COMMONALITY IN DISPARATE TRAJECTORY PREDICTORS FOR AIR TRAFFIC MANAGEMENT APPLICATIONS

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Abstract

Air Traffic Management research and development has placed a heavy emphasis on the application of Decision Support Tools and automation to help provide service improvements under projected increases in demand. As various organizations have been responsible for these R&D efforts, one of the fundamental building blocks, the Trajectory Predictor (TP), has evolved into a collection of disparate TPs with differences in approach, data requirements, performance, capabilities and design. This has led to: little re-use of previously-developed TP capabilities, interoperability issues when attempting to integrate DSTs based upon disparate predictors and when introducing 4D trajectory management, difficulty in communication between TP developers, and ultimately an ATM system that does not perform up to its level of promise.

This paper presents a series of 9 initiatives proposed by the FAA/Eurocontrol Action Plan 16 seeking to establish common trajectory prediction capabilities. We provide the result of an effort to provide a TP structure and vocabulary common to a multitude of TPs for use in air and ground automation components. This structure decomposes trajectory predictors into a collection of processes and services that may or may not be included in all TPs. This paper discusses the benefits resulting from the development of such a structure; in particular, the facilitation of many of the 9 proposed initiatives.

Introduction

The current and envisioned Air Traffic Management (ATM) system contains a variety of applications relying on trajectory prediction to provide the expected functionality as follows:

- Flight Planning / Re-planning – The ability to plan, analyze and optimize individual trajectories and fleet & schedule management is fundamental to airspace user operations.
- TFM – The ability to predict sector loads with long look-ahead times is accomplished using trajectory prediction. Future applications may incorporate the impact of uncertainty (e.g. [1]).
- Flight Data Processing (FDP) – Trajectory prediction is required to provide flight information to the correct sectors at the appropriate times. Very short-term trajectory prediction is required to correlate flight track information with flight identifiers.
- Conflict Alert – Short-term prediction of aircraft conflicts (e.g. [2]) is based upon simple trajectory prediction. This application is often embedded into FDP systems.
- Conflict Probe – Prediction of aircraft conflicts with a longer-term horizon than conflict alert (e.g. [3, 4]). For this application, a more capable trajectory predictor is required.
- Conflict Resolution – The ability to provide conflict resolution advisories to the controllers. Examples include: trial planning and more advanced active advisories (e.g. [5]).
- Sequencing & Metering – Trajectory prediction is required to estimate the arrival time of aircraft at a specified location and generate desired schedule times of arrival [6, 7].
- Conflict-free Metering Conformance – Trajectory prediction is critical to provide tactical control advisories to achieve required times of arrival with conflict-free trajectories (e.g. [8]).
- Flight Management – The ability for flight crews to plan and execute 4D trajectories and to perform Continuous

Descent Approaches (CDA) is critical to many future ATM concepts (see [9]).

In addition to the operational systems listed above, simulators are used for training and both fast time and human-in-the-loop investigations of proposed changes to the system. These simulators are often used during the development of systems and concepts.

While the current system depends on trajectory prediction, this dependence will likely *increase* going forward, as future applications providing controller advisories require greater capabilities and performance (accuracy, speed, and reliability) from trajectory predictors. It is expected that the future ATM system will rely more and more on airborne automation functions like airborne spacing and separation support (e.g. ASAS) and 4D trajectory negotiations. Advanced automation support on the ground will facilitate the introduction of such concepts by providing the automation support needed for those aircraft that are not yet adequately equipped or as a backup in case of failure of airborne elements. Harmonization of TP functionality and performance among ground-based and airborne applications is key for overall system stability and therefore safety.

While a wide variety of applications and organizations require the use of trajectory predictors, developers of TP-dependent applications have been addressing TP-related problems largely independently. Opportunities exist for seeking commonality between TPs in the area of development, data gathering, validation and testing. An initial effort discussing the commonality of some specific TP applications is discussed in [10] together with a discussion of common trajectory services.

Action Plan

In response to the need for harmonization of efforts in the trajectory prediction area, the FAA and Eurocontrol initiated the FAA/Eurocontrol R&D Action Plan 16. This action plan seeks to provide Common Trajectory Prediction Capabilities through the execution of the following nine points [11]:

1. Common TP-related terminology
2. Trajectory Prediction Requirements Survey
3. Proposed Requirements for the encoding of LOA/SOP-defined ATC Constraints
4. Comprehensive Sensitivity Analysis of Trajectory Prediction Factors
5. Evaluation of Performance-Modeling Approaches
6. Requirements for Aircraft Performance Data
7. Comprehensive TP Validation Data Reference Set
8. Assessment of the Operational Application of ATM Constraints
9. Comprehensive Operational Assessment of Intent Prediction Errors

Each of the above nine points is described in more detail below.

Common TP-Related Terminology

This initiative sought to agree on the use of common terms used in the discussion of trajectory prediction and get a common understanding of the components that trajectory prediction functions consist of and the services that they need to provide.

Early discussion (e.g. [12]) on the subject of trajectory prediction, revealed a great deal of disparity in the terms used by differing researchers and organizations. In addition, there was little agreement on the definition of what constituted a TP, or the extent of functionality provided by the TP. As a result, Action Plan 16 sought to harmonize both the terms used for discussion and to develop a mutually agreed upon TP structure to facilitate the exchange of technical information.

This paper presents the TP structure and discusses the benefits of this structure to several of the initiatives under Action Plan 16.

Trajectory Prediction Requirements Survey

This initiative addressed the issue of the lack of available TP requirements for decision support tools (DST) that are: explicit, justified and comparable across DST applications. A survey was initiated to attempt to document trajectory prediction requirements for current and future ATM applications. These applications include: DST, flight data processors (FDP), flight management systems (FMS) and simulators.

This survey led to the initial conclusion that there is a significant gap between the TP performance expected by many DSTs.and the performance that is actually available from current TPs. Consequently, system developers are forced to downgrade the desired DST functionality to the level that is supported by the current TP performance. As future ATM concepts have even higher demands for TP performance, a fundamental change in the TP requirements engineering process is needed. To that effect, initiatives are being developed to have a common approach to requirements engineering, shared amongst the DST development, TP development and Flight Data Management development communities.

Proposed Requirements for the Encoding of LOA/SOP-Defined ATC Constraints

Aircraft trajectories are significantly impacted by ATM constraints (e.g. altitude, speed) that flight trajectories must comply with. Many of these constraints are contained within Letters of Agreement (LOA) and Standard Operating Procedures (SOP) existing within the ATM system. The ability to automatically process these constraints would reduce the burden of manual adaptation for multiple TPs, improve the accuracy for TPs not privy to this information and allow the harmonization of these constraints between applications.

This initiative seeks to revisit international standards and recommended practices supporting the automatic processing of airspace adaptation data and to develop recommendations for the support of trajectory prediction.

Comprehensive Sensitivity Analysis of Trajectory Prediction Factors

The performance of applications relying on trajectory prediction is impacted by the accuracy of the TP. This accuracy is determined by the level of modeling fidelity in the trajectory predictor, along with the accuracy of the data used by the TP. The objective of this initiative is to develop a single, cross-comparable, comprehensive set of results and data that can be used by developers of TPs to identify and trade-off factors (data quality or modeling) most relevant to obtaining desired levels of performance for specific DST applications.

While many prior investigations of TP accuracy have been undertaken (e.g., [13-15]), these have focused on specific DST applications with results not easily cross-comparable to other applications. This activity will analyze the dominant factors to trajectory prediction uncertainty and document the effect in a manner facilitating cross-comparison of results. Initial results and discussions of this initiative can be found in [16].

Evaluation of Performance-Modeling Approaches

Various trajectory prediction approaches have been applied to ATM problems from physics-based to parametric and empirical approaches. The ATM community does not currently have a standardized, objective means for determining which type of TP approach is fit for purpose. As an example, tradeoffs between speed, accuracy and cost should be taken into account.

This initiative seeks to provide a means for objective evaluation of aircraft performance modeling approaches. Various modeling approaches will be evaluated against a broad set of metrics relevant to various applications relying on TP. As part of this initiative, metrics for aircraft performance evaluation will be developed. A discussion of metrics to aircraft performance validation can be found in [17].

Requirements for Aircraft Performance Data

Trajectory predictors will often rely on aircraft-performance model data obtained from aircraft manufacturers. In addition to being tailored to specific TP needs, it can be difficult to impossible for individual organizations to obtain the requisite data from aircraft manufacturers. Confidentiality concerns further limit the ability of one organization from sharing data with other organizations.

This initiative seeks to produce a complete and consistent specification of aircraft performance data that is needed from the aircraft manufacturers to drive the aircraft performance modeling and validation process. Additionally, this may seek to produce a complete and consistent specification for the data required from aircraft operators needed for the modeling of airline operating procedures.

Comprehensive TP Validation Reference Data Set

Organizations currently lack a standard set of reference data and methods to evaluate the performance of their specific predictors under known conditions. Resources must be expended to either collect new validation data, or adapt existing data to validation of their TP. The adaptation of existing data can be costly due to the need to obtain, understand, format, and augment data typically tailored for alternative applications.

This initiative seeks to develop and provide a standardized set of validation data and methods for the application of that data to the TP validation problem. A set of reference trajectories will be designed, collected and analyzed suitable for the validation of trajectory predictors. The provided data is to include the necessary information (e.g. environmental, intent) applicable to the conditions under which the reference trajectory was established. This information will be made available from a remotely accessible data base server using standard internet protocols. Descriptions of the validation methodology and data can be found in [18, 19].

Assessment of the Operational Application of ATM Constraints

This initiative seeks to design and conduct an operational assessment of the type and frequency of "ATM constraints" and the conditions under which they are applied or excluded. These represent the constraints that the ATM system imposes on the trajectories such as crossing restrictions (altitude, speed, and/or spacing at a point), and restrictions that are imposed by the controllers (e.g. in response to letters of agreement between ATC facilities). The assessment will organize a statistically significant sampling of typical regions of US and European airspace.

Comprehensive Operational Assessment of Intent Prediction Errors

Long term trajectory prediction accuracy is driven by knowledge of the intent of the aircraft. Typically this includes altitude, speed and lateral path information, but may also include information on control modes. This initiative seeks to design and conduct a statistically significant operational assessment to determine the distribution of events that can lead to intent errors.

Common TP Structure

In seeking to develop common trajectory prediction capabilities, the first point of the action plan sought to develop a common language. One of the outcomes of this exercise was the development of a common TP structure applicable to a wide range of TP applications.

Motivation and Approach

The common structure was developed in response to conflicting terminology amongst various trajectory predictor (TP) developers. Furthermore, these stakeholders had developed a varied set of trajectory predictors fulfilling differing requirements. As a result the current situation involves a spectrum of TPs providing a collection of processes and services that may or may not be encapsulated within what each developer calls a "TP".

All of the above disparities had led to a climate previously inhospitable to discussions between TP developers. However, the development of a common TP structure provides the first step towards reconciling these differences by defining a generic framework from which any current and envisaged TPs may be described. By developing, *and agreeing to*, a common TP structure, developers can communicate without debate over the definition of "what constitutes a TP". The common TP is described by a collection of processes and services that may or may not be included in a specific TP. For example, certain services may have been included in one product described as a TP, whereas a different TP product may have embedded these services in an external decision support tool.

The trajectory predictor structure presented in this paper (Figure 1) was developed by comparing several existing trajectory predictors, identifying aspects found to be common and combining them into a single yet flexible logical structure consistent with all existing TPs. Once the structure was developed, it was presented at [20]. Consensus was achieved on the part of participating European and US experts in ground and airborne automation that the structure was consistent with existing TPs, including airborne applications. Although past attempts have found it a challenge to relate one TP to another, this structure lends itself as a generic link between any two TPs.

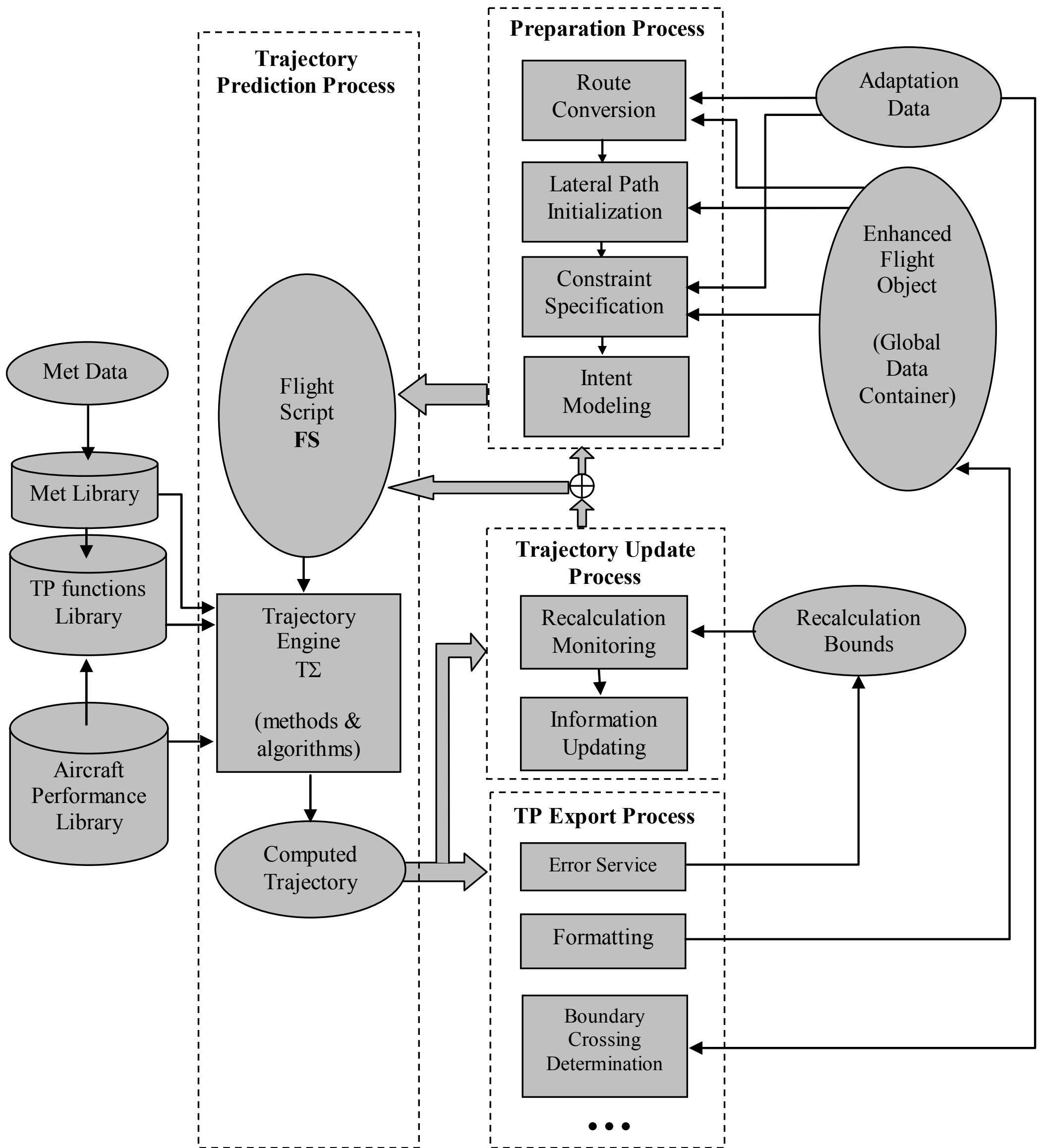

Figure 1. TP Structure

Processes

The following four processes characterize the trajectory predictor:

Trajectory Prediction Process

The Trajectory Prediction process constitutes the kernel functionality of the Trajectory Predictor. The Flight Script contains a description of the way the aircraft will be operated, including the tactical and procedural ATC constraints. The Trajectory Engine integrates this intent information into the 4D trajectory using the predicted information of the atmospheric conditions and an estimate of the performance of the aircraft. One can consider the flight script as the "data" and the engine as the "methods". Consequently, the TΣ and flight script are highly customized and interdependent.

The data structure of the flight script can be described by the Aircraft Intent Description Model (AIDM) [21]. The flight script is formulated to remove all ambiguity in trajectory intent for the purposes of trajectory prediction. The aircraft intent is formed by the set of *instructions* that the TΣ has to be provided with in order to compute a trajectory that complies with all the constraints and requirements defined by the client application. These instructions define how to compute a turn, or how to execute a climb (i.e., the operational constraints on the trajectory segments to be modeled as well as the criteria for transitioning between trajectory segments). Present TP distributions often use different concepts for the AIDM. This constitutes a major issue for system interoperability that needs resolving.

The Trajectory Engine, TΣ, is the computer process that computes a predicted trajectory using different types of algorithms and integration processes. The trajectory engine combines the altitude, speed and lateral trajectory specifications into one unified trajectory. This may be accomplished through a variety of methods such as using trajectory break points, or a mapping of the vertical profile onto the lateral path. The TΣ will access meteorological databases and aircraft performances databases to either compute the impact of met and aircraft performance, or to request the impact directly. Different approaches to aircraft performance modeling exist, e.g., a kinetic model would compute the vertical speed from basic forces, whereas a kinematic model would deliver the vertical speed for a specific operating condition directly.

Preparation Process

The preparation process builds the Flight Script. It is activated the first time a trajectory needs to be computed. Input data needs range from flight plan, aircraft operating procedures, ATC constraints and procedures to now/forecast of atmospheric states and aircraft performance. As currently envisaged, these data may be transported via System Wide Information Management (SWIM).

Trajectory Prediction Update Process

The process of updating the flight script in response to evolving information. Some TPs may do this according to a wall clock as new state and intent data become available, others in response to events such as conformance monitoring or availability of new constraint information, like an updated Required Time of Arrival at a future waypoint. The update process may result in the generation of a new flight script by triggering a new preparation process or it may only modify information.

A practical implementation of a trajectory predictor can be envisaged that does not include a TP update process. Such implementation will require the TP client to perform the necessary trajectory services. Adaptive trajectory predictors may use the update process to alter the models used by the trajectory prediction engine. Automatically updating trajectory predictors result in the update process "zeroing" out any errors that have accumulated since the previous trajectory prediction for a flight.

TP Export Process

This collects all the "output" services of the trajectory predictor and makes the predicted trajectory data available to the TP client applications.

Services

TP-Related Services represent the abstract functions that are typically related to trajectory prediction. For example, route conversion is considered a TP-related service, since this is a common service that must be provided in many trajectory prediction processes. Services may exist prior to, during and after the calculation of a specific trajectory. Through discussions with experts familiar with a variety of existing TPs, the following common services have been identified:

1. **Route Conversion** – This service translates a route, a series of airways and waypoints, into a series of latitude and longitude points. Preferential routes may be applied by this service.
2. **Lateral Path Initialization** -- This service determines the path from the present position to the route.
3. **Longitudinal and Vertical Constraint Specification** – This service determines needed flight plan constraints. Constraints include assigned altitude and speed, altitude, speed and time restrictions, and interim altitude.
4. **Longitudinal Intent Modeling** – This service specifies how the aircraft will fly, given all available information. For example climbs may be conducted at constant power with loop closure on climb rate or speed. Longitudinal intent modeling covers both speed and vertical degrees-of-freedom. Intent modeling may be explicit, or implicit in the trajectory models.
5. **Altitude, Speed and Turn (if applicable) Modeling** – This service is contained in the trajectory engine.
6. **Boundary Crossing Determination** – This is the service of identifying the points where the computed trajectory crosses specific volumes of airspace. This service operates after the trajectory has been computed.
7. **Formatting** – This is the service of packaging a predicted trajectory for the requisite client application.
8. **Recalculation monitoring** – This service monitors information to determine if a new trajectory must be calculated. One approach monitors the trajectory prediction errors to determine if re-conformance is required. (Note this is distinct from the conformance monitoring function performed by the controller to monitor flight plan conformance.) This service requires the specification of a recalculation bound which may be an error tolerance, or a time step depending on the form of the monitoring.
9. **Trajectory Information Updating** – Trajectory information updating is the initial step required to re-calculate a trajectory when indicated by the recalculation monitoring service. This may be accomplished through modification of the flight script, or through initiation of a new preparation process. The updating of information is critical for automatic trajectory updates and adaptive trajectory predictors as described under the *Update Process.*
10. **Trajectory Error Service** – This service monitors the aircraft state and prior predictions to provide measures of trajectory prediction accuracy. These may be used by the recalculation monitoring service. Depending on the design of the trajectory predictor, this service may provide data such as: a trajectory prediction error, a forecast error, historical errors, or error thresholds.

As an example of the application of the above services, the matching of required times of arrival (RTA) would compare the predicted time and flight conditions at a specific trajectory point with a target value. The trajectory error service would provide the time error. The recalculation monitoring function would determine if the error is large enough to warrant an update of the flight script.

Practical Benefits of the Structure

The benefit of improved communication between developers has already been mentioned. However, once the structure was adopted, it has become a useful starting point for discussions on a variety of other subjects such as interoperability, validation and metrics.

The service-oriented decomposition of the TP has allowed stakeholders to discuss common capabilities of TPs without the necessity for a "plug-and-play" decomposition. Through common TP services, required capabilities and performance of those capabilities can be discussed. This provides the first step towards developing interfaces *when it would prove beneficial to do so*. For example, one common service such as route conversion may be a required service for a multitude of applications beyond the TP. The identification of applications requiring (or currently containing) this service would be a first step in providing harmonized route conversion services with uniform quality.

While the decomposition facilitates the harmonization of services, it is not required that all applications requiring TP services share identical implementations of those services. Thus, an application requiring very high-fidelity constraint specification may request these services from a different provider than other applications. These other applications may have stringent computational speed performance requirements necessitating fast constraint specification with lower fidelity.

The common TP structure has enabled Action Plan 16 to move forward with the development of a validation methodology, a collection of common validation reference data sets and ultimately the development of a validation platform applicable to a wide variety of TPs. Given the difficulty and expense of obtaining, scrubbing and analyzing validation data, the provision of data sets is beneficial to a multitude of TP developers and users. The development of a validation methodology indicating the applicability of different data types to different TP services facilitates the validation effort. Furthermore, it enables developers to focus on the specific services requiring improvement.

The service-oriented decomposition and validation of the TPs enables the definition of quality-of-service metrics for each service. These services may be required by multiple applications each with differing performance requirements. The framework enables the validation and performance measurement of individual services, resulting in significant savings in development time and cost for new applications. Furthermore, system performance improvements can sometimes be obtained through the substitution of higher-quality services.

Moreover, where a common TP service is appropriate for use by multiple TPs, stakeholders will reap benefits of scale that both minimize and distribute the costs for the design, development, validation, implementation, and maintenance of the common TP service/capability over a broad set of clients. It is difficult if not impossible to argue for the unique and custom development of every TP service/capability across all TPs when significant cost savings can be gained from at least sharing some services/capabilities in common.

This structure and associated benefits apply to both air and ground TPs. When presented at the FAA/Eurocontrol Technical Interchange Meeting (TIM-2) on Common Trajectory Prediction, industry experts in both ground and airborne automation agreed that the presented structure is equally applicable to their products.

The encapsulation of the Flight Script and Trajectory Engine in the Trajectory Prediction process identified the Flight Script as a suitable interface for purpose of synchronization of air and ground trajectory predictors. Lesson learned from early experiments using 4D trajectory negotiation indicated that identical 4D trajectories can be generated from different Flight Script contents if different meteorological estimates were used in the air and ground systems. This is a significant safety issue. Synchronizing the content of the Flight Script, rather than the output of the Trajectory Prediction process, is a possible way forward way to mitigate this problem.

As an example of practical benefits, in a recent study being [22] performed by the FAA at the William J. Hughes Technical Center, the TP requirements for four DST's were examined using the TP structure. The framework provided a generic model in which to decompose these four TP's services and compare their requirements. These requirements differed tremendously due to the disparate functional requirements in their DSTs and alternative approaches taken by the developers of each TP. In conclusion, the analysis indicated areas of commonality and thus opportunity to leverage limited system resources contrasted with the areas where the four TPs had significantly different implementations and resulting nonfunctional requirements.

As in the study just described, Air Service Providers, faced with increasing demand and ever shrinking resources, will continue to examine their current DSTs to uncover opportunities where TP services can be combined and/or shared. The framework provides an internationally agreed upon model that not only fosters this type analysis but makes it possible.

Future Efforts

This paper describes ongoing efforts seeking to develop common trajectory prediction capabilities. Recent activities have been focused on:

- the development of a report describing the sensitivity of trajectory prediction accuracy to high-impact factors,
- the development of metrics for the evaluation of aircraft performance modeling data quality,
- the development of software to assist users in the evaluation of aircraft performance modeling data,
- the provision of a set of reference data for the purposes of trajectory prediction validation, together with a methodology for the application of this methodology,
- the development of a metrics framework and taxonomy of metrics for TP evaluation, and
- the development of a TP test harness for the purposes of evaluating specific TP applications against the validation data sets

While these activities do not represent the full gamut of all 9 proposed initiatives, the completion of the above will provide future TP developers with a common set of capabilities. These will facilitate the testing and validation process, along with providing the common language and technical measures for building performance requirements and comparing differing TP approaches.

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24th Digital Avionics Systems Conference
October 30, 2005