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NORTH ATLANTIC TREATY ORGANIZATION

DESIGN OF CENTER-TRACON AUTOMATION SYSTEM

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SUMMARY

A system for the automated management and control of terminal area traffic, referred to as the Center-TRACON Automation System (CTAS), is being developed at NASA Ames Research Center. In a cooperative program, NASA and FAA have efforts underway to install and evaluate the system at the Denver area and Dallas/Ft.Worth area air traffic control facilities. This paper will review CTAS architecture, and automation functions as well as the integration of CTAS into the existing operational system. CTAS consists of three types of integrated tools that provide computer-generated advisories for both en-route and terminal area controllers to guide them in managing and controlling arrival traffic efficiently. One tool, the Traffic Management Advisor (TMA), generates runway assignments, landing sequences and landing times for all arriving aircraft, including those originating from nearby feeder airports. TMA also assists in runway configuration control and flow management. Another tool, the Descent Advisor (DA), generates clearances for the en-route controllers handling arrival flows to metering gates. The DA's clearances ensure fuel-efficient and conflict free descents to the metering gates at specified crossing times. In the terminal area the Final Approach Spacing Tool (FAST) provides heading and speed advisories that help controllers produce an accurately spaced flow of aircraft on the final approach course. Data bases consisting of several hundred aircraft performance models, airline preferred operational procedures and a three dimensional wind model support the operation of CTAS. The first component of CTAS, the Traffic Management Advisor, is being evaluated at the Denver TRACON and the Denver Air Route Traffic Control Center. The second component, the Final Approach Spacing Tool, will be evaluated in several stages at the Dallas/Fort Worth Airport beginning in October 1993. An initial stage of the Descent Advisor tool is being prepared for testing at the Denver Center in late 1994. Operational evaluations of all three integrated CTAS tools are expected to begin at the two field sites in 1995.

INTRODUCTION

The development of automated systems for optimizing traffic flow in complex terminal areas has been a long standing objective of aviation researchers and planners. Continued growth of air traffic, world-wide, and worsening terminal area delays have increased the urgency for the development of such systems.

A candidate system for the automated management and control of terminal area traffic, referred to as the Center-TRACON Automation System (CTAS), is under development at NASA Ames Research Center in collaboration with FAA's Terminal ATC Automation Program Office. The collaboration involves developing, installing, and evaluating CTAS at air traffic control facilities serving the Denver and Dallas/Fort Worth airports.

CTAS provides computer intelligence for the planning and control of terminal area traffic by means of advisories presented to controllers on their displays. While initial functions of CTAS concentrate on arrivals, the extension of these functions to handle departures has been accounted for in the design.

The design of CTAS is centered around the human controller in that automation tools augment rather than replace the tasks of controllers. Moreover, CTAS attempts to adapt to the actions of controllers or to unplanned events in a manner similar to a feedback system responding to command inputs. It achieves this adaptation by refreshing advisories automatically whenever controller inputs are received or unplanned events are detected.

The CTAS design grew out of a synthesis of concepts and algorithms formulated in several earlier research studies (Refs. 1-3). Two types of algorithms are at the heart of the CTAS automation intelligence, namely a 4D trajectory synthesis program and a dynamic planning algorithm. These two algorithms operate synergistically. The trajectory synthesis program - a close relative of trajectory programs embedded in on-board flight management systems (FMS) - uses aircraft-specific aerodynamic and propulsion models to generate complex 4D trajectories. The dynamic planning algorithm generates optimized landing sequences and landing times. It is important to note that all types of CTAS advisories ultimately are derived from information generated by a combination of these algorithms.

CTAS software is coded in the C language and contains more than 200,000 lines of application-specific code. It runs on a network of Sun Microsystem, Inc. workstations.

Extensive simulation tests have shown that the benefits of CTAS are significant and extend both to air traffic controllers as well as to aircraft operators. Air traffic controllers provided with CTAS advisories find they can handle complex traffic flows with reduced workload. CTAS advisories have been found to equalize the skill level of controllers by raising the skill of average or below average controllers to that of the top controllers. Aircraft operators will benefit from reduced delays and fuel

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consumption. Simulation tests indicate that the more complex the traffic control environment and the greater the delays, the greater is the potential for efficiency gains from CTAS.

OVERVIEW OF FUNCTIONS AND DESIGN

CTAS functions divide primarily into two categories, planning and control, with each category resident in specific types of controller tools. The planning function resides in the Traffic Management Advisor (TMA), a tool designed for use by Center and TRACON traffic management coordinators (TMC's). The control functions reside in two sets of tools, Descent Advisor (DA) for Center sector controllers and Final Approach Spacing Tool (FAST) for TRACON controllers. Each type of control tool is closely integrated with a co-located TMA at the Center or TRACON, respectively. Furthermore, the separate TMA's at the Center and TRACON are themselves integrated through a data link. Fig. 1 illustrates the functions and integration of these tools and gives examples of controller displays for each tool.

TMA sequences and schedules arrival traffic to all active landing runways at a hub airport. Sequencing establishes landing order for a group of aircraft and scheduling assigns a specific touchdown time for each aircraft in the group. TMA begins the sequencing and scheduling of aircraft when they are approximately 200 n.m. or 45 minutes flying time from the destination airport. It includes in the arrival planning process departures from nearby feeder airports. The overall objective of the planning process is to minimize total airborne delays while ensuring a smooth, controllable, and balanced flow of traffic to all active runways. In addition to its primary function of automated arrival planning, TMA also provides TMC's with various interactive graphical tools and keyboard commands for controlling the flow of traffic. In order to perform arrival planning the TMA's receive sets of estimated times of arrival (ETA's) from their respective control tools, DA or FAST, and then broadcast scheduled times of arrival (STA's) to these tools. The Center and TRACON TMA's exchange ETA's and STA's, as well as airport configuration and flow control data.

The basic purpose of both types of control tools is the same. It is to provide advisories that assist controllers in executing the arrival sequencing and scheduling plan generated by TMA. While their purpose is the same, DA and FAST advisories reflect the different control techniques employed by Center and TRACON controllers, respectively. At the heart of both control tools is the 4D trajectory algorithm which generates the advisories. Most importantly, this algorithm responds dynamically to changing conditions, analogous to a feedback control system responding to disturbances. Thus, a new controller input, a change in STA's, an unplanned aircraft maneuver, or other significant events, will cause updated advisories to be generated and displayed for aircraft.

Accurate models of aircraft aerodynamic and propulsion system performance are most important for generating effective descent advisories. Such models are of lesser importance for FAST where, instead, representations of traffic patterns and approach routes leading to an airport are most important for generating effective advisories. Both types of control tools operate with greatest effectiveness when provided with an accurate model of the atmosphere (winds, temperature).

TRAFFIC MANAGEMENT ADVISOR (TMA)

The functions performed by the TMA divide into four major categories: 1. automatic sequencing and scheduling, 2. interactive graphics and functions for flow visualization and control, 3. Center-TRACON coordination, and 4. automatic record keeping of delays. The last three functions were developed specifically to support the operational duties of Traffic Management Coordinators (TMC's) working within the Center or TRACON. They provide TMC's with information and interactive tools to perform flow control efficiently.

The TMA software and graphical user interfaces are implemented on a Sun Workstation comprising a color monitor, keyboard and mouse. The TMA workstation is linked to a network of Suns which run other elements of CTAS and exchange information with it. The most important information sent to TMA from other workstations are estimated times of arrival (ETA's) generated by the route analysis and trajectory synthesis programs. Various types of ETA's are sent for each aircraft depending on routing options, runway choices and geographical reference points. They are updated whenever CTAS receives new radar tracking data, flight plans or other inputs having an influence on ETA calculation.

Scheduling Algorithm

The automatic scheduling of arrival aircraft from all directions to one or more runway threshholds is TMA's most important function. The scheduling process consists of automatically choosing (a) the order (sequence) that the aircraft should land or cross a particular fix, and (b) the time instants that each aircraft in the sequence should pass over a specified fix. TMA's scheduling algorithm includes the following techniques:

- Time advance. An aircraft that is leading a pack of aircraft may be asked to increase its speed to reduce the delay required for all aircraft following the lead aircraft. The amount of time advance is limited by the fastest time of arrival that has been calculated from the aircraft model-based trajectory analysis.

- Position shift. The algorithm may switch the first-come-first served landing order between two aircraft. This switch in the landing order can take advantage of reductions in required inter-aircraft separation times (based on aircraft type) to improve the efficiency of the arrival stream.

- Runway allocation. Runway allocation is a technique employed by TMA when multiple runways are available for landing. By considering the allowable set of landing runways for each aircraft TMA searches the combinations of aircraft sequence and runway assignment to find a combination that will improve the efficiency of the traffic flow.

Analysis and fast time simulation have demonstrated the potential of these scheduling algorithms to reduce delay and fuel consumption significantly under various types of traffic conditons (Ref. 4). The input to the scheduling algorithm is the set of ETA's for all aircraft intending to land at an airport. Its output is a set of scheduled times of arrival (STA's) at specific runways. Using the techniques listed above, the scheduler transforms the set of ETA's into a set of STA's so as to achieve a feasible, acceptable-to-controllers, as well as optimum flow of traffic. The primary optimization criterion or cost function that the scheduler attempts to minimize is a weighted function of delays and fuel consumption measures subject to constraints on feasibility and acceptability. Parameters in the cost function permit the user to adapt the operation of the scheduling algorithm to changing requirements. The algorithm performing the optimization is a variant of the binary implicit enumeration branch and bound technique. It has been designed to generate an optimum schedule for a large number of aircraft rapidly enough to be used for real time scheduling of arrival traffic (Ref. 5).

In general, TMA may reschedule an aircraft many times after computing an initial schedule. All aircraft outside a certain time range to touchdown, called the freeze horizon, are automatically rescheduled every few seconds to account for new arrivals and other events. Even aircraft within the freeze horizon may be subject to rescheduling because of unplanned events such as pop-up traffic, runway changes or changes in weather minimums.

Scheduling with Dependencies

The scheduler provides operational modes for handling several important types of distance or time separation dependencies between streans of aircraft landing on different runways. Controllers find it difficult to handle such constraints manually under heavy traffic conditions.

One type of dependency handled by the scheduler is known as a stagger constraint. It is used in parallel runway operation under certain conditions. In this mode, the scheduler has to meet two separation constraints simultaneously. First, it must schedule aircraft with specified minimum in-trail separation while aircraft are on final approach to the same runway. The in-trail separations may be 2.5, 3, 4, 5, or 6 n.m. depending on landing order, weight class and weather minimums. Second, any two aircraft on final approach to different runways of the parallel pair of runways must be scheduled to be spatially staggered. The minimum stagger distances, as measured by the slant range between aircraft, is typically specified to be 2 n.m.

A second type of dependency applies to intersecting or converging runway operations. In this case the dependency constraint requires a specified minimum difference in threshold crossing times for any two aircraft landing consecutively on different runways.

It should be noted that the scheduler not only has to meet the dependency constraints but also attempts to minimize delays in generating the landing times.

Interactive Graphics and Functions

The TMA display provides a large repertoire of interactive graphics designed to enhance the TMC's ability to control and monitor traffic flow. A summary of TMA graphics and control options is given below:

Interactive Time Line Display

The display of ETA's and STA's on time lines is as fundamental to the TMA as is the display of radar targets on a plan view display (Fig. 1). Six time lines can be displayed simultaneously, each with selectable scales, time gaps and geographic reference points. Each time line can display ETA's or STA's independently on either the left or the right side. Options for the reference point include the runway threshold, final approach fix, or feeder gate. Using a combination of mouse cursor and pop-up menus, the TMC can interact directly with the time line to enter scheduling commands such as manually rescheduling a flight, blocking out a time range where no aircraft are to be scheduled, adding to or removing a flight from the scheduling list or initiating a complete reschedule of all traffic.

Airport Configuration Window

The Airport Configuration Window lists all landing runway configurations for an airport. On-screen buttons opposite each configuration and a slider allow the TMC to select a new configuration and set the time to change from the current to the new configuration. The TMA for the Denver/Stapleton Airport has 41 major configurations to choose from. Two examples of Stapleton Airport configurations are "26L, 26R, 25 VFR" and "17L, 17R staggered VFR." Selection of a new configuration, a time to change and a maximum acceptance rate causes the scheduling algorithm to generate a new set of STA's and runway allocations for all eligible aircraft arriving at a control point after the specified time to change.

Flow Control Graphics

TMC's at Centers have developed various methods for predicting and controlling the flow rate of traffic into TRACON's in order to prevent an overload. While methods differ somewhat between Centers, they all involve counting the total number of aircraft predicted to enter a TRACON airspace in a fixed time interval, such as 15 minutes. Counting is essentially done manually by controllers, using pencil and paper. TMA has automated three such counting methods. The Traffic Load Graph Display (Fig. 1), when selected by the TMC, plots the number of aircraft predicted to cross a runway threshold or feeder gate as a function of time, from the present to some specified future time. The Rush Alert indicates with a pair of red brackets along the time lines where, in the future, the number of aircraft in any 15 minute time interval will first exceed the maximum airport acceptance rate. The 15 minute traffic count display gives essentially the same information as the Load Graph but in a tabular list format. Each of these counting functions include various user-selectable options and parameters.

Center-TRACON Coordination

It is well known that close coordination of flow control decisions between TMC's at the Center and TRACON is an essential requirement for achieving smooth and efficient traffic flow into an airport. The exchange of data through a data link and the integration of scheduler functions between the Center and TRACON TMA's gives TMC's more precise and effective tools for coordinating traffic flow. One type of data exchange gives the ability to display ETA's and STA's generated by the Center TMA on TRACON TMA time lines. The TRACON TMC can also analyze this data using the flow control graphics described in the preceding section. Furthermore, the TRACON TMC's can send planned changes in runway configuration and acceptance rate to the Center TMA via the data link interface. Likewise, an unexpected buildup of delays in the TRACON due to missed approaches, sudden weather changes or emergency events, will be more quickly detected by the Center TMC and can be evaluated by them to decide if the flow into the TRACON should be changed. This will more likely produce concensus decisions by Center and TRACON TMC's as to when and how to change the arrival flow into the TRACON. Finally, integrated operation of the schedulers provides the ability to automatically allocate a specific proportion of total delay to be absorbed in the Center and TRACON airspace.

Delay Record Keeping

FAA procedures require Center TMC's to maintain a record of all arrivals delayed 15 minutes or longer. The estimation of delays and the record keeping are currently done manually. This process has been automated by making use of the ETA calculations performed by the trajectory synthesis program in CTAS. Owing to the demonstrated precision of these calculations, delays that can be reliably measured to an accuracy of ± 3 minutes. With this level of precision the automated delay records provide a sensitive measure of air traffic control efficiency.

FINAL APPROACH SPACING TOOL (FAST)

FAST provides a set of keyboard functions and on-screen graphical advisories that help the TRACON controller to accurately and efficiently space the flow of aircraft on final approach. FAST is based on a set of 4D trajectory synthesis algorithms with extensive features developed exclusively for TRACON operation. The initial design of FAST and an evaluation of its performance in a real time simulation are described in Ref. 6. The current version of FAST described here has many new functions not included in the initial design. FAST analyzes each arrival aircraft's current state (position, velocity, altitude, heading), classifies its positional sequence in the traffic pattern relative to that of other aircraft in the pattern, and computes routes and estimated times of arrival (ETAs) to the runway threshold. The analysis makes use of the vertical wind profile to the degree known and aircraft performance characteristics. This information is sent to TMA, which computes a landing sequence and associated landing times for all aircraft and then sends that information back to FAST.

FAST then generates a series of indicated airspeed and heading advisories (magnetic headings, corrected for winds) which, if issued as clearances to the appropriate aircraft, will cause it to follow the planned route and space it accurately on final approach relative to other aircraft. The geographical points where speed and heading advisories should be issued are displayed as markers on the controller's monitor. They are always located a short distance ahead of the aircraft along its extended, current course line. The numerical value of the speed advisory is written on the fourth line of the data tag. In addition to the speed and heading advisories, a time line can be optionally displayed to show the landing sequence and time errors relative to the scheduled landing time. An aircraft's relative landing order is indicated by an integer, called the sequence number, which is also displayed on the fourth line of the data tag. Furthermore, when more than one landing runway is active at an airport, the runway assignment is time-shared with the sequence number on the fourth line of the data tag.

One of the most important features of FAST is its resequencing capability. This feature is automatically invoked when FAST has detected a missed approach aircraft or an aircraft that has failed to execute a clearance. A typical event causing a resequence is the failure of an aircraft on downwind to execute a turn-to-base in a timely manner. Once sequencing has occurred, FAST immediately displays a new set of advisories that merges the affected aircraft back into the landing sequence.

Another feature of FAST is its ability to generate *advisories* for aircraft that require large delays in the TRACON airspace. Algorithms for path stretching to absorb such delays in FAST include base extension (tromboning) for aircraft on downwind, extending the final approach course intercept for aircraft on long base (fanning) and extended upwind and downwind turns for aircraft on initial approach segments.

The FAST scheduler, an element of TMA, generates the landing sequence and optimally spaced landing times for arrival aircraft. FAST uses the same scheduler as Center TMA, but with airport-specific constraints on its sequencing algorithm to ensure a landing sequence that is acceptable to controllers. It can handle unscheduled arrivals such as missed approaches and popups and receive sequence order constraints as inputs from the controller.

Using the 4D trajectory synthesizer (TS), FAST calculates when and where an aircraft should change heading or change speed, as well as various other parameters. It

- predicts arrival times of aircraft at the final approach fix based on current position, altitude, speed, heading, and routing.
- computes range of arrival times based on aircraft speed envelope and allowable path extension.
- detects and resolves conflicts for aircraft which are merging into an approach stream on downwind or other route segments.
- detects arrival time errors (early or late) and computes speed and path corrections.
- provides guidance to any capture waypoint selected manually by the controller for special situations (e.g., missed approach, emergency)

The following symbols and graphics are displayed on the controller's screen. These are in addition to the previously discussed information on the fourth line of the aircraft data tag.

- an optional timeline for each arrival runway showing Scheduled Times of Arrival and Estimated Times of Arrival, at the threshold or final approach fix.
- speed advisory - circular marker at point to deliver advisory
- heading advisory - marker at point to deliver, with a data field and turn arc

Example Use of FAST

The FAST advisory process will be illustrated by describing the sequence of events for an example jet aircraft arriving over the feeder gate for an approach and landing to Runway 17L at the Dallas/Ft Worth Airport. The traffic pattern used in this example consists of a transition segment along an inbound VOR radial to a turn downwind, turn to base and finally a turn onto the final approach course. As the jet arrives over the VOR at the corner post (feeder gate), the pilot is following the published Standard Terminal Arrival Route (STAR) which specifies a radial to fly to the airport from the VOR as well as altitude, speed, and heading restrictions to be observed along the way. There are separate STAR instructions for turbo-prop aircraft which are separated in altitude from the jets at the corner post and are split off into a separate stream that will be remerged with the jet traffic in the downwind area. The FAST site adaptation has detailed knowledge of the STAR's at Dallas/Ft. Worth, and incorporates these into its trajectory and advisory calculations. Neither the controller nor FAST will issue any clearances that are implied in the STAR clearances. As the aircraft enters the TRACON at the corner post, its runway assignment is frozen by FAST and displayed to the controller on the fourth line of the data block, time-shared with the sequence number. The controller can manually override the runway assignment. In the absence of a controller override, FAST will assume that the controller has accepted the runway assignment advisory. Procedures at Dallas/Ft. Worth are such that if an aircraft is assigned to a runway on the opposite side of the airport relative to the TRACON entry point, the aircraft is vectored over the top of the airport to a downwind for that runway; however, the STAR specifies that an aircraft turn to a downwind heading from the STAR termination fix for an approach to the same-side runway. If an aircraft has been assigned to an opposite side runway by FAST or by the controller, FAST will issue a revised heading for the aircraft to depart the STAR termination fix. This heading is displayed in the fourth line of the data block, time-shared with any existing speed advisories. The advisory accounts for winds and ensures that the aircraft will merge conflict-free into the new downwind traffic.

As the jet proceeds along the inbound radial, the trajectory and conflict resolution logic may detect that this jet, which is currently in-trail with other jets, will compress to less than legal separation if it continues on the published procedure. The conflict resolution logic may also detect a future conflict with a merging turbo-prop on downwind or in merging with traffic on the opposite downwind as described above. In these cases, FAST will issue a speed advisory which slows the jet in order to avoid the loss of legal separation at the merge point.

For the remainder of this example, it is assumed that the jet is assigned a same-side runway in which case it will turn to its downwind heading without any clearances from FAST or the controller. Once on downwind, FAST continues to search for future conflicts which include both preceding and trailing aircraft as well as turbo-prop traffic which was split off earlier but is now being vectored to remerge with the jet traffic. FAST may issue additional speed advisories to avoid these conflicts. FAST is also computing the location at which to turn the aircraft from downwind to base such that it will be set up for a nominal 20 deg. intercept to the final approach course. As the aircraft approaches the turn location, FAST will display the turn advisory to the controller as a point at which to issue the turn, a magnetic heading in tens of degrees, and an arc which graphically depicts the projected turn of the aircraft. Once on base, FAST will continue to check the aircraft's trajectory against those of other relevant aircraft in order to compute any necessary speed advisories as well as its turn to final intercept. These last advisories are designed to bring the aircraft onto the final approach course with minimum, but safe, legal separation. Both the speed and turn advisories will be displayed as previously described. For aircraft on final, FAST will issue speed advisories only if necessary to maintain legal separation, and once inside the final approach fix, FAST discontinues its trajectory calculations for that aircraft. In order to reduce display clutter in the final approach zone FAST advisories are displayed only briefly prior to and slightly past the point, but still long enough for controllers to observe them.

DESCENT ADVISOR

The Descent Advisor (DA) comprises a set of automation tools to help Center controllers in managing sector traffic (Ref. 2). It provides information to descend aircraft in a conflict-free and fuel efficient manner while delivering aircraft on time at the arrival gates for handoff into the TRACON.

DA Trajectory Computation

The 4D trajectory synthesis program is at the heart of all DA functionalities. The essential computation performed by the program is a fast time integration of the aircraft equations of motion beginning at the current position of the aircraft and terminating at the runway. The program contains detailed models of aerodynamic and propulsion system performance, incorporates preferred descent procedures for each type of aircraft and uses three-dimensional models of winds, temperatures and pressures. Over 400 aircraft- specific models are included in the program's data base. The real time atmospheric model used in CTAS is the so called Mesoscale Analysis and Prediction System (MAPS) model developed by the National Oceanic and Atmospheric Administration's Forecast Systems Laboratory in Boulder, Colorado. The MAPS model covers the continental U.S. with a grid of data points, 60 km x 60 km in size. CTAS accesses the MAPS data, which is updated every three hours, via a data link connection.

The program recomputes 4D trajectories for all aircraft in response to any events that can influence the outcome, such as new radar position updates, controller inputs or STA changes. Each update cycle produces a basic set of trajectories, which include fastest, slowest, nominal and specified arrival time trajectories along a specified horizontal route. In general, many additional trajectories may have to be computed if it is necessary to change the horizontal route or to resolve conflicts.

Speed and Top of Descent Advisories

The DA translates the 4D trajectory solutions into controller advisories that satisfy all relevant constraints and conditions. The basic types of advisories are the following:

- Cruise speed (Mach or calibrated airspeed)
- Top of descent point (nautical mile range to a navigation fix)
- Descent speed profile (Mach and/or calibrated airspeed)

The most important condition the advisories have to satisfy is producing trajectories that meet the Scheduled Time of Arrival (STA) at the arrival gate. In addition, when executed by the pilot, they result in aircraft flying fuel efficient descent profiles.

Off-Route Vectoring

This type of advisory is designed to create larger delays than can be obtained with speed reductions along the currently specified horizontal route. If the STA to the metering gate is outside the aircraft's accessible time range for speed control, a "PS" (path stretching) message is displayed in the aircraft's data block on the controller's monitor, also known as the Plan Video Display (PVD).

Upon noticing this message, the controller can invoke an "autopath stretch tool" to obtain precise guidance in modifying the horizontal route for specific delay absorption. With the tool "armed", the controller starts by issuing any heading vector larger than about 20° off-course from the current route direction. Once the aircraft has stabilized on its off-course heading, the tool displays a marker and turn arc at the position along the off-course direction in front of the aircraft where the required delay will have been absorbed. When the aircraft's target reaches the marker, the controller issues a heading vector which returns the aircraft to a predesignated capture waypoint on the original route. The magnetic heading to capture the waypoint is also displayed next to the turn marker. It is important to note that the trajectory program updates the location of the path stretch marker dynamically in response to changing conditions, such as changes in off course heading, speed, altitude, etc. The controller is thus free to give additional clearances, perhaps to avoid a weather cell or restricted airspace, while continuing to receive accurate path stretching advisories. Finally, it should be noted that speed advisories and top of descent points continue to be computed and displayed during path stretching maneuvers. It is therefore possible to combine path stretching, speed control and altitude control in any combination to meet an STA at a feeder gate. This flexibility avoids dependence of the DA tools on specific airspace and operational constraints, thereby ensuring their applicability to a wide range of Center air traffic control environments.

Conflict Checking and Resolution

The feeder gate STA's generated by TMA and sent to the arrival sector PVD's are appropriately separated in time and therefore conflict-free at the feeder gate, but that condition does not ensure conflict free trajectories prior to the gate. For example, trajectories may exhibit large differences in speed and altitude profiles during descent to meet a particular STA, depending on aircraft type and initial conditions. If aircraft with such differences in profiles are scheduled consecutively, a loss of minimum allowed separation, if not a conflict, may occur at some point before the gate. Such conflicts can be predicted by analyzing 4D trajectories generated by the trajectory synthesis program and therefore can be avoided by replanning of the profiles.

Conflict detection and resolution analysis is fully integrated with all DA advisory functions. The resolution logic allows controllers to choose the level of automation and to direct the strategy for resolution. A concept for using an air-ground data link to integrate ground-based conflict resolution with on-board FMS generated descent profiles has been studied in a real time simulation (Ref. 7). Such a concept potentially offers the highest level of automation and operational efficiency.

The conflict detection algorithm searches for a loss of minimum separation at all future positions of eligible aircraft, using the 4D trajectory data base. The search is done in short time increments (~ 10 sec) and may proceed 20 minutes into the future, or until the end of a trajectory is reached, which^Gurs first. Pairs of aircraft predicted to be in conflict are displayed in a conflict table on the controller's display (PVD). In addition, the color of the 4th lines of the data block of all conflict pairs is changed from green to red. Also, the predicted location of the conflicts are indicated by a red marker on the PVD.

The automatic conflict resolution algorithm incorporates the strategy of first changing only speed and altitude profiles to resolve conflicts while keeping horizontal paths and feeder gate STA's fixed. By working with one aircraft of a conflict pair at a time, the algorithm first changes that aircraft's descent speed in 5 knot increments while making a compensatory change in its cruise speed in order to keep the arrival time fixed, if that is possible. If conflicts remain after testing all feasible speeds, an intermediate cruise altitude is selected and the search of descent speeds is repeated. With a maximum of 15 speed levels and 10 altitude levels to search over, the algorithm could potentially require the computation of 150 different trajectories for each aircraft involved in the resolution search. However, many combinations will be found ineligible because they violate some constraint. In practice, a conflict-free solution is usually found after only a few trajectories have been computed. If, under that rarest of circumstances, no resolution is found, a " PS" message advising the controller to path stretch is displayed in the 4th line of the data tags for the pair of aircraft in conflict. It indicates to the controller that the aircraft must be vectored off-route or assigned a new route, thereby creating new opportunities for the resolution search. This process can also be invoked automatically.

Fig. 2 shows the altitude profiles corresponding to 4 example sets of trajectories that may be generated during a conflict resolution search. Two sets are obtained by keeping the initial cruise altitude fixed and varying the descent speeds. Two other sets are obtained by introducing an intermediate altitude segment of 27,000 ft and varying the speed in the final descent segment. In each of the sets, the speeds in the constant altitude segments and the final descent segments are changed in opposite directions so as to keep the arrival time fixed. Differences in descent angles seen in the trajectories reflect the effect of changes in aerodynamic drag with changes in speed when thrust is held at a fixed minimum value during the descent In general, several other speed profiles (not shown) would also be attempted at each of the two altitudes.

Advisories shown on the Plan View Display

Descent Advisor information can be displayed in several ways and in several places on the Plan View Display. A time line, referenced to the arrival gate of a sector, displays estimated and scheduled times of arrival (ETA's and STA's) for all arrival traffic. Because of the continuous updating of ETA's by the trajectory synthesis algorithm, controllers can use the time line data as a responsive monitor of arrival time errors or as a supplement to the advisories in controlling the time errors. Time line graphics, however, cannot easily be added to Plan View Displays (PVD's) currently in use and thus will not be included in the initial DA implementation. Such graphics will be incorporated in the next generation color monitor displays, which will replace existing PVD's in the late 1990's.

The most important advisories have been incorporated into the aircraft data block where they are easiest to observe by the controller. Since all three lines of a normal data block are dedicated to show basic ATC data, a fourth line was added exclusively for the display of DA information.

In addition to the 4th line data, markers and arcs are drawn at the future position of an aircraft where a heading clearance is to be issued. A special marker also indicates the top of descent point. On color monitors these advisor graphics are color coded to further enhance their rapid perception.

A wide range of additional information relating to use of the DA can be displayed in pop-up windows or selected from menus by the controller.

SOFTWARE ARCHITECTURE

The CTAS software has been extensively rearchitectured during the last year. The new architecture evolved from the experience of developing diverse, new automation tools and integrating them into a growing and increasingly complex body of software. A further impetus for rearchitecturing of the software was provided by FAA's plan to pursue a limited national deployment of CTAS.

The new architecture is based on several generic software modules which form the building blocks for all application-specific automation tools in CTAS. These modules play the role of atoms in the universe of ATC automation. Thus, previously developed tools such as TMA, FAST and DA have all been re-synthesized from the generic modules. Moreover, by using these modules as universal building blocks, the development effort for several planned extensions of CTAS functionalities will be greatly reduced. The new architecture also makes it possible to adapt CTAS more easily to different airports and different operational procedures. Most importantly, the new architecture gives software developers a friendlier and more efficient environment for integrating and validating complex changes to automation tools. Finally, the new architecture allows additional workstations to be integrated into the CTAS network whenever the computational load on any of the generic modules becomes excessive. The major software modules in this archictecture, including interactions with external systems, are shown in Fig. 3. Brief descriptions of these modules are given below:

Dynamic Planner (DP) contains the algorithm that optimally sequences and schedules aircraft to one or more landing runways. It operates on a set of aircraft ETA's provided by the RA module and outputs a set of STA's used by PFS and GUI. Users can set values of parameters in the cost function optimized by the algorithm.

Trajectory Synthesis (TS) generates 4D trajectories along a fixed horizontal route for a wide range of constraints. Its data base is a set of aircraft models. It also accesses a gridded atmospheric model in real time. TS receives inputs from RA and PFS and returns its synthesized trajectories to these modules.

Route Analysis (RA) generates a set of horizontal routes from site-adaptable input files and flight plans and calls on TS to generate 4D trajectories for these routes. The degrees of freedom in the horizontal routes are defined by the types of path stretching maneuvers controllers use under various conditions. The six major types built into RA are shown in Fig. 4. The ETA range determined by the longest and shortest flight paths (enclosing the shaded regions) together with the ETA of the nominal path are computed for each type and are sent to DP for scheduling analysis.

Another function of RA is to analyze the speed degrees of freedom as defined in Fig. 5. The first two types apply to TRACON and the third to Center airspace situations. As in the case of horizontal route analysis, the speed analyses produces a set of time ranges which are sent to DP for purposes of establishing a feasible landing time.

The RA software organizes the analysis of these many degrees of freedom into a hierarchical tree-like structure that is based on preferred controller procedures.

Profile Selector (PFS) selects one specific route and vertical profile to meet an STA and resolve conflicts. Calls TS to generate the 4D trajectory and the corresponding advisories.

Graphical User Interface (GUI) displays all graphical information on a controller monitor, including advisories, time lines, aircraft data blocks, etc. Also responds to controller inputs made from the keyboard or mouse, and sends messages to CM when appropriate.

Communications Manager (CM) acts as the central switchboard for CTAS by distributing data between the other modules. It also receives from and sends data to external agents in real time. These agents include the Center Host Computer, the TRACON ARTS, piloted simulators, ATC simulators, weather source, etc.

TMA, DA, FAST represent specific automation tools built from the above modules and defined by input files and adaptation data.

IMPLEMENTATION AND EVALUATION PLANS

CTAS is being implemented for field evaluation at both Denver and Dallas/Fort Worth airports. The implementation at these two field sites will proceed in several stages and is a cooperative and closely coordinated effort between NASA, FAA, and several FAA sponsored organizations, which include the MIT Lincoln Laboratory, the FAA Technical Center and the MITRE Corporation. The initial stage consists of installing interconnected TMA's at both Center and TRACON. This stage was completed at the Denver Center and TRACON in mid-1992. Since that time the system has been in continuous operation at both facilities. Installation of a similar system at the two Dallas/Ft Worth area facilities begins in June 1993. The currently installed version of TMA operates in a standalone mode which provides limited functions for operational use by Center and TRACON traffic management coordinators. These functions include graphical display of traffic flows, automatic aircraft counts, rush alert and delay record keeping. The greatest impact of this version of TMA has been in the TRACON where it has given TMC's heretofore unavailable real time information on the arrival time of all flights predicted to cross into the TRACON from Center airspace.

The next version, called Operational TMA, will broadcast TMA generated schedules and delay information for display on Center arrival sector PVD's. The TMA will thus replace the existing metering program, also known as the Arrival Sequencing Program (ASP), which has been an operational system at Denver, Ft Worth and certain other Centers for several years. While this version of TMA does not yet provide descent advisories to sector controllers, it will bring into operation several functions unique to CTAS such as using the CTAS scheduler and 4D trajectory modeling. It is thus an important precursor to the DA. A test of Operational TMA is scheduled to be conducted at the Denver Center before the switchover to the new Denver airport takes place in late fall of 1993. The next level of Center automation will concentrate on the DA, which is scheduled for installation and operational tests at the Denver Center in late 1994.

Concurrent with the TMA/DA development, extensive preparations are underway to begin testing an initial version of FAST at the Dallas/Ft Worth TRACON. Installation of Sun Workstations running the FAST software and an interface unit linking the Suns with the existing operational systems at DFW will begin in the fall of 1993. Operational tests are scheduled to begin in early 1994.

After a Center or TRACON tool has been made operational at its initial site, that tool will then be adapted to the second site, thereby achieving full CTAS functionality at both sites in late 1995.

In addition to the two field evaluation sites, FAA has recently selected Centers and TRACON's serving eight major airports as sites to be equipped with elements of CTAS.

Under a cooperative agreement with NASA, workers at the NLR in the Netherlands recently extended CTAS to operate as a fully automatic ATC system (Ref. 8). They have also adapated it to Dutch airspace and Schiphol Airport and are studying its performance in their simulator.

French and Canadian civil aviation authorities have also entered into agreements with FAA to permit them to adapt CTAS, with NASA assistance, for testing in ATC simulations of major airports in those countries. These independent simulation tests focused on airports outside the U.S. will aid developers at NASA by providing valuable information on the adaptability and performance of CTAS under a wide range of ATC operational conditions.

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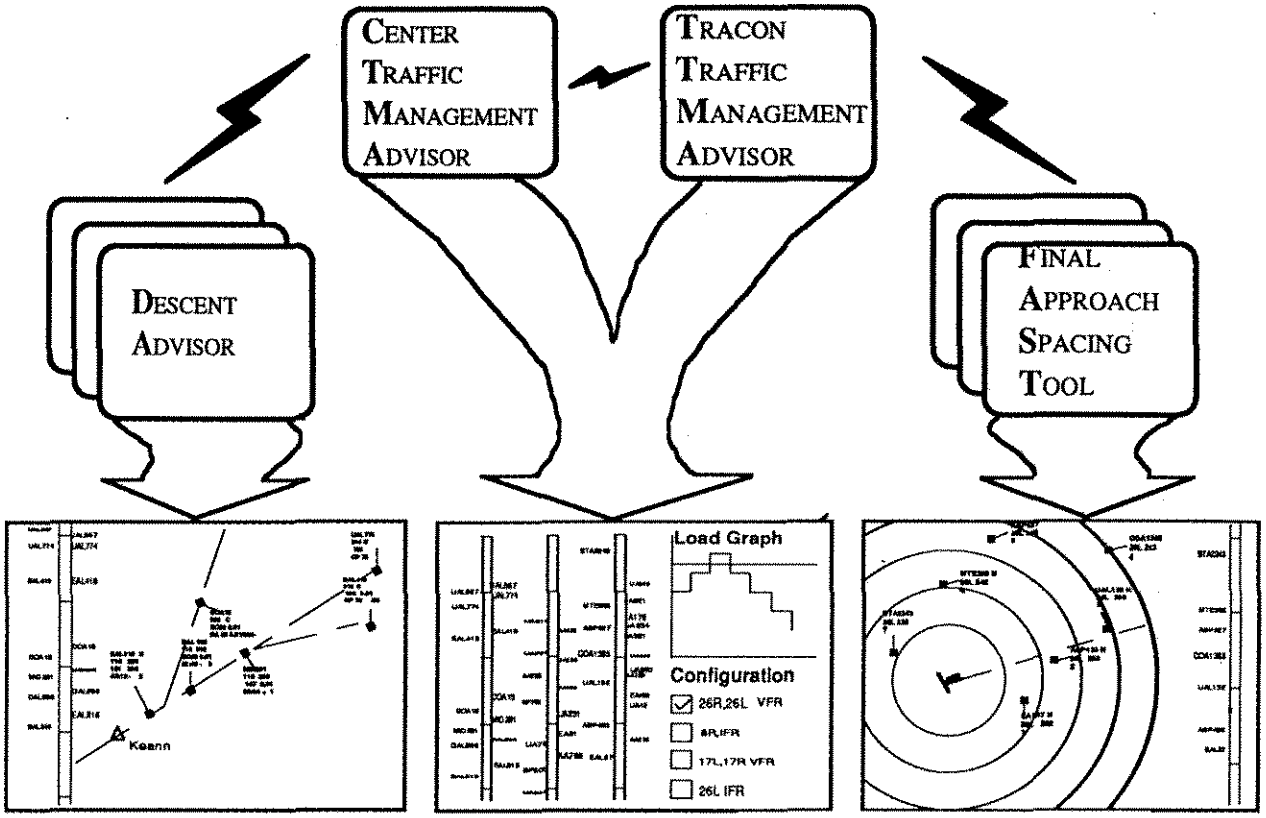


Fig 1 : Block diagram of integrated CTAS tool and corresponding controller displays

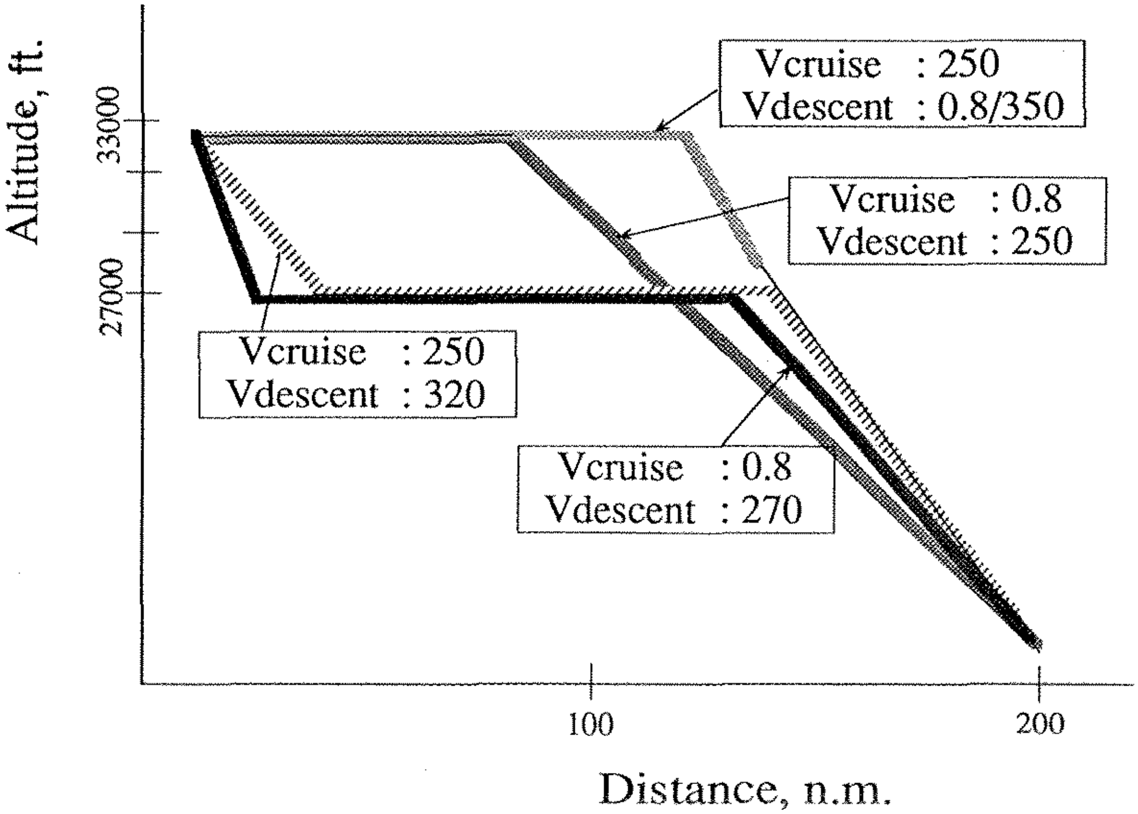


Fig 2 : Trajectories for conflict resolution

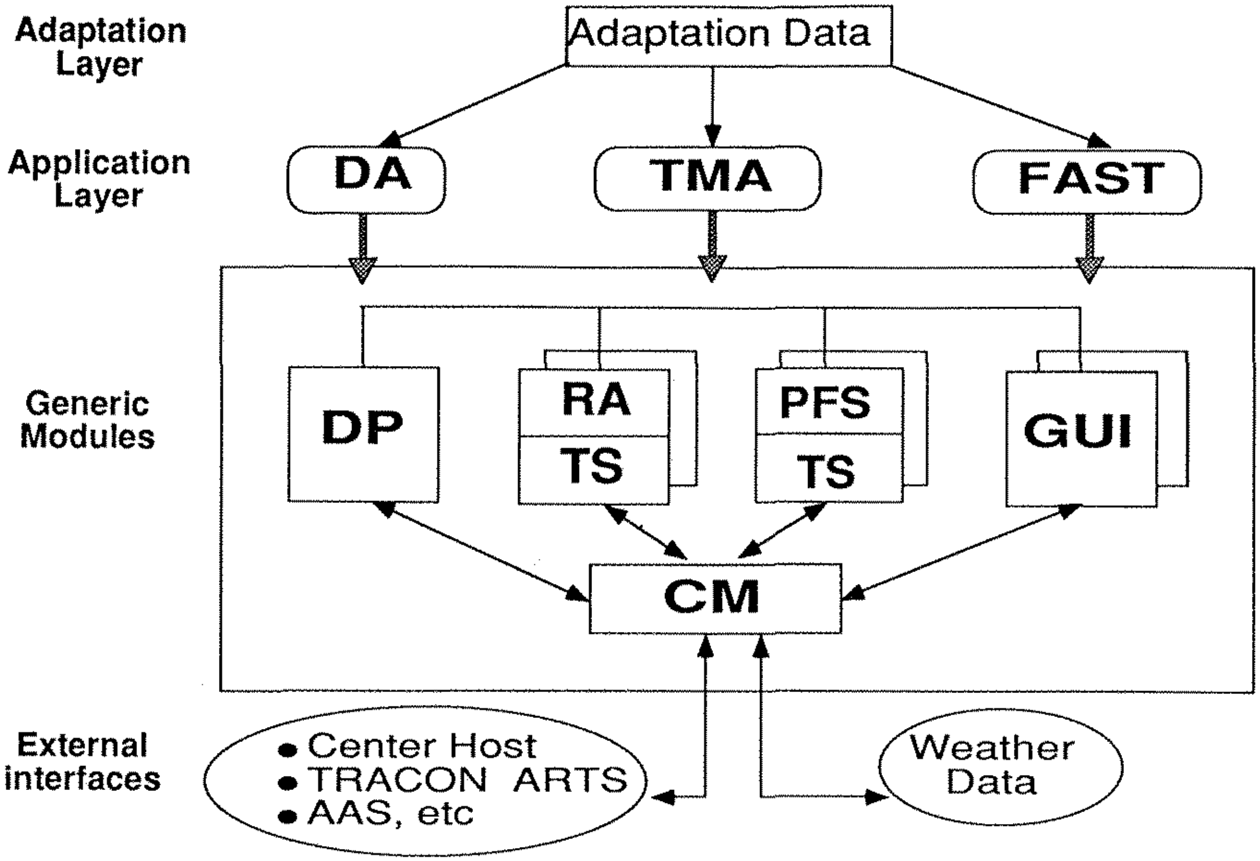


Fig 3 : CTAS software architecture

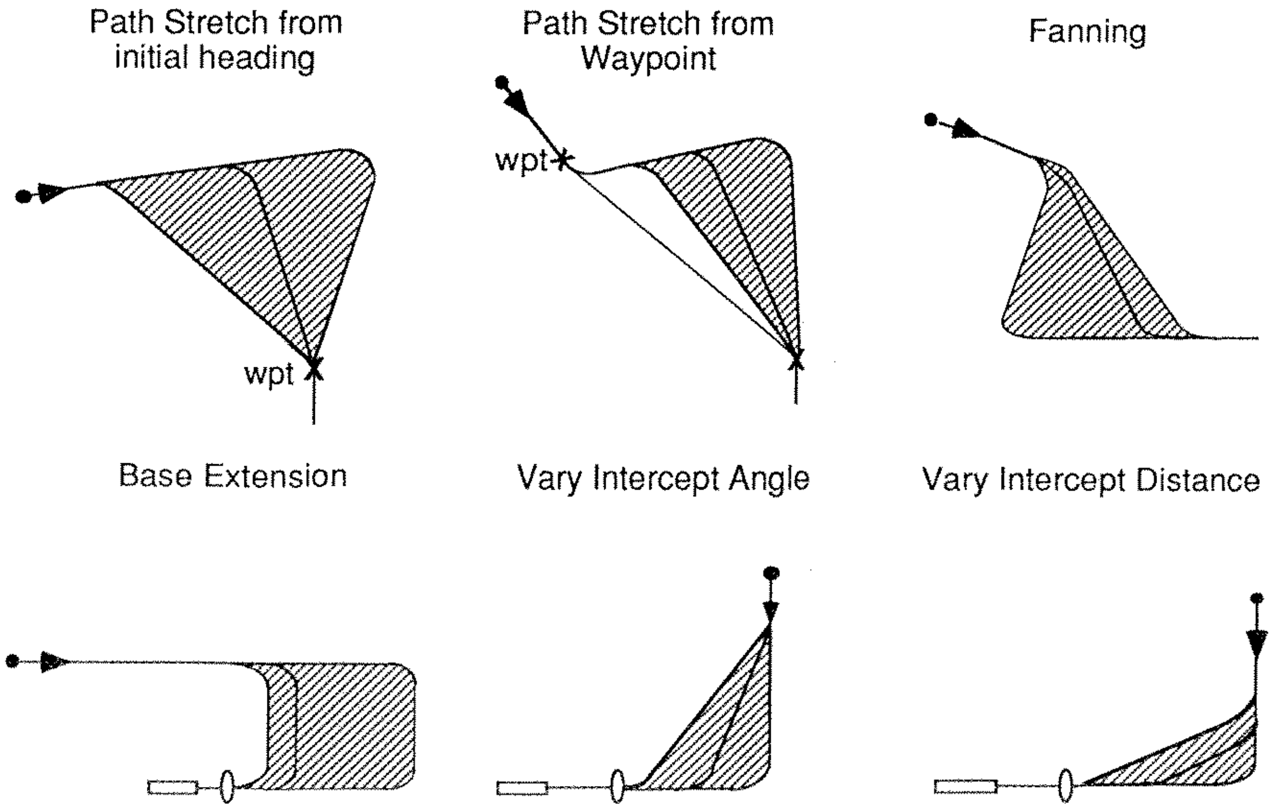
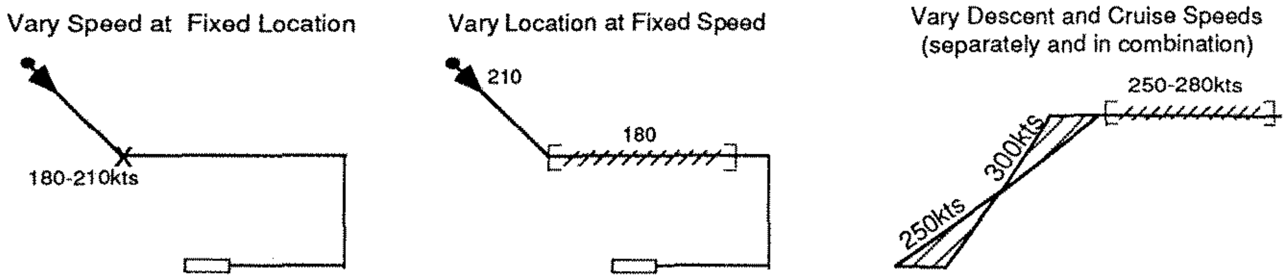


Fig 4 : Horizontal degrees of freedom in RA



Vary Speed at Fixed Location

Vary Location at Fixed Speed

Vary Descent and Cruise Speeds (separately and in combination)

Fig 5 : Speed degrees of freedom in RA