A Representation of Air Traffic Control Clearance Constraints for Intelligent Agents

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Abstract—**This paper presents an object-oriented representation of environmental constraints that are conveyed by air traffic control (ATC) clearances. It presents background research, describes the representation, and discusses how it enhances context representation in an intelligent agent called the Crew Activity Tracking System (CATS). The paper also discusses implications of such a representation for related intelligent agent research in the aviation domain.**

Keywords: **Environmental constraints, ATC clearances, intelligent agents, representation.**

I. Introduction

Environmental constraints play a key role in defining the goals that shape worker behavior in complex sociotechnical systems [14]. In aviation today, for example, flight crews act to meet goals derived from environmental constraints in the form of air traffic control (ATC) clearances. Air traffic controllers formulate the clearances they issue in accordance with environmental constraints imposed by the current air traffic situation.

An important area of research addresses the development of intelligent agents that act to perform various functions in both real and simulated complex systems. The 'intelligence' of such agents hinges on their ability to act in a 'context-aware' manner. Context awareness is difficult to characterize, largely because 'context' is a multi-faceted term (see [1]). It is often used to mean the current 'situation,' which may in turn be comprised of the current system 'state,' and so on. This paper defines context, from a human operator's perspective, to be the situation plus any activities the operator is engaged in performing. The situation is defined as the system's state, together with environmental constraints and all salient relationships between the state and constraints. Each of these elements is additionally considered to have historic, current, and planned (or predicted) future components, and be decomposed hierarchically at multiple levels of abstraction.

This paper focuses on the role played by environmental constraints in this formulation of context. It specifically examines environmental constraints imposed by ATC clearances, and presents an explicit object-oriented representation of ATC clearance constraints suitable for use by intelligent agents in the aviation domain.

II. Crew Activity Tracking System

One computer-based system that uses a normative model of preferred operator activities as the basis for several types of intelligent agents (depending on the specific model and how it is processed) is the Crew Activity Tracking System (CATS). In the aviation research domain, CATS has proven useful as a tool for visualizing and analyzing pilot performance [6], and as an agent capable of simulating aspects of pilot and air traffic controller procedure execution [2]. CATS could also anchor an intelligent aid or tutoring system [4].

Like all human-machine system models, regardless of application, a CATS model benefits from a representation of context that is of the highest possible fidelity (see [3]). A high fidelity context representation captures nuances that make one context subtly different from another. This enables CATS-based agents to use 'richer' models to 'understand' or simulate operator behavior.

CATS flight deck activity tracking applications have long relied on a representation referred to as the 'limiting operating envelope' to capture the set of constraints that bind flight operations [7]. In the absence of a clearance, an aircraft's trajectory is constrained (vertically, in this example) by the operating ceiling above and the terrain below. As the aircraft maneuvers, constraints related to performance limits like climb or descent rate bound the trajectory. And in current day operations, ATC clearances impose another set of constraints on the required trajectory. These ATC clearance constraints typically constitute the binding (or 'limiting') constraints.

The representation of ATC clearances this paper presents enhances the CATS limiting operating envelope representation and defines how various clearances modify it, so that constraints imposed by new ATC clearances are reflected in an integrated manner. The paper also discusses how the representation can be used in a system like CATS to record compliance information, and to make predictions about required future activities.

The remainder of the paper is organized as follows. It first provides background on previous work to represent how ATC clearances convey constraints. It then describes a representation of ATC clearance constraints, and discusses how it is used to enhance context awareness in a CATS application designed to detect flight crew errors from flight data [5]. It concludes with a discussion of how the representation could convey flight crew intent, and how intelligent ATC agents under development can benefit from an explicit representation of environmental constraints imposed by ATC clearances.

III. Background: Representation and Use of ATC Clearances in Intelligent Agents

Adequately representing the context relevant to a flight crew requires an examination of how ATC clearances convey environmental constraints. This is not a new assertion. Wagner and Curry [16] performed an analysis of ATC clearance constraints as part of early research on developing intelligent agents to support flight crews. Their expressed purpose was to:

> "explore the feasibility of general flight plans in computer compatible forms to support goal understanding systems, and to explore the feasibility of an ATC language interpreter which would modify the flight plans based on ATC language [16, p. 15]"

They recognized that the 'general flight plan' representation would not only need to capture what the aircraft plans to do, but also what it is actually doing as a result of 'temporary' clearances (e.g., heading vectors that take the aircraft off its filed flight plan). The representation would then provide the 'coverage' an intelligent agent would require.

For their representation, Wagner and Curry proposed 'frames' (after [9]) to represent the horizontal and vertical components of a flight plan. The frames contain "objectives/target variables," "constraints," and "terminating conditions/ continuations" that define the "logical end" to a frame. The representation also includes frames that represented horizontal transitions; it does not include transitions in the vertical dimension. Fig. 1 shows the first few frames of Wagner and Curry's example of a Standard Instrument Departure (SID) from the Paris Charles de Gaulle airport, as presented in [16].

In addition to representing a static flight plan, such as that specified by a SID, Wagner and Curry also sought to cast ATC clearances into a pattern of "VERB, OBJECT/VALUE, CONSTRAINT/RESTRICTION," and examine how the proposed frame representations would be modified dynamically, given ATC directives of this form. They investigated how this might be done for a variety of clearances. They further envisioned that, in the future, clearances of this form might be data-linked to an aircraft, where an intelligent system would modify the so-called 'general flight plan' and use it for goal understanding in order to assist the flight crew. The literature, however, reveals no indication that the ATC clearance representation portion of their research progressed beyond that reported in [16].

IV. ATC Clearance Representation

A representation of environmental constraints derived from ATC clearances was developed for use in CATS by extending the research in [16]. Context in CATS has a 'situation' portion comprised of the constraint representation, together with system state information. This section describes the ATC clearance constraint representation; the two following sections illustrate how the representation is instantiated in CATS, and how ATC clearances modify the representation.

Fig. 2 shows the class hierarchy of 'frame objects' used, and Fig. 3 shows important contents of each object class. The representation includes three dimensions of constraints— vertical, lateral, and speed—and transition frames for each dimension. The basic constraint classes are designed to represent 'steady states' the flight crew should maintain, and transition classes represent required changes in the vertical, lateral, or speed dimensions.

Because of the importance of flight management system (FMS) routings, constraints are annotated with 'references' to any such named routings. Constraints also have a 'source' field useful for specifying whether the constraint derives from a filed flight plan, regulations, an ATC clearance, aircraft performance limits, or (looking ahead to operations where separation responsibility is delegated to the flight deck, e.g., [15]) pilot preferences. Constraints in each dimension contain information about the values they constrain; transitions contain both 'from' and 'to' values. For example, a lateral transition to turn from an intercept heading to intercept an FMS route would have values for 'from heading' and 'to track.' A Mach-to-calibrated airspeed transition similarly has 'from Mach' and 'to speed' values.

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                    ****** HORIZONTAL FRAMES ******

START:          RUNWAY HEADING 269 Magnetic
                +/- XWIND EFFECT ON AIRCRAFT HEADING AT TAKEOFF
FRAME H001
                VARIABLES/OBJECTIVES:     MAINTAIN HEADING 269 Magnetic
                CONSTRAINTS:
                TERM. CON.:               UPON REACHING 5.5 DME CDG OR
                                          UPON CROSSING 050 BT --> H002
FRAME H001.TRANSITION
                INITIAL CONDITION:        HEADING 269 Magnetic
                TRANS. TARG. VAR.:        TURN AIRCRAFT TRACK TO THE RIGHT
                FRAME TRANSITION:         STOP TURN TO INTERCEPT 322R FROM BT
FRAME H002
                VARIABLES/OBJECTIVES:     MAINTAIN 322R BT FROM BT
                CONSTRAINTS:
                TERM. CON.:               UPON REACHING 8.5 DME BT --> H003
FRAME H002.TRANSITION
                INITIAL CONDITION:        ON 322R BT FROM BT
                TRANS. TARG. VAR.:        TURN AIRCRAFT TRACK TO THE RIGHT
                FRAME TRANSITION:         INTERCEPT 320R CDG TO CDG
FRAME H003
                VARIABLES/OBJECTIVES:     MAINTAIN 320R CDG TO CDG
                CONSTRAINTS:
                TERM. CON.:               UPON REACHING CDG --> H003

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                    ****** VERTICAL FRAMES ******

FRAME V001
                VARIABLES/OBJECTIVES:     IAS=V2 + 10
                                          THRUST=T/O THRUST
                CONSTRAINTS:
                TERM. CON.:               1000FT AGL --> V002
FRAME V002
                VARIABLES/OBJECTIVES:     IAS=290
                                          THRUST=CLB THRUST
                CONSTRAINTS:
                TERM. CON.:               FL120 --> V003
                                          UPON REACHING 7 DME FROM CDG --> V004
FRAME V003
                VARIABLES/OBJECTIVES:     IAS=290
                                          ALTITUDE=FL120
                CONSTRAINTS:
                TERM. CON.:               UPON REACHING 7 DME FROM CDG --> V004
FRAME V004
                VARIABLES/OBJECTIVES:     IAS=290
                                          THRUST=CLB THRUST
                CONSTRAINTS:
                TERM. CON.:               UPON REACHING FL190 --> V005

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Fig. 1. Excerpt of frame representation of ATC clearance constraints [16, Table 1].

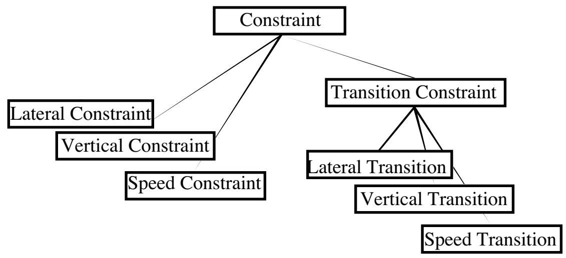

Fig. 2. Object class hierarchy for ATC clearance constraint representation.

Links between the constraints are another important feature of the representation. Constraints are linked sequentially within each dimension, and may also be cross-linked between dimensions, when constraints in different dimensions are associated with one another. An example of this is when a navigation fix in the lateral dimension has a speed and altitude restriction associated with it. In this situation, the lateral node that represents tracking to the fix is cross-linked with both a speed constraint representing the speed restriction and a vertical constraint representing the required crossing altitude. The next section provides examples of the representation as it is used in CATS.

V. Enhanced CATS ‘Limiting Operating Envelope’

CATS implements the representation to enhance the fidelity of the constraints that make up its ‘limiting operating envelope.’ Fig. 4 depicts an example. The bottom portion of Fig. 4 is a continuation of the top; for both portions, the top row represents constraints in the vertical dimension, the middle row the lateral dimension, and the bottom the speed dimension. The whole of Fig. 4 depicts a ‘limiting operating envelope’ as it exists for the aircraft just after takeoff. ATC has already issued an ‘after takeoff’ clearance to the aircraft (“turn left heading 010, climb and maintain 12,000 feet”), so the active vertical constraint is “CLIMB_TO_12000,” the active lateral constraint is “TURN_TO_HDG_010,” and the active speed constraint is “MAINTAIN_CLIMBOUT_SPDS.” As the aircraft meets each *next* constraint—or attains a state that indicates when a transition constraint (gray in Fig. 4) should become active—CATS updates the set of active constraints. The constraints shown in Fig. 4 are those that are known at the current time; ATC clearances that will be received later are required to form an ‘unbroken’ sequence of constraints. The representation uses placeholder constraints (e.g., “<VECTORS_TO_FILED>”) to complete the sequence for the time being. Constraints that the aircraft must meet for the approach are also currently unspecified in this example, and will be added when the approach clearance is received.

This representation affords CATS several advantages. First, in earlier versions, CATS represented constraints on target headings, altitudes, and speeds as ‘point’ values, distinct from constraints defined by programmed FMS routes. FMS route constraints separately represented navigation fixes together with any crossing restrictions. Among the difficulties with this approach is determining when one constraint entered the currently binding (limiting or ‘active’) set, and another left. For example, a required turn to track to a specified fix might not, in reality, be temporally associated with a requirement to achieve the crossing altitude; the turn might need to be accomplished first, followed later by the climb or descent

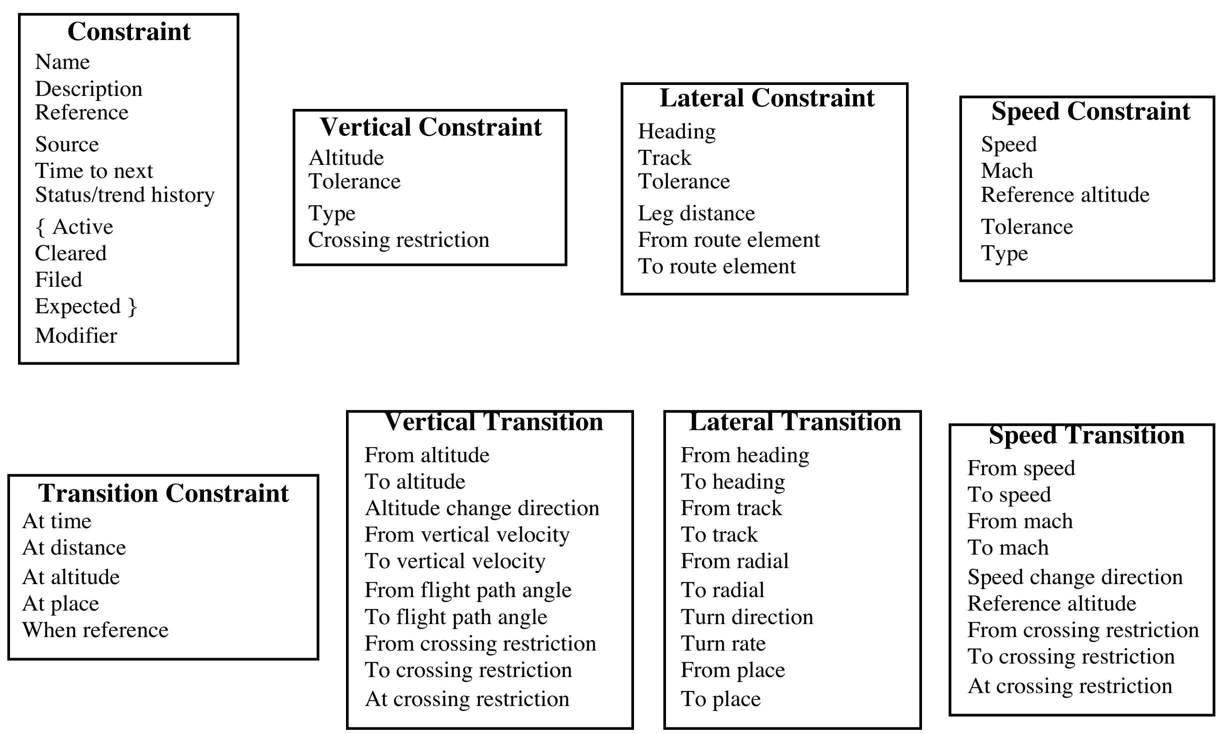

Fig. 3. Important constraint object contents; contents are inherited according to the object class hierarchy.

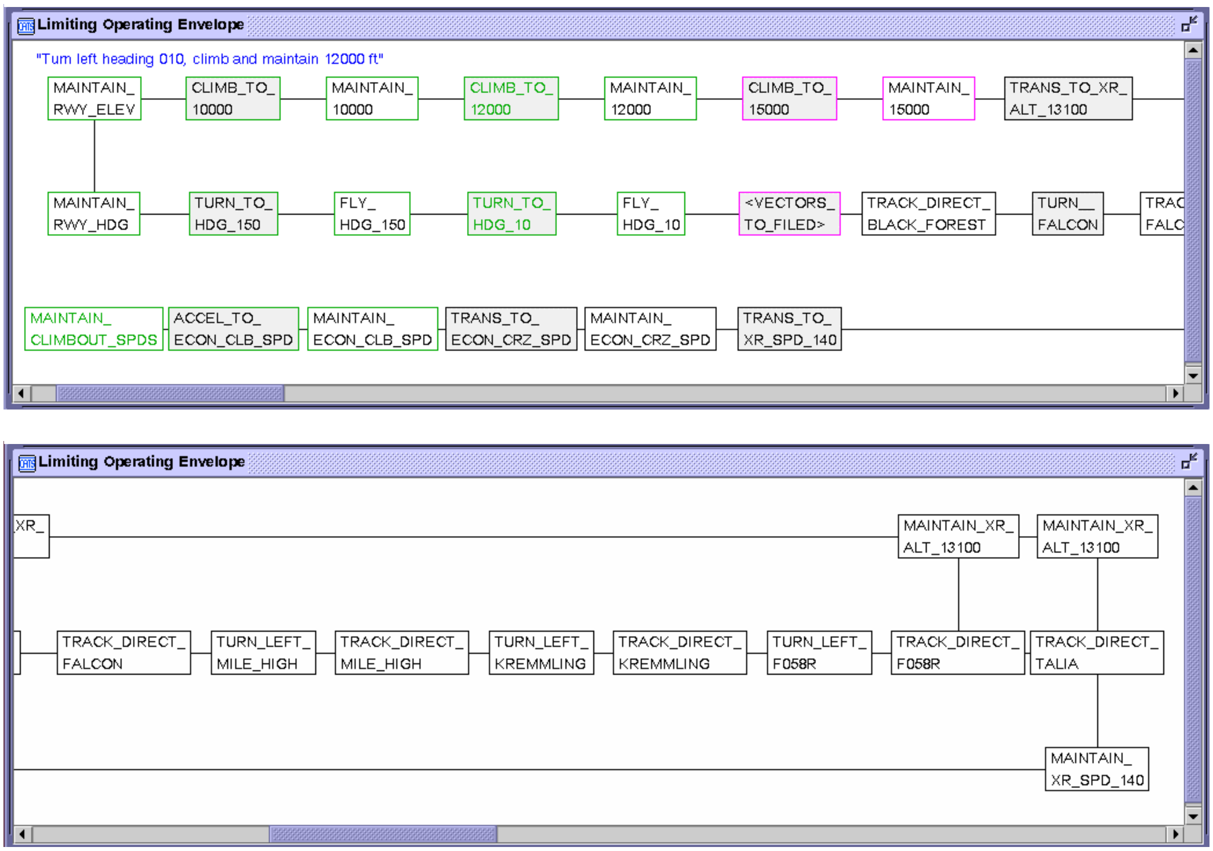

Fig. 4. Example of the ATC clearance constraint representation in CATS; clicking the mouse on a particular constraint pops up a window that displays its contents.

to the crossing altitude. The current representation solves these problems by dissociating the constraints in the vertical, lateral, and speed dimension while still keeping them linked, so that during processing, the relationship of a crossing constraint to a ground-referenced fix is still evident (e.g., the crossing restriction at TALIA in Fig. 4). Most importantly, temporary modifications to the planned route are inserted into the overall route, to explicitly represent how the planned route might be rejoined.

A second related advantage stems from the capability to make temporal predictions using the representation. Because constraints can contain information about when they become active (e.g., 'at place' or 'at altitude'), CATS can invoke models of climb or descent rate, or simple computations based on ground speed, to determine the time until a constraint will enter the active set. The capability to project constraint information into the temporal domain enables CATS to determine whether, for example, there is enough time to successfully employ a particular method for accomplishing some function. For example, a crossing restriction can be met by appropriately programming the aircraft's Flight Management System, but this takes time; if a new ATC-specified crossing restriction is too close, quickly adjusting speed and/or altitude targets using the aircraft's Mode Control Panel makes more sense. In the error-detection application described below, this 'temporal projection' capability enables CATS to determine when a required activity has been omitted in context-specific fashion. Rather than setting an arbitrary time as the threshold for determining that the flight crew has omitted an activity, CATS can base its determination on the time available to meet the associated constraint.

A third advantage concerns recording compliance information (using the 'status/trend history' contained in a constraint object) within the representation itself. If a constraint is violated during the time it is 'active,' an analyst can easily inspect this information by clicking on the constraint in question. Compliance information enhances the overall fidelity of the context information available in CATS.

VI. ATC Clearance Input and Translation

For applications that run 'live' (such as when CATS is used to analyze flight crew performance online [6]), a means for modifying the ATC constraint representation dynamically is needed. Fig. 5 shows a prototype control panel constructed for this purpose. The control panel enables an analyst to compose the majority ATC clearances identified in [8], together with some that have been developed for use in novel air traffic management concepts (e.g., [12]). The panel enables individual clearance components to be selected or entered; check boxes indicate which pieces comprise the current clearance. Once it is composed, the "ISSUE" button sends the clearance to CATS, which uses a rule base to determine

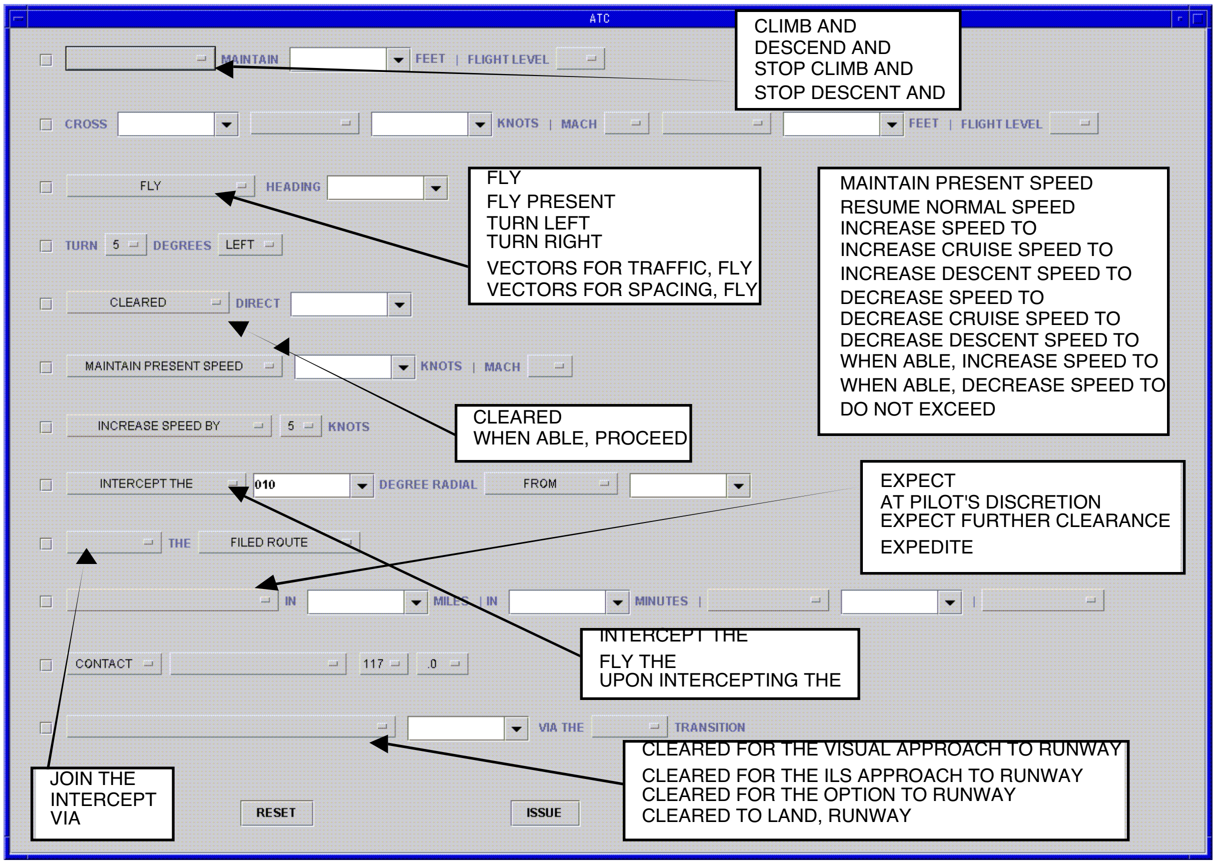

Fig. 5. Prototype control panel for formulating ATC clearances (boxes show hidden drop-down menu contents).

how to insert or delete constraints from the current representation to reflect the clearance.

VII. Discussion

A. Pilot Error Detection via Activity Tracking

The representation of ATC clearance constraints presented was effective in a recent application of CATS for offline detection of flight crew errors from flight data [5]. Actual flight data were obtained from the NASA Langley Boeing 757 Airborne Research Integrated Experiment System (ARIES) aircraft. These data were supplemented with observations of the actual ATC clearances received during each flight. A data server with event filters was developed to provide CATS with aircraft and autoflight system state data, together with detected crew actions and the observed clearances. CATS used the clearance information to construct and update a limiting operating envelope of the form described above. CATS tracked flight crew activities, and successfully detected some minor procedural deviations involved with autoflight system usage.

B. Constraints for Conveying Pilot Intent

Knowing the constraints under which an operator is working now and will be working in the future improves one's understanding of the operator's intent. Work on developing requirements for future implementation of Automatic Dependent Surveillance-Broadcast (ADS-B) identifies the importance of representing both programmed trajectory information, as well as tactical information (e.g., assigned heading and altitude) (e.g., [13]). Supplemental information about the current flight mode of an aircraft is also included as a means of communicating the validity of the other intent information. Current development focuses on only the horizontal and vertical flight path dimensions, although speed constraints are slated for future examination. For trajectory information, current development focuses only on the next two trajectory-change points. Thus, the current representation further enhances the detail with which constraint information for an aircraft might be communicated to other agents within the National Airspace System.

C. Constraints for Intelligent ATC Agents

The representation scheme presented here appears also to be valuable for representing context in intelligent ATC agents. ATC agents that use the CATS model framework are currently under development. The agents are designed to control traffic in *en route* airspace (cf. [2]), and coordinate with each other to manage air traffic across multiple sectors. In this application, the constraint representation affords many of the same advantages described above, including a higher-fidelity context representation, the capability to make temporal predictions, and a means of monitoring aircraft compliance with clearances. In addition, the constraint representation provides the ATC agents with much of the same information that real air traffic controllers have

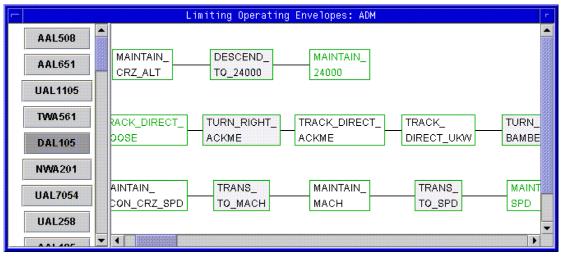

Fig. 6. Constraints for an aircraft as implemented by a CATS-based ATC agent; list at left enables examination of representations for other aircraft.

traditionally recorded on 'flight progress strips' (see [11]). This information is crucial not only for quickly accessing where a flight is going, and how it was most recently cleared, but also for providing this information to the next controller when the controller for an upstream sector 'hands off' the aircraft.

More importantly, the current and planned future constraints on an aircraft are vital for assessing how best to separate it from the surrounding traffic. Without first understanding the routing for each aircraft, a controller cannot reasonably determine how one or another aircraft should be cleared, if at all. For example, two aircraft that appear to be on conflicting trajectories, from inspection of the radar display, may in fact be on routes that never come within the minimum required separation distance of each other. In this case, the controller need not worry about separating the two aircraft, and can direct attention elsewhere. The converse may also be true; thus, some representation of the current and future constraints on each aircraft's trajectory is crucial.

The representation of ATC clearance constraints described here also helps resolve separation issues in the vertical and speed dimensions. Fig. 6 depicts a limiting operating envelope for an aircraft under control of an ATC agent. Thus far, the agent has issued a descent clearance to 24,000 feet, a new Mach and, subsequently, a new airspeed. Current research seeks to develop representations of the current ATC context that consist of the states of the aircraft under control, together with the constraints of each, and salient relations between them (just as CATS does for a single aircraft in a flight deck activity tracking application). This context will enable formulation of CATS models that operate on it to determine how to control aircraft under various strategies. Future research will extend these ATC agent models to simulated future operational environments.

VIII. Summary

This paper described a representation of the constraints imposed by ATC clearances on the trajectories of aircraft. The representation extends early work that sought to devise a representation suitable for developing intelligent agents to support flight crews. The representation is object-oriented, and enables intelligent agents to represent context at a level of fidelity suitable for 'understanding' or simulating operations in a complex flight or ATC environment. One such agent, called CATS, has used the representation to enhance its representation of context to enable temporal reasoning and easily log information about compliance with ATC clearances—capabilities that have proven valuable for flight crew error detection using flight data. The representation also appears promising for developing CATS-based intelligent ATC agents.

Acknowledgements

This research was supported by the System-Wide Accident Prevention element of the FAA/NASA Aviation Safety Program, and by the Advanced Air Transportation Technologies element of the NASA Aviation System Capacity Program.

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