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Autonomous System for Air Traffic Control in Terminal Airspace

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In this article we present recent work towards the development of an autonomous system that performs conflict resolution and arrival scheduling for aircraft in the terminal airspace around an airport. An autonomous air traffic control system is defined as a system that can safely solve the major traffic management problems currently handled by human controllers. It has the potential to handle higher traffic levels and a mix of conventional and unmanned aerial vehicles with reduced dependency on controllers. The main objective of this paper is to describe the fundamental trajectory algorithms that must be incorporated in such a system. These algorithms generate arrival trajectories that are free of conflicts with other traffic, and meet scheduled times of arrival for landing with specified in-trail spacings. The maneuvers the system employs to resolve separation and spacing conflicts include speed control, horizontal maneuvers, and altitude changes. Furthermore, the system can reassign arrival aircraft to a different runway in order to reduce delays. Examples of problems solved and performance statistics from a fast-time simulation using simulated traffic of arrivals and departures at the Dallas/Fort Worth International Airport and Dallas Love Field Airport are also provided.

I. Introduction

With demand for air transport expected to continue growing in the next fifteen years, higher levels of automation in air traffic operations are likely to be needed to handle a denser and more diverse mix of air traffic, especially to accommodate the rapid growth of Unmanned Aerial Vehicle (UAV) traffic. Moreover, as the need for environmentally friendly aviation is stronger than ever before, automation in air traffic control may enable removal of procedural separation of aircraft to permit more optimal aircraft trajectories that are difficult for controllers to handle. In response to anticipated need for handling the mix of conventional and UAV traffic efficiently, NASA has conducted research towards the development of a system for automated conflict resolution, arrival management, and weather avoidance that could be the basis for autonomous air traffic control. This system is referred to as the Advanced Airspace Concept[1] (AAC) and it has so far been developed for traffic in en-route airspace including descents to a meter fix. Recently, a research effort was initiated to extend AAC to terminal area airspace, referred to as Terminal AAC (TAAC). This papers aims to delineate the principal components of TAAC as well as its methods and algorithms for conflict resolution and management of arrival traffic.

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The design objective of TAAC differs from previous work on developing automation aids for handling traffic in the terminal area in that it aims to achieve a high level of autonomy in the decision making process. In earlier work, such as the design of the Final Approach Spacing Tool[2], the objective was to generate a defined set of advisories that could assist controllers in sequencing and spacing traffic on the final approach. Automation with limited scope and authority is classified as a decision support tool. In using it, the controller retains responsibility for maintaining separation between all aircraft, including those for which automated advisories are presented to controllers on their displays. When automated advisories are limited to solving only a subset of the problems occurring in managing traffic, controllers must maintain full situational awareness of all types of problems that can occur. That approach limits the usability and effectiveness of such decision support tools and can add to controller workload. In contrast, the algorithms in TAAC are designed to generate trajectories and clearances that obey all safety constraints and operational limits controllers are expected to provide.

Although the TAAC-generated trajectories could be adapted to provide classical decision support advisories to controllers, the more significant use of this approach is in a future air traffic control system that operates with a high degree of autonomy. In such a future system, the role of controllers would change from handling tasks, such as routine separation assurance and arrival sequencing, to responding to exceptional traffic situations. A key technology that will enable increased autonomy in air traffic management is the ground-air data link, which will allow ground-based automation systems to uplink clearances and trajectories directly to onboard systems without prior approval of a controller.

Similar to AAC's architecture[1], TAAC incorporates two independent systems for conflict detection and resolution. One element of this system is designed to handle conflicts and solve problems predicted to occur in the range of approximately 1–15 min. It would be the mainstay for solving separation assurance and related problems including arrival management. This element can be considered the strategic problem solver in TAAC and is referred to as the Terminal AutoResolver (TAR). The second separation-assurance element in TAAC will focus exclusively on handling tactical conflicts, defined as those with times to loss of separation of less than approximately 1 min. This separate and independent system would come into play whenever TAR failed to detect or resolve a conflict for which the time to first loss had become less than approximately 1 min. The hierarchical structure for separation assurance in AAC and adopted for TAAC is described in Ref. 1.

Development of Terminal AutoResolver was based on AutoResolver, the strategic problem solver of AAC. Its design and performance for resolving conflicts in en-route airspace are described in several papers[1,3]. The new functions as well as performance enhancements to existing functions that have been specifically designed for operations in the terminal airspace are the subject of this paper.

Section II of the paper provides an overview of TAR's algorithm for conflict resolution and arrival management. Section III describes the functionality of TAR's module for arrival management, while Section IV describes the principal maneuvers used for both conflict resolution and arrival management. The results of fast time simulation runs with traffic to and from Dallas-Fort Worth International Airport and Dallas Love Field Airport are presented in Section V. Finally, Section VI summarizes the key points of this paper and outlines future work to be pursued.

II. Overview of Terminal AutoResolver

The basic process for conflict resolution and arrival scheduling of TAR is depicted in Fig. 1. Aircraft-related information is an input, with data for type of aircraft, destination airport, aircraft's current state of motion, as well as a plethora of weather and terminal airspace configuration information. Employing these data, an external trajectory predictor module computes each flight's projected four-dimensional trajectory inside the Terminal Radar Approach Control (TRACON) airspace, with time being the fourth dimension.

TAR's conflict probe uses the predicted trajectories to check all aircraft in the TRACON airspace for future loss-of-separation conflicts. In addition to loss-of-separation conflicts, each arrival aircraft is checked for future time-based spacing conflicts at the final approach fix against every eligible aircraft in the arrival stream destined for the same runway. A spacing conflict arises when two aircraft crossing the final approach fix (FAF) to the same runway are separated by less than a minimum time interval, which itself depends on the sequence order and weight category of the two aircraft.

The process of arrival scheduling and resolution of predicted spacing and loss-of-separation conflicts is coordinated by TAR's scheduling module, referred to as Arrival Manager. The Arrival Manager's basic approach to problem solving is to first resolve a predicted spacing conflict and then a loss-of-separation conflict if needed. In this way, an orderly and efficiently spaced stream of arrivals is achieved, free of both types of conflicts. Arrival Manager checks whether an aircraft's remaining time to fly to the FAF has become less than a specified minimum time, referred to as the freeze time interval, in which case the aircraft is assigned a scheduled time of arrival (STA) at the

FAF. The aircraft's STA would be set equal to its unconstrained arrival time if this would not cause a spacing conflict with a previously scheduled aircraft or a loss of separation conflict with any other aircraft. Otherwise, Arrival Manager will employ its scheduling algorithm to assign an STA to the aircraft that is currently being scheduled. For new arrivals that have just crossed the freeze horizon, the sequence order is generally determined by the first-come-first-served (FCFS) rule, but with some exceptions. Deviations from FCFS, termed as position shifts, are allowed if the aircraft currently being scheduled can be assigned a landing slot between previously scheduled aircraft without requiring these aircraft to be rescheduled. The Arrival Manager also has the capability to reassign aircraft to a different runway at airports with more that one active landing runway. Normally, new aircraft entering the TRACON have a runway preassigned to them, but occasionally a reassignment becomes desirable in order to reduce delays.

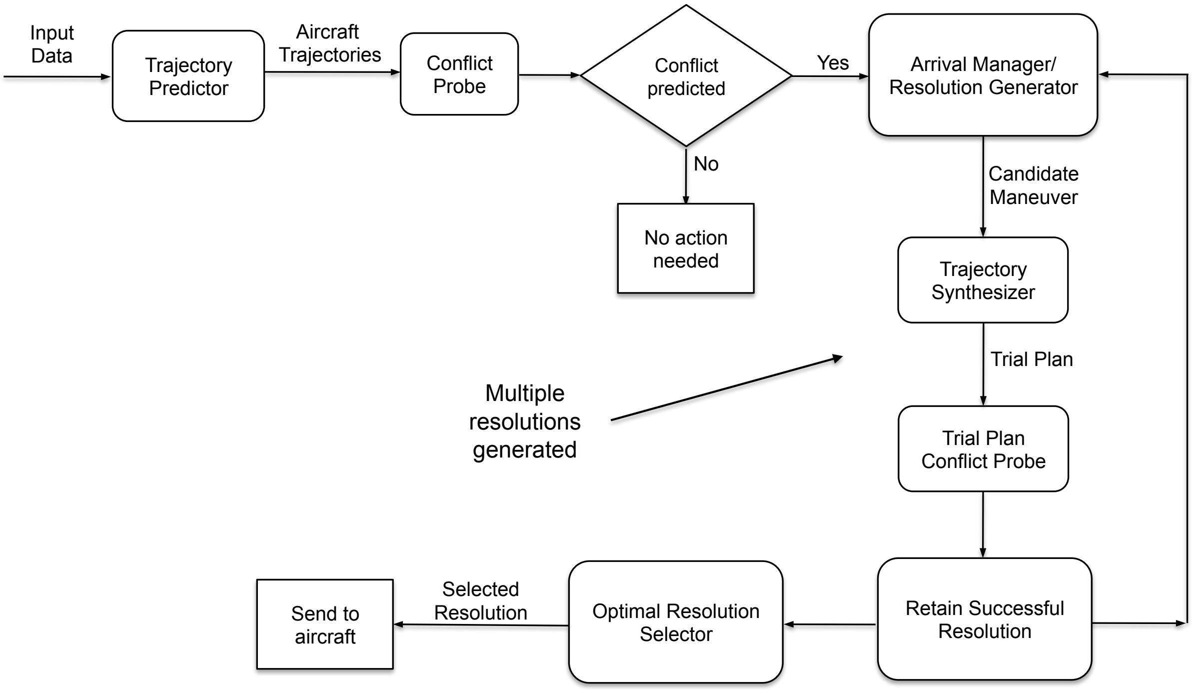

Figure 1. Functional diagram of Terminal AutoResolver

TAR uses a trial planning process as the basic algorithm for solving combined spacing and loss-of-separation conflicts. For each type of conflict, either meeting an aircraft's STA generated by the Arrival Manager or resolving a predicted separation conflict, the Resolution Generator module proposes different maneuvers to solve the problem using speed control, horizontal maneuvers, and altitude changes. Each candidate maneuver is sent to the external trajectory synthesizer module which creates a full four-dimensional trajectory of the aircraft from its current position to the runway. This four-dimensional trajectory that implements the candidate solution is referred to as a trial plan. Each trial plan is sent to the conflict probe to determine whether it has solved the original problem and has not introduced new conflicts. Instead of stopping the resolution process after finding the first successful resolution, TAR continues searching for additional resolutions. Trial planning can, therefore, yield more than one successful resolution. When more than one successful resolution is found, the resolution generator calls an algorithm which selects the maneuver that gives the least delay while conforming to operational practice as the solution to be implemented. The selected resolution maneuver is then issued to the conflict aircraft.

The above process is repeated periodically, at epochs of at least once per minute. In the current version of TAR, it is assumed that the trajectories generated by the external trajectory synthesizer are flown with a high level of accuracy, essentially without errors. Future work on TAR will account for trajectory prediction and execution uncertainty.

The Terminal AutoResolver processes the list of detected conflicts in a time ordered sequence. The predicted conflicts are further sorted by level of urgency based on time to loss of separation. Since TAR's conflict probe checks pairs of aircraft for loss-of-separation conflicts, only two aircraft are involved in each conflict that is passed to Resolution Generator for resolution. Each resolution is constructed so as to avoid causing new (secondary) conflicts to be introduced. Thus, each resolution trajectory becomes a constraint on the resolution of the next-in-sequence conflict. In other words, the resolution maneuvers for all previously resolved conflicts at any moment in time are taken into account when working on the next conflict. This strategy guarantees that pairwise generated resolutions do not interfere with previous resolutions. It is therefore considered a fully coordinated resolution process.

III. Arrival Management

Terminal AutoResolver will attempt to first resolve a predicted spacing conflict and then a loss-of-separation conflict if needed, as previously explained. An exception arises when the time until first loss-of-separation is below a certain threshold, in which case priority is given to resolving separation conflicts first, followed by resolution of spacing conflicts. Moreover, when an arrival aircraft is in loss-of-separation conflict with a departure or an over-flight that traverses the TRACON, preference is given in maneuvering the non-arrival aircraft so as not to disrupt the arrival schedule. The following subsections describe TAR's logic for managing arrival traffic, which is encapsulated in the Arrival Manager module.

A. Eligibility for Scheduling

Arrival Manager checks periodically, at scheduling epochs of at least once per minute, the state of those aircraft already inside terminal airspace and whether new aircraft have entered the TRACON. Trajectory Synthesizer provides the Arrival Manager with updated values of estimated times of arrival to the FAF. When an aircraft's remaining flying time to FAF first becomes less than a specified amount, referred to as freeze time interval, the aircraft becomes eligible to be assigned an STA at the FAF. In case the aircraft's flying time to the FAF is already less than the freeze time interval by the time it enters the TRACON, the aircraft is assigned an STA immediately upon entering the TRACON. To ensure stability of the arrival process, once an STA is assigned to an aircraft it is not amended by the Arrival Manager at a later time unless it encounters an unplanned loss of separation conflict. This is an important concept of TAR's scheduling process and it is similar to the so-called 'freeze horizon' concept of the Traffic Management Advisor[4] (TMA), a system for sequencing and scheduling arrivals installed at large Air Route Traffic Control Centers in the US.

For the case of the Dallas/Fort Worth TRACON, experience from simulation experiments suggests that suitable values for freeze time interval range between 9 to 12 minutes. Shorter values frequently resulted in more aggressive resolution maneuvers – such as large heading changes or large reductions in speed – due to smaller available time for aircraft to meet their STAs. On the other hand long freeze horizons will be more susceptible to aircraft trajectory errors which can result in additional maneuvers to avoid conflicts.

B. Spacing and Loss of Separation Conflicts

A time-based spacing conflict arises when two aircraft cross the FAF within less than a minimum time interval, which itself depends on the sequence order and weight category of the two aircraft. In practice, successive arrivals must maintain a minimum required separation distance throughout final approach, which starts at the FAF and ends at the runway threshold, as shown in Table 1. Arrival Manager, taking into account the speed on final approach of successive arrivals, converts the minimum required separation distances of Table 1 into minimum required time separations at the FAF, shown in Table 2. Whereas future versions of Arrival Manager should perform an aircraft-specific calculation, in the current version an average speed by aircraft weight category was used that yielded the minimum time separations listed in Table 2. It should be noted, though, that for cases when the trailing aircraft was significantly faster than the leading aircraft on final approach, the time

Table 1. Minimum required separation distance in nautical miles under Instrument Flight Rules (source: Ref. 5)

		Trailing aircraft			
		Heavy	B757	Large	Small
Leading aircraft	Heavy	4	5	5	6
	B757	4	4	4	5
	Large	3	3	3	4
	Small	2.5	2.5	2.5	3

Table 2. Minimum required time separation in seconds used by Arrival Manager

		Trailing aircraft			
		Heavy	B757	Large	Small
Leading aircraft	Heavy	82	118	118	150
	B757	60	64	64	94
	Large	60	64	64	94
	Small	60	64	64	68

separation of Table 2 was increased as necessary to ensure that minimum required separation distance was not violated anywhere on final approach.

A loss of separation (LOS) conflict occurs when two aircraft anywhere in TRACON airspace come within a certain horizontal and vertical distance. While many special regulations exist in practice, the general rule of 3 nautical miles horizontal and 1000 ft vertical distance was used in this research. Future work will include more detailed rules for defining a LOS conflict.

C. Scheduling Process

At each scheduling epoch, the Arrival Manager attempts to assign an STA to those aircraft that are eligible for scheduling and have not been assigned one. For each of those aircraft, the Arrival Manager computes its original estimated time of arrival (OETA) to the FAF. This OETA is the time the aircraft will cross the FAF if it follows its nominal flying procedure inside the TRACON and no conflict resolution maneuver is assigned to it. Arrival Manager first checks if setting the aircraft's STA equal to its OETA causes any spacing conflicts with aircraft that have already been assigned a frozen STA. If no problems are detected the aircraft is scheduled to cross the final approach fix at its OETA.

If a spacing conflict arises, the Arrival Manager searches for gaps in the schedule of frozen aircraft where the new arrival can fit in. In the majority of the cases, a slot is added at the end of the scheduling queue behind all frozen aircraft. We term the additional flying time with reference to OETA as *delay*. The Resolution Generator module of TAR (see next section), in collaboration with the Trajectory Synthesizer, is responsible for generating a trajectory that is free of loss of separation conflicts with other air traffic and delivers the new arrival at the FAF with proper spacing from other frozen aircraft. To achieve that, Resolution Generator initially generates a trial maneuver that is estimated to absorb the delay needed for the new arrival. However, if the full four-dimensional trajectory corresponding to this trial maneuver does not meet the specified STA within specified tolerance bounds (typically ±5 seconds) at the FAF then Resolution Generator generates new trial maneuvers iteratively resulting in small increments/decrements of STA. After a trial trajectory has been found that achieves the specified STA and a conflict check determines that no loss of separation conflicts have been introduced, the Arrival Manager designates that aircraft as frozen and scheduled. If, however, a loss-of-separation conflict is discovered in the conflict checking process, the Resolution Generator first tries an elliptic path stretch[3] to modify the trajectory spatially without changing the specified STA in an attempt to clear the loss of separation conflict. If those attempts fail to clear the conflict, the Resolution Generator increases the STA in small increments of time and repeats the procedure used to achieve the original STA. This process continues until a conflict-free trajectory is found. Thus, it is possible that the resolution of a loss of separation conflict remaining to be solved, after a trajectory that meets the specified STA has been found, can introduce additional delays. Simulation results described in Chapter V indicate this situation occurs relatively infrequently.

The Arrival Manager then waits for real time to advance to the next scheduling epoch. When that time is reached, the Arrival Manager repeats the process for all new aircraft that have crossed the freeze horizon. The Arrival Manager performs this process for traffic flowing to all runways at an airport.

The procedures described are illustrated in Fig. 2, which shows both a time line plot and horizontal view of traffic converging on a final approach fix. A new arrival, A4, has crossed the freeze horizon and has become eligible for scheduling. Its OETA indicates it is in spacing conflict with the frozen aircraft A3. By computing the time difference between the A4 OETA and the A3 STA, the Arrival Manager determines that a sufficient time gap is available to try decreasing the speed of A4 in order to resolve the spacing conflict between A3 and A4. The arrival manager then calculates the STA for A4 by adding the minimum required time separation – extracted from Table 2 - to the STA of A3. Next, the arrival manager asks the resolution generator to find a conflict-free trajectory for A4 to meet the specified STA. In this case, a reduced-speed descent profile that meets the required conditions is found. After the scheduling process for all new arrivals is completed, the arrival manager waits for time to advance to the next scheduling update cycle.

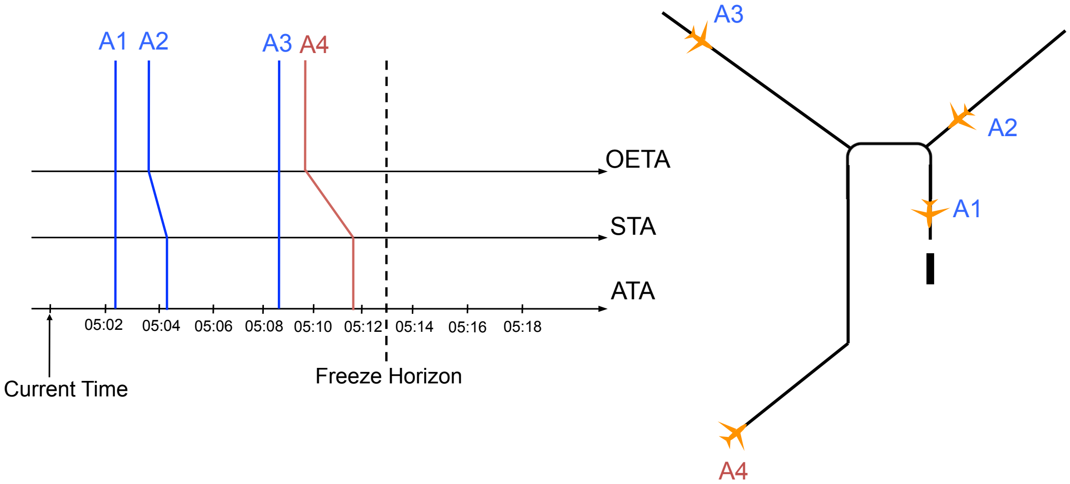

Figure 2. Scheduling process for new arrival A4.

D. Change of Runway

Although changing the landing runway close to the airport adds to the flight crew's workload, it may sometimes be a desirable action in order to keep the arrival flow balanced on all active landing runways of an airport. Arrival Manager issues a change of runway if landing on the alternate runway saves more than one minute of delay than landing on the preferred runway. The choice of one minute as the triggering criterion for initiating a runway change is somewhat arbitrary and can easily be changed in the software. However, because of the extra workload on pilots to reconfigure their Flight Management Systems for a change in runway while close to the airport, it is appropriate to require some minimum payoff in delay reduction before initiating such a change.

In particular, Arrival Manager will attempt to find a conflict free trajectory for landing on an alternate runway and assign a provisional scheduled time of arrival STA^{alt}. If the difference $STA^{pref} - STA^{alt}$ is larger than one minute, where STA^{pref} is the provisional STA for landing on the aircraft's preferred runway, then a change of landing runway will be issued. In case there are more than two active runways for landing and all alternate runways yield more than one minute of delay saving, the alternate runway with greater delay savings is preferred.

Finally, it should be noted that the Arrival Manager has been designed to operate either standalone or in conjunction with a separate scheduling and metering system such as TMA, which is widely used to control arrival traffic at US airports[5]. If the latter is the case, Arrival Manager then accepts as input STAs or runway assignments from the external metering system and searches for conflict-free trajectories that satisfy those inputs.

IV. Resolution Generator

The Resolution Generator is TAR's module that orchestrates the trial planning process for resolving predicted conflicts. The role of Resolution Generator is to generate a set of alternative maneuvers that resolve a predicted conflict. In addition, Resolution Generator assigns preference rankings to the alternative maneuvers that prove to be successful in resolving the predicted conflict. Higher priority is given to those maneuvers that create less delay and that deviate less from the nominal flight plan trajectory or, if delay is not a significant factor, to those maneuvers that follow rules controllers would typically use to resolve a similar type of conflict. The following subsections describe TAR's primary resolution maneuvers in further detail.

A. Speed Reduction

Speed reduction is the most desirable type of maneuver for pilots and air traffic controllers, since it does not modify the aircraft's planned horizontal route to the airport. Figure 3 shows an aircraft's calibrated airspeed (CAS) as a function of time, both for the nominal case of its descent to the final approach fix and for the case of speed reduction. The aircraft's initial speed of 250 knots is reduced to 220 knots. As a result, the aircraft crosses the final approach fix approximately 90 seconds later. In general, speed reduction is the preferred method for resolving spacing conflicts. It can absorb up to about 2 minutes of delay inside typical TRACON airspace.

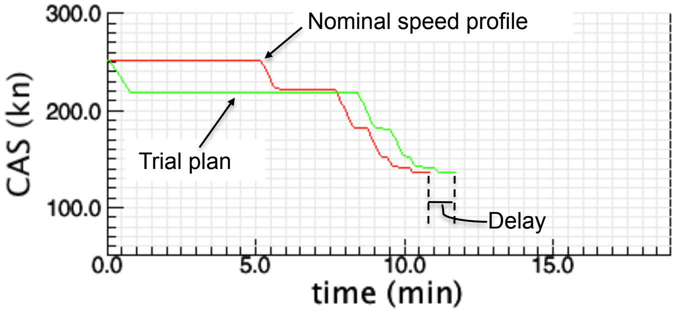

Figure 3. Reducing speed.

B. Hold Speed

When an arrival aircraft is being scheduled to the FAF earlier than its OETA, increasing the aircraft's speed is usually not an acceptable maneuver since it is constrained by the speed limit of 250 knots CAS in the TRACON. Instead, TAAC computes a maneuver that requires the aircraft to maintain its current speed for a longer time interval compared to its nominal descent procedure. In this way, the aircraft spends more time flying at a high speed and it arrives at the FAF earlier (see Fig. 4 for an example). The extended hold of a higher speed must be terminated when the aircraft crosses a specified altitude and/or range to the final approach fix where deceleration to a reduced speed must begin. That limits the time reduction achievable by this method to less than one minute for most aircraft types.

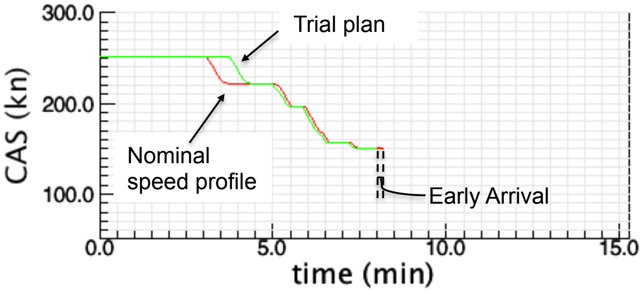

Figure 4. Holding CAS for early arrival.

This maneuver is defined by one parameter, namely the additional time interval of maintaining the aircraft's current speed. Maintaining a high speed for a longer time interval, however, might result in a steeper descent to the FAF. The Trajectory Synthesizer module will reject those trial plans that yield a trajectory with a descent rate outside of the aircraft's performance envelope.

C. Offset of Base Leg ("Trombone")

For aircraft whose trajectory includes a downwind leg, extending this downwind leg prior to turning to base leg is a frequently used maneuver by air traffic controllers. Figure 5 depicts a case where the base leg of the aircraft was offset by 3 nautical miles in order to resolve a spacing conflict. In TAR, such trombone resolutions are used if speed reductions alone are insufficient to solve the spacing conflict. Trombone solutions are always used in combinations with speed reductions as much possible. In the trial planning process, the turn to base is extended in increments of half a mile which yields adequate time control accuracy.

Unlike the other horizontal maneuvers of the TAR that require the aircraft to deviate from its planned route immediately, the trombone maneuver begins only when the aircraft is about to turn to the base leg from its downwind leg. Therefore, it has the advantage of being

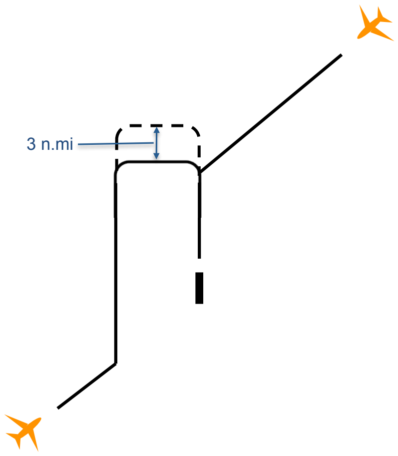

Figure 5. Trombone.

available for modifications to correct imprecise projections of the aircraft's trajectory or of loss-of-separation conflicts. Such modifications can be done even if the aircraft is only a short time (30-60 seconds) from the revised turn-to-base waypoint.

The trombone maneuver has the capability of absorbing large amounts of delay as it can extend the downwind leg for an additional 5 or even 10 nautical miles. Moreover, it can do so in small increments, thus proving a powerful tool for efficiently resolving spacing conflicts.

D. Path Stretch

Two types of path-stretch maneuvers are used in TAR. Trial planner first attempts to find a resolution using a symmetric path stretch (see Fig. 6). It selects an auxiliary waypoint that lies on the perpendicular and midway to the vector that connects the aircraft's current position and the return waypoint. Symmetric path stretch generates a one-parameter family of maneuvers, defined by the turn angle from the aircraft's current heading. Symmetric path stretch maneuver is a powerful means to resolve spacing conflicts, where the primary goal is generating additional flying time for the trailing aircraft. As in trombone maneuvers, aircraft's current speed is first reduced as much possible, and it is this new speed profile that is used in generating a trial path stretch maneuver. The trial planner generates both left and right handed turns when maneuvering airspace is available in either direction.

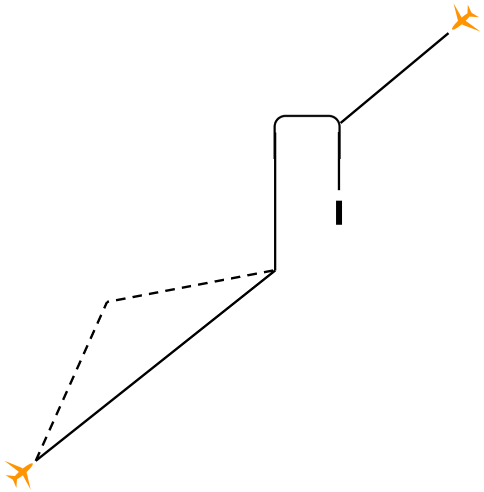

Figure 6. Path stretch

If no successful resolution is found using a symmetric path stretch maneuver, TAR will conduct a more extensive search for resolutions by employing the constant-delay elliptic path stretch algorithm. This type of path stretch is characterized by two parameters: a specified delay and the turn angle relative to current heading. A detailed description of the algorithm can be found in Ref. 4. Such resolutions can resolve loss-of-separation conflicts even when an aircraft has its landing STA frozen, by trying different turn angles that yield the same time-to-fly until touchdown. It is the only maneuver available that can modify a trajectory spatially without changing its landing time.

E. Horizontal Vector Turn

The horizontal vector turn (hvt) was originally designed[5] to resolve short-range conflicts such as in TSAFE where it is important to include the effects of turn rate limits in the generation of the resolution maneuver. The algorithm has also been adapted for use in the Autoresolver to resolve conflicts over longer time ranges while retaining its ability to resolve short-range conflicts.

The hvt algorithm determines the minimum heading change required to achieve a specified separation distance, assuming both conflict aircraft are flying at constant airspeed. The algorithm gives an explicit solution for a specified minimum separation without trial planning. It also generates a return path for the aircraft via an auxiliary waypoint and a return waypoint, as illustrated in Fig. 7. The algorithm provides the coordinates of a point on the straight-line segment that follows the vector turn where minimum separation of the resolution maneuver is reached. Then, the auxiliary waypoint is located on the straight-line segment an incremental distance beyond this point. The incremental distance, taken to be the equivalent of about 30s of flight time, ensures that a turnback maneuver starting at the auxiliary waypoint will not cause the original conflict to reappear. Although the trajectory segment to the auxiliary waypoint is designed to be conflict free, trial planning followed by a conflict check is still needed to ensure that the entire trajectory is free of secondary conflicts.

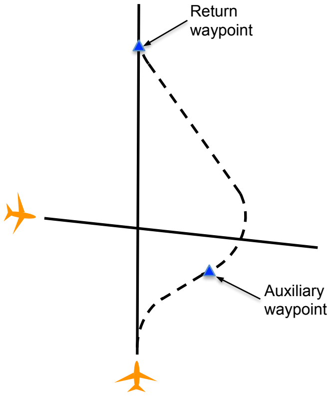

Figure 7. Horizontal vector turn

F. Delayed Turn Back

Similar to the trombone maneuver for arrival aircraft, the *delayed turn back* (dtb) algorithm is designed to maneuver climbing aircraft whose departure route inside the TRACON involves a large change of heading after take-off; see Figure 8 for an example. Specifically, eligible for this maneuver are aircraft whose ultimate heading toward its destination requires the aircraft to make a large heading change (more than 90 degrees) from its initial heading following takeoff. For those aircraft, the algorithm creates an auxiliary waypoint, located on the line segment that connects their current position with the next waypoint on their original route and an incremental distance beyond this point. In this way, the aircraft delays the first turn on its planned route. A second auxiliary waypoint, located at a 90 degrees angle from the first auxiliary waypoint, is used as a turn back point where aircraft can resume their flight towards a downstream fix on their flight plans.

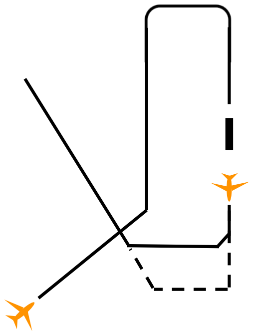

Figure 8. Delayed turn back maneuver.

The dtb algorithm increases the set of candidate solutions for departure aircraft. It is used as an alternative to path-stretch resolutions, when the latter either fails to find a conflict-free resolution trajectory or generates a trajectory that imposes a large delay to the departure aircraft.

G. Extension of Final Approach ("Fanning")

In certain situations, when an aircraft is on a heading to intercept the final approach path, an alternative to path stretching is to change the heading of the aircraft so that it intercepts the final approach path further upstream (see Fig. 9). In this way, the need for specifiying an auxiliary waypoint is avoided and the entire maneuver can be communicated more easily to the pilot. The pilot is simply given a new heading and the instruction to intercept the final approach. Again, the aircraft's current speed is reduced to the lower limit of its speed envelope prior to trying a fanning maneuver.

A somewhat restricting factor for this maneuver is the interception angle with the final approach path. In order to ensure a smooth transition into the final approach, the algorithm requires that the interception angle is not greater than 60 degrees. It turns out that in most of the cases, that translates to an extension of the final approach by only a few miles which is typically less than five nautical miles. That limits the amount of delay that can be absorbed by this maneuver to relatively small values. However, it is still a useful tool for situations where speed reduction is not sufficient to absorb all delay, since it has the advantage of not requiring the specification of auxiliary waypoints.

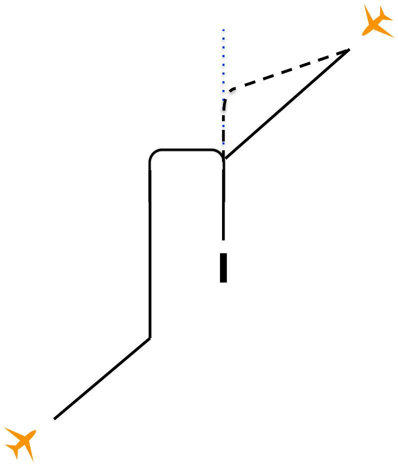

Figure 9. Extension of final approach.

H. Compound Horizontal Maneuvers

A combination of two horizontal maneuvers can also be employed to resolve spacing conflicts that require a large amount of delay to be absorbed. When extension of final approach does not resolve the conflict, a symmetric or elliptic path stretch can be applied in conjunction with extending the final; Figure 10a illustrates an example. This type of resolution can absorb more delay compared to what a symmetric path stretch or extension of final can absorb separately.

There are situations where the return waypoint of a path-stretch maneuver lies on the final approach. Depending upon the position of the turn back point, it may happen that the aircraft must perform a turn of more than 90 degrees to align on final approach. Such a large heading change to capture the final approach is generally considered undesirable by pilots, and the Resolution Generator will discard such maneuvers. To address this issue, a special type of compound maneuver has been created that consists of a path-stretch and a constructed base-leg segment that provides a more acceptable transition to final approach; Figure 10b provides an example. At the end of the path-stretch maneuver the aircraft transitions to a base-leg segment, which ensures a smoother turn to final approach segment.

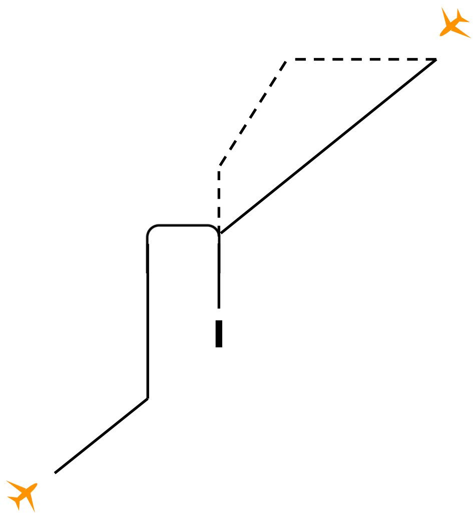

Figure 10a. Path stretch with extension of final approach

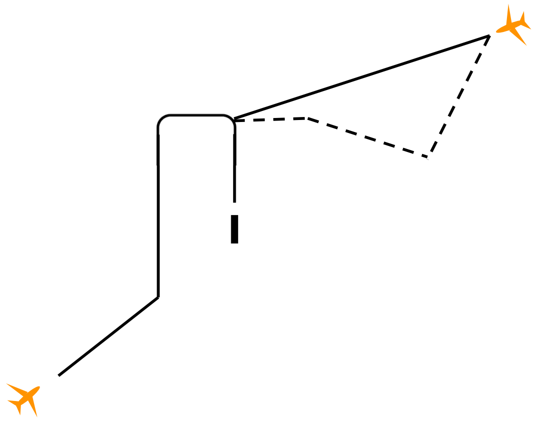

Figure 10b. Path stretch with base leg

I. Temporary Altitude during Climb

In this case the aircraft assigned by the Resolution Generator to perform the altitude resolution maneuver is currently climbing toward its assigned cruise altitude. The time of first loss with the conflict aircraft may occur during the climb segment or after the aircraft has leveled out at its cruise altitude. The specification of the parameters for the trial resolution trajectory is the same for both situations.

A temporary altitude maneuver for an aircraft in climb is defined by two parameters. The first specifies the flight level at which the maneuvering aircraft must level out (also referred to as the temporary altitude level). Only flight levels at least 1500 ft. above the current altitude of the climbing aircraft and 1000 ft. below the flight level of the altitude where first loss occurs are eligible for temporary altitude levels. The second parameter that defines the temporary altitude maneuver is the time at which the maneuvering aircraft can resume its climb to capture the originally assigned flight level.

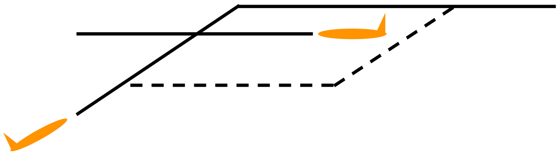

Figure 11. Temporary altitude during climb

V. Simulation Results

A fast-time simulation environment was employed to test Terminal AutoResolver's performance in spacing and deconflicting traffic, namely the Airspace Concept Evaluation System (ACES). ACES is a gate-to-gate simulation of air traffic at airport, regional, and national levels, developed by NASA.[6] ACES generates flight trajectories using aircraft models obtained from the Base of Aircraft Data[7] (BADA) and traffic data consisting of departure times and real-world flight plans obtained from Airline Situation Display to Industry (ASDI) files. These trajectories are then fed into TAAC for resolution of spacing and loss-of-separation problems.

In this study, air traffic to and from the Dallas/Fort Worth metropolitan area was considered. Arrival and departure data for the two major airports of the area, the Dallas/Forth Worth International Airport (DFW) and the Dallas Love Field Airport (DAL), were used as input to the simulation. Figure 12 shows the Dallas/Fort Worth TRACON area, with the runway system of DFW and DAL included. The flight plan data used in the analysis presented here include a 24-hour period that begins at 00:00 Coordinated Universal Time (UTC) on 4/25/2012. According to the methodology defined in Ref. 8, this traffic sample can be characterized as a high traffic volume and low delay day in the National Airspace System. The input scenario consisted of 900 arrivals and 915 departures at DFW and 229 arrivals and 245 departures at DAL totaling 2289 flights. Inbound and outbound flows are almost balanced, with the largest proportion of flights landing or taking off from DFW.

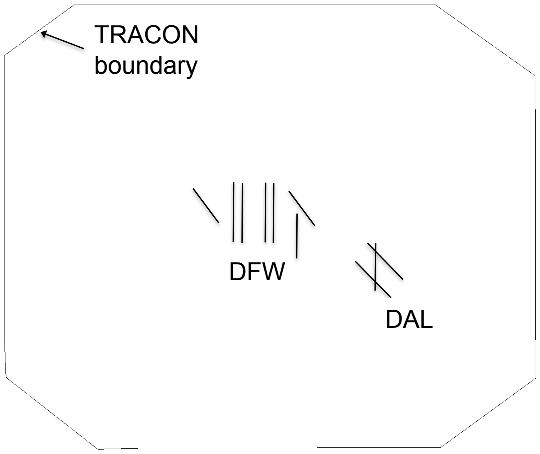

Figure 12. Diagram of the DFW TRACON. Runways not on scale.

The south flow runway configuration was assumed for operations. Thus, landings at DFW were assumed to take place simultaneously and independly on runways 18R and 17C and take-offs on runway 18L and 17R. Similarly for DAL, it was assumed that aircraft were landing on runway 13L and taking off from runway 13R. Furthermore, in the simulation the TRACON area was treated as a single sector with no procedural constraints to separate arrival and departure traffic. The purpose here was to determine what kind of problems the Terminal AutoResolver and Arrival Manager would encounter without the airspace segregation and procedural rules used in current operations.

It should be noted that during rush periods this traffic sample produced delays which sometimes exceeded three minutes per aircraft. Under a typical south flow configuration scenario at DFW, up to two additional runways, 13R and 17L, may be used for landings at the input traffic levels. Moreover, it was assumed that Arrival Manager was operating with no external metering system to control the rate of arrivals from Center airspace into the TRACON airspace. This input scenario exposed the Arrival Manager to a complex and heavy traffic load, which is useful in exploring its limits of performance.

Table 3 provides conflict resolution statistics for the study. Data are provided for both airports considered, while all conflicts were resolved. At DFW, 900 arrivals were handled, of which 413 encountered spacing conflicts that were resolved. In only 15 of those 413 cases, resolution of a spacing conflict created a LOS with another aircraft that Arrival Manager treated as non-maneuverable, either because it was an arrival with a frozen STA or a departure that had already received another resolution maneuver. Arrival Manager resolved such secondary LOS conflicts by adding further delay to the resolution maneuver. The relatively small percentage of such cases confirms the hypothesis that resolution of spacing conflicts also minimizes the occurance of secondary conflicts, though it does not completely eliminate them. The result supports the usefulness of controller decision support tools that provide time-of-arrival advisories without a method for detecting and resolving upstream conflicts. Controllers monitoring the traffic detect these occasional conflicts and can resolve them by issuing corrective clearances manually. However, the potential for such conflicts, even though infrequent, is not acceptable for an autonomous control system where controllers are not assumed to be in the loop to detect them.

Table 3. Conflict resolution statistics

	DFW	DAL
Total number of arrivals	900	249
Total number of departures	915	245
Total spacing conflicts resolved	413	60
Spacing conflicts that required an additional solution of a LOS conflict with a frozen aircraft destined to same runway	15	5
LOS conflicts Arrival vs Departure	196	0
LOS conflicts Departure vs Departure	124	6

The number of LOS conflicts resolved between arrival and departure traffic was 196, which would probably be unacceptable in a manual controller environment. Furthermore, 124 conflicts between departures were resolved, which in today's operations departure controllers prevent by manual procedures. We expect to eliminate most of those conflicts in an upadated version of TAR by incorporating an additional automation function. This function will predict such conflicts while aircraft are in position for takeoff on the runway. The function will issue a brake release time to the pilot that includes an appropriate amount of delay to eliminate the conflict. This approach is the preferred strategic solution since it will result in fewer tactical conflicts in flight.

In Table 4, delay statistics are summarized. Total as well as average delay values are provided for both airports. Average delay per arrival flight at DFW is considerably higher than at DAL indicating the limited capacity due to using only two runways for landings in this simulation. The last row in Table 4 indicates the additional amount of delay that was required to resolve a LOS conflict that had to be solved after a spacing conflict was cleared. Thus, the 15 arrivals at DFW that experienced a spacing conflict as well as a LOS conflict (see table 3) had to absorb, on average, an additional 30 seconds of delay to clear that LOS conflict. Although this amount of additional delay is considered low, it may be possible to reduce the frequency of such conflicts further by slightly modifying the descent trajectories.

Table 4. Delay statistics

	DFW	DAL
Total delay for departures (hh:mm:ss)	2:05:25	0:38:22
Average delay per departure flight (sec)	8	10
Total delay for arrivals (hh:mm:ss)	9:45:24	1:08:36
Average delay per arrival flight (sec)	39	18
Extra amount of delay incurred for resolving a LOS conflict after the original arrival spacing conflict was solved (avg/flight) (sec)	30	45

Next, a second simulation run was performed in which runway reassignment was not permitted and all aircraft landed on their preferred and preassigned runways. Table 5 includes metrics that compare this scenario with the base case, where runway reassignment was allowed. As mentioned previously, a runway reassignment was executed only if the delay saved from the change was at least 1 minute.

The first row in Table 5 indicates that Arrival Manager found 70 cases at DFW and 9 cases at DAL where delay savings for switching the landing runway was large enough to justify this action. The second and third rows show the delay impact on the entire arrival traffic, not just on the reassigned aircraft.

The second row in Table 5 gives the dimensionless ratio of the total delay savings due to runway reassignment relative to the total delay savings only from runway-reassigned flights. Similarly, the third row gives the delay saving per runway-reassigned aircraft. For each ratio we have subtracted out the individual delay savings from the reassigned aircraft. This procedure reveals explicitly the delay reduction amplification effect of the runway change.

Thus, as shown in the second row for DFW, each minute of delay reduction for the reassigned aircraft generated 1.5 minutes of delay reduction for the traffic that followed. Equivalently, as shown in the third row, at DFW the average aircraft that changed its landing runway generated an average of 3.1 minutes of additional delay savings for the traffic that followed it.

Table 5. Runway reassignment statistics

	DFW	DAL
Number of aircraft assigned to different runway	70	9
Change in delay for all arrivals except reassigned aircraft divided by change in arrival delay of reassigned aircraft	1.5	0.9
Change in delay for all arrivals except reassigned aircraft divided by number of reassigned aircraft (min/flight)	3.1	0.2

Thus, altering the landing runway of an arrival aircraft when the potential delay savings is estimated greater than one minute for that aircraft alone reduces the delay for all traffic significantly. This is a well known phenomenon in queueing theory when demand is at or above capacity of a system. The benefits of runway reassignment are considerably less for DAL, since the traffic at that airport is below capacity most of the time. In the current version of TAR, the algorithm for runway reassignment tests only one aircraft at a time, and it does not evalutate the delay effect of the change on the traffic that is known to follow behind it. Neverthless, the delay reductions obtained from the current version of the algorithm for reassignments are substantial.

Finally, two examples of conflict resolutions are discussed. Figure 13a shows a spacing conflict due to insufficient time separation at the final approach fix between leading flight AAL2069 and trailing flight DAL1299. The trial planning process resulted in a trombone type resolution which delayed the turn to the base leg of flight DAL1299 by 3 nautical miles. It should be mentioned that path-stretch maneuvers beginning near the start of the trajectory also succeeded in solving this problem, but were considered less desirable than base extension for this specific situation.

In another example, shown in Fig. 13b, arrival flight COA1815 is in a loss-of-separation conflict with departure flight EGF503. To resolve the conflict, the departure flight was issued a path-stretch maneuver. In TAR's logic, it is preferred that departures be manuevered over arrivals in order to preserve the scheduled time of arrival for landing aircraft.

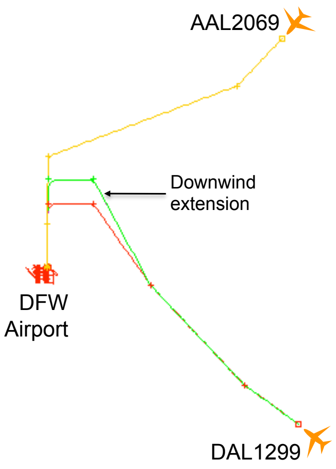

Figure 13a. Example of spacing problem resolution.

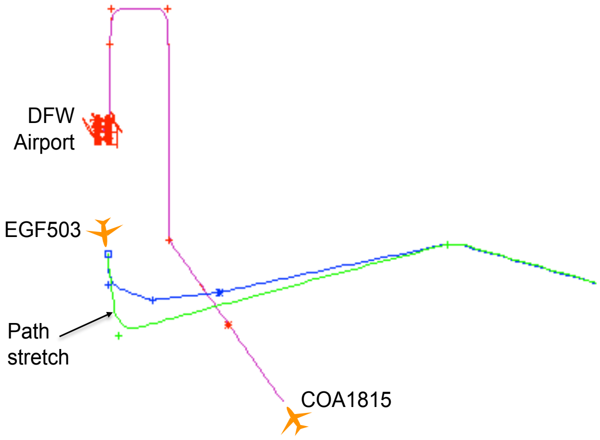

Figure 13b. Example of loss-of-separation resolution.

VI. Concluding Remarks

This paper has introduced the basic functionalities and algorithms of a system for automated conflict resolution and arrival scheduling for aircraft inside the terminal airspace. The so-called Terminal AutoResolver (TAR) employs maneuvers such as speed control, path stretching, or turn to base leg, to deconflict air traffic and handle arrival scheduling problems.

At present, TAR's logic has been implemented in the Java programming environment and experiments have been run using the ACES simulation platform. The DFW and DAL airports were used as a case-study, and arrival and departure data for 24 hours of operations were an input to the simulation. Analysis of simulation results indicates that TAR was able to solve all types of conflicts encountered, including combinations of arrival spacing problems and separation conflicts.

Future work will focus on developing algorithms for solving special problems such as handling missed approaches, giving priority to emergency aircraft, avoiding encounters with convection cells along arrival routes, and generally accounting for errors in trajectory execution. Another step in the development of this concept will be to evaluate it in Human-In-The-Loop simulations wherein controllers will be assigned to handle only exceptional problems, such as change of runway configuration for landings and take-offs, or addressing special requests by pilots. A data communications link will be simulated to send TAR-generated trajectories to the aircraft.

The long term objective of the research is to create and validate a system design that provides the basis for an autonomous air traffic control system where routine controller tasks can safely be delegated to the autonomous agent and controllers can instead focus on handling special problems that require a human's unique problem solving skills.

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