along a trajectory needs to be modeled in the future TP. Note the variation in the responses; some describe the turn model used in a legacy system while others have not determined what is required. None of the responses, with the exception of the response from super-density operations, gives requirements for turn modeling for future trajectory prediction. For surface operations, for example, the turn modeling required for a future TP is unknown. Turn modeling is also a functional requirement decision that may have a significant impact on TP performance under TBO and deserves serious consideration. Figure 1 illustrates three ways to model a turn along a trajectory: an instantaneous turn, a constant-radius turn at a constant speed, and a turn with roll-in, roll-out, and speed dynamics modeled. The figure shows the differences in path distance corresponding to the choice of turn model. These differences result in three different trajectory predictions at different levels of prediction accuracy. Therefore, the performance of the TP is affected by this modeling decision, and a requirement on the turn model of the TP may be needed to meet the prediction requirements needed to support the client automation. The different turn models described in table 1 show that the functional requirements for trajectory prediction may vary greatly with the client application. In addition, lacking a complete set of requirements, the designers of the client applications studied here do not yet have a complete understanding of what is required to operate in the NextGen system. The separation-assurance and super-density operations research areas are both operating in the terminal area. For separation assurance, turns are modeled as circular arcs of constant radius. Super-density operations will need additional turn models that consider roll and speed dynamics. Both are operating in the same domain but seem to have contradicting requirements for trajectory prediction.

Table 2 is the response to the question "Have any performance requirements been defined for the future trajectory predictor?" In all areas interviewed the answer is "No." In all cases the researchers do not know what performance is required for their future system. The responses they did provide did not give enough information to form a requirement for the TP. For example, for surface operations the trajectory must be very accurate for monitoring conformance and conflict detection and resolution, but this accuracy cannot be quantified. In many cases, the researchers are not sure how to determine TP requirements and request help with this task.

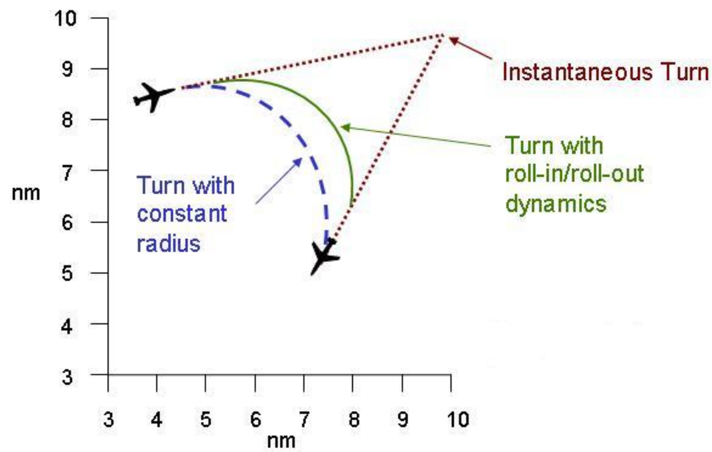


Figure 1. Effects of turn modeling on path distance.

In the absence of requirements for future systems, one way to make progress is to look at the current state of the art. In particular, this research looks for common requirements in the research areas interviewed. These common requirements may represent some minimum or initial requirements for future TPs. Table 3 lists the only requirements consistent in all five of the interviews: the input and output to the TP. The fact that input and output are the only areas found with consistent requirements demonstrates the small amount of progress made by clients knowing and understanding the uniqueness of their TP requirements. However, the general nature of the input and output requirements provided is little more than self-evident and provides no specifics that can be used to identify similarities or differences in the TP requirements for each area. Consistent details relating to modeling and performance requirements will provide insight as to what is needed for the future.

In summary, few TP requirements are identified from the survey. Of those obtained, most are incomplete requirements for trajectory prediction or legacy capabilities of a legacy system. Few requirements are defined for the performance or functionality of the predictor. Often the requirements are confused with the higher-level automation-system requirements. Some researchers are not sure how they will determine the requirements needed for their future concepts and requested help. Given that the original objective of the research cannot be reached, an alternative approach is pursued.

V. PROCESS FOR DETERMINING REQUIREMENTS

While the results include a few functional requirements, the distinct lack of performance requirements is problematic. The performance requirements for a system, if defined, drive a great portion of the functional requirements. Alternatively, if functional decisions precede the definition of performance needs, the performance of the system may be limited unnecessarily. Once the client automation system or concept has defined the performance requirements for its supporting TP, the definition of functional requirements is a much simpler task. Overall, the results of the survey show that the researchers need help determining requirements for their TP. This finding is consistent with the prior AP16 survey and shows that clients of trajectory prediction in general need help with TP requirements.

The results also imply that researchers are attempting to design TPs without having well-defined trajectory-prediction requirements. The risks involved with this behavior are major. One major consequence is a TP that does not meet the needs of the client or operational concept. In this case, the researcher can attempt to change the TP to meet the client's requirements or, alternatively, change the corresponding operational concept. Altering the TP will involve additional effort and costs along with delay to implementation. Even with the additional effort it may not be possible to meet the desired performance with the existing system architecture of the TP. The researcher may then opt to change the operational concept, but that decision may be met with some resistance from the client and the original need for the predictor would be left unfulfilled. Consequently, the second objective of this research is identified: establish a process to determine TP requirements, particularly performance requirements, for future automation systems.

The method of finding TP requirements proposed in this paper begins with the following two steps: 1) obtain the client's performance requirements for the automation system, and 2) determine the sensitivity of the automation-system performance to the TP performance. Before requirements for the TP performance can be defined, the client must have clear and comprehensive performance requirements for the concept or automation system. The critical TP performance requirements are directly dependent on the unique performance requirements of the automation system itself. The choice of performance metrics is the responsibility of the client. This information must be provided by the client before seeking help to define performance. Knowledge of the automation-system performance requirements is important to ensure the TP performance meets the needs of the concept but does not unnecessarily exceed those requirements. This way, the client can avoid additional effort and costs.

Another prerequisite to determining performance requirements is to understand the relationship between the performance of an automation system and its supporting TP. Two parts of this relationship are of interest: the sensitivity of the automation-system performance to the TP performance, and the sensitivity of the TP performance to key functional components of the predictor (including inputs to the predictor and models and algorithms used for prediction). It is in determining this sensitivity that this research can aid TP clients.

There are numerous possible approaches to determine the sensitivity discussed previously. This work considers an analytical approach, a real-world experiment, a human-in-the-loop (HITL) simulation, and a fast-time simulation. An analytical approach, while having the potential to provide the fastest results, faces significant challenges. TP performance is multidimensional, time-varying, and nonlinear—not the best form for an analytical approach. It will be very difficult, if not nearly impossible, to derive an analytical expression representing a wide range of conditions and error possibilities for the TP performance. A real-world experiment to study the sensitivity will require personnel and equipment over an extended period of time. The costs associated with this type of experiment will be very high, data collection will be limited, and only a limited number of cases can be studied. A HITL simulation will introduce greater experimental control, but there will still be significant costs associated with personnel that will significantly limit the number of cases. While a fast-time simulation approach will be missing the human element, it can be much more cost and time efficient than the real-world experiment or HITL simulation. Setting the sensitivity analysis aside, however, the HITL simulation approach will provide an excellent way to address the first step discussed previously: to help the clients of TP (automation system/concept developers) determine the performance requirements for their automation system.

A fast-time simulation approach is advocated to determine the sensitivity. With this approach, a modeling and simulation platform will be used to evaluate the effects of several factors on TP performance and their impact on the automation-system performance. With such a platform, the performance of an automation system/concept can be modeled and evaluated as a function of TP modeling assumptions under a wide range of operational conditions, aircraft performance errors, and input uncertainty. This approach will serve as the basis for establishing relationships between TP performance and automation-system performance. Development and application of this approach to a specific automation system/concept may take a year, if not longer. An alternate method is needed to start progress towards determining TP performance requirements now while the fast-time simulation concept is being further developed. The characterization method presented in the following paragraphs provides a way forward.

VI. CHARACTERIZATION OF TP ERRORS

The characterization method described in this paper can help TP clients begin to approximate performance requirements by providing a relatively quick and easy way to study the sensitivity of TP performance to critical dynamics involved in its application. The objective of the characterization is to identify potentially critical dynamics that the TP may need to model in order to meet the requirements for the client automation-system performance. The characterization analysis begins with identifying dynamics that are likely to be crucial to the performance of the TP. The critical dynamics will vary, depending on the domain in which the TP is applied. The next step is to define metrics and test conditions that will excite problems or behaviors of interest in these dynamics. With these metrics defined, then trajectories can be computed with the corresponding test conditions with and without the dynamics modeled. Finally, the results—the sensitivity of the trajectories to the dynamics—can be presented to the client. The client can use these results to judge the impact of errors on the automation system caused by modeling, or not modeling, the dynamics. The characterization method is applied to the surface-operations research area as an example. At the time of the survey, the surface-operations research area did not have a 4-D TP to be used in the NextGen, but was beginning development. For this reason, the surface-operations research area is a suitable choice for the application of characterization method.

A challenge for surface operations is computing the estimated time of arrival (ETA) of the aircraft at different places of interest along its taxi route. Trajectories are used to compute ETAs for managing aircraft crossing a runway, managing the usage of intersections, and determining the location of an aircraft along its taxi route at any given time. Better ETA predictions are needed for the cases mentioned previously for scheduling, conflict avoidance, detection, and resolution purposes. The objective of the characterization method applied to surface operations is to evaluate the effects of modeling decisions for trajectory prediction on the total surface-trajectory durations. The modeling decisions include determining what dynamics will be modeled by the TP to improve its predictions. Four types of dynamics are modeled in this example of the characterization method. The modeling decisions related to these four dynamics are illustrated in figure 2, which is a representation of a taxi route.

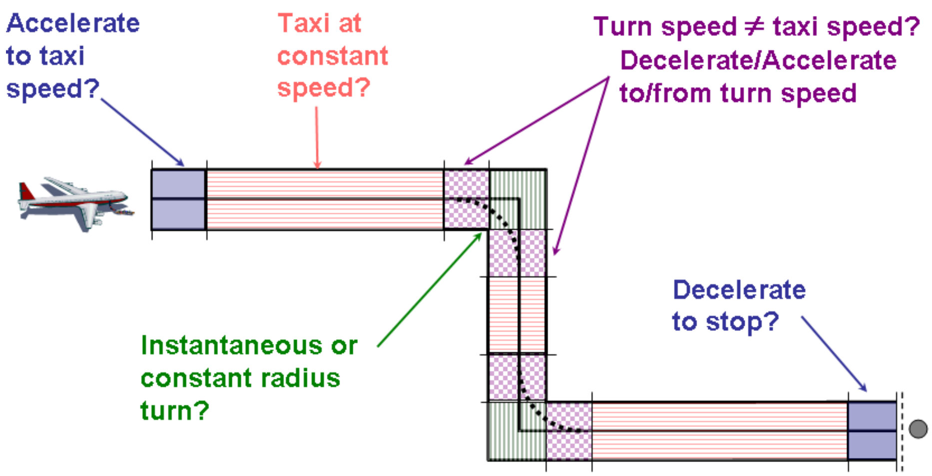
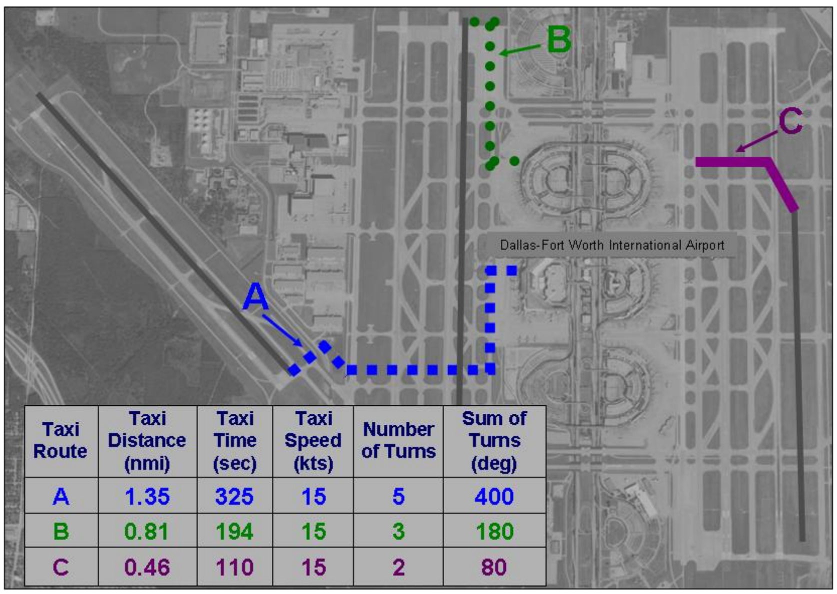


Figure 2. Surface-dynamics modeling decisions.



Taxi Route	Taxi Distance (nmi)	Taxi Time (sec)	Taxi Speed (kts)	Number of Turns	Sum of Turns (deg)
A	1.35	325	15	5	400
B	0.81	194	15	3	180
C	0.46	110	15	2	80

Figure 3. Taxi-route description.

The different color regions represent different modeling techniques for surface-trajectory prediction along the route. The first dynamic to consider in the figure is acceleration. Specifically, how will the TP model how the aircraft will accelerate to the desired taxi speed from a stop or decelerate to a stop? The next dynamic is the taxi speed. Will the aircraft travel at a constant or variable taxi speed? A few decisions are involved for aircraft approaching a turn. Will the turn speed be different from the taxi speed? If so, will the predictor model deceleration to and acceleration from the turn speed? Will the path of the turn be a point where an instantaneous turn or a constant-radius arc occurs?

Given a specified taxi trajectory, the duration is computed with and without each of the four dynamics modeled. Three example taxi routes are chosen from the map of the Dallas–Fort Worth International Airport (fig. 3). As can be seen in the figure, each route varies in total distance and number of turns to be traversed. The figure also shows the nominal taxi time for each route, which is the computed total trajectory duration for a baseline reference.

In the surface-operations example, instantaneous acceleration and constant acceleration are the two methods considered for computing trajectories. The duration of the trajectory is computed both ways. The value of constant acceleration used is 2 ft/sec2. A constant taxi speed with a nominal value of 15 knots is used. To study the impact of the predicted taxi speed on the trajectory duration, trajectories are also computed with off-nominal values of taxi speed from +/–1 up to +/–5 knots from the nominal value. The trajectory time is also computed for trajectories modeled with instantaneous turns or constant-radius turns and deceleration into and acceleration out of the turns to characterize the turn dynamics. The total trajectory times computed for each condition are compared to a chosen baseline to determine the maximum prediction error resulting from the speed model, the acceleration model to and from a stop, the turn-path model, and the model for decelerating to turn speed when entering a turn and then accelerating back to the taxi speed at the exit. The details of the conditions used to calculate the trajectory time and the description of each baseline case are shown in table 4.

Table 5 shows the maximum prediction error in seconds resulting from each of the four dynamics. This table demonstrates the effect of the modeling decision for each dynamic on the total surface-trajectory duration.

TABLE 4. CHARACTERIZATION TEST CONDITIONS

Dynamic tested	**Description of test conditions**
Speed	Constant taxi speed, instantaneous turns, instantaneous acceleration
Baseline	Taxi speed of 15 knots, instantaneous turns, instantaneous acceleration
Acceleration to/from stop	Constant taxi speed, instantaneous turns, constant acceleration
Baseline	Constant taxi speed, instantaneous turns, instantaneous acceleration
Turn model	Constant taxi speed (no slowing for turns), turn modeled with curve segment length, instantaneous acceleration
Baseline	Constant taxi speed, instantaneous turns, instantaneous acceleration
Deceleration to turn speed	Constant taxi speed, turn modeled with curve segment length and constant turn speed (less than taxi speed), constant acceleration, and deceleration to turn speed
Baseline	Constant taxi speed, instantaneous turns, instantaneous acceleration

TABLE 5. TRAJECTORY PREDICTION ERRORS

Route	**Maximum prediction error (sec)**			
	Speed error (+/–3 knots)	**Acceleration to/from stop**	**Turn model**	**Deceleration to turn speed**
A	92	18	18	129
B	55	18	7	73
C	34	18	3	47

For route A, there is a 92-second error resulting from 3 knots of deviation from the predicted (nominal) taxi speed. This error accounts for 28% of the total trajectory duration. The resultant prediction error from modeling versus not modeling the deceleration to a slower turn speed is 129 seconds, which is 40% of the total trajectory time. The errors caused by not modeling accelerations to and from stop and the decision to model an instantaneous versus a constant-radius turn each are 6% of the total trajectory duration. From this table, the client can see the error contribution from each of the dynamics. In this case, one can conclude that, at the minimum, the TP for surface operations must have accurate models of the taxi speeds, turning speeds, and the transition between them for each aircraft to avoid critical prediction errors.

VII. CONCLUSION

The objective to survey and document TP requirements for the future air transportation system cannot be completed. NASA researchers are able to articulate few TP requirements. The survey concluded that little progress has been made in the knowledge and understanding of the TP requirements needed to support future trajectory-based automation systems. Some of the researchers are unsure how to define future requirements and asked for help. As a result, the second objective of this research is formed to define a process for determining future TP requirements. While a modeling and simulation approach may provide a way to determine the TP performance needed to support future concepts, such an approach will need to be developed and tested. In the meantime, the characterization method introduced in this paper provides a relatively quick and simple way to begin defining TP performance requirements. Airport surface operations are analyzed to demonstrate this method for providing a relatively fast, first-order-of-magnitude understanding of the impact of modeling factors on the predictor performance. Results indicate that the error associated with accelerations to and from turn speeds is unacceptable, the error associated with the turn-path model is acceptable, and the error associated with taxi speed is of concern and needs a higher-fidelity concept simulation to obtain a more precise result. The characterization allowed the client to approximate the TP accuracy needs based on consideration of typical errors that will occur because of modeling dynamics and expert judgment on the impact of those errors on client performance.

The next steps for this research include enhancing the characterization of the surface applications by a comprehensive analysis of recorded surface-trajectory data and identifying and characterizing other important dynamics for surface-trajectory prediction. The characterization will also be applied to other clients. Another objective is to develop and use the fast-time modeling and simulation approach presented in this paper to study the sensitivity of the TP performance to key components of the predictor.

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