Research Progress on an Automation Concept for Surface Operation with Time-Based Trajectories

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Abstract

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 counts on the availability of advanced surveillance data to plan the execution of timed surface operations to enhance movement efficiency and safety. Communication of the clearances will require the availability of digital data link for sending the data for executing the time-based trajectories—known to some as 4-dimensional (4D) trajectories. The concept also features a flight-deck automation system that counts on the availability of advanced navigation data to enable the flights to execute the 4D trajectories with high timing precision. The arrangement results in a collaborative concept where the tower and flight-deck automation systems count on each other’s abilities to jointly deliver the efficient and safe surface traffic. 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 serves as a progress update of the SOAR development effort. Specifically, it covers recent human-in-the-loop experiments to study procedures and controller roles and responsibilities involving the tower automation system, as well as development of the flight-deck automation system in terms of its guidance and control functions.

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 areas1. 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 (SOAR) concept has been proposed as 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.

Tower automation is based on the Ground-Operation Situation Awareness and Flow Efficiency (GoSAFE™) concept previously developed under a NASA-sponsored research program to ease runway access conflicts, 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 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.

Previous publications have documented the SOAR concept2,3,4, the automation systems5,6, and some evaluation activities7 based on computer simulations of surface operations at a single hub...
airport\textsuperscript{8} as well as the effect on the NAS-wide traffic\textsuperscript{9}. This paper serves as a progress update of the development of these automation systems and the assessment efforts.

In particular, 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. Since the role of the automation system is not to eliminate controller positions, but rather to assist the controllers in handling a larger amount of traffic as predicted for the future, the experiments focused on scenarios involving significantly higher demand levels. Different operational procedures involving voice clearances and data-linked clearances were tested, as well as variations in the controllers’ roles and responsibilities. The experiments have generally supported the controllers’ receptiveness to automation systems, and revealed the need for serious investments in technology development to transform the experimental prototype of the automation system into a mission-ready system. A summary of the experiments is provided below, with more detailed accounts of the experimentation efforts to be presented in other publications\textsuperscript{10,11}.

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 the last year\textsuperscript{12}. The development includes consideration of the flight-deck operational procedure, which is being formulated to incorporate lessons learned from the GoSAFE experiments.

The next section provides an overview of the SOAR collaborative surface-operation automation concept, followed by a description of the human-in-the-loop experiments of the GoSAFE system, and recent development effort of the FARGO system.

**Overview of Collaborative Automation Concept**

Airport capacity, or the lack thereof, is reflected in the amount of delay incurred by the traffic\textsuperscript{13}. Figure 1 illustrates some of the factors contributing to taxi delays on the airport surface. 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. Waiting for gate access at the passenger terminal and the need for deicing are also notable causes. The first two factors are related to runway access, and they 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.

Figure 1. Operational Factors of Taxi Delays

The SOAR concept tries to achieve the precise control in taxi operations through collaborative automation between the tower and the flight deck, as illustrated by Figure 2.
In the control tower, the Strategic Automation depicted in Figure 2 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.

With GoSAFE issuing the clearances, the FARGO system provides the Flight-Deck Automation functions suggested in Figure 2 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

**Tower Automation**

The STM functions of the tower automation have been extensively studied by NASA under the research activities involving the Surface Management System (SMS)\(^1\), whereas research of the GoSAFE system has focused on the STC functions. This separation of the functions is not intentional, and has emerged as a result of two independent efforts with their scopes limited by research resources. It is conceivable that practical tower automation will encompass both STM and STC functions in an integrated system.

The STM functions include automation assistance to help the Air Navigation Service Provider (ANSP)\(^1\) in the control tower to plan and schedule airport runway configurations, and to schedule runway usage for the arrival and departure flights, of which the flight plans should have been filed by the Flight Operations Center (FOC) of each individual carrier. The functions should be performed in coordination with the ANSP in charge of the terminal airspace.

With the airport runway configuration determined and flight details made available by the STM functions, the STC automation would plan out the surface operation details for execution by the flights. The GoSAFE system in its current state contains the following key functions\(^2\), though at different levels of maturity:

- **Planning** functions for generating efficient taxi clearances: The current implementation of GoSAFE uses a dynamic programming approach to optimize individual taxi routes, and then adjusts the timing at intersections and the runways to avoid conflicts and incursions. The key objective is to plan the 4D trajectories so that runway occupancy can be kept to a minimum, including the occupancy by the runway crossing traffic. This means that the runway crossing flights are expected to continue taxiing without holding and to cross the runways at the assigned times. Calculations of taxi routes and timing take into account aircraft performance according to aircraft type, and weather conditions including surface winds and surface conditions. The resulting 4D trajectories can be edited by the controller manually. Future research will consider integrating the route planning and deconfliction functions into a unified solution for enhanced performance.

- **Traffic control** functions to facilitate issuance of clearances to flight deck: The 4D trajectories for the taxi operations are converted into clearances that resemble current-day versions—represented by a list of taxiways, runways, exits, ramp spots, etc.—so that they can be easily understood by the controllers and pilots. The 4D nature of the trajectories is realized by embedding in the clearances timing constraints for crossing selected locations along the taxi routes.

- **Traffic monitor** functions to ensure safety of traffic while executing demanding operations: Since the clearances are supposed to contain conflict-free trajectories, any conflict or incursion by any flight under tower control would involve at least one flight deviating from the cleared trajectory. The GoSAFE system contains a Conformance Monitor function to detect flights that deviate from their clearances by cross-checking the clearances with surveillance data. A Conflict Prediction function is also planned for identifying potential conflicts and incursions. This function should provide improved performance over the
Airport Movement Area Safety System (AMASS) because it has access to (a) more accurate surveillance data complete with aircraft identification, and (b) intent of the flights deduced from the clearances.

- **Graphic user interface** (GUI) to support the aforementioned functions: Each controller station can be tailored to the specific controller’s needs and preferences, even though all the stations are accessing data from a central GoSAFE system. The station’s GUI allows the controller to monitor the traffic, view and edit taxi routes, issue clearances and check their status. It also provides the interface to alert the controllers of impending problems, including flights deviating from their clearances and potential conflicts or runway incursions.

**Flight-Deck Automation**

Technical feasibility of a flight-deck automation system has been investigated in previous studies. Development of the automation technologies is currently being undertaken by a FARGO project. The following functions are envisioned as part of the FARGO automation.

- **Planning** functions for planning the surface operations: This function involves 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.

Discussion of the FARGO development effort is provided later in the paper.

**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 considered impractical and the use of digital data link is considered necessary. With so much information embedded in the clearances, the procedures use 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 to go beyond that point. This means that the pre-clearance in fact consists of a number of segments, each of which need 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 option 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. 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 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 given 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.

Human-in-the-Loop Experiments of Tower Automation

The SOAR concept was given the opportunity in the last two years to benefit from human-in-the-loop experiments to study the plausibility of the concept. Furthermore, since the goal of the automation concept is to enable the tower ANSP to handle heavier traffic in a complex environment, the experiments also serve to explore what roles and responsibilities are most appropriate for the human operators to achieve this goal. The subject matter experts (SME) participating in the experiments all had working experience as tower controllers.
**Simulation Facilities**

As a future concept that involves sophisticated automation, the SOAR concept will require a lot of testing to verify its efficacy and reliability of its systems before it can be considered for field tests. Such tests can benefit tremendously from a realistic simulation environment, and the project was fortunate to have a world-class tower simulator—the FutureFlight Central at NASA Ames Research Center—available for this advanced research topic. Figure 4 contains a wide-angle view of the tower simulator, which is a full-scale representation of a control tower with a full 360° airport view.

An experimental prototype of the GoSAFE system was installed at the tower simulator, with the GoSAFE GUI installed at four controller stations to support two Local and two Ground Controller positions. The traffic was provided by a pseudo-aircraft system called Airspace Traffic Generator (ATG), with pseudo-pilots controlling the simulated flights and communicating with the controller subject experts. Figure 5 illustrates how the simulation facilities and experimental systems are networked together based on DoD’s High-Level Architecture (HLA).

**Experiment Scenarios**

The experiments have been designed around the east side of Dallas/Fort Worth International Airport (DFW), with the controllers operating from the vantage point of the East ATC Tower as depicted in the layout of Figure 1. A South Flow airport configuration was used for all the experiments, where typically runways 17R and 13L are for departure, and runways 17C and 17L are for arrivals. Some experiment runs tested the use of runway 17R for mixed arrival/departure traffic, when the scenario included a heavy arrival demand. The traffic demand used in the simulations was set at about 150% of current-day levels, partly to account for the anticipated increase in air traffic, and partly to account for the absence of ground vehicles in the scenarios. Simulation of arrival flights started at about 12 nmi out, and departure flights would end at about 5 nmi after takeoff. Simulation on the surface was limited to the movement area up to the ramp spots. Operations within the ramp area were not included.

Three scenario data sets of flight schedules were generated for the experiments to represent three different arrival/departure mixes and transition characteristics. In order to verify that GoSAFE could actually handle this level of demands, verification simulations were run with GoSAFE automatically issuing the clearances to the pseudo-aircraft system, which would in turn automatically accept the clearances and cause the simulated flights to execute the clearances as if there is a FARGO system doing the auto-taxi. These runs were successful in verifying the route planning functionality of GoSAFE, but they were not considered part of the experiments because fully
automatic surface traffic control was not an operational concept being studied.

**Options on Operational Procedures, Roles, and Responsibilities**

With the operational procedure described above, several options were explored for varying the procedure:

**Voice vs. Data-Link Clearances**

The main variation of the procedure was to compare the issuance of clearances by voice versus by data link. A special keypad was provided at each controller station with a key for sending a data-linked clearance. If it is issued by voice, the controller will have the task of informing the GoSAFE system whether the clearance is accepted or rejected; for this the controller has two keys to enter these two respective responses.

**Handoffs**

Handoffs of flights between controllers involve frequency changes, and the controllers were given the option to perform the handoff by voice or by data link. A key stroke would be required if the handoff was to be done by data link.

**Replanning for New Clearances**

The controllers had the option of adjusting a taxi route manually using the GoSAFE GUI—spatially or temporally. In this case, a new pre-clearance would be automatically generated and communicated to the flight deck.

In addition, a function was introduced as the experiments progressed to allow the controller to request GoSAFE to replan only the timing constraints. The need for this function was identified when controllers began to deviate from issuing the recommended clearances and caused the flights to miss the timing constraints. This function would also be useful for restarting flights held at contingency hold points.

**Controller Roles and Responsibilities**

The original experiments were set up for the controllers to maintain the usual tower controller positions similar to today’s operations: specifically, the SOAR experiments focused on Local and Ground Controllers. Typically, the SMEs would play the role of two Local and two Ground Controllers for the DFW East ATC Tower operations.

With the extra heavy traffic defined in the demand scenarios, it was evident that the Local Controller responsible for runway 17R had the heaviest workload, since this position had to deal with every flight operating to/from all four runways—the flights either take off or land on 17R, or they have to cross 17R when taxiing between their arrival/departure runway and the ramp area. To help relieve this controller position’s workload, some experiment runs were performed with the Ground Controller responsible for the south-side traffic to take over the runway 17R crossing traffic near the south end. This means that the two controllers had to share the responsibility of controlling the traffic over runway 17R—a procedure that should require serious coordination between the two positions to prevent runway incursions.

Another key change of controller responsibilities is associated with the introduction of an automation system. How this change affects the controller’s performance of controlling the traffic and keeping a mental picture to detect operational hazard will remain an important research issue through the course of this research.

**Brief Discussion of Experimental Findings**

**Voice vs. Data-Link Clearances**

Although the controllers have the flexibility to choose between voice or data link for issuing each clearance, the experiments were set up to ask them to nominally use one or the other in a single run. It was observed that after having used the keypad one way for one run, if the controllers were asked to use the second approach for the next run, there seemed to be an increase in likelihood of them pushing the wrong button on the keypad. This suggests that keypad design may be important in distinguishing the actions for voice and data-link clearances.

In general, the controllers could handle the clearances better with data link than with voice. A possible reason is that, with data link, the controller did not need to wait for the acknowledgment before working on another flight as he/she would by voice. The amount of time that the controller had to wait could have been inflated as a result of the
experimental set up: specifically, a pseudo-pilot controlling multiple aircraft might take longer to respond than in the actual situation when the flight crew is concerned with controlling only one vehicle, as the pseudo-pilot often had to take some time to locate the appropriate flight on the ATG station.

**Handoffs**

Initially some of the simulation runs were designed to do handoffs either by voice or by data link. As the experiments progressed, the SMEs pointed out that handoff events were often done automatically by the flight crew according to published procedures for the airports. Since then, the ATG software was modified to simulate this type of handoff procedure and the controllers would no longer need to initiate handoffs.

**Replanning for New Clearances**

Early in the experiments, it was soon obvious that the existing route editing functions in GoSAFE were too time-consuming when the controllers already had to deal with the extremely heavy traffic load. The function introduced later for replanning timing constraints was in comparison relatively easy to use, and it was desired by the SMEs. Regarding the need to replan taxi routes, the SMEs have suggested the ability to generate multiple routes from which the controllers could easily choose. The development of this function remains a research topic.

**Controller Roles and Responsibilities**

All the SMEs who participated in the experiments were receptive to the idea of the automation concept and their new roles in working with the automation system, with the understanding that the system used in the experiment was only an experimental prototype with incomplete functionality.

Digital videos were captured for some of the controller positions to provide data for studying the level of interactions the controllers had with the automation system. Ref. 11 includes some analyses of the data to reveal how the controllers’ activities were affected by the automation, though the level of these activities may change as the automation technologies mature. One observation is that the automation system would likely lead to more head-down activities and reduce the amount of head-up time to monitor traffic by looking out the window. This might have been due to both good or bad reasons: there might be more useful surveillance and situational data available on the GUI, but operating the experimental automation system might have required too much attention.

In any case, additional experiments have been run to use only the automation system in a windowless room, and the SMEs were able to control the traffic without the benefit of out-the-window view. This suggests that it may be possible to provide virtual tower operations by using automation.

Regarding the sharing of responsibilities by two controllers over the jurisdiction of one runway, the SMEs felt that the change did reduce the workload of the Local Controller, but they believed that it would be possible only with the help of the automation system, which allowed them to coordinate tightly timed but safe operations. SME feedback exposed some undesirable effects. They felt that the automation had diminished their decision-making role. Future research will need to focus on redefining the controllers’ role by raising them to a higher level of responsibilities of assuring safe and efficient operations under very heavy traffic conditions. This will require good judgment in rebalancing the functions allocated to the controllers and the automation.

**Impact on Controller Workload**

During each 45-min simulated scenario, the controllers had to periodically report their perceived workload using a workload assessment keypad, and then again after the end of the run through the NASA Task Load Index (TLX)\(^7\). The collected data indicates that perceived workload was significantly reduced under advanced automation conditions, more so as the automation assumed more functions. Detailed analysis results are discussed in Ref. 11.

**Information Requirements and Presentation**

Whereas the experiment results indicate that the SMEs were generally receptive to the automation concept, and that workload generally decreased when the controllers were assisted by the tower automation system, they also revealed deficiencies in the current implementation of the
GoSAFE prototype. Many of these issues relate to what type of information would benefit the controllers’ understanding of the intent of the automation system, and how to present the information to the controllers so that the controllers can act on the GoSAFE events in a timely manner. These issues have implications on whether the GoSAFE clearances can be issued to the flights consistently, which in turn affects whether the GoSAFE plans are effectively carried out by the flights. Failure to achieve a high level of compliance with GoSAFE plans will lead to a domino effect causing the collaborative automation concept to break down.

Development of Flight-Deck Automation

FARGO’s automation functions include the use of digital communication via data link to accept clearances with embedded “4D trajectory” information in the taxi route. Advanced navigation is assumed for the aircraft to interpret the clearances and execute the 4D trajectory with high-precision performance. The following summarizes the FARGO design, with details provided in Ref. 12.

Guidance Function for Trajectory Generation

A guidance function is designed to accept the taxi route specified by the clearance with embedded timing constraints to generate a “detailed 4D trajectory” that the aircraft is expected 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 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 smooth acceleration profile in defining the trajectory.

Nonlinear Controller for Aircraft Taxi Control

A nonlinear controller is designed to generate the control signals to effect the 4D-trajectory tracking, based on the Nonlinear Synthesis Tools (NST) product. Of the many nonlinear control design techniques included in NST, the feedback linearization methodology is being considered for the current FARGO design. NST provides the necessary tools in synthesizing a superior nonlinear controller with a software model of the aircraft dynamics embedded in its own code. The current FARGO design is being produced for a B-737-type aircraft, for which a software model has been extracted from NASA’s Transport System Research Vehicle (TSRV) simulation. Performance of the nonlinear controller has been verified based on computer simulations.

Interface for Piloting

Figure 6 illustrates various proposed displays as part of the pilot interface. Textual clearance data can be shown on the Engine Indication and Crew Alert System (EICAS) displays. The flight crew has the option of viewing the route information extracted from the pre-clearance on an electronic moving map (EMM). The head-up display (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. Figure 7 contains an illustration of the HUD graphical design proposed to display the FARGO guidance and control data.

Figure 6. FARGO Pilot-Interface Displays
Suggestions for Future Research

Concerning the technologies for the SOAR concept, we believe that the feasibility has been proven through early prototypes and experiments. The concept is ready for transition into the next phase of development, where full-feature functions should be developed along with experiments to help shape the operational procedures and the roles and responsibilities between operators and automation. The following is a brief discussion of recommended research activities.

Technical research should be dedicated to optimal route planning to design 4D trajectories which are coordinated for the complete surface traffic. While route optimality is a desirable performance metric, it is also desirable to trade some of the optimality for inter-flight separation margins to alleviate the potential impact of non-conformance events.

The human-in-the-loop experiments for GoSAFE have revealed the need for extensive research to define the roles and responsibilities between human operators and automation. The research needs to be tied to the design of procedures and user interfaces that promotes synergy from operator/automation interaction. Procedure research also needs to address off-nominal situations.

It is expected that the tactical automation functions for trajectory and separation management being studied with the GoSAFE prototype will need to be integrated with strategic automation functions responsible for airport/airspace configurations and surface traffic flow management.

Research and development of flight-deck automation should continue with the FARGO development. Human-in-the-loop experimentation of the technologies should be included in the next phase of research to ensure that human-operator considerations are addressed early in the process.

As both tower and flight-deck automations mature, integrated testing of these technologies should follow. Field testing of the SOAR technologies should be considered in far-term planning. The issue of traffic with mixed equipage—i.e., not all aircraft are equipped with flight-deck automation—also needs to be addressed.
to study the transition into a highly automated future environment.

Concluding Remarks

This paper has provided a progress update of the Surface Operation Automation Research (SOAR) at Optimal Synthesis Inc. SOAR is not a single research program, but instead a collection of research activities with the common goal of applying automation technologies to enhance airport surface operations. Specifically, the SOAR approach advocates a concept that involves collaboration between automation systems in the Air Traffic Control Tower and the flight deck, making use of advanced Communication, Navigation, and Surveillance technologies. The tower automation makes use of advanced surveillance data to plan complete surface traffic operations in the form of 4D trajectories for all flights, taking into consideration aircraft performance data and environmental conditions. Advanced communication technologies are assumed to support the issuance of clearances containing the 4D trajectories to the flights via digital data link. The flight-deck automation makes use of accurate navigation data to perform the taxi operations in accordance with the 4D trajectories embedded in the clearances.

Feasibility of the concept has been verified through simulations and experiments with early prototypes of the automation systems. Human-in-the-loop experiments involving tower-controller subject experts have been performed in the last couple of years to study operational procedures in the control tower, using an experimental prototype of the tower automation system. The subject matter experts have been generally receptive to the automation concept, and they have contributed directly in the investigation of new roles and responsibilities of tower controllers working with the automation. Development of the flight-deck automation is not as mature, but an experimental prototype suitable for human-in-the-loop testing is expected to be available in another year.

The progress thus far supports the assertion that the SOAR concept can be part of the solution to increase capacity of the National Airspace System (NAS). In particular, it can help alleviate the congestion problem associated with airports being the bottleneck of NAS traffic. To pursue this collaborative automation concept further, serious investments will be required for technology development for the automation systems. This paper has included suggestions for future research to identify key areas essential for the success of the approach.

References


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