

COLLABORATIVE AUTOMATION SYSTEMS FOR ENHANCING AIRPORT SURFACE TRAFFIC EFFICIENCY AND SAFETY

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Abstract

Airport congestion constitutes a key traffic capacity problem in the National Airspace System. Constrained by separation requirements, efforts to increase airport capacity ultimately needs to increase the number of runways with a corresponding increase in taxiways. To realize the operational throughput offered by the available runways, operational procedures favoring landing and takeoff operations over other runway occupancies such as crossing by the taxiing traffic have to be adopted. Consequently, the increase in surface traffic complexity leads to an efficiency penalty in the form of taxi delay. This problem is exacerbated by the increase in traffic density enabled by the improved landing/departure rates. This paper considers a concept for improving the surface operations at major airports through the use of automation to manage the complex traffic. The concept includes advanced surface-traffic-control automation and flight-deck automation, and it builds on advanced Communication, Navigation, and Surveillance technologies to achieve a seamless integration of these two major components. The surface-traffic-control automation is based on the Ground-Operation Situation Awareness and Flow Efficiency (GO-SAFE) concept previously proposed and studied to enable more efficient usage of runways, especially in situations where active-runway crossing constitutes a significant taxi delay problem. To help achieve the potential GO-SAFE benefits, the Flight-Deck Automation for Reliable Ground Operation (FARGO) concept is proposed to provide the necessary flight-deck automation for enabling precision taxi control to comply with GO-SAFE advisories. The integrated system with the highly coordinated automation systems will push the envelope of surface traffic performance to enhance capacity without compromising safety and taxi performance.

Introduction

The problem of air traffic growth unmatched by commensurate growth in capacity has been witnessed with the peak summer flight delays in recent years, and well documented and recognized by all concerned parties including the Federal Aviation Administration (FAA) and NASA. In the National Airspace System (NAS) Operational Evolution Plan (OEP) [1], FAA recognizes the capacity problem, and specifically identifies congestion at key airports as one of the domains where the problem is most prominent.

As arrival flights descend from cruise to the airport for landing, they transition from the 3-dimensional (3D) space of the Air Route Traffic Control Center (ARTCC) to enter the Terminal Radar Approach Control (TRACON), where the traffic patterns are basically 2D, and subsequently to final approach and landing, where trajectory control is limited to 1D. The funnel effect on the arrival traffic is evident, and the presence of departure traffic further complicates the arrival traffic control. Traffic on the surface reverts back to a 2D pattern made up of the runways and taxiways. Efforts to increase airport capacity approach the problem on two fronts: the first obvious solution is to increase the number of runways and other important surface space, and the second approach is to develop new technologies to achieve reduction in aircraft separation and consequently increase in traffic density. It is the product of space and density that determines the total available capacity of the system.

The intention of the governing bodies to improve airport capacity by increasing usable surface area is evident from the FAA's NAS OEP, which includes constructing new runways or extensions at 14 major airports by 2010. In view of landing and departure rate limits, constructing 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 has other indirect costs such as increased workload and reduced traffic efficiency in terms of taxi delays.

Consider, for example, the expansion of the Dallas/Fort Worth International Airport (DFW), which is in the middle of the expansion effort and currently has seven runways. Figure 1 labels in parentheses the proposed changes in runway layout due to the addition of an eighth runway. Under most airport configurations, adding runways results in some runways blocking the traffic between the terminal ramp area and other runways further out. As the tower controllers have more flights to control, they also have more taxiway intersections and runway crossings to worry about. Any increase in throughput of the outer runways via operational changes to reduce aircraft separation for increasing efficiency will lead to a further increase in the need for runway crossings. Furthermore, a similar increase in throughput of the inner runways reduces the opportunity for runway crossings to take place.

These operational changes to accommodate the increasing traffic compound the safety and efficiency issues.

More specifically, it can be seen in the DFW example that all arrival flights to runways other than 17R/35L and 18L/36R will need to cross at least one runway in order to gain access to the ramp area around the terminals, which are located at the center of the airport. Current south-flow operations at DFW, which account for the majority of the operations at this airport, use Runway 17R for departure and 17C for arrival. During rush periods, the arrival flights on 17C often have to queue up at the three taxiways EL, EM and B (see Figure 2) after exiting from M3, M5 and M6, respectively, before they are cleared to cross 17R together as a group. The rationale behind this practice is to minimize the total runway-crossing time and the interruption on the takeoff operations on 17R. On the other hand, such holding prior to active-runway crossing means that sometimes three flights would line up on each of the three taxiways, a total of nine

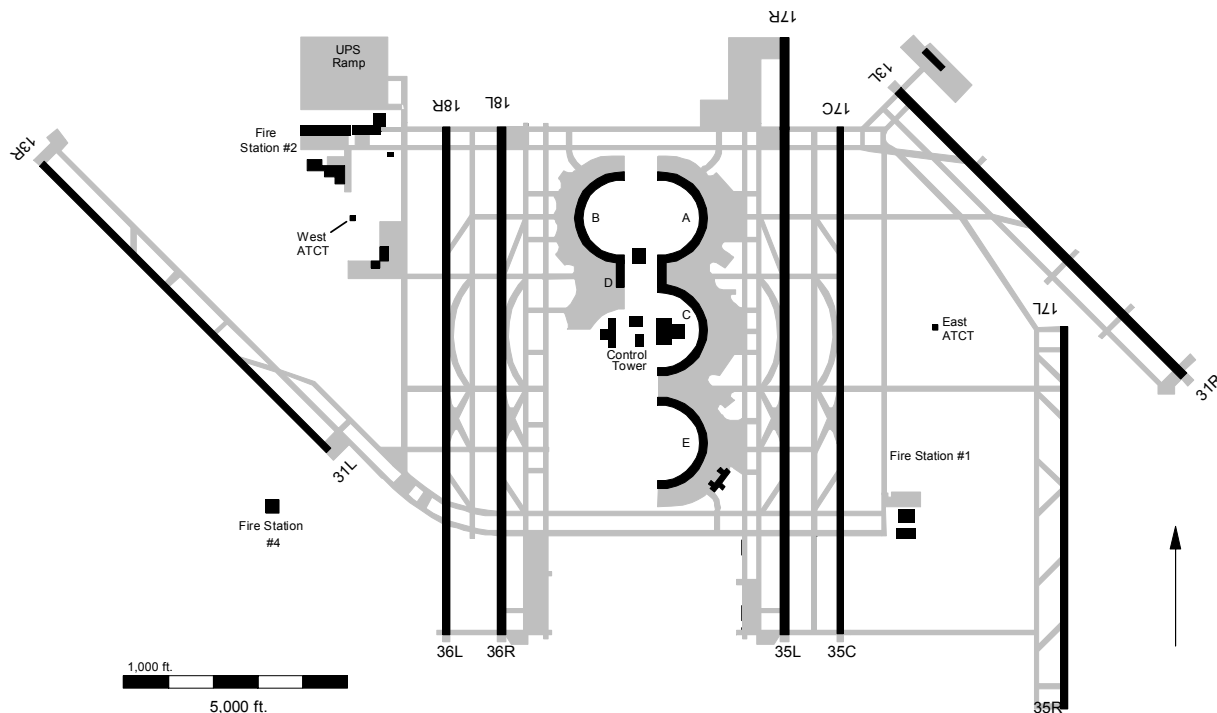


Figure 1. Layout of Dallas/Ft. Worth International Airport (DFW)

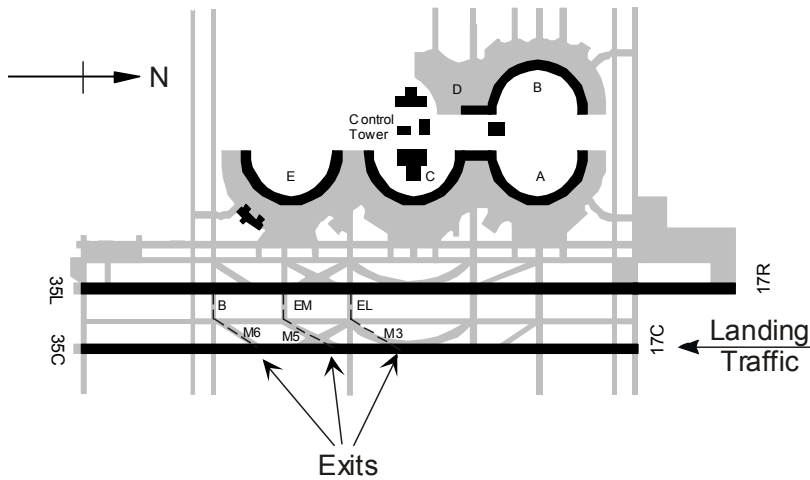


Figure 2. Example of Landing, Turn Off and Runway Crossing at DFW

flights, before they are allowed to cross. This introduces substantial taxi delay to most of these flights. The DFW Airport Development Plan [2] includes two proposed ideas to ease the active-runway-crossing problem, but neither is particularly attractive [3][4].

Other studies have corroborated the issues of surface traffic efficiency. The results from an MIT study [5] are consistent with the notion that the taxiing traffic requiring active-runway crossings experiences substantial taxi-delays when the runways are heavily occupied by takeoff and landing traffic. Reference [6] indicates that, for departure traffic, there would be substantial savings by converting runway queuing time into gate delays, implying that minimization of unnecessary taxi time would increase savings for both departure and arrival traffic, even if it means more gate holding delays.

As much as the need to increase runways and other surface space such as taxiways, ramp areas and gates is indisputable, these expansion plans have to be augmented by the development and deployment of advanced technologies before their full potential in capacity enhancement can be realized. The NAS OEP recognizes these needs and has included the following items in addition to the aforementioned airport expansion plans.

- Improved runway configuration coordination between facilities and carriers

- Surface navigation using cockpit display to augment visual data and provide common situational awareness
- Enhanced surface management coordination

The collaborative automation system concept described in this paper can potentially deliver these enhancements. The concept includes technologies to automate the surface-traffic control operation and the flight deck, with seamless integration to achieve efficient, orderly surface traffic to maximize the capacity achievable with the complex airport configurations resulting from the anticipated airport expansions.

Whereas it is the intention of the concept to address the efficiency issues of surface operation, its development cannot ignore associated safety issues. Even in the absence of advanced surface-operation automation systems, serious surface-traffic safety issues already exist in today's environment. One such issue is the runway incursion problem, the seriousness of which is exemplified by major programs sanctioned by the FAA and the International Civil Aviation Organization (ICAO). As discussed in [3][4], the FAA Runway Incursion Reduction Program (RIRP) [7] studies surveillance technologies to enhance situation awareness of air traffic control (ATC) and the flight crew: Airport Target Identification System (ATIDS) [8], Airport Surface Detection Equipment (ASDE-3 and ASDE-X) [9], Inductive Loop Technology [10], Automatic Dependent Surveillance – Broadcast (ADS-B) [11], and the Surface Surveillance Data Server. The ICAO Advanced Surface Movement Guidance & Control System (A-SMGCS) [12] includes features and functions to enable safe and efficient airport surface operations.

The concept based on collaboration between the automation systems at surface-traffic control and the flight deck will help reduce runway incursions and incidents of clearance nonconformance, which was the cause of recent incidents [13] and accidents [14].

Collaborative Automation Concept for Airport Surface Operation

The collaborative automation concept includes the introduction of advanced automation to the two main environments responsible for surface operation: the surface-traffic control environment and the flight deck. The automation technologies will provide maximal performance when these two environments can be tightly integrated in a Centralized Decision-Making, Distributed Control (CDDC) paradigm. Figure 3 contains a top-level block diagram of the concept, the development of which represents work in progress.

The surface-traffic-control automation system will provide the centralized decision-making functionality, shown as the Traffic Control block in Figure 3. It will base its decision on the surveillance data, flight plans and Airline Operational Control (AOC) requirements, to generate time-based taxi routes for optimum traffic efficiency. An experimental version of such a surface-traffic-control automation system, known as the *Ground-Operation Situation Awareness and Flow Efficiency (GO-SAFE)* system, was previously developed and now forms the basis for the Traffic Control block of Figure 3 [4]. Advanced data-link may be required for issuing the complex taxi clearances for the flights to taxi according to the desired time-controlled taxi routes and

monitoring the vehicles' compliance.

The flight-deck automation systems in the aircraft participating in the surface operation will collectively provide the distributed control of the overall traffic system in a collaborative manner, as shown by the Aircraft Control block in Figure 3. Advanced automation technologies will provide auto-taxi capabilities or automation aids to the pilots for performing precision taxi to achieve the time-controlled taxi routes issued as clearances by surface traffic control. 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). Previous research has demonstrated through computer simulations that advanced nonlinear control methods can be deployed to control the aircraft's taxi operation to track very precisely defined time-controlled taxi routes, even in the highly dynamic environment of executing active runway crossing immediately after the aircraft lands on an adjacent runway [3]. An automation system known as the *Flight-deck Automation for Reliable Ground Operation (FARGO)* system is being developed based on this idea.

With this CDDC paradigm, the tighter the margin tolerable by FARGO to carry out the taxi operation, the better will GO-SAFE perform in delivering efficient surface operations and hence

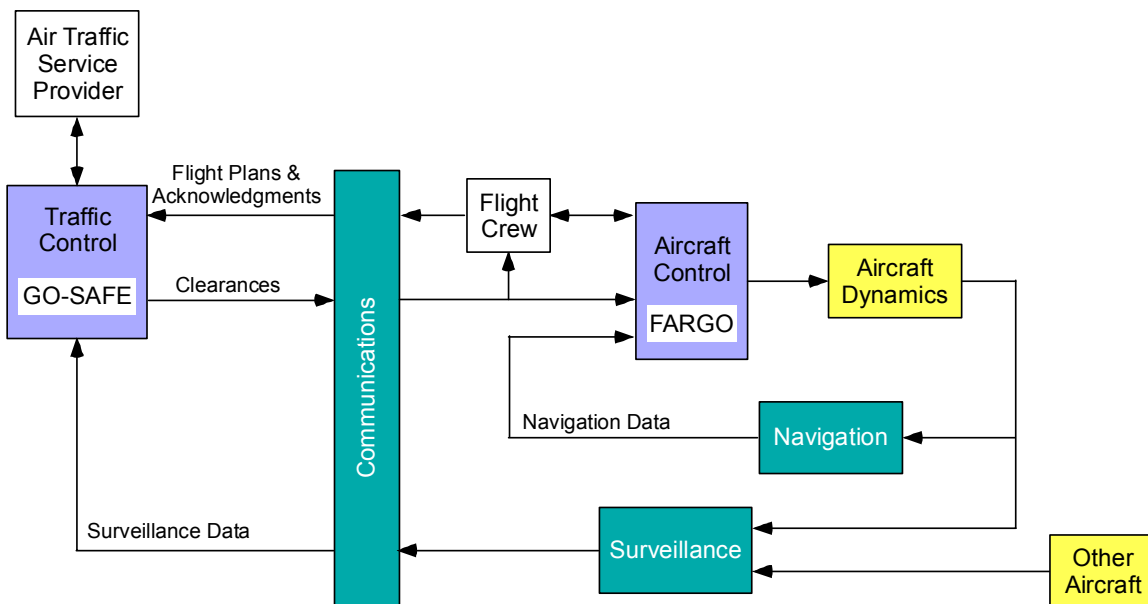


Figure 3. Top-Level Block Diagram of the Collaborative Surface Automation Concept

realizable capacity. It is evident from the conceptual block diagram of Figure 3 that successful integration of the CDDC automation concept systems depends heavily on technologies in communication, navigation, and surveillance (CNS) [15][16].

For the surface-traffic-control automation system, accurate surveillance data is critical for the system to generate clearances that enhance traffic efficiency. Existing systems such as the Airport Surface Detection Equipment (ASDE-3) lacks aircraft identification and is difficult to use even in current operations. The automation system concept will require more accurate and unambiguous surveillance data. Such data is expected to be readily available when Automatic Dependent Surveillance – Broadcast (ADS-B) is widely adopted. The FAA has recently announced the decision on the 1090 MHz Extended Squitter (1090ES) and the Universal Access Transceiver (UAT) technologies for realization of ADS-B [17]. In the nearer term, the deployment of ASDE-X with transponder multi-lateration sensors will provide the required data. Even when ADS-B is available, multi-lateration surveillance sources such as ASDE-X will provide surveillance data on aircraft not equipped for ADS-B, and availability of this data will also enable the Traffic Information Service – Broadcast (TIS-B) to provide ADS-B-equipped aircraft information on the unequipped aircraft for added situation awareness.

For the flight-deck automation system, accurate navigation data is critical for the system to follow clearances issued by the surface-traffic-control system to achieve maximum traffic efficiency without violating predetermined safety margins. The wide adoption of satellite-based navigation such as the Global Positioning System (GPS), with accuracy provided by differential GPS, or similar accuracy provided by the GPS P-code recently released by the US government for use by the public, will provide the necessary accuracy in navigation data for realization of the flight-deck automation system.

Integrated operation of the automation systems will require advanced communication technologies including both voice and data-link communications. Implementation of the data-link communications necessary for the concept will depend initially on

the Controller-Pilot Data Link Communications (CPDLC) using VHF digital link (VDL) Mode-2 technology. Further out, digital voice and data communications via digital radios may be provided by the Next Generation Air/Ground Communications (NEXCOM) program, involving VDL Mode-3 ground and airborne radios to improve spectrum utilization.

Aside from the technological challenges, procedural and acceptance issues are critical for the successful implementation of the concept. Past experiences have revealed that it is often difficult to promote highly automated systems, both on the flight decks and in the air traffic control (ATC) environment. Many of these concerns are justifiable due to the critical impact of the systems on safety and the responsibilities of the different parties. Human-related challenges will need to be addressed with careful engineering of the systems, with due regards given to the human-factor concerns, and through proper training and education of the users. If such human-related concerns are not properly addressed, political barriers may result from organized resistance by the intended users.

Surface-Traffic-Control Automation System

The surface-traffic-control automation system GO-SAFE is envisioned to include the following major functions:

- User interface including situational display to allow the ground controller to monitor all surface traffic, with advanced functions to alert the controller of impending traffic difficulties
- Taxi-route generation and editing capabilities
- Conflict detection and resolution
- Decision support tool for planning and adjusting taxi routes for delivering efficient and safe traffic
- Clearance manager for generating and processing advisories and clearances, and for monitoring the resulting progress
- Information exchange with relevant systems in the NAS infrastructure and other automation systems

These functions are discussed in the following subsections.

GO-SAFE User Interface

As with any advanced automation systems, an effective user interface is essential for the GO-SAFE system. The experimental GO-SAFE system reported in [4] includes a relatively rudimentary graphical user interface (GUI) for the user to access the automation functions. Figure 4 illustrates the various graphical components in this experimental GUI. It has five panes, the most prominent of which is the plan-view display, which as an example shows the DFW airport layout. Future enhancements of this GUI will include data tags for the flights to convey relevant information to support the controllers.

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, which are currently restricted to nodes as defined by the intersections of the taxiways/runways. Above the plan-view display are traffic load graphs, which show the predicted traffic density across user-selected locations. Future enhancements may include aggregate load graphs that provide more relevant information to the controller for predicting surface traffic congestions.

Conflict information is displayed in table form in the upper-right corner. It allows the controller to identify the conflict and resolve them manually or using 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.

The experimental GUI was developed solely for the purpose of evaluating the underlying experimental automation software, and has not been evaluated by any subject experts. It will serve as a

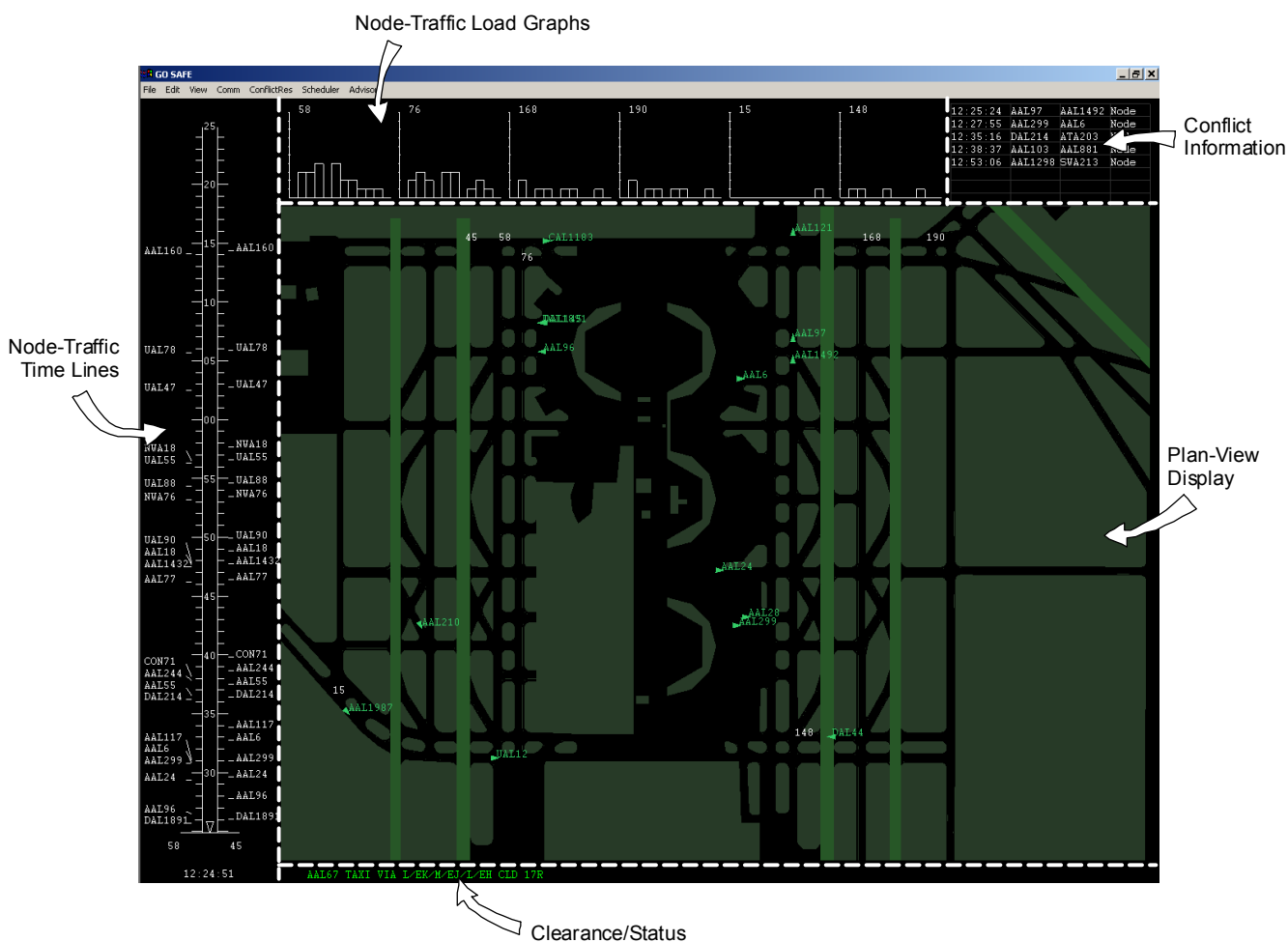


Figure 4. Overview of Experimental GO-SAFE Graphical User Interface

starting point for developing an enhanced GUI for the future GO-SAFE implementation.

Taxi-Route Generation and Editing

The experimental GO-SAFE system includes one automatic taxi-route generation capability based on Dynamic Programming for route optimization. However, in anticipation of future enhancements and addition of new route-generation schemes developed by future research, including those developed based on feedback from subject experts, the software implementation of GO-SAFE includes a route manager for accommodating multiple schemes and maintaining their resulting routes. The experimental GO-SAFE system has been implemented as an object-oriented computer program, and addition of a new scheme requires only the preparation of a new object class that implements the new scheme.

The experimental GO-SAFE system also has several simple route-editing functions.

- modifying a taxi route by dragging its final taxi location to a new location
- manually modifying a taxi route using simple mouse clicks
- temporally adjusting the predicted location of a flight along its defined route

These sample functions demonstrate simple concepts that allow the user to manually adjust the taxi routes. The editing operations are performed using simple mouse clicks and drags, but these operations are not necessarily convenient with the track-ball devices used in today's ATC environment. The editing functions and the user input devices will be subject to future research. It is not yet clear what input devices will be available in the future, when use of more advanced devices such as touch screen, voice recognition, and Virtual Reality devices may be commonplace.

Conflict Detection and Resolution

It should be noted that the notion of conflicts in the surface-traffic environment is different from that for the air traffic, such as that under Instrument Flight Rules (IFR). During ground operations, the cockpit crew is responsible for safe aircraft

separation, which in general is not particularly difficult for normal taxi operations with visual contact and the flexibility to taxi at varying speeds and even to stop. Consequently, the conflicts that appear in the GO-SAFE route computations often do not represent real danger. For example, conflicts of traffic converging at an intersection, or internal representations involving one flight overtaking another on a taxiway, will not normally result in accidents under normal pilot control. Other conflict types such as two flights taxiing towards each other on a taxiway are unacceptable because they will lead to situations difficult to resolve, even if the pilots can still assure safety under manual control. When fully auto-taxi is contemplated, however, any issued route clearances must be conflict free. To otherwise issue a time-constrained taxi route clearance with known conflict will be unreasonable.

The current implementation of GO-SAFE contains functions for resolving identified conflicts, and these functions will be improved as needed.

GO-SAFE Decision-Support Tool

This represents the core function of the automation concept for achieving efficient surface traffic. The current experimental GO-SAFE system has implemented a runway-usage scheduling program for enhancing active-runway crossing. Future research should evaluate the merit of this implementation, and include other decision-support functions to optimize the efficiency of the traffic over the entire airport surface.

GO-SAFE Clearance Manager

The experimental GO-SAFE system has some basic functionality for generating route clearances based on a time-based route definition, and issuing the clearances to a specially designed ground-operation simulation. The simulation is designed to interpret the clearances and execute the taxi operation to comply with cleared crossing times at specified locations. As the collaborative automation concept evolves, much more sophisticated schemes may be required to work with the operational concept, with the proper interface designed to achieve controller acceptance.

Information Exchange

GO-SAFE will need to exchange data with various facilities within the NAS infrastructure. At a minimum, it needs to interface with flight-plan processing and surveillance systems. The following surveillance tools should be included for near-term considerations, with the understanding that more advanced system will be available as defined by the NAS architecture:

- Automatic Dependent Surveillance – Broadcast (ADS-B)
- Airport Surface Detection Equipment (ASDE)
- Airport Movement Area Safety System (AMASS)
- Airport Target Identification System (ATIDS)
- Automated Radar Terminal System (ARTS)

Furthermore, GO-SAFE should be able to collaborate with other automation systems when exchange of information between them would enhance the performance of either system. In recent years, NASA and FAA have had several programs that address the efficiency and safety of air traffic: Center/TRACON Automation System (CTAS) [18][19], Terminal Area Productivity (TAP) program [20]–[24], Surface Movement Advisor (SMA) [25], Advanced Air Transportation Technologies (AATT) program, and Aviation Safety Program. CTAS in turn contains several tools that may mutually benefit GO-SAFE through data exchange: Traffic Management Advisor (TMA), Final Approach Spacing Tool (FAST), Collaborative Arrival Planner (CAP), and the Expedite Departure Path (EDP) tool. Furthermore, the SMA has transitioned into a more advanced Surface Management System (SMS). Figure 5 illustrates the possible information exchange

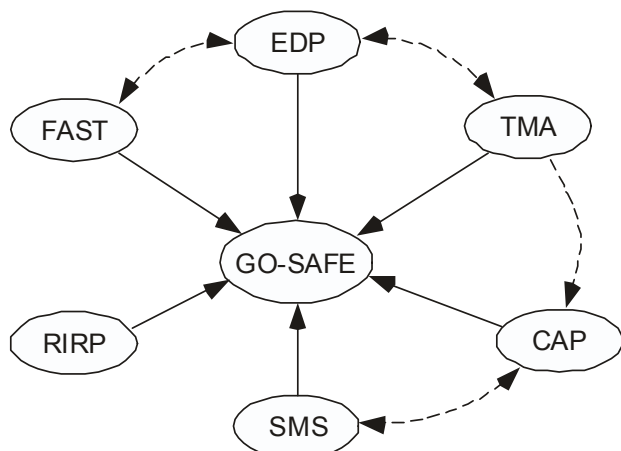


Figure 5. Data Exchange between GO-SAFE and other Information and Automation Tools

between GO-SAFE and these and other tools in the near term, and the information may flow from GO-SAFE to these other systems in the far term.

Although this discussion is directed at the information exchange between GO-SAFE and these other systems, it may be beneficial to consider tighter integration of synergistic systems, e.g. GO-SAFE and SMS, to further enhance the performance of the combined systems.

Flight-Deck Automation System

The flight-deck automation system FARGO is envisioned to include the following main functions:

- Auto-taxi function for precisely controlling the aircraft taxi to accomplish taxi clearances, including potentially time-based clearances
- Pilot interface to allow the pilots to perform precision-taxi in the far-term by allowing fully automatic taxi, and in the near-term by using control signals generated by the auto-taxi function to direct manual control

Figure 6 contains a general block diagram of the aircraft control including these FARGO functions.

FARGO Auto-Taxi Function

To fully realize the potential benefits of the collaborative concept, the aircraft have to be able to deliver the required high-precision taxi performance. The FARGO concept will provide the necessary functionality to enable collaborative taxi control to achieve the high-precision taxi performance that will allow the GO-SAFE system to plan more efficient traffic.

A previous study has verified that, with the synthesis of a nonlinear guidance and control system in a simulation based on a B-737 model, the aircraft can achieve high-precision taxi control [3]. The study applied a form of feedback linearization [26]–[28] to design the control function. That study contained various runway-crossing analyses, including a series of analyses to study high-precision taxi control for taxiing continuously immediately after landing to cross an adjacent runway with the tightest of time margin. The results showed that the guidance and control function was able to perform high-precision taxi

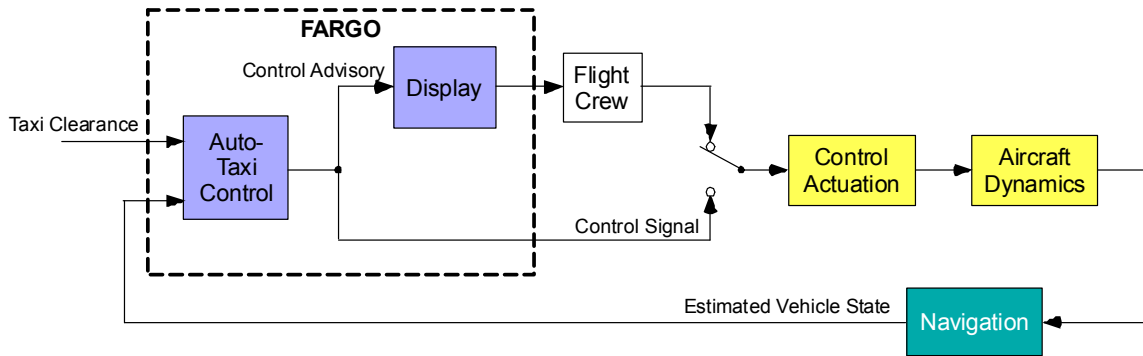


Figure 6. General Block Diagram of Aircraft Control with FARGO Concept

operations, limited only by the accuracy of the navigation system that provides the position and velocity estimates of the vehicle. 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. If properly deployed, such precision taxi capability will allow efficient traffic planned by GO-SAFE to be realized. Furthermore, it will help to cut down on the need for the infamous land and hold-short operations (LAHSO), which have caused several runway incursion incidents in recent years.

Development of the FARGO concept will need to address the integration of precision-taxi control into the flight-management system (FMS). Since FARGO can take over the taxi operation immediately after landing, it should provide a seamless integration with the auto-land function.

FARGO Pilot Interface

Notwithstanding the possibility of an auto-land auto-taxi capability in the far term, a more realistic implementation of the envisioned FARGO will involve pilot control assisted by some sort of flight director to provide information for tracking the reference trajectory. Traditionally a cockpit display with 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 roll out and turn off after landing, the control involves a deceleration segment followed possibly by a constant-speed taxi segment. It is obvious that such a display scheme may not be appropriate during the deceleration phase since the speed is constantly decreasing and a time-varying

speed bug may not be the proper choice. In addition, deviation of the speed from the predetermined profile will require consequential corrections in order to achieve the time window cleared by ATC.

Realization of the FARGO concept should include the operational design of pilot interface for carrying out the taxi maneuver. One possible display scheme during deceleration is the necessary brake setting, followed by either a throttle setting or speed bug during the constant-speed phase. This, however, may introduce a mode-awareness problem when the reference display switches mode from deceleration to constant-speed. Another possibility is to use the required time of arrival (RTA) at a key transition point, e.g. the threshold for the active-runway crossing, to define the reference display. This approach will provide continuity in the reference parameter, but the pilot may still need a separate mode-switch warning to be made aware of the switch from deceleration to constant-speed taxi. Without adequate awareness, the pilot may be slow in detecting the phase change and thus introduce an unnecessary delay in the control action.

Even with the proper display, it is unlikely that a pilot will adjust the control input continuously, which is otherwise possible in an auto-taxi implementation. The pilot may be able to vary braking continuously by varying the pedal pressure, but throttle settings tend to be more discrete in nature since the throttle is not spring-loaded and the pilot needs to adjust the throttle position with push and pull actions. The effect of this intermittent control needs to be analyzed to identify its impact on taxi accuracy. In addition, the pilot normally would consistently need to switch his/her attention

back and forth between speed adjustment and path following. This introduces another type of intermittent control effects.

These characteristics of control action will be analyzed in conjunction with the different possibilities of reference display towards the development of the FARGO concept to enable precision taxi control.

Integration of Operational Functions

In determining the success of deploying advanced automation systems, often the automation technologies are secondary to operational issues. With human in the loop and lives on the line, machinery reliability is not sufficient for validation of system safety. There are various operational issues that must be addressed for the collaborative concept to be successfully realized. They involve the issuance, acknowledgment, and execution of the clearances.

Since the efficient traffic envisioned by the concept will require issuance of clearances that contain taxi routes with tight time constraints, it will be difficult to issue such clearances with today's voice communication and thus the use of data-link seems inevitable. However, experience in the past with data-link experiments has shown that there are many issues associated with data-linked clearances. On the traffic-control 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 responsibility to reading the clearance, followed by acknowledging it with key strokes on the control console. Since a clearance involving the complete taxi route with time constraints is quite complex, the clearance will need to be sent as a pre-clearance to allow the crew ample time to understand it. On the other hand, route information included in the data-linked clearances can be conveniently loaded into the FMS for use by the FARGO function. These operational issues will need to be addressed rigorously with full expert participation to ensure acceptance of the concept by all stakeholders.

Concluding Remarks

Built upon previous research and development efforts, a concept involving the collaborative operation of a surface-traffic-control automation system and flight-deck automation is proposed to improve on the efficiency of airport surface traffic. This concept targets major airports with complex runway configurations imposing runway-crossing requirements on arrival and departure traffics. In order to realize the potential capacity made available by the runways, the surface traffic control at these airports often needs to hold up the taxi traffic from runway crossing to minimize the impact on the landing and takeoff operations, resulting in unnecessary taxi delay.

The surface-traffic-control automation system helps to coordinate traffic by tightening taxi operation margins to improve traffic efficiency, while the flight-deck automation enables precision taxi control in order to operate within the tightened margins. A previous development effort has produced an experimental version of a computer program named Ground-Operation Situation Awareness and Flow Efficiency (GO-SAFE), which will form the foundation for future study of the surface-traffic-control automation. Another previous research employed nonlinear control in simulation analyses to establish the feasibility of aircraft automation for precision taxi control. This effort has led to the proposed Flight-deck Automation for Reliable Ground Operation (FARGO).

Development of the collaborative concept will require research on the GO-SAFE and FARGO systems as well as proper operational integration of these systems. Besides the obvious engineering development of these two systems, they will require effective user interface designs. Integration of these systems hinges on advanced communications, navigation, and surveillance (CNS) technologies. The individual systems and integrated concept will require verification and validation through human evaluations, which should address safety and other cost factors in addition to efficiency.

As a final note, the collaborative concept discussed in this paper has recently received support from NASA for further development as the Surface Operation Automation Research (SOAR) concept.

Acknowledgment

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