Surface Operation Automation Research (SOAR)—A Company’s Research Perspective on Airport Surface Trajectory-Based Operations

Victor H. L. Cheng  
Optimal Synthesis Inc.  
Los Altos, California

IEEE Control Systems Society, Santa Clara Valley  
June 20, 2012
Motivation behind SOAR Concept
Trajectory-Based Operations

• Joint Planning and Development Office (JPDO): DoT, DoD, DoC, DHS, FAA, NASA, White House Office of Science and Technology Policy
• Next-Generation Air Transportation System (NextGen): 2025
• Trajectory-Based Operations:
  – “A 4DT is a precise description of an aircraft path in space and time … Some of the waypoints in a 4DT path may be associated with CTAs”
  – “…precise 4DTs dramatically reduces the uncertainty of an aircraft’s future flight path, in terms of predicted spatial position (latitude, longitude, and altitude) and times along points in its path”
  – “…enables airspace to be used much more effectively”
Surface Trajectory-Based Operations (STBO)

- Assumes **agreement** of 4D taxi trajectory between tower and flight deck: CTAs typically assigned at intersections and runway crossings

- **Flight deck** can achieve **high-precision taxi** to meet any reasonable CTAs along a pre-specified taxi route

- **Tower automation** can count on flight deck’s precision-taxi capability to plan **efficient and safe** surface operations
Surface Trajectory-Based Operations

Datalinked Clearances

Flight-Deck Automation

Tower Automation
OSI Research in STBO

Surface Operation Automation Research (SOAR): Collaborative Automation Concept
Infrastructure and Technology Requirements

• Infrastructure Requirements
  – Communication: Voice + Data Link
  – Surveillance: Surface Radar, ASDE-X, ADS-B
  – Navigation: INS/GPS, GBAS

• Technology Requirements
  – Tower Automation: Planning, Conformance Monitoring, Conflict Detection and Resolution
  – Flight-Deck Automation: 4D Trajectory Control
Overview of GoSAFE GUI

- **Plan-View Display**
  - Surveillance
  - Route editing
  - Clearance alerts
  - Conformance alerts

- **Clearance Text – Segmented**

- **Conflict Information**
  - Planning
  - Real-time traffic

- **Node-Traffic Time Lines**

- **Node-Traffic Load Graphs**

- **Clearance Status**
Roles and Responsibilities

Clearance by voice

Notification of Acknowledgement

Acknowledgement

Clearance via data link

Acknowledgement

GoSAFE

FARGO
4D Trajectory Clearances

Complete route broken into segments

Timing constraints

“Contingency hold”

EFG381: [1] TAXI VIA K/Z (#L@ ...)(#17R@ ...)|HS 17R.

[2] TAXI VIA Z (#M@ ...)(#17C@ ...)|HS 17C.

[3] TAXI VIA Z/P (#R@ ...)(#13L@ ...)|HS 13L.

[4] TAXI VIA P CLD 13L.
EVALUATION OF SOAR CONCEPT
“The benefits that result from capacity-related airport projects and other initiatives will largely consist of cost savings to current and future airport users associated with reduced time spent in the airport system. Reduced time in system may take the form of reduced delay, more efficient processing, or reduced idle time.”

— FAA Airport Benefit-Cost Analysis Guidance, December 1999
Metrics

- Capacity: Achievable Arrival/Departure Throughputs
- Surface Traffic Efficiency: Taxi Delay/Efficiency

Taxi Delay = Actual Taxi Time – Unimpeded Taxi Time ≥ 0

Taxi Efficiency = \frac{\text{Unimpeded Taxi Time}}{\text{Actual Taxi Time}} = \frac{\text{Actual Effective Speed}}{\text{Nominal Effective Speed}} ≤ 1

Surface Traffic Efficiency = \frac{\sum \text{Unimpeded Taxi Time}}{\sum \text{Actual Taxi Time}}
SOAR Benefits of Capacity Gain and Delay Reduction

- Ideal/Peak Capacity
- Current/Baseline Operation
- SOAR Operation
- Delay Reduction
- Capacity Gain
- Airport Periphery Capacity/Throughput
Sample Results from 2003 Evaluation: Baseline vs SOAR for 250-Airport Demand Set

Current Operation vs SOAR Operation

Average Taxi Delay (min) vs Total Hourly Throughput
Anticipated Improvement in Efficiency/Capacity Tradeoff

- Ideal/Peak Capacity
- SOAR Operation
- Current/Baseline Operation

Surface Traffic Efficiency vs. Airport Periphery Capacity/Throughput
Sample Results from 2003 Evaluation: Baseline vs SOAR for 250-Airport Demand Set
SOAR Assessment Activities
Surface-Domain Computer-Simulation Evaluation

GO-SAFE GUI

GO-SAFE
- Runway Scheduler
- Route Manager
- Clearance Manager
- Conflict Resolution

GO-Sim
- ATC
- Flight Control

ACES NAS-Wide Assessment

Human Performance
- Surveillance
- Environment

Safety
- Efficiency

GO-SAFE
- Procedures
- Communications

FARGO
- Pilot
- Navigation

Capacity

Real-Time Human-in-the-Loop Evaluation

Pilot Navigation

© Optimal Synthesis Inc., 2012
Human-in-the-Loop Tower Automation Assessment

FutureFlight Central Tower Simulator

GoSAFE

DoD High-Level Architecture (HLA)

Pseudo-Aircraft Station

ATG
GoSAFE Station
FLIGHT-DECK AUTOMATION
FARGO Concept

FARGO Concept

Current  8.0 kts
Required  8.0 kts
16:48:20  ETA
16:48:20  RTA

Alpha 3
| Bravo 2
| Alpha 3

SLOW
Right Turn
Max. 8 kts
SLOW
Right Turn
Max. 8 kts

Display
Flight Crew

Auto-Taxi

Control Advisory

Guidance
Control

Taxi Clearance

Manual
Auto

Control Actuation

Aircraft
Dynamics

Estimated Vehicle State

Navigation

Control Signal

Control

© Optimal Synthesis Inc., 2012
STBO Benefits Based on Reduced Uncertainties

High Probability of Conflict

Low Probability of Conflict Despite Reduced Separation
High-Precision Taxi Control

- High-precision taxi control for arriving at runway for crossing at pre-assigned arrival time without stopping
- Overall automation concept involving guidance and control subsystems
- Control input in terms of commands for aileron, elevator, rudder, tiller, throttle, and left and right brake pedals
Control Law Design

- Based on Feedback Linearization Formulation
- Design Model extracted from TSRV simulation in the form of Throttle, Braking, and Turning Performance
Flight Deck Automation Environment

Head-Up Display
- Taxi Control
- Conflict Avoidance

Electronic Moving Map
- Taxi Route Preview
- Navigation
- Traffic Monitoring

Upper EICAS
- Clearance Alert

Lower EICAS
- Textual Clearance
Human-in-the-Loop Flight-Deck Automation Assessment
Video of FARGO Run
Human-in-the-Loop Flight-Deck Automation Assessment
ECOFRIENDLY REFERENCE-TRAJECTORY DESIGN
Variety of Speed Profiles

- Option A
- Option B
- Average Speed Profile

$V$ vs $t$ with points $t_1$, $t_2$, and $t_3$.
Aircraft Emissions

- Jet fuels very similar to kerosene or No. 2 distillate oil
  - can be reasonably represented by N-decane, $C_{10}H_{22}$
  - Ideal combustion

$$C_{10}H_{22} + 15.5O_2 + 3.76(15.5)N_2 \rightarrow 11H_2O + 10CO_2 + 3.76(15.5)N_2$$
## Gas Turbine Exhaust Products

<table>
<thead>
<tr>
<th>Major Species</th>
<th>Typical Concentration (% Volume)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen (N₂)</td>
<td>66 – 72</td>
<td>Inlet Air</td>
</tr>
<tr>
<td>Oxygen (O₂)</td>
<td>12 – 18</td>
<td>Inlet Air</td>
</tr>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>1 – 5</td>
<td>Oxidation of Fuel Carbon</td>
</tr>
<tr>
<td>Water Vapor (H₂O)</td>
<td>1 – 5</td>
<td>Oxidation of Fuel Hydrogen</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Minor Species Pollutants</th>
<th>Typical Concentration (PPMV)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitric Oxide (NO)</td>
<td>20 – 220</td>
<td>Oxidation of Atmosphere Nitrogen</td>
</tr>
<tr>
<td>Nitrogen Dioxide (NO₂)</td>
<td>2 – 20</td>
<td>Oxidation of Fuel-Bound Organic Nitrogen</td>
</tr>
<tr>
<td>Carbon Monoxide (CO)</td>
<td>5 – 330</td>
<td>Incomplete Oxidation of Fuel Carbon</td>
</tr>
<tr>
<td>Sulfur Dioxide (SO₂)</td>
<td>Trace – 100</td>
<td>Oxidation of Fuel-Bound Organic Sulfur</td>
</tr>
<tr>
<td>Sulfur Trioxide (SO₃)</td>
<td>Trace – 4</td>
<td>Oxidation of Fuel-Bound Organic Sulfur</td>
</tr>
<tr>
<td>Unburned Hydrocarbons (UHC)</td>
<td>5 – 300</td>
<td>Incomplete Oxidation of Fuel or Intermediates</td>
</tr>
<tr>
<td>Particulate Matter, Smoke</td>
<td>Trace – 25</td>
<td>Inlet Ingestion, Fuel Ash, Hot-Gas-Path Attrition, Incomplete Oxidation of Fuel or Intermediates</td>
</tr>
</tbody>
</table>
Effect of Engine Operating Condition on Emissions

Fuel/air ratio & temperature increase with throttle
Multiple Shooting Method

- Divide trajectory time interval into N sub-intervals
- Assume controls are constant on each sub-interval
- Pick an initial condition for each sub-interval and numerically integrate (i.e., simulate)
- Enforce continuity at endpoints: equality constraints
- Minimize total fuel consumption: performance index
- Becomes a parameter optimization problem (NLP)
Example

• Distance = 5000 ft
• Initial speed = 0
• Final speed = 17 ft/s (~10 kn)
• Range of travel times: 125 s – 1000 s
• Throttle limit = 40%, idle = 10%
• Brake limit = 30%, dead band = 5%
Optimal Speed Profiles

- \( t_f = 120 \text{ s} \)
- \( t_f = 150 \text{ s} \)
- \( t_f = 200 \text{ s} \)
- \( t_f = 250 \text{ s} \)
- \( t_f = 500 \text{ s} \)
- \( t_f = 1000 \text{ s} \)
Optimal Throttle Inputs

- $t_f = 120$ s
- $t_f = 150$ s
- $t_f = 200$ s
- $t_f = 250$ s
- $t_f = 500$ s
- $t_f = 1000$ s

Lower limit

Throttle Input (percent)

Time (sec)
Optimal Brake Inputs

- Brake input percent over time for different final times ($t_f$) ranging from 120 s to 1000 s.
- The graph shows the optimal brake input over time for each $t_f$ value.
- The brake input increases sharply at specific points, indicating optimal braking input.

© Optimal Synthesis Inc., 2012
Evaluation of Trajectory Optimization

<table>
<thead>
<tr>
<th>Automation Level</th>
<th>Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal trajectory – estimated</td>
<td>NWA1254: 250.10</td>
</tr>
<tr>
<td>Optimization result</td>
<td>NWA1254: 244.45</td>
</tr>
<tr>
<td>Pilot model with optimized reference trajectory</td>
<td>NWA1254: 246.22</td>
</tr>
</tbody>
</table>
CONFLICT DETECTION AND RESOLUTION (CD&R)
Near-Term Operational Concept

Tower Automation

Databases
- Flight Plans
- Airport Layout and Configuration
- Aircraft Performance

CD&R

Controller Display

Conflict Alert/Resolution

Surveillance

Air Traffic Controller

Voice-Based Clearances

Cockpit Crew
Mid-Term Operational Concept

Databases
- Flight Plans
- Airport Layout and Configuration
- Aircraft Performance

Surveillance

Tower Automation
- Planner
- CD&R
- Controller Display

Re-Plan Request
Spot Release and Runway Schedules
Conflict Alert/Resolution
Speech Recognition

Voice-Based Clearances
Air Traffic Controller
Cockpit Crew

© Optimal Synthesis Inc., 2012
Far-Term Operational Concept

Tower Automation
- Planner
- CD&R
- Controller Display

Databases
- Flight Plans
- Airport Layout and Configuration
- Aircraft Performance

Surveillance

Flight Deck Automation
- Conflict Alert/Resolution Messages
- 4D-Trajectory Messages

Speech Recognition

Voice-Based Clearances

Air Traffic Controller

Cockpit Crew
Integration Concepts

Basis of Integration

Information Exchange between Tower and Flight-Deck Automation Systems Using Datalink Communications

Two Types of Information: Alerts & Intent

Alerts: Conflict Alerts and Resolution Alerts Generated by Tower and Flight-Deck CD&R Systems

Intent: Airport Operational Plan, Aircraft Operational Plan
## CD&R Integration Options

<table>
<thead>
<tr>
<th></th>
<th>Without Intent</th>
<th>With Intent</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Without Alert</strong></td>
<td>Baseline</td>
<td>B</td>
</tr>
<tr>
<td><strong>With Alert</strong></td>
<td>A</td>
<td>C</td>
</tr>
</tbody>
</table>
# CD&R Integration Options

<table>
<thead>
<tr>
<th></th>
<th>Without Intent</th>
<th>With Intent</th>
<th>With Intent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aircraft Intent + (Taxi Route + Runway Sequence)</td>
<td>Aircraft Intent + (Taxi Route + RTAs)</td>
<td></td>
</tr>
<tr>
<td>Without Alert</td>
<td>Baseline</td>
<td>B₁</td>
<td>B₂</td>
</tr>
<tr>
<td>With Alert</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tower Conflict Alert Info, No FD CD Logic</td>
<td>A₀</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conflict Alert Info</td>
<td>A₁</td>
<td>C₁₁</td>
<td>C₁₂</td>
</tr>
<tr>
<td>Conflict Alert Info + Reconciliation Info</td>
<td>A₂</td>
<td>C₂₁</td>
<td>C₂₂</td>
</tr>
</tbody>
</table>

© Optimal Synthesis Inc., 2012
Voice-Based Communications
Conflict Info, Resolution Advisory

Conflict Info, Resolution Action

ATC Flight Crew Conflict Info, Resolution Advisory

AI AI Display/UI

Tower Automation Flight Deck Automation

Route, RTA, Taxiway, Runway Sequence
Clearances
Conflict Info, Resolution Info
Conflict Reconciliation Info
Intent, Clearance Acceptance/Rejection

Planner CD&R

Airport Surveillance System

Datalink Communications

Optimal Synthesis

© Optimal Synthesis Inc., 2012

Airport Navigation, & Surveillance System
Integrated CD&R Example
Integrated CD&R Example
### Integrated CD&R Example

#### Message List

<table>
<thead>
<tr>
<th>Destination</th>
<th>Segment Route</th>
<th>RTA</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAMP 10 x RAMP 10E</td>
<td>RAMP 10 &gt; RAMP 10E</td>
<td>00:01:41 @ RAMP 10 x RAMP 10E</td>
</tr>
<tr>
<td>RAMP 10E x K</td>
<td>RAMP 10E &gt; K</td>
<td>00:01:41 @ RAMP 10E x K</td>
</tr>
<tr>
<td>K x Z</td>
<td>K &gt; Z</td>
<td>00:01:41 @ K x Z</td>
</tr>
<tr>
<td>Z x F</td>
<td>Z &gt; F</td>
<td>00:01:41 @ Z x F</td>
</tr>
<tr>
<td>F x WF</td>
<td>F &gt; WF</td>
<td>00:07:52 @ F x WF</td>
</tr>
<tr>
<td>WF x RWY 18L</td>
<td>WF &gt; Hold at RWY 18L</td>
<td>00:00:28 @ RWY 18L Hold</td>
</tr>
</tbody>
</table>

#### Traffic

<table>
<thead>
<tr>
<th>Traffic</th>
<th>Conflict Type</th>
<th>Flight Deck</th>
<th>Ground Side</th>
<th>Time To Conflict</th>
</tr>
</thead>
</table>
Contributors and Collaborators

- Anthony D. Andre
- Debbi Ballinger
- Shih-Yo Cheng
- Lara S. Crawford
- Gerald M. Diaz
- Andrew Fong
- David C. Foyle
- Yoon C. Jung
- Thomas Kozon
- Jason Kwan
- Tony Lam
- Paul Lin

- Vivian Lin
- Sandra D. Lozito
- Lynne H. Martin
- Jimmy Nguyen
- Anthony Seo
- Vivek Sharma
- Gregory D. Sweriduk
- V. V. S. Sai Vaddi
- Savita A. Verma
- Sandy Wiraadmaatja
- Andrew Yeh
- Jack Yeh