FAA/EUROCONTROL COOPERATIVE R&D

ACTION PLAN 16: Common Trajectory Prediction Capability

Generic Trajectory Predictor Structure

EXECUTIVE SUMMARY

This paper describes the common trajectory predictor structure developed by the FAA/Eurocontrol Action Plan 16 – Common Trajectory Prediction Capabilities. While originally developed for the purposes of resolving some terminology difficulties between various TP developers, additional uses of this structure have become apparent. In particular:

1. The ability to efficiently discuss TP capabilities with a common understanding, avoiding the previous pitfalls of miscommunication and endless debate on the definition of trajectory prediction related terms.

2. The decomposition into services enables the harmonization of services provided by disparate TPs where it is beneficial to do so. This approach still allows for a variety of TPs to use or bundle different combinations of services where required.

3. This structure applies 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.

4. The structure supports common validation efforts, including methods, reference (benchmark) data sets and the development of a validation platform. The result significantly reduces stakeholder time and cost for TP validation and may facilitate "apples to apples" comparisons across various TPs.

5. The decomposition into services facilitates the definition of consistent performance metrics for each service. Moreover, the use of common services offers stakeholders benefits of scale that both minimize and distribute the costs across the lifecycle over a broad set of clients.

Motivation and Approach

Under the auspices of the FAA/ Eurocontrol Action Plan 16 – Common Trajectory Prediction Capabilities – a "common" trajectory predictor structure was developed. This 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 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 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 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 a technical interchange meeting (TIM) sponsored by Action Plan 16 (C-TP TIM/2, Toulouse, December 2004). 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.

Applications Dependent on TP

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.
- 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 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. 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.
- Sequencing & Metering – Trajectory prediction is required to estimate the arrival time of aircraft at a specified location and generate desired schedule times of arrival.
- Conflict-free Metering Conformance – Trajectory prediction is critical to provide tactical control advisories to achieve required times of arrival with conflict-free trajectories.
- Flight Management – The ability for flight crews to plan and execute 4D trajectories is critical to many future ATM concepts.

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. Examples of these advisories include: conflict resolution, metering, sequencing and merging advisories.

Common TP Structure

A Trajectory Predictor generates an aircraft's forecast trajectory, typically for client applications. The TP is associated with four distinct and closely related processes, the core of which is the trajectory prediction process (see Figure 1). Several of the processes can be further decomposed into "services" (see Figure 2) previously described in the FAA Research Management Plan (RMP) on Common Trajectory Modeling[1 2]. In practice, few, if any, organizations/TP developers (across the globe) aggregate these processes and services consistently. Although Figure 1 provides a universal TP framework, individuals may only be referring to a subset of processes when discussing TP. It is critical, when discussing trajectory prediction, to be clear what processes/services are assumed to be included in "TP".

[1] FAA/NASA Interagency ATM Integrated Product Team Cross-Cutting Area Work Team. *Common Trajectory Modeling Services for NAS Decision Support Tools – Research Management Plan*. May, 2002.
[2] Lindsay, K., Green, S., Mondoloni, S., and Paglione, M., *Common Trajectory Modeling for National Airspace System Decision Support Tools*. ATC Quarterly, 2005.

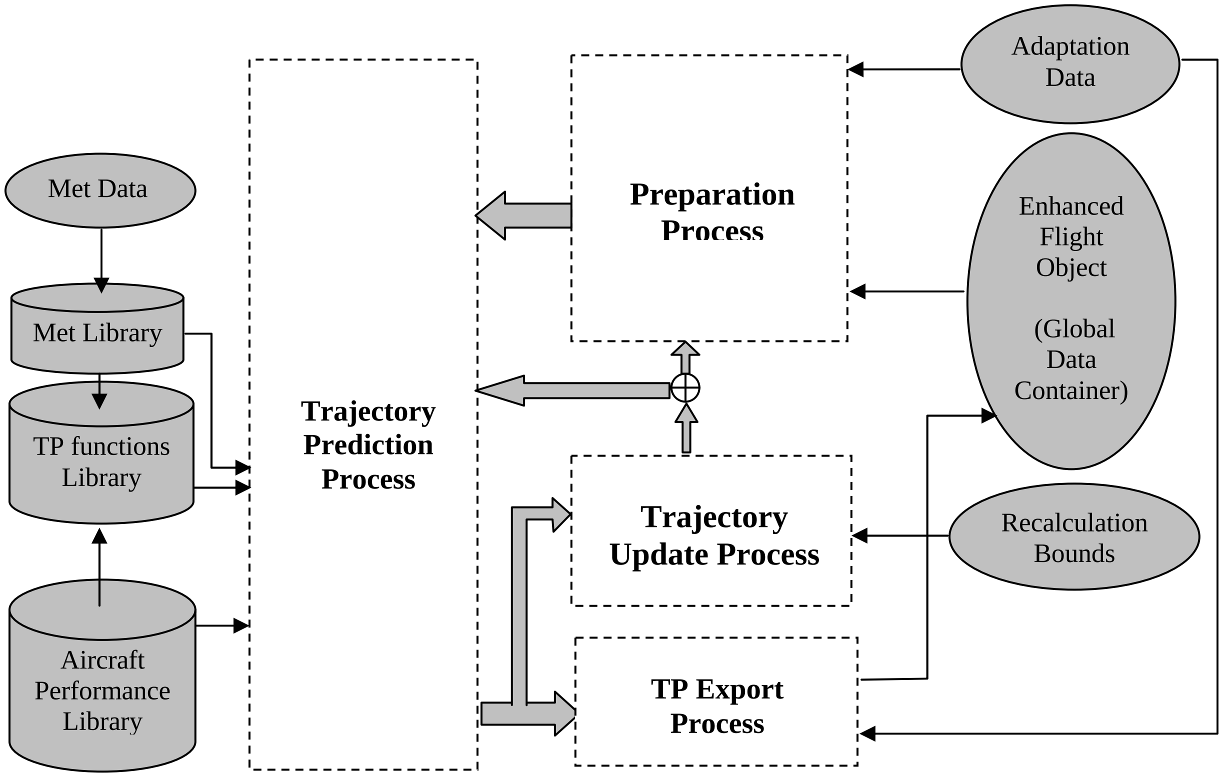

Figure 1. Trajectory Predictor (TP) Related Processes

The following four processes characterize the trajectory predictor:

Preparation process – The process of creating the initial version of the *flight script* (defined below). This process is activated the first time a trajectory needs to be computed for a flight. Input data needs range from flight plan, airline operating procedures, ATC constraints and procedures to now/forecast of atmospheric states and aircraft performance. As currently envisaged, this data may be transported via System Wide Information Management (SWIM). The service will concatenate the data and build a flight script describing the flight segment(s) being predicted.

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. The update process may result in the generation of a new flight script, or it may modify information and trigger a new preparation process. Externally updated trajectory predictors do not involve an update process, whereas automatically updated trajectory predictors do. Adaptive trajectory predictors 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.

Trajectory Prediction Process – This is the trajectory engine calculation using the information contained in the flight script. Since the interface between the flight script and the TΣ is highly customized and interdependent, these elements are grouped into the trajectory predictor process. From an object-oriented view, the flight script is considered as the data and the engine as the methods.

TP Export Process – This collects all the "output" services of the trajectory predictor.

The preparation process creates a data element called the flight script. The flight script contains all the flight-specific data required by the Trajectory Engine (TΣ) to compute a trajectory. The flight script is formulated to remove all ambiguity in trajectory intent for the purposes of trajectory prediction. The flight script includes "instruction" type data such as 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). Consistency must be ensured between the flight script and the engine so that the engine supports all instructions commanded by the script.

The flight script is used by the trajectory engine (TΣ), the core of the trajectory prediction process. The TΣ is the computer process that computes a predicted trajectory using different types of algorithms and integration process. All the data specific to an individual trajectory prediction is identified within the flight script.

The TΣ will also access meteorological databases and aircraft performances databases. These databases are used by the TΣ to either compute the impact of met and aircraft performance, or to request the impact directly. For example, a kinetic model would compute the vertical speed, but a kinematic model would obtain the vertical speed for a specific condition.

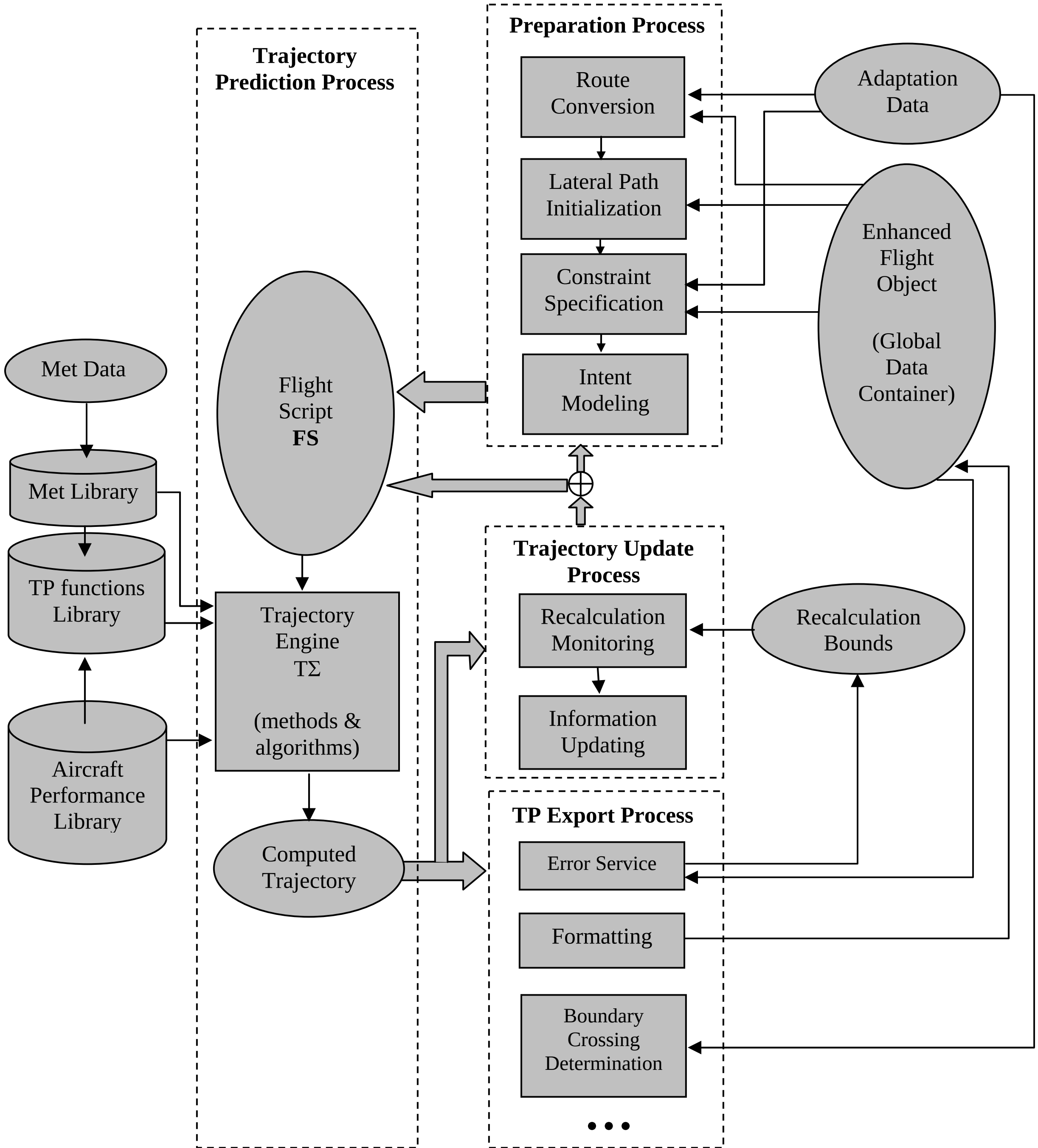

Figure 2 represents a schematic view of the TP structure

The trajectory engine also 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.

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.

Practical Benefits of the Framework

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 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.

As an example of practical benefits, in a recent study being performed by the FAA at the William J. Hughes Technical Center, the TP requirements for four DST's were examined using the TP structure[3]. 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.

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[3] Lowe, T., Schwartz, A., Timoteo, B., Lanier, R., Paglione, M., *Survey of the Trajectory Predictor Requirements of Selected Federal Aviation Administration Decision Support Tools*, FAA WJHTC, (Draft v1.8), January 31, 2005.