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Ground Operation Concept Testing Requirements and Challenges

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In view of the increasing air traffic demand as well as the increasing complexity of systems that operate in the Air Traffic Management (ATM) environment, many future concept research topics involving automation have been proposed to improve traffic efficiency and safety. The development of far-future concepts has a disruptive research path in which the concepts work with a future automation scenario that requires the consideration of transition from the current-day operation scenario. This research path allows for greater creativity in the re-thinking of air traffic control management systems without being tied into the pre-existent systems. However, such freedom comes at a cost of making assumptions pertaining to transition plausibility. This research strategy poses difficult challenges in creating the right environment to support development of the concept and other future concept research. This paper summarizes the requirements identified through experiments, including the use of suggestions from subject-matter experts, for implementing a proper research environment that can ultimately simulate the automated operations intended for air traffic controllers in the future. The purpose of this paper is to identify and address the factors limiting concept development and testing, and use lessons learned to improve the chances of viable concepts maturing to deployment readiness.

I. Introduction

Air Traffic Management (ATM) concepts require rigorous testing prior to deployment. The Surface Operation Automation Research (SOAR) is a concept under exploration at the NASA Ames Research Center with the goal to increase surface capacity at airports without compromising safety, as prescribed by NASA's Airspace Systems Program (ASP).

SOAR has proposed a collaborative concept that provides automation for surface-traffic management (STM) and the flight deck to enhance the operational efficiency in complex airport environments and mitigate the penalties of increases in airport demand. The STM automation system, known as Ground-Operation Situation Awareness and

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Flow Efficiency (GoSAFE™)[1], has been developed to the point where an experimental prototype is available. The GoSAFE concept has been previously reported 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 advisories. Development of the flight deck automation is in a less mature state. The STM automation concept technology was tested and evaluated using the Virtual Airspace Simulation Technology (VAST) tools developed at NASA Ames Research Center[2].

Numerous research questions regarding building of Air Traffic Control (ATC) automation have been answered with the help of the VAST integration of human-in-the-loop research facilities. VAST is designed to support simulation and modeling that aids in both the development and verification of advanced ATM concepts. This paper reviews the process of concept evaluation and development using the human-in-the-loop simulation environment provided by VAST by providing a perspective on the challenges, issues, requirements, and suggestions that have been unearthed when implementing the concept in the simulation environment. The fundamental challenges are analyzed to reveal inherent challenges in the concept, as well as issues that arise from the actual implementation of the concept in the human-in-the-loop simulation and modeling system.

II. Overview of SOAR Concept and Experimental Setup

The SOAR concept[3-11] introduces advanced automation to the two main environments for surface operation: the tower control environment and the flight deck. This collaborative automation concept will provide maximum performance when these two environments can be tightly integrated in a Centralized Decision-Making, Distributed Control (CDDC) paradigm, as illustrated by the block diagram in Fig. 1. There are two core systems behind the SOAR concept:

I. Surface Traffic Management (STM) automation in the ATC tower to enable efficient surface traffic flow

II. Flight-deck automation to enable Aircraft Control for performing high-precision taxi operations

Fig. 1 describes the interaction of the two automation environments and with the human operators and the aircraft. It also shows the integrated operation of these systems with advanced communication, navigation, and surveillance (CNS) systems, which represent major enabling technologies for the concept. The two core SOAR systems are discussed individually in the following subsections.

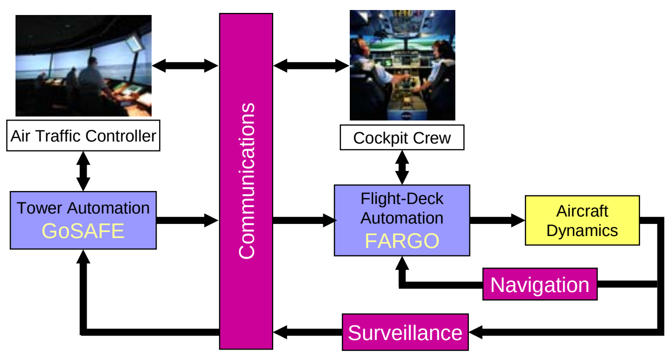


Figure 1. High-level block diagram of SOAR's collaborative automation concept.

A. Surface Traffic Management Automation

The ground-control component of the SOAR concept consists of an STM automation system to provide the centralized decision making functionality. It bases its decision on the surveillance data, flight plans and Airline Operational Control (AOC) requirements, to generate time-based taxi routes for optimum traffic efficiency. The envisioned STM automation technologies include the following functions:

- Planning functions for generating efficient taxi clearances
- Traffic control functions to facilitate issuance of clearances to the flight deck
- Traffic monitor functions to ensure safety of traffic while executing demanding operations
- Graphic user interface (GUI) to support the aforementioned functions

Optimal Synthesis Inc. (OSI) has previously developed an experimental version of the GoSAFE STM automation system. The experimental GoSAFE system serves as the foundation for building the ground-control automation system envisioned by the SOAR concept.

B. Flight Deck Automation

The flight-deck automation systems in the aircraft envisioned in the SOAR concept collectively provide the distributed control of the traffic in collaboration with GoSAFE. Advanced automation technologies provide auto-taxi capabilities or automation aids to the pilots for performing precision taxi to achieve the time-controlled taxi routes issued by GoSAFE. New operation procedures will need to be defined for carrying out data-linked clearances, and for automatic loading of the clearances into the flight deck's flight management system (FMS). The envisioned flight-deck automation technologies will include the following major functions:

- Planning functions involving obtaining clearances and inputting them into the flight control computer
- Auto-taxi functions to generate aircraft taxi control commands for achieving the precision taxi requirements demanded by GoSAFE-generated clearances
- Pilot interface to enable pilots to execute precision taxi operations either in fully automatic mode or automation-assisted mode
- Traffic monitor functions provided through pilot interface to alert pilots of deviation from cleared taxi routes or impending incursion by other vehicles

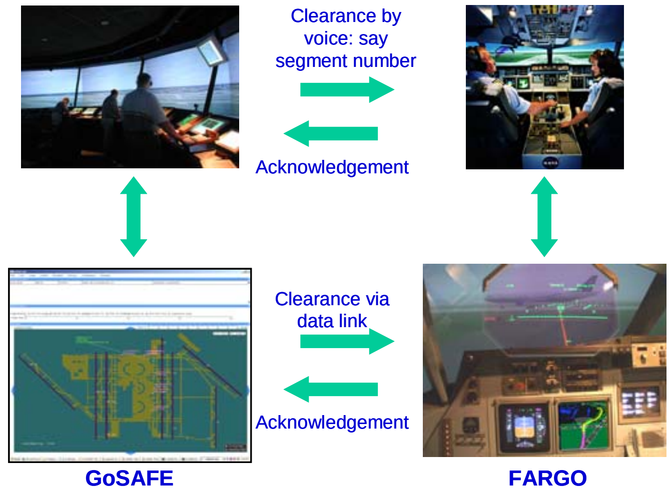


Figure 2. Illustration of SOAR clearance execution.

OSI has demonstrated previously that advanced nonlinear control methods can enable the aircraft to track precisely defined time-controlled taxi routes[5], even in the highly dynamic environment of performing active-runway crossing immediately after landing on an adjacent runway. The FARGO system represents further development of this idea to achieve the flight-deck automation component of the SOAR concept.

The planning functions are concerned with preparing the FARGO system for executing the clearance issued by GoSAFE via data link. The time required by the pilots to review the complex clearance will make it difficult for the controllers to expect a timely acknowledgment by pilots; hence a pre-clearance would likely be used, with subsequent clearances to be abbreviated with identifiers for referencing the pre-clearance. The data-linked pre-clearance can be conveniently downloaded into the FARGO flight-control computer to support further planning and subsequent execution of the taxi operation. The desired route information can be displayed to the pilots on a FARGO display. Although the pre-clearance may cover the complete taxi route, it may be broken down into multiple segments that will require separate clearances to ensure safety of the operation. For instance, if the taxi involves crossing an active runway, the first part of the clearance may involve taxiing to the active runway, with the second part of the clearance issued as soon as it is confirmed that the crossing will not lead to any incursion.

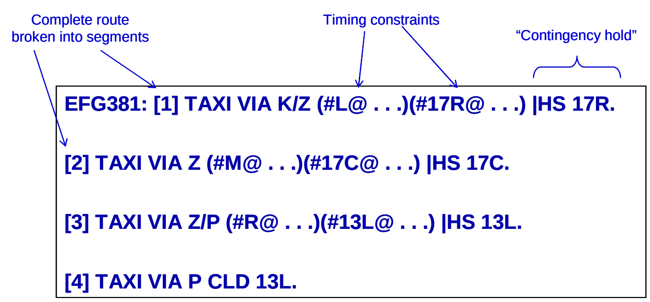


Figure 3. SOAR pre-clearance.

C. Operational Procedure

SOAR concept promotes traffic efficiency through the use of time-based route clearances. Clearances in this concept can only be executed with the existence of flight-deck automation. Since it is not practical to send timing information of the clearances via voice, use of digital data link is considered necessary. Fig. 2 illustrates how a SOAR target airport would ideally execute a clearance from the SOAR concept. A 4-D trajectory is embedded in the clearances of SOAR. The 4-D trajectory information is sent following these rules:

- Use pre-clearances to initially send the complete route information for pre-visualization of taxi-operations.
- Divide taxi route into segments ending at locations where safety maybe a concern (e.g., active runway crossings are used as ending locations for our experiment).
- Insert "contingency holds" at end of segments to require active clearance control for continuing.
- Clear each segment as a separate clearance, which automatically removes the contingency hold.

Fig. 3 shows a complete dissection of one sample pre-clearance containing 4-D trajectory information.

D. Experimental Setup

The experimental setup of SOAR in VAST-RT involved the replacement of FARGO functionalities with Air Traffic Generator (ATG) as provided by VAST. As seen in Fig. 4, the communication between GoSAFE and the flight-deck components of the experiment was executed through DoD's High-Level Architecture (HLA). ATG had the responsibilities of providing surveillance, managing flight-plans, as well as managing multiple pseudo-pilot stations that represent the functional equivalents of SOAR's FARGO. The experiment used three separate scenarios, all of which specialized for the DFW East ATC Tower in accordance with, a South Flow airport configuration. The traffic demands were set at about 150% of current-day levels. Arrival flights would start at about 12 nmi out while the departure flights are removed at about 5 nmi after takeoff.

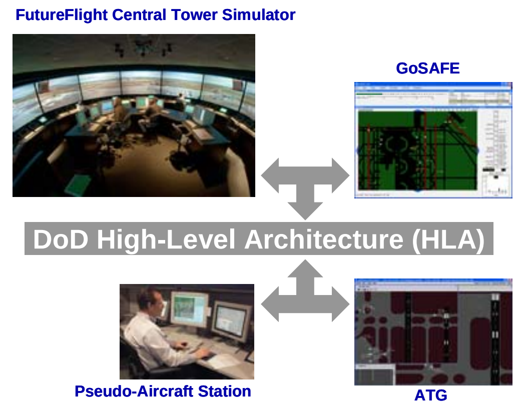


Figure 4. Real-time simulation architecture.

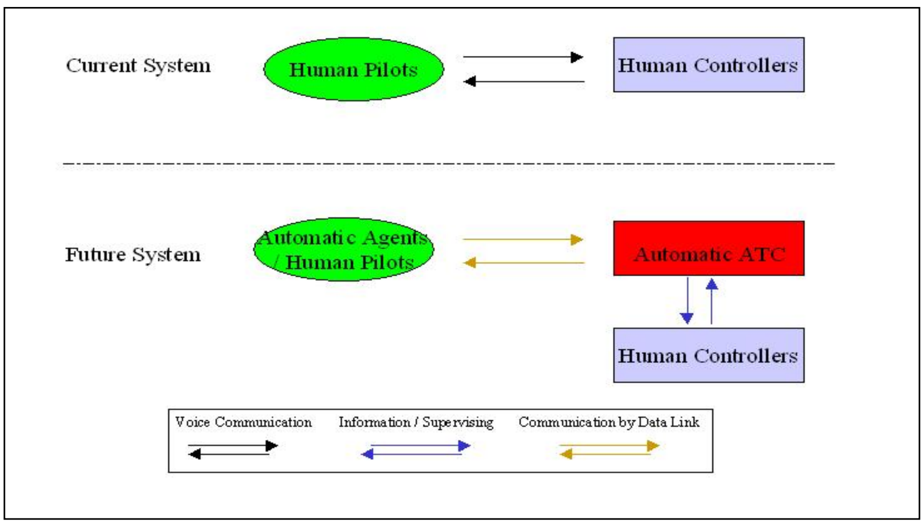


Figure 5. High-level human/automation relationships.

III. Motivation and Related Research

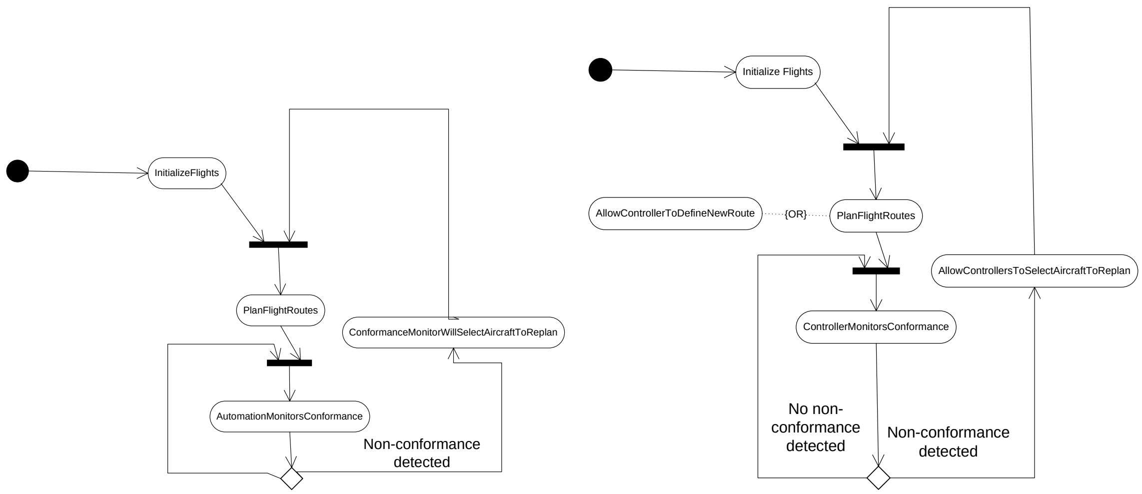
The development of concepts that are radically different from current operations has only recently been explored. These concepts deal with research paths that begin with the formulation of distant-future automation operation followed by tracing backwards to determine the transition from current-day operations. This kind of research path allows for greater creativity in the re-thinking of air traffic control management systems by not requiring them to grow from current systems. However, such freedom comes at a cost of making assumptions pertaining to transition plausibility. This strategy in conducting research poses difficult challenges in creating the correct intermediate steps, which require a special supporting research environment. Fig. 5 shows the necessary new components required for the envisioned future ATC automation concept. The extra control system layer poses many new requirements in order for the independent entities to function as a whole.

In this paper, we shall try to address some of the technical challenges that we as concept developers faced in implementing a highly automated concept for the air traffic control tower. Furthermore, we shall address some of the requirements that we have discovered to be essential for either the development of an STM automation system or for running a realistic simulation of a concept to represent the deployment environment.

These lessons learned are discussed in the sections below according to the following categories:

1) Inherent challenges
2) Implementation issues
3) Design requirements

4) Future technical and operational improvements and features
5) Future structural improvement and features
6) Future research topics



Automation controlled time-adjustment re-plan *Controllers controlled time-adjustment re-plan*

Figure 6. Activity diagram of route planning algorithm.

IV. Identification of Inherent Challenges

A. Designing a proper procedure and parameters for re-plan

The biggest challenge of automation and pre-planning is handling changes and non-conformance to timed routes without causing an unstable response. During optimal operation in the presence of automation, a pre-planned route will be sent to an aircraft ahead of time before the aircraft gets onto the controlled movement areas of the airport. However, in a case of non-conformance, the aircraft with a pre-planned advisory can deviate from its original precision taxiing clearance. Our research question was to find ways to avoid the inevitable slippery slope in which the adjustment of one aircraft's temporal route while fixing a non-conformance will massively affect other aircraft on the airport. Such a problem can occur especially when there is a significant number of aircraft taxiing on the airport, and the temporal occupancy of the real estate on the airport is so closely spaced that any aircraft missing its time to cross a runway will require a delay in every other aircraft behind it until the onset of a low-demand period.

While we have not yet found a permanent solution to this challenge, several implementations have been tried. One of the solutions is implementing manual selection of aircraft for re-planning in real-time to allow for a complete re-planning of only those aircraft the controllers believed to be urgent. Any aircraft that cannot fit into the allotted time will be flagged as having a large waiting time during which a controller would either have to do a manual taxiing adjustment or a larger set of aircraft would have to be replanned. Another solution that has been examined is to look for non-conformance every time the automation receives surface surveillance data, and re-plan any set of aircraft that are out of conformance in that update. This solution has proved to cause a high workload for both controllers and pilots due to the high sensitivity of the conformance monitor. The exact optimal sensitivity of detection of aircraft for re-planning is another research topic of its own. While both paths of re-planning have problems of their own, any situation where re-planning occurs automatically will always decrease the controllers' ability to properly predict surface behavior and communicate their intentions to other controllers and pilots.

The challenge in the re-planning process resides in two basic systems. First is a system that defines who will select aircraft to be re-planned; this can be the controller or the automation. The second system defines whether the controller or the automation re-plans the aircraft and whether the controller specifies the routing or a regular automated route re-planning function does. In Fig. 6, the two particular combinations of the systems as tested in our simulation are shown.

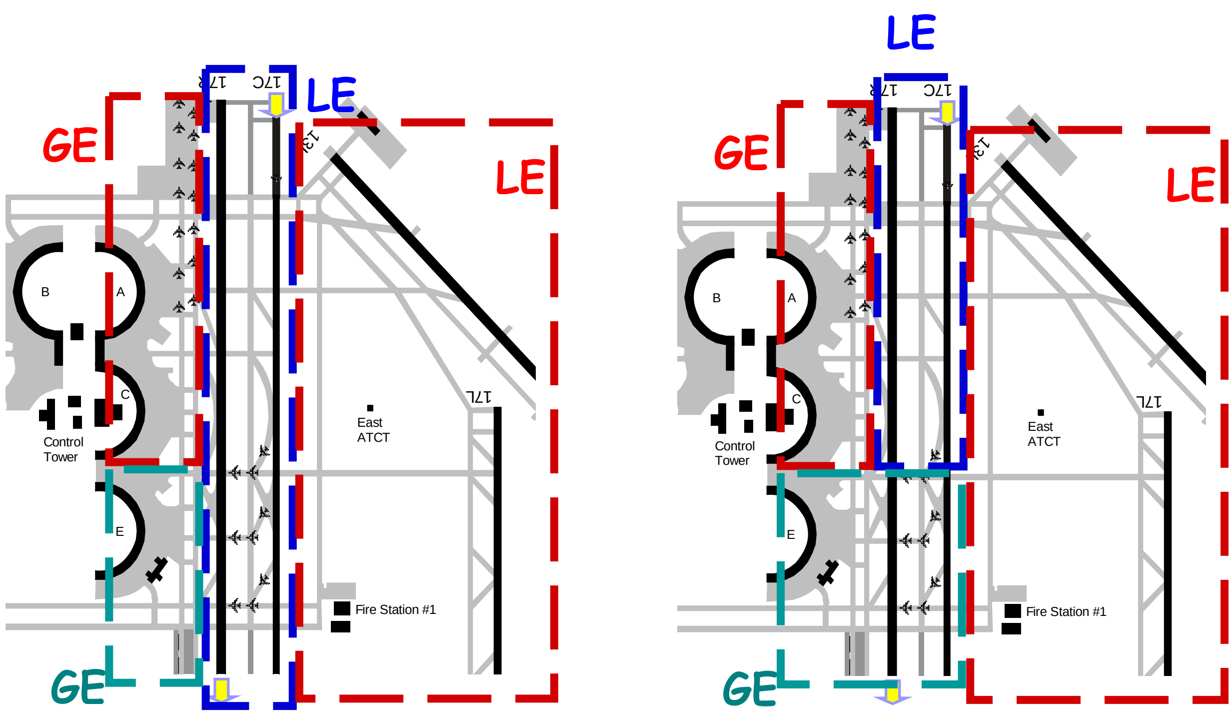
B. Designing for the scope of control

Something else that is possible in surface traffic management research is to rethink the scope of the real estate controlled by human controllers when automation is present. Moreover, because of the computer intelligence in our FARGO concept, we must also carefully consider whether or not to allow pilot-side computer systems to be responsible for some amount of automatic control. The three automation functions in the simulation that fall into this question are controller handoffs, jurisdiction changes, and automatic separation. Due to the introduction of automation, we had to redesign the scope of control for these three functions to better fit the system.

In current-day operations, a controller handoff is either initiated by the controller or published so the pilots manually switch sector frequency where it is appropriate. However, with the onset of automated jurisdiction, it becomes necessary for both the controllers and pilots to have the ability to initiate automated handoffs from one jurisdiction window to another. Automation faces the challenge of seamlessly integrating radio communications to insure pilot awareness and the safety of operations.

Controller jurisdiction, under the new automation concept, can be more easily changed because the relationship between an individual controller and a particular runway is eliminated. As an example of jurisdiction changes allowed by this new concept, Fig. 7 shows two different jurisdictional scenarios used in a simulation of DFW airport. This rearrangement allows us to ease the workload of a normally overworked local east (LE) tower controller by switching some of his crossing traffic to another controller's jurisdiction.

Lastly, the scope of control of automatic separation and merging collision needs to be either on the pre-planning tower-side automation system or on board the aircraft with the precision taxiing automation. Our simulation and current concept implementation assumes a self-separation algorithm in place on the flight-deck control systems to simulate the kind of intelligence that could be in the precision taxing automation to avoid merging collisions and to inform the pilot of separation needs.



Original assignment of jurisdiction **Assignment of jurisdiction with SOAR**

Figure 7. Change of scope to controller jurisdictions with introduction of automation.

C. Design of practical procedure regarding emergency operation

A realistic challenge in future deployment of automation concepts is handling emergency cases smoothly without disturbing operation. One challenge is to consider the emergency procedures during concept development and think about a default action for aircraft when communications between systems are lost. In GoSAFE, our attempt to combat this challenge is the "contingent hold short" command for each segment of our pre-clearance.

This hold short command acts as the default action when the automation or communication system breaks down. While this serves to stop aircraft in case of emergency, the exact procedure of how to switch a SOAR-operated airport to the manual control of current-day operation remains a challenge for the concept development team.

D. Designing for robust communication message system

The design of a robust failsafe communication message system requires two critical functions. The first and foremost is an accurate recognition of system failures to receive, send, acknowledge or execute a particular packet of information. The second critical function involves the proper correction and recovery of the misinformation or lost information. The basis of our communication message system relies on a consistent assignment of sequence numbers to each of the messages sent and subsequently received. The unique sequence numbers serve as a simple solution for creating a more robust communication system.

E. Time limitation on solving complex problems

VAST is a real-time simulation environment. Real-time simulation forces computations to be completed in a constant time frame, typically with a period of 1 sec. The control system has to execute complex path-finding algorithms to generate conflict-free taxi routes, and the simulation systems have to be able to parse and execute the commands in parallel within 1 sec as well. Development of highly efficient algorithms is one of the main challenges, and is often overlooked. In order to create valid data for analysis of concepts, an efficient performance of the software supplementing adequate hardware is necessary.

F. Accommodating human errors

Based on the observations in our simulation experiments, there is a lack of accommodation for human errors in the current simulation environment of SOAR in VAST. It has been found that the fully automated system without any human involvement produces more reliable results. Human controllers' delay in reaction aggravates the situation of surface traffic, requiring previously planned routes to be re-planned. It is desirable to have a more forgiving automation system design that exhibits wider latitude in accommodating inherently different reaction times of controllers and inadvertent human errors.

V. Implementation Issues

A. Assumptions on the dynamics modeling between taxiing and planning systems

Modeling the real-world taxiing situation has potential inconsistencies between the taxiing automation (e.g., FARGO) and the planning automation (e.g., GoSAFE). The VAST Air Traffic Generator (ATG), a target generator simulation tool, was used in the experiments. The ATG managed the scenarios, generated the targets, produced surveillance data, and simulated the FARGO concept including self-separation and precision taxiing functions. In the design of the GoSAFE concept implementation, the communication between the systems had to be realistic. GoSAFE and the taxiing system (in our case, ATG) each have an aerodynamics model for each type of aircraft, which governs acceleration and deceleration rates, runway usage characteristics, and maximum taxi speeds. The database of these aircraft types must be matched between the precision taxiing system and the control tower automation simulation on GoSAFE. In our experience, a slight difference in takeoff profile can have a dramatic effect on safety in the simulation. A difference in taxiing acceleration can easily change the sequence of two aircraft as they merge onto the same taxiway. Special procedures to introduce additional timing constraints at potential trouble spots may need to be considered to prevent inaccurate models in the planning from creating dangerous taxi plans.

B. Assumptions on the hardware resources

Research on software concepts should be simulated in a likely deployment hardware environment. The computing power and distribution of the route planning algorithm must be able to plan relentlessly for all new flight plans and possible aircraft needing re-plans. The delay in network communication must also be taken into account in the implementation design. We built a manual delay into our communication so as to simulate the actual network delay in a real-world situation. Another possible implementation to improve the performance is to separate database accessing, re-planning and pre-planning algorithms so as to distribute the computation workload on different process threads on our hardware.

C. Assumptions on boundary systems

Software implementation involving multiple systems will often face boundary conditions that will be disruptive to the entire operation. In the realm of airport traffic management, the two obvious boundary systems are the airline systems and the terminal area controllers. These two boundaries control the arrival rate, departure rate and in some sense traffic bottlenecks out of the ramp spots. In a simulation, we must build scenarios that will be able to reflect the effects the boundary systems have on the operating control tower automation system in order to analyze our experimental data with a deeper understanding. Our initial failure to recognize the effect of the scenario on the flow rate and distribution of vehicles coming out of the ramp spots prevented us from accurately understanding the traffic jam that was happening at other bottlenecks on the airport.

D. Assumptions on scenario complexity

Simulation scenario design is another big issue in concept implementation due to its effect on the understanding of data attained from concept research. This paradigm of scenario design has historically complicated research development and validation. Scenario boundaries such as initial placement of aircraft on the simulated airport or overloading runways from unrealistic distribution of flight plans all may influence our understanding of a concept's true capacity.

(a) Before **(b) After**

Figure 8. Quick right-click of flight tag to hide information as an automated de-cluttering method.

VI. Identification of Design Requirements

A. Information accessibility requirements

Information accessibility is a main topic in the development of any software interface. In the case of the controllers, this is even more essential. Throughout the research and implementation of the SOAR concept, a few essential requirements in defining a proper interface became evident.

I. Shortcuts to access combinations of commands must be configurable.

II. Minimizing head-down time in order to maximize time for controllers to look out the window.

III. Centralizing area of focus so that for any given command procedure, the controller will not need to scan across two areas of attention simultaneously.

IV. Minimizing the number of mouse clicks required to access information since mouse clicks give room for the greatest number of errors such as extra clicking, slow response, and clicking outside the desired area.

V. Ability to quickly hide information that is unnecessary while preserving quick access back to the information when needed later.
GoSAFE has implemented a quick right-click on the flight tag to hide information (see Fig. 8).

VI. Ability to bring up history of previous executed commands. An example of this is shown in Fig. 9.

VII. Ability to control relatively distanced areas on the airport without needing to pan and zoom constantly. There are two ways to go about this. One is to assign and recall a preset zoom and location of the plan-view map, which has been implemented in GoSAFE. The other method is implementing a secondary plan-view map.

VIII. Object-oriented access of information in which the mouse-over of one button or tag representing a particular flight will highlight all other representations of this particular flight throughout the interface.

IX. Ability to access information of the spatial and temporal trajectory of the aircraft.

X. Keyboard shortcuts to frequently used mouse commands. Due to the limited two/three buttons on a regular mouse, keyboard shortcuts can be effective to execute commands quickly as controllers mouse-over or click on flight objects.

XI. Multiple dimensions of representations of flight states are necessary. As shown in Table 1, flights can simultaneously have color representing its clearance status and a bold vs. regular flight tag font to represent whether it is the selected attention of the controller.

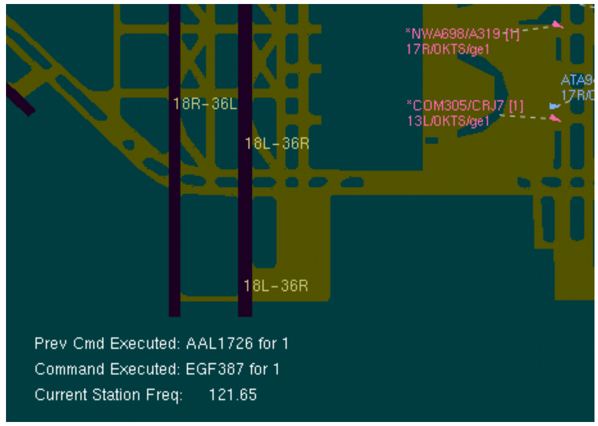
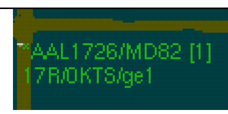


Figure 9. History of flight clearance is recorded and displayed for controllers' convenience.

Table 1. Representations of flight states.

Dimension	**Flight State**		
Color	"Clearance pending for approval" vs. "No pending commands"		
Shade	Selected vs. Mouseover highlighted		
Color Fill	"Aircraft within jurisdiction" vs. "Aircraft outside of jurisdiction"		

B. Configuration and routing cost requirement

In the beginning of the SOAR research, we defined a preliminary set of costs, or penalties such as time or fuel, associated with each taxiing section on the Dallas/Fort Worth airport. This set of costs allows us to essentially find the "shortest path" from any source position to any destination. However, we discovered throughout the simulation that certain costs should be increased or decreased depending on the demand scenario such as departure rush, heavy arrival flow, or heavy bridge traffic. Preset cost maps for different demand scenarios can help optimize the flow of the airport to avoid traffic jams or bottlenecking that appears at various spots on the airport. This type of flexibility of the concept implementation is useful in reaching the optimal capacity and flow efficiency of an airport, unless another optimal route planning scheme can be conceived to adapt to the demand scenario.

C. Clearance segment labeling requirements

The first task in the implementation of SOAR was creating the concept of a pre-clearance, a complete timed route generated by automation and sent via data link to the flight deck in a format understandable by the pilot. In some sense, the pre-clearance is in the language much like a current-day clearance except in a text format. To get the pre-clearance executed on the field, it is important to consider how to implement clearance segments—segments of a pre-clearance divided for approval by human controllers prior to clearing pilots to execute that part of the pre-clearance. A few fundamental questions regarding sending clearance were answered through controller participant interviews during our simulations.

Topics under debate regarding the design of pre-clearance involves dimensions in the representation of the segment labels—e.g., representing the segment based on its geographic location on the airport surface vs. its segment sequence along the cleared route—and, in the latter case, in the symbology of the labels—e.g., denoting the sequence information numerically or alphabetically. Regarding the representation of the labels, one can represent a set geographical locations by jurisdiction (e.g., [LE1] for local east 1), or represent the temporal order of clearance segment from the route origin, where the symbology of the labels can be in alphabets (e.g., [α], [β], [γ]) or numerics (e.g., [1], [2], [3]). Examples of these are shown in Table 2.

The majority of participants suggested using the sequential representation due to unwanted confusion between jurisdiction changes and approval of clearance segments. After selecting a sequential representation, the numeric labeling was used due to its sequential nature. Alphabetic characters were not used so as not to confuse the controllers and pilots with the taxiway names.

Under a re-plan, the research engineers decided not to keep the same segment numbers of the previous pre-clearance if only the timing restrictions were adjusted. A brand new pre-clearance always started with segment [1] even if this segment was segment [2] in the previous pre-clearance. This kept the automation system stateless, and avoided the problem of lost data from previously sent routes.

Table 2. Examples of possible pre-clearance formats with clearance segment labels for arrival and departure aircraft using the runway 17L.

	Geographic	Sequential	
		Numeric	Alphabetic
Arrival	[LE2] TAXI VIA ... [LE1] TAXI VIA ... [GE2] TAXI VIA ...	[1] TAXI VIA ... [2] TAXI VIA ... [3] TAXI VIA ...	[α] TAXI VIA ... [β] TAXI VIA ... [γ] TAXI VIA ...
Departure	[GE2] TAXI VIA … [LE1] TAXI VIA … [LE2] TAXI VIA …	[1] TAXI VIA ... [2] TAXI VIA ... [3] TAXI VIA ...	[α] TAXI VIA ... [β] TAXI VIA ... [γ] TAXI VIA ...

VII. Future Technical and Operational Improvements and Features

During concept development and experimentation, possible improvements to GoSAFE functions and displays were identified. These are described below.

A. Seamless time adjustment

The capability to handle small changes in taxi route timing in the automation without human intervention was suggested by controllers and adapted into GoSAFE. In the GoSAFE system, as pre-clearances are sent to the controllers, the controllers must manually clear each segment. When a route or timing constraint changes, a new pre-clearance is always sent to the pilot from GoSAFE's automation, and new segments have to be cleared. This poses a problem when a lot of minor non-conformances occur throughout the airport. In order to avoid non-conformances as explained in Section IV-A, many re-planed pre-clearances will have to be sent. As controllers pointed out, corrections that do not affect the sequence or location of aircraft should be handled internally between the Tower and cockpit automation systems without requiring the controller's attention, and without requiring new clearances as long as the temporal change is minor and below some reasonable threshold. This reduces controller and pilot workload. The argument is that the time constraint is managed solely by the systems in such a way that controllers will rely on the automation to calculate proper timing constraints to cross, depart or land aircraft as minor non-conformances occur throughout the airport. Table 3 shows the suggested approval oversight the controllers have over the automation decisions and vice versa.

Table 3. Recommended amount of controller oversight required in each of ATC responsibilities.

	Automation Initiated	Controller Initiated	Controller Approval
Plan	X		X
Emergency stop	X	X	X
Handoff		X	X
Re-plan with only temporal adjustment not changing sequence of aircraft	X		
Re-plan with special re-routing		X	X

B. Visual of time occupancy

As indicated in Section VI-A the accessibility of information is very important. However, the representation of information is important, too. Currently the GoSAFE displays crossing times at each of the time restrictions as shown in Fig. 10. Also, GoSAFE is capable of showing the crossing aircraft by their call sign in any intersection or runway entry point on a timeline display as in Fig 11. This timeline shows the time when aircraft will arrive according to the dynamics model. It was suggested that even more advanced visual display of temporal occupancy of an aircraft be provided on the timeline as well. This additional graphical information allows the controller to get a deeper insight into the time slots allotted for each aircraft to perform crossings, landings and takeoffs from any particular intersection on the airport. A mockup of the suggested timeline is shown in Fig 11.

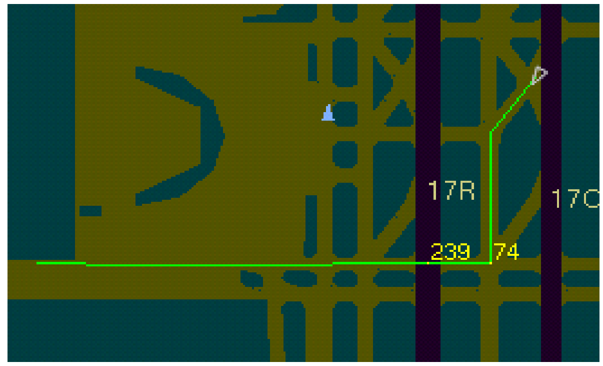


Figure 10. GoSAFE displays crossing times at each of the time restrictions.

C. Route selection optimization

Route selection can be divided into two categories. One category of route selection is static, based on the airport layout and configuration. The other category is dynamic, based on the current traffic. To generate incursion-free taxi routes, the airport layout configuration as well as current and near-future traffic condition should be taken into account. Mechanisms to actively share information on all aircraft are needed. Based on this information, all latent conflicts including runway incursions can be considered at the very moment when the system plans new taxi routes.

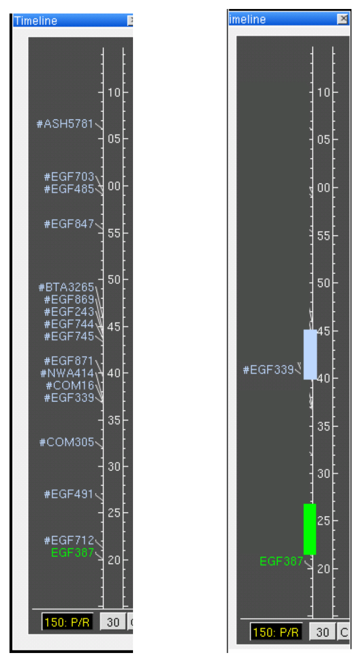
Traditionally the optimization of route selection also followed the two categories of information. For the taxi path selection in the current system, only information of layout and configuration are considered. For optimization of temporal sequencing and taxiing flow, only traffic occupancy and surveillance of airport are considered given the static routes. However, it is expected that algorithms that can create an incursion-free optimal path by considering all of the information simultaneously will be developed. This would give more flexibility to increase the efficiency of flow management. Furthermore, while the optimization in the current implementation of SOAR is on a per-aircraft basis, development of multi-vehicle optimization to further improve the overall performance of the airport is underway.

D. Way to increase computational power of the system

As mentioned earlier, the current automation system has been developed using personal computers. To deal with real-time operations, computational power of the computers and an efficient software system are important factors. It is necessary to search for ways to mitigate limitations in computation power. Multithreading software design and delegating repetitive algorithms to a field programmable gate array (FPGA) may be used. This would give more flexibility in developing algorithms.

E. Virtual wall specification on controller GUI

A feature conceived during development is a capability to allow controllers to define a "virtual wall." Routes are generated continuously as new flight plans and new traffic data are accrued in the automation system. However, controllers or supervisors might wish to close a taxiway or taxiway direction for some time. When this situation occurs, controllers should be able to construct directed virtual walls through the GUI in order to constrain the automation. These inputs serve as the simplest form of feedback a controller can give to automation without disturbing the other responsibilities the automation might have.



(a) Current (b) Suggested

Figure 11. Current GoSAFE timeline display and suggested timeline display with time occupancy visualization.

F. What-if visualization for controllers to see effect of automation decisions

One key feature of an automation system is that it must be able to perform some form of prediction of the traffic based on current state of the airport in order to do traffic optimization. While this type of prediction usually stays internal to the automation system, it can also be displayed to the controllers to provide situation awareness of the automation planning. This type of visualization would work almost as if a traffic simulation was going on in fast-forward mode, showing the controllers the expected movements of the taxiing aircraft.

G. Automation controlled configuration change

A conceived but not-yet-implemented feature of the surface automation is the ability to change the configuration of the airport. While the configuration settings can be easily stored in a database, a smooth transition requires the automation to perform the change without causing any overlapping occupancy of the taxiways and runways. This feature is currently missing in the GoSAFE implementation. However, it should be noted that software responsible for this feature must be in direct communication with the STM automation and the human controllers.

H. Diverting routes based on machine-learning functions of operation history

The controller participants suggested that there should be multiple-choice optional routes to select from when a controller is dissatisfied with the route selected by the automation. Prior to a re-plan, the controllers wish to see a selection of route options which can be based on published standards, controller preference, supervisor preference, location, time of day, traffic situation, or any other information.

I. Speech recognition for GoSAFE mixed-mode operations

In order to reduce the workload of controllers in mixed-mode GoSAFE operations (where the controller would give a clearance by voice, but would need to inform the GoSAFE system that the clearance has been issued and acknowledged), a suggestion was to introduce a simple speech recognition system that is capable of translating call signs and acknowledgements from the controllers and the pilots over radio. It is necessary for the feature not to require either the pilot or controller to use any computer function, but to just speak on the radio so that no workload is added. The simple speech recognition system, if accurate, can provide the missing link that bridges the current-day operation with hand radio communication and far-future operation with digital communications.

VIII. Future Structural Improvements and Features

During the development and testing of GoSAFE, possible software improvements were identified. These are described below.

A. Modular independence

The importance of modular independence is that each functional class or data-storing class of the automation software should be able to avoid crashing or giving bad data when its adjacent classes are temporarily shutdown or in the process of a restart.

B. Effective synchronization

The importance of effective synchronization is in preventing misunderstandings of timestamps, time restrictions, state data and flight plan data in any of the external communications of the automation system, either in the tower or in the flight deck. Currently a synchronization message is sent at system initialization. However, as an improvement to the existing system, this message should be sent frequently during the system’s runtime.

C. Centralized data access

To support both debugging and logging, future structural improvements that centralize data access are proposed. This serves several purposes. One purpose is to limit the number of agents that can write into the data, while allowing multiple agents to read from the data. This would minimize the possibility of error. Another purpose is to support real-time monitoring of the automation operation so that it collects research data as well as debug data.

D. Separation of data-storing classes and automation classes

Relating to the structural improvement of centralizing the data, the separation of data-storing classes and automation classes will encourage modular independence. If one independent functionality fails, the other functional classes should still be able to access the data-storing classes without being affected.

E. Network Error Robustness

One of the most essential structural improvements should be network-independent stability. For a variety of reasons any particular communication link can drop off, but the system has to stay functional until the communication link recovers. The system should be able to detect instantly when a particular communication socket is malfunctioning and initiate a procedure to recall emergency operation if the communication link becomes permanently disabled.

F. Replay capability on simulation runs

In support of research activities, the ground automation tools should be able to re-construct any simulation by capturing all of the inputs to the surface automation system including the flight plans, state data and controller interface inputs. Replay capability is extremely useful to researchers looking at specific events that occurred during an experiment.

G. Real-Time visualization of GoSAFE's internal data structures

Also in support of research, there should be a way for some external functions to tap into the surface automation tool's internal data structure to visualize the internal data structures of time occupancy of aircraft vehicles in real time. Having a centralized data access can support this particular structural feature.

IX. Future Research Topics

During SOAR development and experimentation, possible future research topics were identified. These are described below.

A. Route diversification algorithm

This research topic refers back to the suggestion (in Section VII-H) of having different methods of diversifying the automation's selection of routes based on human preference input, optimization algorithms, statistics, or operational history. Such diversification would give greater flexibility to the automation and reduce controller workload when dealing with off-nominal situations.

B. Supervisor/controller concept with automation

This proposed research would test and address additions to the ground operation concept that would support the functions of an automated controller, a human controller, a human supervisor and an automated supervisor. The collaboration of human and automated supervisors will be able to affect jurisdiction-wide handoffs, traffic flow adjustments, and airport configuration changes. This research will explore automation capabilities of both tactical and strategic planning via automation.

C. Speech recognition system for mixed-mode operations

This research topic would test both the feasibility of speech recognition as a bridge between advanced concepts and current-day operations, and the accuracy of speech recognition systems on radio communication.

D. Temporal occupancy visualization

This research topic proposal is to test human participants on their preferential methods of visualizing the aircraft's temporal data structures within ground operation automation. Because this type of awareness data is essential in human/automation collaboration, research on this topic should be rigorous.

E. Attention sequencing

This research topic proposal is to address controller participants' suggestion that the priority of information displayed on the controller stations should be obvious. The interface study should include different methods of time-sequencing the attention cues of aircraft that require attention from the controller of the aircraft's jurisdiction.

F. Automatic conformance re-planning with different levels of controller awareness

There have been both positive and negative comments about an automatic conformance monitor that re-plans timed clearances whenever aircraft move out of conformance. However, there can be different levels of controller awareness from the extreme of neither the controller nor the pilot being informed of the automation time-adjustment change in the auto taxi system, to the other extreme of requesting detailed approval from both the controller and the pilot whenever a timing adjustment occurs. Optimal awareness levels can only be found through human-in-the-loop experiments in research.

X. Concluding Remarks

The VAMS Project includes many advanced capacity-increasing concepts to address the anticipated increase in air traffic demands in the National Airspace System (NAS). Among these concepts, Surface Operation Automation Research (SOAR) was given the opportunity to perform real-time research with human-in-the-loop simulations. The development and evaluation unveiled many challenges and issues, as well as providing many lessons learned and suggestions for the future. The research of each advanced concept with the goal for eventual deployment will involve significant research and continue to be subjected to rigorous evaluation in the realm of pre-planning, re-planning, interface and system integration. Each research topic will face the numerous inherent challenges and implementation issues, examples of which are outlined in this paper. Because of the lack of advanced concepts heretofore in the tower controller community, it is even more essential to explore new guidelines to develop a system in performing research in this particular unexplored territory.

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