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Flight-Deck Automation for Trajectory-Based Surface Operations

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To address anticipated growth in air traffic demand, the Surface Operation Automation Research (SOAR) is a collection of research activities designed with the common goal to explore and develop automation technologies for enhancing surface movement efficiency at major airports. The concept features a tower automation system that collaborates with a flight-deck automation system to jointly deliver highly efficient and safe surface operations. The tower automation counts on the availability of advanced surveillance data to plan timed surface operations. The time-based trajectories are communicated to the flight decks as 4-dimensional (4D) trajectory clearances via digital data link. The flight-deck automation counts on the availability of advanced navigation capabilities to execute the 4D trajectories with high timing precision. Several publications have documented the SOAR concept and initial feasibility studies of the tower and flight-deck automation systems based on early experimental software prototypes of the automation functions. This paper reports on the latest development of the flight-deck automation system, including its clearance handling capabilities, guidance and control functions, pilot interface, conflict and incursion monitoring functions, as well as plans for the assessment of an experimental prototype implementation.

I. Introduction

THE predicted growth in air travel requires capacity enhancement in the National Airspace System (NAS), and congestion at key airports has been recognized as one of the most prominent problem areas[1]. With flights operating at limits dictated by operational requirements associated with current airport configurations, airport expansion plans involving addition of new runways and taxiways are being realized to increase the airports' capacities. However, the expansion plans necessarily increase the complexity of the airport configurations, and the increase in complexity tends to penalize the efficiency of the system, partially offsetting the capacity-related benefits of the investments. The *Surface Operation Automation Research*[2,3,4] (SOAR) project has proposed a collaborative concept to provide tower and flight-deck automation systems to enhance the operational efficiency in complex airport environments, thus softening the penalties to fully realize the capacity benefits sought by the airport expansion plans. The concept depends on advanced *Communication, Navigation, and Surveillance* (CNS) as enabling technologies to achieve a seamless integration of the tower and flight-deck automation systems.

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While the SOAR concept examines the surface traffic control problem as an integrated system involving the Air Navigation Service Provider (ANSP), the flight deck, and their associated automation systems and other enabling technologies, other studies have investigated individual aspects separately. The Surface Management System[5] (SMS), developed by NASA in cooperation with the FAA, is a valuable decision-support tool for service providers and NAS users for providing situational awareness of the airport traffic[6]. The route generation capability of the Surface Decision Support System (SDSS)—the SMS testbed fielded by the FAA—has been used to study the feasibility of a conformance monitoring function[7]. The study compared surveillance data with routes automatically generated by the SDSS, but it was not designed to address the 4D-trajectory conformance problem: (i) the study did not consider the timing nature of 4D trajectories, and (ii) the controller's clearances were issued independently of the automatically generated routes. The EUROCONTROL Advanced Surface Movement Guidance and Control System[8] (A-SMGCS) concept includes research on optimization of airport taxi scheduling[9]. A-SMGCS consists of automated monitoring and alerting functions, and includes the prediction of conflicts on active runways or incursions into restricted areas. The European Airport Movement Management by A-SMGCS (EMMA) project defines A-SMGCS operational requirements[10] for the ANSP and flight deck, and other important services such as CNS[11].

In the SOAR concept, tower automation has been studied as the *Ground-Operation Situation Awareness and Flow Efficiency* (GoSAFE) concept[12] to coordinate taxi operations, especially in situations where active-runway crossings constitute a significant taxi delay problem. To help achieve the potential GoSAFE benefits, the *Flight-Deck Automation for Reliable Ground Operation* (FARGO) concept[13] has been proposed to provide the necessary flight-deck automation for enabling precision taxi control to comply with GoSAFE clearances. Fundamentally, the GoSAFE/FARGO integration is based on "4D trajectories" consistent with the airport configuration. Although the taxi operation is constrained on the airport surface, the taxi route with timing constraints at specified locations is still referred to as a "4D trajectory" in the same spirit as 4D trajectories in flight, with the caveat that the altitude dimension of the 4D space is constrained to the surface. Others have referred to this notion of surface 4D trajectories as "2D + time."

In addition to have documenting the SOAR concept and its automation systems, previous publications have covered some evaluation activities based on computer simulations of surface operations at a single hub airport[14, 15] as well as the effect on the NAS-wide traffic[16]. Furthermore, the tower operations involving the GoSAFE automation system has been subjected to a series of human-in-the-loop experiments involving tower-controller subject experts in a full-scale tower simulator with realistic visual and system capabilities[17, 18, 19].

Though the development of GoSAFE has reached a level that high-fidelity human-in-the-loop evaluation can be performed, development of the FARGO system is less mature. In the human-in-the-loop assessment of GoSAFE, it was assumed that the flight decks were equipped with FARGO automation, which was emulated in the simulation of the surface traffic. In the mean time, actual development of the FARGO technologies has progressed in parallel in recent years[20]. This paper serves as an update of the FARGO development effort. It considers the flight-deck operational procedure, and covers the development of an experimental prototype that includes all the key subsystems of the FARGO system: clearance handling, guidance, control, conformance monitoring and conflict handling, and pilot interface.

The next section provides an overview of the SOAR collaborative surface-operation automation concept, followed by a description of the FARGO system, followed by description of the separate system components in Section III.

II. Overview of Collaborative Automation Concept

A. Background

Airport capacity is often measured in terms of achievable runway throughputs for arrival and departure operations. This obvious type of metric, however, may not adequately capture the complete trade space related to capacity. In order to maximize runway throughputs for arrival and departure, a common practice for surface operations is to queue up the departure traffic at the departure runways to ensure that no departure slot is lost. Similarly, arrival controllers would try to bring the arrival traffic down onto the runway without wasting runway resources. In order to minimize the impact on the arrival and departure operations at the runways, taxiing traffic requiring active-runway crossing can be queued up before they are cleared to cross as a group. Although these common practices serve to maintain the landing and takeoff rates at a high level at the runways, they achieve the results by introducing additional operational delays for the flights at the queues depicted in Figure 1. To adequately account for the costs associated with capacity gains, the FAA Airport Benefit-Cost Analysis Guidance[21] captures the lack of capacity through the measurement of delays incurred by the traffic. As the increase in runway throughput serves to reduce operational delay, any additional delay accrued in the taxi operations to facilitate such throughput increase should be discounted against the delay reduction. The SOAR concept attempts to reduce the overall surface operational delays through improved efficiency at the runways as well as throughout the rest of the airport movement area. The savings in delay affect not only the air carriers' crew costs, but they also affect passengers' cost for their travel, fuel costs, and environmental factors such as noise and emissions.

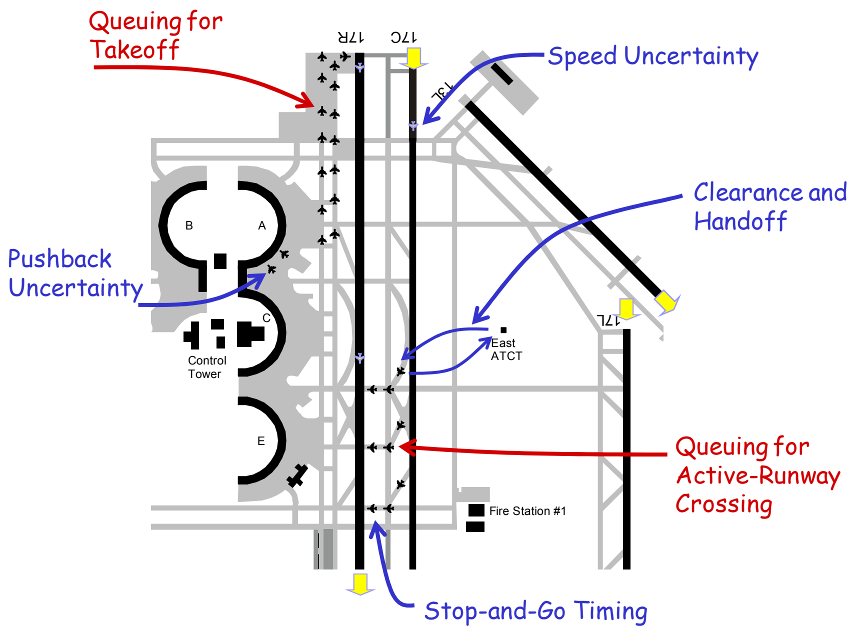

Figure 1. Operational Factors of Taxi Delays.

The most prominent delays felt by the traveling public in the movement area are associated with the queuing for departure and the queuing for active runway crossing. Much of the need to queue up the traffic is tied to the uncertainties associated with the operations, and Figure 1 illustrates some of these uncertainty factors. Pushback operations at the gates are difficult to predict, and allowing pushback to take place and queuing up at the departure runways ensures a consistent departure stream at the expense of taxi-out delay. Timing uncertainties for taxi operations—including speed control, clearance and handoff, stop-and-go timing, etc.—have resulted in the need to queue flights up for runway crossing so as to minimize the need to hold up landing and takeoff operations at the runways. Waiting for gate access at the passenger terminal and the need for deicing are also notable causes for surface operational delays. The delay factors related to runway access become worse as airport expansion plans introduce more runways, which lead to increased amount of active runway crossings. Moreover, having more traffic at the airport further exacerbates the runway access problem. It will be beneficial if the traffic can be precisely controlled so that the flights can perform active runway crossings in between takeoffs and landings, without introducing takeoff or landing delays. This level of precise traffic control is difficult in the presence of control-timing uncertainties associated with current operational practices of voice clearances, voice-based handoffs, and manual control of the aircraft that do not lend themselves to operating according to strict timing constraints. The SOAR concept tries to achieve the precise control in taxi operations through collaborative automation between the tower and the flight deck.

B. Automation Systems in Collaborative Concept

Figure 2 illustrates the collaborative concept of employing automation systems in the tower for traffic planning and at the flight deck for executing. In the control tower, the *Strategic Automation* is responsible for *Surface Traffic Management (STM)* functions including decisions on airport configurations and coordination of the runway assignment, sequencing and scheduling of arrival and departure flights with Terminal Control. The *Tactical Automation* is responsible for *Surface Traffic Control (STC)* functions that involve taxi operation planning, clearance management, and surface conflict management including the prevention of runway incursions. The GoSAFE technologies explored to-date have focused on these STC functions.

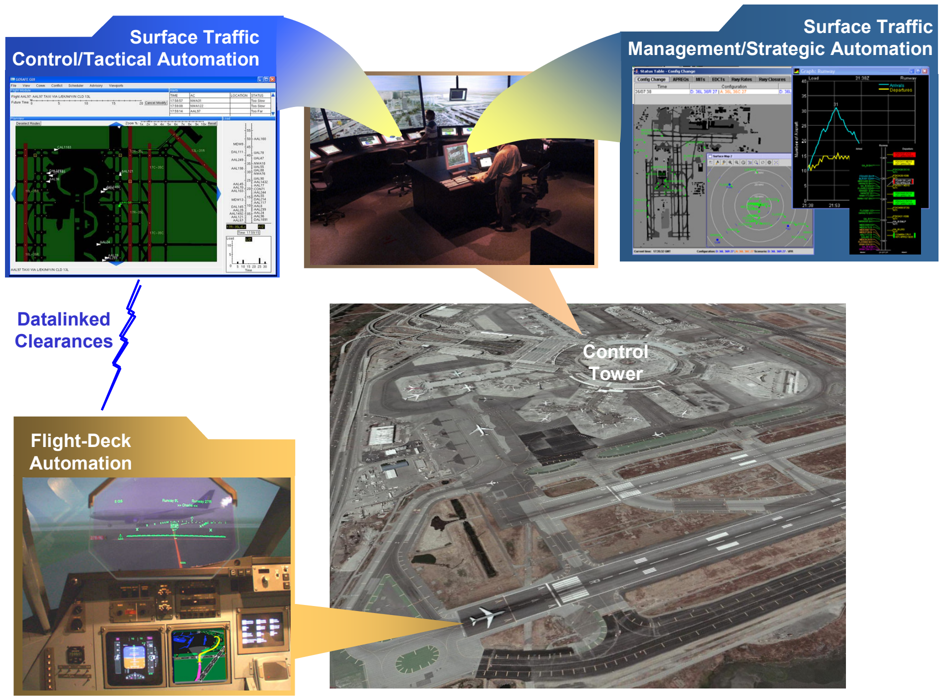

Figure 2. Collaborative Automation between Tower and Flight Deck Operations.

With GoSAFE issuing the clearances, the FARGO system provides the *Flight-Deck Automation* functions to execute the clearances. The SOAR concept is built upon the following coupled assumptions:

1. The FARGO automation system can achieve high-precision taxi to allow the flight to meet any reasonable crossing times at selected points along a pre-specified taxi route on the airport surface.
2. The GoSAFE automation system counts on the availability of FARGO's precision-taxi capability to plan efficient and safe operations for the surface traffic.

The precision-taxi capability reduces operational uncertainty that impacts the separation margins the controllers have to introduce to assure safe operations. Reducing the separation margins will result in improved efficiency. Furthermore, the reduced uncertainty allows the more efficient operations to be delivered with at least the same level of safety as in existing operations, even in the presence of reduced temporal or spatial separation between aircraft operations. Safety in this case is defined based on the probability of conflicts, not merely the nominal separation between vehicles. Reduced uncertainty can produce lower probability of conflict even when the nominal separation is reduced.

The block diagram in Figure 3 illustrates the interaction between the GoSAFE and FARGO automation systems, and the interactions of the operators—air traffic control and flight crew—with these systems. It also depicts the feedback nature of the whole traffic control operation with CNS functional blocks, where advanced CNS are considered enabling technologies for the automation concept.

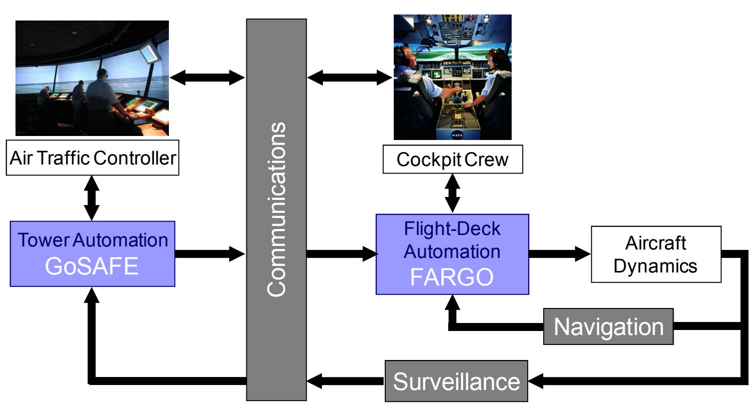

Figure 3. Block Diagram of SOAR Concept.

C. Operational Procedure

Since the SOAR concept promotes traffic efficiency through the use of time-based route clearances that can be accomplished only with automation such as FARGO, the use of voice clearances to send the timing details is impractical and the use of digital data link is considered necessary. With so much information embedded in the clearances, the procedure uses pre-clearances to initially send the complete route information, to allow the flight crew ample time to comprehend the intended operation and identify any potential cause for concern.

Furthermore, as the taxi route nominally would contain locations where safety may become a serious concern if the aircraft is unable to achieve the precise timing (e.g., active-runway crossings), "contingency holds" are inserted along the route at these locations to give the controller the option of allowing the aircraft to come to a stop if the controller chooses not to clear it beyond that point. This means that the pre-clearance in fact consists of a number of segments, each of which needs to be cleared as a separate clearance, and each segment contains a contingency hold at the end except for the final segment. The contingency hold is automatically removed when a subsequent segment is cleared.

The SOAR operational procedure for handling pre-clearances contains the following events:

- Minutes before the clearance is needed, GoSAFE sends FARGO a data-linked pre-clearance containing taxi route information similar to conventional clearances, with the addition of time constraints where necessary to resolve conflicts with other vehicles and runway usage.
- FARGO would automatically access airport layout database to convert the pre-clearance into route-segment information ready for access by the cockpit crew.
- When selected by the pilot, FARGO would display the clearance in both textual and graphical forms, with the crossing constraints appropriately emphasized. If the pre-clearance involves more than one segment, the locations of the contingency holds for the segments are also displayed to the flight crew.
- The FARGO interface provides the pilot with options to accept or reject the pre-clearance. Acceptance of the pre-clearance automatically saves the information for later use.
- Acknowledgment of the pre-clearance is data-linked back to GoSAFE to help the controllers keep track of the status.

With the taxi route information already sent to the flight deck in the form of a pre-clearance, there is no need to repeat all the information when the subsequent clearances are issued. The individual clearance segments can be abbreviated with identifiers to reference the pre-clearance. This abbreviated form allows the controller the options to issue the clearances by voice or by data link. Since timing is important in executing the timed clearances, a clearance should be issued sufficiently early ahead of time (e.g., tens of seconds) so that FARGO can initiate the operation at the moment the segment is supposed to commence; for subsequent segments, the clearance should be issued early enough before FARGO is forced to slow down for the contingency hold. The SOAR procedure for handling clearances contains the following events:

- A tower controller issues a clearance for a segment by voice or by data link, as desired.
- The flight crew either accepts or rejects the segment clearance, using the same mode of communication (i.e., voice or data link). Acceptance of the clearance by data link will automatically activate FARGO for the segment; otherwise, the pilot has to manually activate the segment.
- Acceptance of a segment clearance will automatically remove the contingency hold at the end of the last cleared segment, and append the new segment to it.
- Data-linked acceptance of a clearance also automatically notifies GoSAFE; otherwise, the controller will need to manually update GoSAFE with the clearance status. (Speech recognition is being considered for future research to convert voice acknowledgment into the signal to update GoSAFE.)
- Rejected clearances will lead to GoSAFE replanning taxi operations, including the operations of other affected flights. The replanning normally involves adjusting the timing constraints, but in serious situations may require completely new pre-clearances.
- Handoff between controllers can be done by voice or data link, or independently by the flight crew based on published procedures.

Procedures dealing with emergency situations such as reacting to conflicts or incursions typically will involve some flights performing an emergency maneuver (e.g., stop) that will cause the conformance monitor functions of the automation systems to detect the problem. The controllers will likely give voice clearances to resolve the problem promptly, and proceed to use GoSAFE to replan the operations. This subject is an important item for future research on off-nominal situations.

III. Flight-Deck Automation

Technical feasibility of a flight-deck automation system has been investigated in previous studies[13], and development of the FARGO automation technologies[20] is ongoing. Figure 4 contains a general block diagram of the FARGO concept that shows the major components of the automation system. The following are envisioned functions of the FARGO automation.

- *Clearance Processing and Planning* functions for the surface operations: These functions involve handling the clearances issued by tower, and inputting them into the flight control computer for pre-visualizing the surface operations and eventually for performing the taxi operations.
- *Auto-taxi* functions to generate aircraft taxi control commands: Advanced guidance functions convert the clearance information into 4D trajectory information for achieving precision taxi requirements demanded by GoSAFE-generated clearances. Advanced controller designs provide the means to track the 4D trajectory. The automation functions take into account aircraft performance and weather conditions.
- *Pilot interface* to enable pilots to execute precision taxi operations: Displays are included in the FARGO concept to process the clearances and present the 4D trajectory information to the flight crew. Other control displays provide control information to the pilots either for monitoring performance in a fully automatic mode or for conveying control cues in an automation-assisted mode.
- *Traffic monitor* functions provided through pilot interface to alert pilots of impending danger: FARGO can monitor the aircraft's navigation state to alert the pilot of any significant deviation from its cleared taxi routes. It can also track the surveillance data from other flights on the surface to alert the flight crew of any impending conflict or incursion by other vehicles.

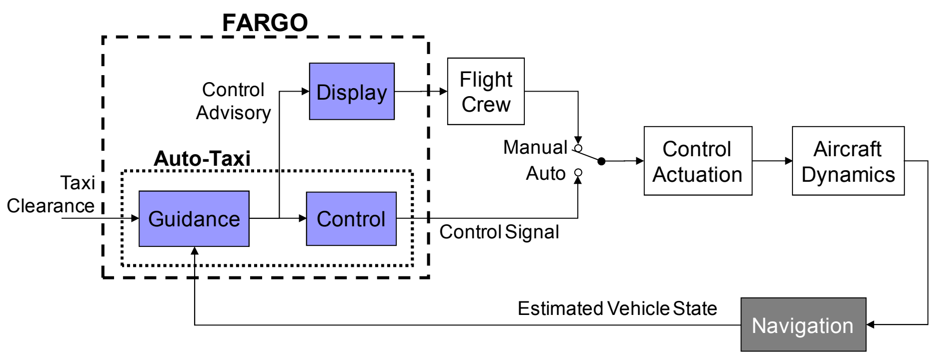

Figure 4. General Block Diagram of FARGO Concept.

These functions are shown in more details in the "data flow" diagram of Figure 5, which shows the functional blocks (in rectangular blocks) as well as the data items (in ovals) between the blocks. These blocks and data items are discussed in the following subsections.

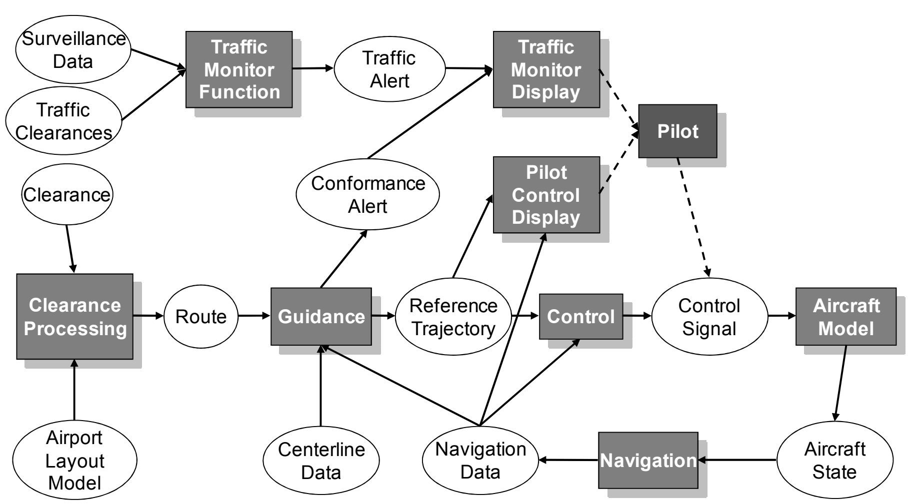

Figure 5. Data Flow Diagram of FARGO Processes.

A. Digital Clearance Processing

FARGO's clearance handing capability includes two parts: (a) processing of the pre-clearance including complete route information sent automatically by the tower automation via data link, typically minutes ahead of time of execution, and (b) processing of the actual clearances.

The following is an example of a pre-clearance for an arrival flight:

[1] TAXI VIA 17C/M5(#EM@1141946344)/EM(#17R@1141946469) |HS 17R. [2] TAXI VIA EM CR 46

As FARGO receives this pre-clearance, it is downloaded onto the flight computer for processing. The text message is displayed to the flight crew on a display such as the Lower EICAS shown in Figure 6, and it is also parsed for extraction of the route information to be displayed graphically to the flight crew, who can pre-visualize the route on the Electronic Moving Map (EMM) shown in Figure 6. The pre-clearance example above carries the following information:

- The numbers in square brackets indicate that the pre-clearance includes two segments [1] and [2].
- Segment [1] says the taxi is expected to begin on runway 17C (after landing), followed by a turnoff at M5 and taxiway EM. These taxiways are delineated by the slashes in the pre-clearance.
- The # sign within the parentheses following M5 indicates that there is a crossing constraint on M5 to cross the intersection with EM at the time specified by the number in sec following the @ sign. This numbering system is based on UTC timing convention relative to some standardized reference datum.
- Similarly, there is a crossing constraint on taxiway EM for crossing runway 17R.
- The vertical bar followed by the letters "HS" indicates a "Contingency Hold" defined for the end of segment [1]. It means that the flight is expected to stop short of runway 17R if the clearance for segment [2] is not received in time. Typically the clearance for segment [2] is expected to arrive early enough so that it can be acknowledged and executed before the system has to slow down to execute the "Contingency Hold." If the clearance for segment [2] does arrive in time as expected, the "Contingency Hold" will be lifted.
- Segment [2] says the taxi should continue on taxiway EM.
- The "CR" command indicates that the flight will be cleared to enter the ramp area at spot 46 as part of segment [2].

The following is a similar pre-clearance example, but this time for a departure flight:

[1] TAXI VIA L(#EH@1141951893)/EH(#17R@1141952016) |HS 17R. [2] TAXI VIA EH CLD 17R

- Again this example involves two segments, where segment [1] expects the flight to be coming out of a certain ramp spot which the tower automation knows about but has not indicated here explicitly.
- Segment [1] expects the taxi to go through taxiways L and EH, with crossing constraints at EH and runway 17R, respectively.
- A Contingency Hold is specified at the end of segment [1] at runway 17R.
- Segment [2] expects the taxi to continue on taxiway EH onto runway 17R.
- The "CLD" command indicates that the flight will be cleared to take off from 17R as part of segment [2].

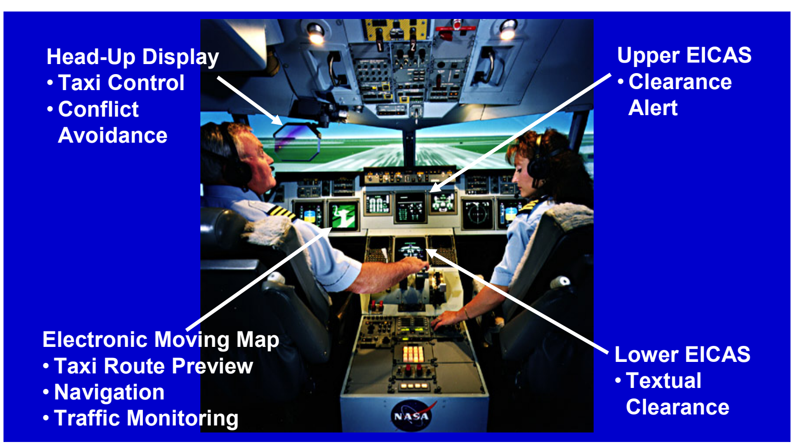

Figure 6. FARGO Pilot-Interface Displays.

The pre-clearance format described above has been used in human-in-the-loop assessment of the tower simulation using pseudo-pilots to simulate operation of the traffic[17, 18]. For the current FARGO prototype being implemented, a new data-link message based on XML format of the route has been designed to reduce the amount of processing to parse the route information.

With information from the pre-clearance already loaded on the flight computer, clearances for the individual segments have the flexibility to be issued by data link or by voice.

- The clearance for each segment can make use of the segment identifier (i.e., segment number) so as to reduce the amount of communication required without the need to repeat the route information.
- Acknowledgment of the clearance by the flight crew should be in the same communication mode as the clearance itself—voice or data link, as appropriate.
- Once the clearance of a new segment is received and acknowledged, the flight computer should be updated to load and execute the segment, overriding any Contingency Hold as appropriate. If the clearance is issued by data link, acknowledging the clearance through FARGO should automatically load the segment for execution. If the clearance is issued by voice, then the flight crew will have to explicitly notify FARGO that the segment has been cleared for execution.

B. Guidance System for Reference Trajectory Generation

The role of the guidance function is to accept the taxi route specified by the clearance with embedded timing constraints to generate reference "4D trajectory" information for the aircraft to track. This trajectory is more than a route with required times of arrival (RTA) at selected points: it is a complete trajectory where every point along the way is mapped to a point in time.

This guidance function takes into consideration airport layout standards[22] with respect to turning requirements. There are a number of factors that go into the computation of the trajectory, including turn radii, hold distances, aircraft performance, and passenger comfort. The turn radii and hold distances are based partly on the largest aircraft that an airport is expected to handle, and the numbers are therefore defined for approach categories and design groups. The FARGO design imposes a reasonable acceleration profile in defining the trajectory.

GoSAFE plans the 4D-trajectory clearances using a graph-theoretic link-node model, where the links are straight lines that represent sections of taxiways and runways. Most turns for a taxi trajectory between two links that meet at a node can be modeled by a curve of constant radius (i.e., a true arc), based on an assumed taxi speed and lateral acceleration. This situation is shown in Figure 7.

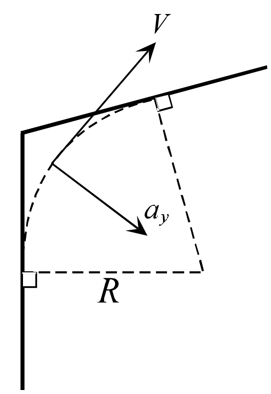

Figure 7. Turn Arc between Connected Linear Segments.

However, not all taxiway intersections are laid out with a constant radius. According to the FAA's Advisory Circular[22] (150/5300-13) on airport design, exit taxiways from runways do not have a constant radius throughout. As is the practice with highway ramps and railroads, there is a transition zone of increasing curvature, where the radius of the turn goes from infinity to a circular arc of finite, constant radius. This zone is called the entrance spiral in the Advisory Circular and is also known in civil engineering as a transition spiral. The curvature of the spiral is proportional to the arc length. For a constant speed, then, this relationship produces a lateral acceleration that is linear with time. If the turn were to be a simple arc of constant radius, then there would be a step change from infinite to finite radius and consequently a step change in the lateral acceleration. This would require a sharp input to the nose wheel steering in order to follow a centerline. The spiral creates a smoother entry into the turn.

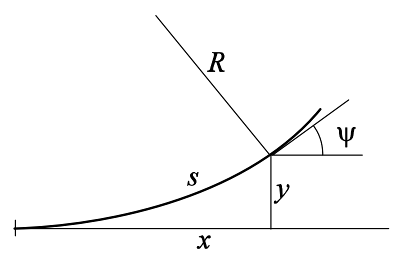

Figure 8. Transition Sprial.

While the spiral is more pleasing for pilots and passengers, it is less so for engineers, because generating the trajectory coordinates is more complicated. Referring to Figure 8, where s is the arc length, the relationship between curvature and arc length gives:

$$\frac{1}{R} = 2b^2 s = \frac{d\psi}{ds} \Rightarrow \psi = (bs)^2 \tag{1}$$

where b is a proportionality constant. The coordinates x and y are related to the arc length s by the relationships

$$\frac{dx}{ds} = \cos\psi = \cos(bs)^2, \quad \frac{dy}{ds} = \sin\psi = \sin(bs)^2$$

These equations are integrated to obtain the solutions[23]:

$$x = \int_o^s \cos(bs)^2 ds = \frac{1}{2b}\sqrt{\frac{\pi}{2}}\int J_{-\frac{1}{2}}(u)du = \sqrt{\frac{\pi}{2b^2}}\sum_{n=0}^{\infty} J_{\frac{4n+1}{2}}(u) \tag{2}$$

$$y = \int_o^s \sin(bs)^2 ds = \frac{1}{2b}\sqrt{\frac{\pi}{2}}\int J_{\frac{1}{2}}(u)du = \sqrt{\frac{\pi}{2b^2}}\sum_{n=1}^{\infty} J_{\frac{4n-1}{2}}(u) \tag{3}$$

where $u = (bs)^2$ and $J_n(u)$ are Bessel functions. To avoid computing these Bessel functions, an alternative solution is to use a Taylor series expansion[24]:

$$x = \sqrt{\frac{\pi}{2}}\frac{1}{b}\sum_{n=0}^{\infty} c_n z^{4n+1}, \quad c_{n+1} = \begin{cases} 1, & n = 0 \\ \dfrac{-\pi(4n+1)c_n}{4(2n+1)(2n+2)(4n+5)}, & n > 0 \end{cases} \tag{4}$$

$$y = \sqrt{\frac{\pi}{2}}\frac{1}{b}\sum_{n=0}^{\infty} s_n z^{4n+3}, \quad s_{n+1} = \begin{cases} 1, & n = 0 \\ \dfrac{-\pi(4n+3)s_n}{4(2n+2)(2n+3)(4n+7)}, & n > 0 \end{cases} \tag{5}$$

where b is the spiral coefficient, s is the arc length along the spiral, and

$$z = \sqrt{\frac{2}{\pi}}bs \tag{6}$$

This series is valid when the product bs is sufficiently small, as it is in this case. It has been found that truncating the series after five terms still produces very accurate results. Since $s = \int v dt$, x and y can be expressed as functions of time.

When the 3D trajectory is defined with all the turns and straight segments, there are still many degrees of freedom in defining the velocity profile to meet the timing constraints. The current prototype implementation of FARGO imposes additional model behaviors for the velocity profile, hence on the final 4D trajectory. It models movements in intersections with constant speed of reasonable value to control the intersection occupancy time, taking into account dimensions of intersections. This restricts the change in speed to take place only in the segments outside the intersections. Since all turns are modeled as intersections in the link-node model, all turns are modeled with constant speed. Figure 9 is a notional plot that illustrates the definition of the speed profile to complete the 4D trajectory, where the “handles” represent the crossing constraints, and the acceleration and deceleration are restricted to the “legs” of the trajectory.

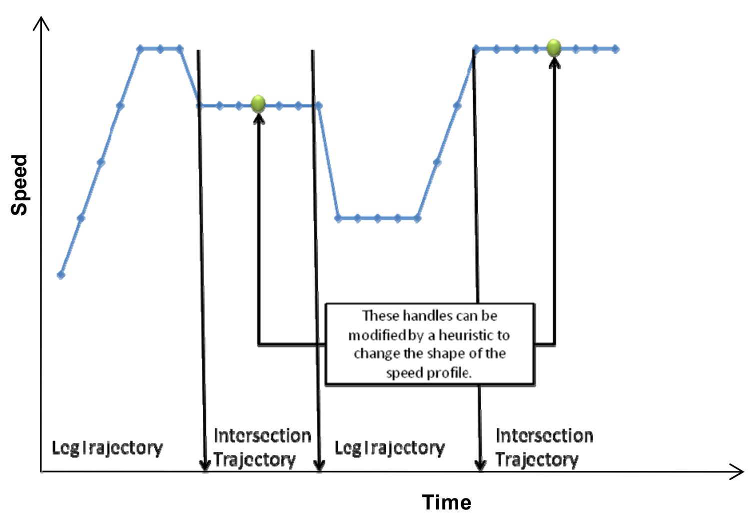

Figure 9. Definition of Speed Profile for 4D Trajectory.

C. Advanced Control for High-Precision Reference Trajectory Tracking

A nonlinear controller is designed to generate the control signals to effect the 4D-trajectory tracking, based on the Nonlinear Synthesis Tools[25] (NST) product. Of the many nonlinear control design techniques included in NST, the *feedback linearization* methodology[26, 27] has been adopted for the current FARGO design. NST provides the necessary tools in synthesizing a superior nonlinear controller with a software "design model" of the aircraft dynamics embedded in its own code. Figure 10 illustrates this design concept. The current FARGO design has been produced for a B-737-type aircraft, for which a software model has been extracted from NASA's Transport System Research Vehicle[13] (TSRV) simulation. Performance of the nonlinear controller has been verified based on computer simulations as reported in Ref. 20, which also contains a detailed discussion of the design of the nonlinear controller. Readers interested in the design should refer to that paper.

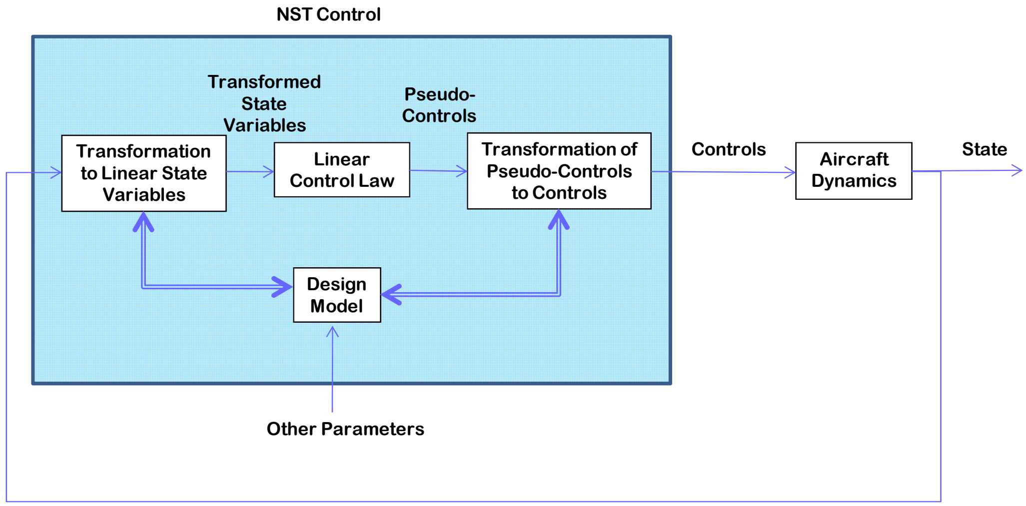

Figure 10. Concept of Nonlinear Controller Based on Feedback Linearization.

D. Conformance Monitoring and Conflict/Incursion Detection

Advanced surveillance services such as ADS-B and TIS-B are assumed available to allow the FARGO automation to detect and react to potential conflicts with other surface traffic. Typically the potential problems are detected through prediction of traffic movement based on the surveillance data. Examples include the Airport Movement Area Safety System (AMASS), Runway Incursion Reduction Program (RIRP) Surveillance System[28], and NASA's Runway Incursion Prevention System[29, 30] (RIPS) and Collision Avoidance for Airport Traffic[31, 32] (CAAT).

The approach taken by the SOAR concept—and the FARGO system in particular—is to include flight-deck control intent based on the clearances issued by the GoSAFE automation system. This type of intent information is therefore available to cover all flights for which clearances sent via digital data link contains sufficient intended route information for the FARGO automation system to comprehend. Consequently, the FARGO system will be able to determine not only the trajectory that the own-aircraft is supposed to execute, but it can also interpret how the nearby flights are supposed to maneuver. This helps to cut down on the amount of false alarms of conflicts or incursions inferred from surveillance data alone.

Specifically, since taxi clearances issued by GoSAFE are meant to contain conflict-free routes, any potential conflicts will involve non-conformance of at least one flight from its cleared route. The FARGO system provides an own-vehicle performance monitor function—a process separate from its guidance and control functions—to detect unreasonable deviation of its own state from the intended trajectory. Such information will serve as alerts to the pilots, and it can also be communicated to the GoSAFE system to improve overall situation awareness. In addition, by examining surveillance data from ADS-B and TIS-B as well as data and alerts from GoSAFE, the FARGO system can perform trajectory prediction of all nearby flights to detect potential conflicts. One key difference between FARGO and existing conflict/incursion detection concepts is FARGO's ability to use the aircraft's cleared route information as intent to augment the detection logic. Again any resulting prediction of conflict or incursion needs to be promptly relayed to the pilots as alerts and to the GoSAFE system as well. Communication back to GoSAFE will help it plan for remedial actions in a timely manner.

The EMM display discussed in the next section is appropriate for providing traffic information and alert in anticipation of conflicts with other vehicles, by superimposing aircraft icons on the display showing locations of the nearby traffic. It is also beneficial to post conflict alerts on the head-up display (HUD) even though the HUD's field of view is limited, since the HUD is likely the primary display used by the pilot performing taxi operations.

E. Pilot Interface Subsystems

The FARGO pilot interface will build on the experience from a previous NASA research product: Taxiway Navigation and Situation Awareness (T-NASA) system[33, 34]. Figure 6 illustrates various proposed displays as part of the pilot interface, and Figure 11 provides a closer view of the HUD and EMM from the T-NASA system. Textual clearance data can be shown on the Engine Indication and Crew Alert System (EICAS) displays shown in Figure 6. The flight crew has the option of viewing the route information extracted from the pre-clearance on the EMM. The HUD is preferred as a control display to enable the pilots to monitor FARGO's performance during auto-taxi operations, and to enable the pilots to perform manual taxi control by display control advisories for the pilots to follow.

The FARGO displays are designed to convey the following list of information elements:

- Desired taxi path and segments
- RTA (and acceptability interval) for given points along path
- Traffic information (location, ID, intent)
- Incursion alerting
- Current location
- Current ground speed
- Timing (or speed error)
- Path/route error
- Contingency conformance monitor
- Mode indicator
- Messages such as Hold/Stop, Contact ATC, Expedite, New Route, etc.

The system is designed to support both automatic and manual operational modes for taxi control. Figure 12 contains an illustration of the HUD graphical design to display the FARGO guidance and control data for manual control under FARGO's automation assistance. A key indicator here is the timing error indicator to help the pilot meet the timing constraints. Figure 13 shows the difference in the HUD display when FARGO is in the auto-taxi mode. In this case, the timing error indicator is replaced by a list of control indicators that show the values of the control inputs such as throttle, brakes, and tiller commanded directly by FARGO, and the centerline dots have been replaced by a solid line to enhance mode awareness for the pilots.

Figure 11. Cockpit Simulator with T-NASA Displays[33, 34].

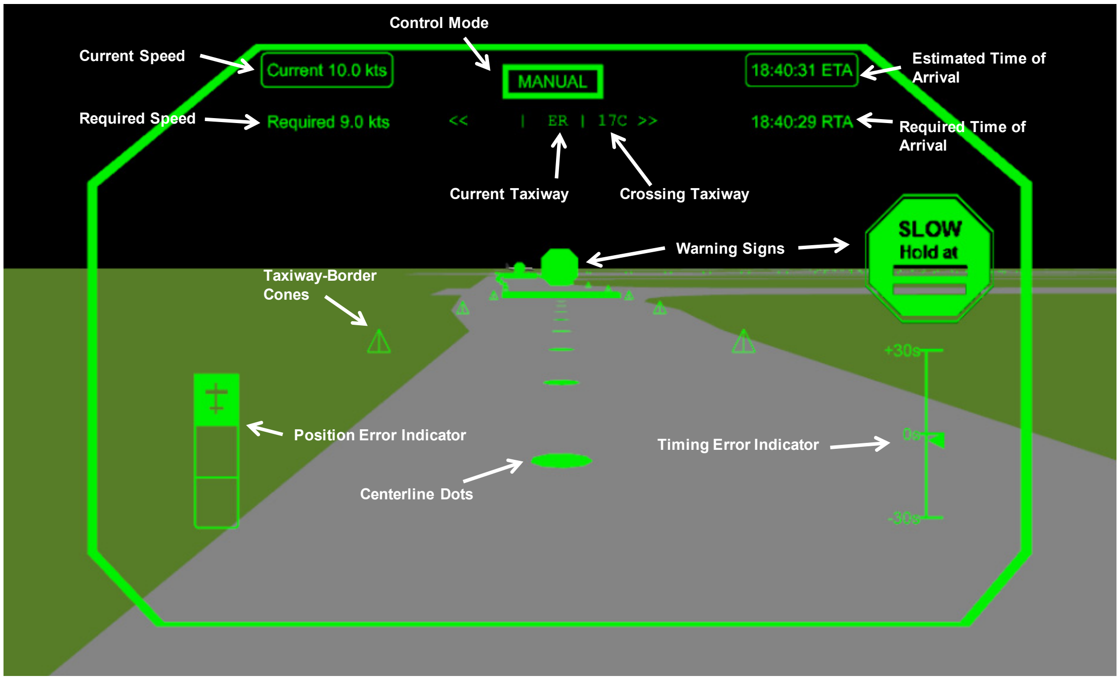

Figure 12. Sample HUD Display for Manual Control Mode.

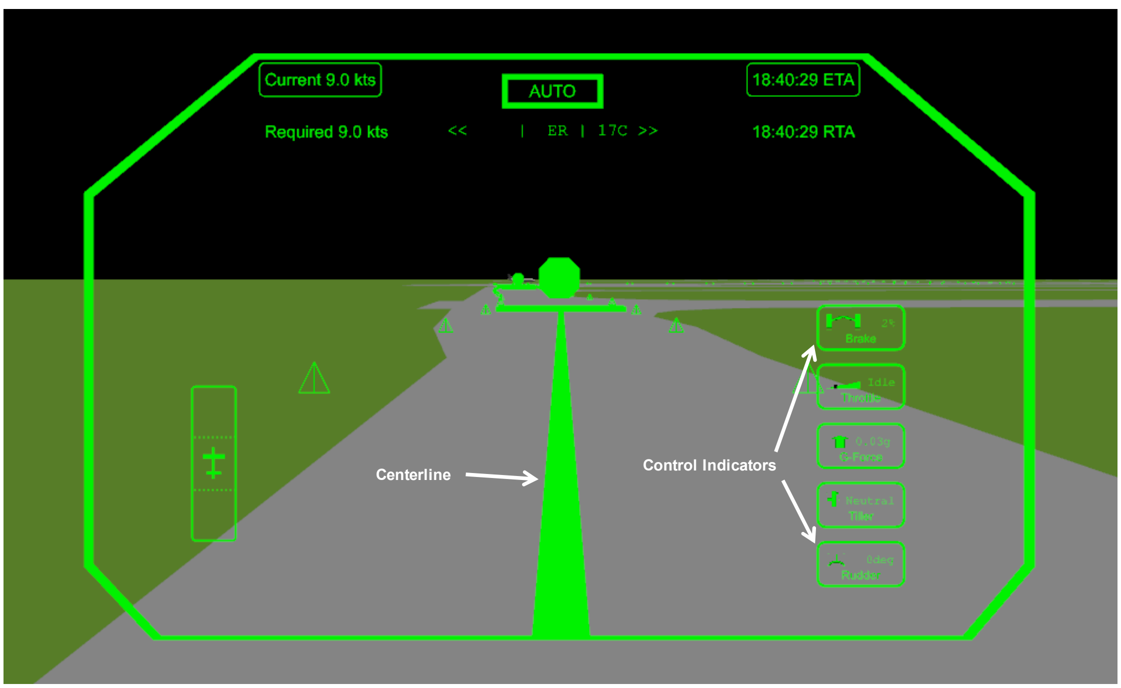

Figure 13. Sample HUD Display for Auto-Taxi Mode.

Advanced surveillance services are assumed that will allow the FARGO automation to detect and react to potential conflicts with other surface traffic. The EMM display as shown in Figure 14 is appropriate for providing traffic information and alert in anticipation of conflicts with other vehicles, by superimposing aircraft icons on the display showing locations of the nearby traffic. It is also beneficial to post conflict alerts on the HUD even though the HUD's field of view is limited, since the HUD is likely the primary display used by the pilot performing taxi operations.

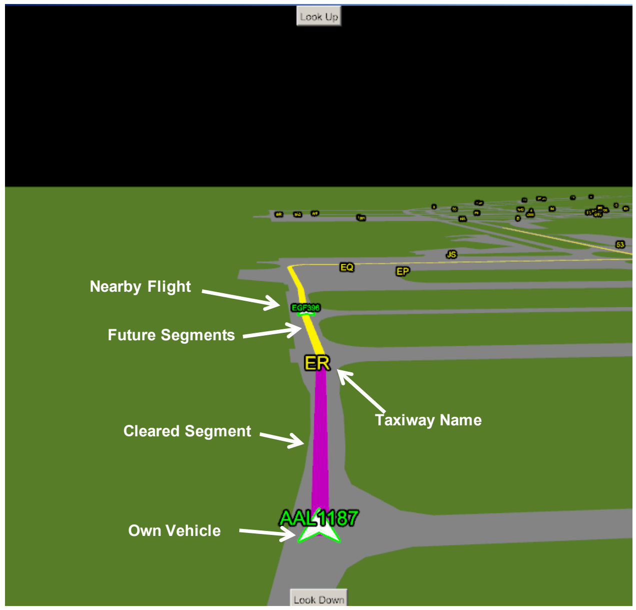

Figure 14. Sample EMM Display.

IV. Assessment Plans

The FARGO experimental prototype system described herein will be the subject of a human factors study to obtain high-level feasibility data on the concept and feedback on display specifics related to information requirements and interface design. A computer simulation with joystick and paddle inputs will be used. General aviation (GA) pilots will serve as subject matter experts for the experiments. Three conditions will be tested:

- Current equipage except for data-linked clearances, i.e., no FARGO
- FARGO manual mode with automation assistance
- FARGO auto-taxi mode

A total of 18 scenarios will be prepared for the trials. Each pilot subject will have:

- 3 practice trials, 1 for each of the 3 conditions
- 5 time-based taxi trials for each condition, with counter-balanced order of conditions among different pilots

The measures for the assessment will include:

- The ability to meet time-based segment requirements
- Overall taxi success
- Participant comments and suggestions

V. Concluding Remarks

This paper has described the design and development of the *Flight-Deck Automation for Reliable Ground Operation* (FARGO) system, one of the two key automation systems envisioned by the *Surface Operation Automation Research* (SOAR) concept to promote efficient surface operations at major airports. FARGO is a flight-deck automation system that is supposed to work in conjunction with the tower automation system— *Ground-Operation Situation Awareness and Flow Efficiency* (GoSAFE)—where GoSAFE can count on the availability of FARGO's precision-taxi capability to plan the operations.

This paper has covered all the key subsystems of the FARGO system: clearance handling, guidance, control, conformance monitoring and conflict handling, and pilot interface. These subsystems have been implemented in an experimental prototype to support human-in-the-loop assessment with a computer simulation. The system will be evaluated to measure its efficacy in supporting the pilot's execution of time-based trajectory taxi operations.

The development effort has revealed how the notion of 4D trajectories changes through the systems comprising the SOAR concept. More specifically, surface 4D trajectories in the GoSAFE traffic planning phase consist of piecewise-linear taxi route segments with required times of arrival (RTAs) at specified locations. As the routes are converted into clearances and sent to FARGO, the guidance function transforms these 4D trajectories into detailed reference trajectory signals, including speed and acceleration profiles that can be realistically tracked by the dynamic control system while maintaining the original timing constraints. Future research should investigate optimal ways to generate these 4D reference trajectories so as to improve the robustness and predictability of trajectory-based surface operations, ultimately affecting the efficiency, safety, and acceptance of such operational concepts.

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