Surface Operation Automation Research for Airport Tower and Flight Deck Automation

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Abstract — **Air traffic growth has resulted in serious peak-traffic flight delays in our National Airspace System, and congestion at key airports has been recognized as one of the key factors contributing to the problem. Airport expansion plans designed to increase the airports' capacities cannot fully realize their potential benefits because they tend to increase the complexity of the airport configurations, thus reducing the efficiency of the system. The Surface Operation Automation Research (SOAR) concept was proposed in a previous article as a collaborative concept to provide automation for surface-traffic management and the flight deck to enhance the operational efficiency in complex airport environments. Development and evaluation of the SOAR concept is being pursued in a 5-year program. This paper presents a progress update of the program.**

I. Introduction

THE problem of air traffic growth unmatched by commensurate growth in capacity has been witnessed with the peak summer flight delays prior to the September 11, 2001 terrorist attack. The flight-delay problem has been recognized by the Federal Aviation Administration (FAA), NASA, and other concerned parties. The slow down in air travel since the 2001 attack was temporary, and the traffic has already reached a level that led to an FAA order in January 2004 to limit scheduled operations at Chicago O'Hare Airport. In the National Airspace System Operational Evolution Plan (OEP) [1], FAA has identified congestion at key airports as a domain where the problem is most prominent. Airport expansion plans seek to increase the airports' capacities with the addition of new runways and taxiways. However, the expansion plans necessarily increase the complexity of the airport configurations, which tends to reduce the efficiency of the system, partially offsetting the capacity-related benefits of the investments. The Surface Operation Automation Research (SOAR) concept [2] was proposed as a collaborative concept to provide automation for surface-traffic management and the flight deck to enhance the operational efficiency in complex airport environments. Development and evaluation of the SOAR concept is being pursued in a 5-year program. This paper provides a progress update of the SOAR program.

Three air traffic domains are commonly defined in the National Airspace System (NAS): en route, terminal, and surface. Whereas air traffic in en route airspace enjoys the flexibility of variable flight levels and headings to allow popular ideas such as "free flight," taxi operations on the surface are confined to the planar network of runways and taxiways that they need to be more orderly for efficiency.

With surface operations constituting a potential bottleneck, major airlines practicing hub-and-spoke operations for cost savings often suffer major delays at the hub airports. In view of landing and departure rate limits, construction of new runways is ultimately inevitable to achieve capacity gain. In addition to the cost of construction, the increase in surface traffic complexity resulting from the airport expansion will incur other indirect costs or penalties. The SOAR concept [2], [3] was proposed to provide automation tools for coordinating efficient surface traffic movement. Development and evaluation of the SOAR concept is currently being supported by the NASA Virtual Airspace Modeling and Simulation (VAMS) program. An evaluation plan of the SOAR concept was provided in [4].

II. SOAR Concept

The SOAR concept 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 maximal 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 describing the roles of the automation components. There are three core ideas behind the SOAR concept:

I. Surface Traffic Management (STM) automation to enable efficient surface traffic flow
II. Flight-deck automation to enable Aircraft Control for performing high-precision taxi operations
III. Integrated operation of automation and other advanced systems to accomplish CDDC for optimum surface traffic efficiency

Fig. 1 describes the interaction of the two automation environments and with the human operators and the

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aircraft. It also reveals the integrated operation of these systems with advanced communication, navigation, and surveillance (CNS) systems, which represent major enabling technologies for the concept. The three core ideas are discussed individually in the following subsections.

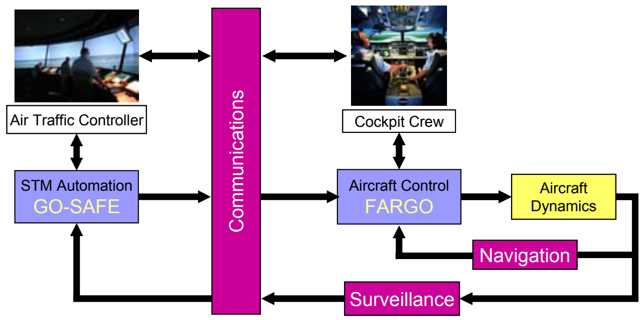

Fig. 1. High-Level Block Diagram of SOAR Collaborative Automation Concept

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 categories of functions:

- *Planning* functions for generating efficient taxi clearances
- *Traffic control* functions to facilitate issuance of clearances to 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 STM automation system, known as the *Ground-Operation Situation Awareness and Flow Efficiency* (GO-SAFE) system [5]. The experimental GO-SAFE system serves as the foundation for building the ground-control automation system envisioned by the SOAR concept. The functions of the envisioned GO-SAFE system are described in more detail in the following.

1) *Planning Functions*

The GO-SAFE system concept contains the following set of planning functions:

- Automatic Taxi-Route Generation
- Manual Taxi-Route Editing
- Decision Support Functions for Traffic Optimization
- Taxi-Route De-Confliction
- Adaptive Airport Configuration Function
- Surface Traffic Data Processing

Early investigation of the GO-SAFE concept [5] included the experimental development of functions to support the automatic generation of taxi routes, manual editing of the routes with graphical interaction, automatic de-confliction of the routes and runway scheduling for the flights. SOAR involves more advanced technologies to fully realize the complex functions envisioned for the GO-SAFE software system: an integrated function for automatic route generation, de-confliction, and runway scheduling; an adaptive airport configuration function to access multiple airport runway configurations simultaneously to aid the transition from one configuration to another; and data-processing functions to give the controllers and coordinators a more strategic view of the traffic.

2) *Traffic Control Functions*

Air Traffic Management (ATM) automation systems such as the Center-TRACON Automation System (CTAS) [6], [7] and GO-SAFE generate advisories that can be converted to clearances for the flights. The CTAS tools traditionally assume that the use of verbal clearances, and not require that all advisories would be issued as clearances. Instead, the CTAS software system continuously monitors the traffic under surveillance to update the advisories. In the case of GO-SAFE, effective conversion of the time-based taxi-route advisories to verbal clearances is unlikely; hence the complex clearances will most likely be transmitted to the flight deck via data link. GO-SAFE needs to keep track of the clearance status, and the *Clearance Manager* in GO-SAFE provides this functionality. The Clearance Manager software function keeps track of the possible clearance status for the flights, whether a new advisory is available and its clearance ready to be sent, a clearance has been sent, an acknowledgment has been received to affirm or reject the clearance, etc. These different conditions can be conveyed to the controller via the GO-SAFE GUI. In addition, since the various GO-SAFE functions of manual route editing, automatic runway-usage scheduler and route de-confliction can individually change a flight's time-based taxi route, the Clearance Manager needs to update the clearances when necessary. With the manual route-editing functions, the Clearance Manager also provides a "what-if" capability to help the controller understand how possible changes in the route would affect the other flights and their clearances.

3) *Traffic Monitor Functions*

The GO-SAFE concept includes two automation functions to help air traffic controllers monitor the traffic: a *Conformance Monitor* function for detecting flights that deviate from their clearances, and a *Conflict Prediction* function for identifying potential conflicts based on surveillance data.

As the Clearance Manager keeps track of the status of clearances issued, it can combine this information with surveillance data from Automatic Dependent Surveillance (ADS) and primary and secondary radars to monitor the state of the flights. As long as the flights are in conformance with the clearances, which are assured to be conflict-free by the automatic route de-confliction function, there is no danger of conflicts of any kind, including runway incursions, taxiing on the wrong taxiway, or accidents/incidents similar to some of the notorious events of landing or taking off from the wrong runway [8] or taking off from a taxiway [9]. Only when the Conformance Monitor detects sufficient deviation by a flight from its clearance that it should alert the controller. Furthermore, only under such situation will GO-SAFE need to search for potential conflict with other flights. This systematic process will simplify the runway incursion and other vehicle conflict problems.

Even when the Conformance Monitor detects clearance deviation by one or more flights, it does not always imply imminent danger of conflict or incursion. The Conflict Prediction function would analyze the situation and determine if other flights are affected. This involves extrapolating the trajectories of all the affected flights forward in time. The approach may be as simple as that used in the Airport Movement Area Safety System (AMASS), which involves a relatively short extrapolation, or it can be more sophisticated and include consideration of the pilot's intent, possible misinterpretation of clearances, or misreading airport signage.

4) User Interface Functions

GO-SAFE needs an effective GUI to help the tower controllers perform the functions discussed above. Fig. 2 shows a GUI for the experimental system reported in [5]. It has five panes, the most prominent of which is the plan-view display, which shows the Dallas/ Fort Worth (DFW) airport layout, with the aircraft location provided from surveillance data. The time-line display lies to the left of the plan-view display. It shows the predicted time instants at which the flights will cross user-selected locations. Above the plan-view display are traffic load graphs, which show the predicted traffic density across user-selected locations. Conflict information on GO-SAFE-generated taxi routes is displayed in table form in the upper-right corner. It allows the controller to identify the conflict and resolve them manually or with the automation functions provided by GO-SAFE. The bottom of the GUI displays clearances and advisories for flights selected by the user, and the status of any issued clearances.

In addition, the GO-SAFE plan-view display supports the display of flight data in the form of data tags, taxi routes with time-based information, and warnings for clearance noncompliance and traffic incursions. It also supports the editing functions of GO-SAFE for the controllers to adjust the preferred taxi routes. Most of these conceptual functions will require further technology development for full realization of their functionality.

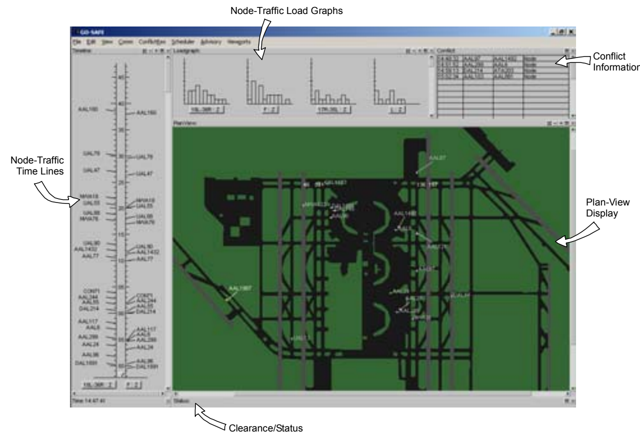

Fig. 2. Overview of Experimental GO-SAFE GUI

B. Flight Deck Automation

The flight-deck automation systems in the aircraft collectively provide the distributed control of the traffic in collaboration with GO-SAFE. 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 as clearances. New operation procedures will need to be defined for carrying out data-linked clearances, and for automatic loading of the clearances into the flight decks' flight management systems (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 precision taxi requirements demanded by GO-SAFE-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

OSI has demonstrated previously that advanced nonlinear control methods can enable the aircraft to track precisely defined time-controlled taxi routes, even in the highly dynamic environment of performing active-runway crossing immediately after landing on an adjacent runway [10]. The *Flight-deck Automation for Reliable Ground Operation* (FARGO) system represents further development of this idea to achieve the flight-deck automation component of the SOAR concept. The functions of the envisioned FARGO system are discussed in the following.

1) Planning Functions

The planning functions are concerned with preparing the FARGO system for executing the clearance issued by GO-SAFE 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; 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.

2) Auto-Taxi Functions

With the time-based taxi-route already downloaded into FARGO's flight-control computer, the auto-taxi capability consists of two levels of automation functions for precision taxi: a *guidance* function for converting the taxi route into guidance commands for accomplishing the taxi clearance, and a *control* function for controlling the aircraft taxi to precisely track the guidance commands. Fig. 3 shows where the auto-taxi capability fits in the general aircraft-control block diagram of the FARGO system.

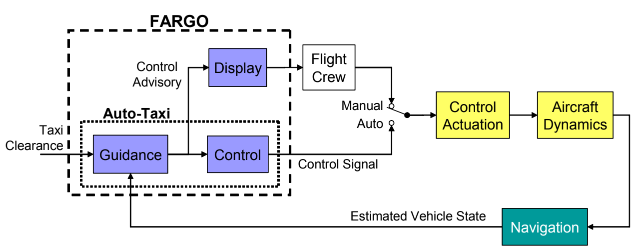

Fig. 3. General Block Diagram of Aircraft Control with FARGO Concept

Previous analysis results [10] showed that advanced guidance and control would be able to perform high-precision taxi operations, limited only by the accuracy of the navigation system. With current technology on differential Global Positioning System (DGPS) and the recent decision by the US to release GPS P-code for public use, the tracking would be accurate to the order of a meter.

The guidance function in the Auto-Taxi Control subsystem of Fig. 3 generates a reference trajectory as a precursor to the control signal. The reference trajectory and/or the resulting control signal can be provided as the Control Advisory to the pilot for manual taxi control.

3) Pilot Interface

If full auto-taxi capability is available, a display interface will be useful for the pilots to monitor FARGO performance; otherwise, the display will provide reference trajectory information to the pilot for performing manual control. Traditionally a speed bug serves well as a pilot interface for speed control when constant airspeed is expected, as in the cases of cruise, climb, and descent. In the case of rollout and turnoff after landing, the control involves a deceleration segment followed possibly by a constant-speed taxi segment, but a time-varying speed bug would not be an effective display for controlling the taxi speed. OSI has been exploring a display concept based on the definition of a phantom vehicle driven by the FARGO reference trajectory [2]. Fig. 4 shows an experimental FARGO display implemented as a head-up display, with the phantom-vehicle symbology, and indicators based on acceleration and timing information derived from the reference trajectory. Early tests using this display have confirmed that its indicators provide good information for the pilot to meet tight crossing constraints. This display can be integrated with NASA's Taxiway Navigation and Situation Awareness (T-NASA) system [11].

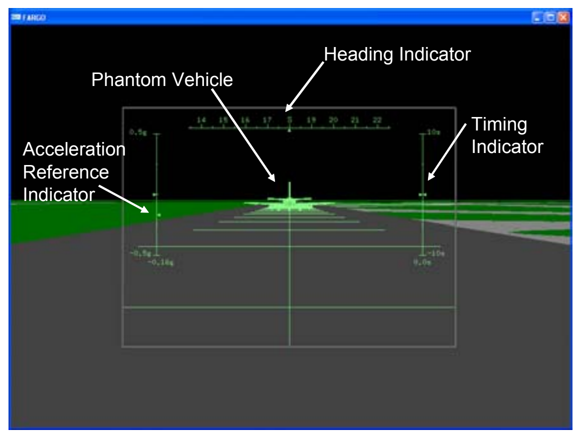

Fig. 4. Overview of Experimental FARGO GUI

4) Traffic Monitor Functions

In parallel with the GO-SAFE system, the FARGO concept includes two automation functions for traffic monitoring: *Conformance Monitor* and *Conflict Detection*. The Conformance Monitor function is very similar to the one in GO-SAFE, except that FARGO only needs to worry about the aircraft's own performance. As in GO-SAFE, the Conflict Detection function in FARGO will involve extrapolation of the aircraft's and other aircraft's trajectories. Both FARGO and GO-SAFE are assumed to have access to ADS-Broadcast (ADS-B). However, FARGO does not have access to all the primary and secondary radars that provide surveillance data for non-ADS-B-equipped vehicles, including ground vehicles. For conflict detection of these vehicles, FARGO can depend on Traffic Information Service – Broadcast (TIS-B) [12].

C. Operational Integration of Automation Systems

Integrated operations of the SOAR concept can be considered as two categories: procedures for integrated operations of the SOAR-specific components, i.e., the GO-SAFE and FARGO systems; and information exchange between the SOAR components and other systems.

1) Operational Procedures

In the deployment of advanced automation systems, automation technologies are often secondary to operational issues. With humans in the loop and lives on the line, machinery reliability alone is not sufficient for validating system safety. Crucial operational issues must be addressed for successful realization of the SOAR concept.

It has already been stipulated that SOAR clearances will require data link for issuance. However, past experience with data-link experiments has shown that there are many issues associated with data-linked clearances. On the controller side, the controller can no longer issue a clearance and expect an immediate acknowledgment. On the cockpit side, the data-linked clearance may need to be read out to ensure that both pilot and co-pilot agree on its content. Moreover, visual attention has to be re-directed from the crew's aircraft-control function to reading the clearance, followed by acknowledging it with key strokes on the control console. On the other hand, route information embedded in the data-linked clearances can be conveniently loaded into the FMS for use by FARGO.

The SOAR concept will also impact surface operational procedures in other ways. The SOAR concept may be able to reduce the number of controller handoffs commonly used in current STM practice.

2) Information Exchange

Effective operation of GO-SAFE will depend on the quality of information it has access to, including information on anticipated arrival and departure traffics and the current state of the flights. The information is available from various facilities within the NAS infrastructure, including flight-plan processing and surveillance systems. Flight plan information is available from the Host Computer and from the Enhanced Traffic Management System (ETMS). Surveillance data are available from ADS-B, TIS-B, Airport Surface Detection Equipment (ASDE), AMASS, Airport Target Identification System (ATIDS), and Automated Radar Terminal System (ARTS).

In addition, GO-SAFE should be able to collaborate with other automation systems, including tools from recent NASA and FAA programs that address air traffic efficiency and safety: CTAS [6], [7], Terminal Area Productivity (TAP) [13], [14], Surface Movement Advisor (SMA) [15], Surface Management System (SMS) [16], Advanced Air Transportation Technologies (AATT), Aviation Safety and Security, and VAMS.

D. Enabling Technologies

Much of the advancement of the CNS enabling technologies is included in the NAS modernization plan [17], which is implemented through 2015, with ample time for realization of SOAR by the target time frame of 2020.

III. Evaluation Efforts

With some of the early GO-SAFE and FARGO ideas developed between 1998 and 2001, a 5-year effort was initiated in 2002 to develop and evaluate the SOAR concept with support from the NASA VAMS program.

A. Single-Airport Evaluation Results

An evaluation of the SOAR concept was performed in 2003 using computer simulations developed for studying surface operations [5]. The evaluation was based on a simulation of the surface traffic at DFW. Traffic demands were provided by the VAMS program to represent typical current demands and future demands predicted from a transportation demand and economic analysis forecast for the year 2022 [18]. The evaluation results [19] show the ability of the SOAR concept to enhance traffic throughput and reduce taxi delay over current operational practices.

B. System-Wide Evaluation Plan

The benefits of the SOAR concept on the whole NAS are being assessed in 2004 using the Airspace Concept Evaluation System (ACES) [20] from the VAMS program. The evaluation again uses demand data sets representing current-day traffic as well as future demands forecast for the 2022 time frame. The effects of the SOAR concept are modeled as enhancements in airport capacities and reduced taxi delays. The system-wide impact is expected to emerge as reduced system delays associated with the ripple effect caused by missed connections and flight cancellations [21].

C. Human-in-the-Loop Evaluation Plans

The possibility of assessing the SOAR concept in high-fidelity human-in-the-loop simulations is being explored for the 2005–2006 phase of the program. The FutureFlight Central (FFC) tower simulator and the Crew Vehicle Systems Research Facility (CVSRF) are world-class facilities at NASA Ames Research Center that are ideal for integrated evaluation of the SOAR systems. The FFC is a full-scale tower simulator with a 360° tower view for assessing GO-SAFE, and the Advanced Cockpit Flight Simulator (ACFS) in the CVSRF is a motion simulator suitable for FARGO assessment. Fig. 5 and Fig. 6 contain views of the FFC and the ACFS, respectively.

IV. Concluding Remarks

This paper provides a progress update of the Surface Operation Automation Research (SOAR) program to develop a collaborative automation concept between taxiing aircraft and tower control to enhance airport surface traffic efficiency and safety. The concept development effort has been under support from the NASA VAMS program since 2002. Early investigative development of the technologies to explore the feasibility of the automation systems started as early as 1998, and the continued support from the VAMS program has helped the research effort in identifying critical technologies for fully realizing the benefits of the concept.

Although the basic, high-level definition of the SOAR concept has not changed substantially since the early investigations, it has continually gone through the critical stages of formalization and refinement under the VAMS program. VAMS is also providing the opportunities to evaluate the concept's potential benefits, using computer simulations in 2003 to assess the impact on airport capacity and taxi delays for a single hub airport, and a NAS-wide simulation in 2004 to expand the evaluation to study the concept's system-wide benefits. As any automation system involving human operators must be compatible with the operators' work practices and environment, plans are being explored to provide human-in-the-loop evaluation of the SOAR concept with world-class simulation facilities at NASA Ames Research Center.

Fig. 5. View of the FutureFlight Central (FFC) Tower Simulator

Fig. 6. View of the Advanced Cockpit Flight Simulator (ACFS)

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