Autonomous Surface Operations: Operational Architectures and Paths to Deployment

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Outline

- Autonomy for Airport Surface Logistics
- Operational Architectures for Autonomy
- Pathways for Deployment: the Search for ‘Low-hanging Fruit’

Airport Surface Operations

- A large **logistics** problem involving the coordination of humans and machines
- Mechanical skills include driving, coupling/uncoupling, loading/unloading
- Cognitive skills include sensing, communication, planning/sequencing
- Goals: **efficiency** and **safety**

Logistical Problem

General Airspace

Traffic Control

Ground Crews

Manned Aircraft

Fuel Trucks

Mobile Stairways

Aircraft Tugs

Military Airspace

Mission Control

UAS Ground Station

Unmanned Aircraft

Munition Loaders

Challenges for Logistics

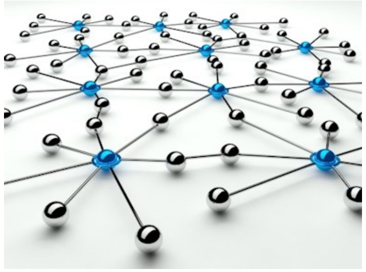
Operator Workload Management

Scheduling & Deconfliction

Environment Robust Operations

High Traffic Throughput

Connectivity & Interoperability



Human Machine Interaction

Situational Awareness Sharing

Distributed Safety Assurance

Airport Capacity Problem

"Air travel in the US is projected to increase by 64% between 2005 and 2020, according to the FAA. One of the greatest constraints on that projected growth is airport capacity, especially of 35 large hub airports that the FAA identifies as capacity-constrained…If those airports' capacity is not expanded, continued growth in air travel demand will lead to ever-worsening congestion". (Butler 2008)

Congestion at hubs means congestion everywhere.

Airport capacity can be expanded in two ways:

1. Building new runways
2. Making more efficient use of existing space.

Constraints on Capacity

- In-trail separation of aircraft
- Lateral separation of air craft
- **Sequencing and separation** of departing and arriving aircraft on a single runway or intersecting runways
- A large logistics problem in air traffic control.

Technologies in communication, sensing, and path planning are being developed that collectively will allow aircraft to safely land, takeoff and taxi with considerable less spacing than required today, thereby improving capacity.

These technologies form the basis of autonomous systems.

Can advances in vehicle autonomy contribute here?

Autonomy for Logistics

Robotic warehouses for Ecommerce

Autonomous Hospital Tugs

(These are more similar to airport surface logistics than the “self-driving car” problem).

Levels of Autonomy

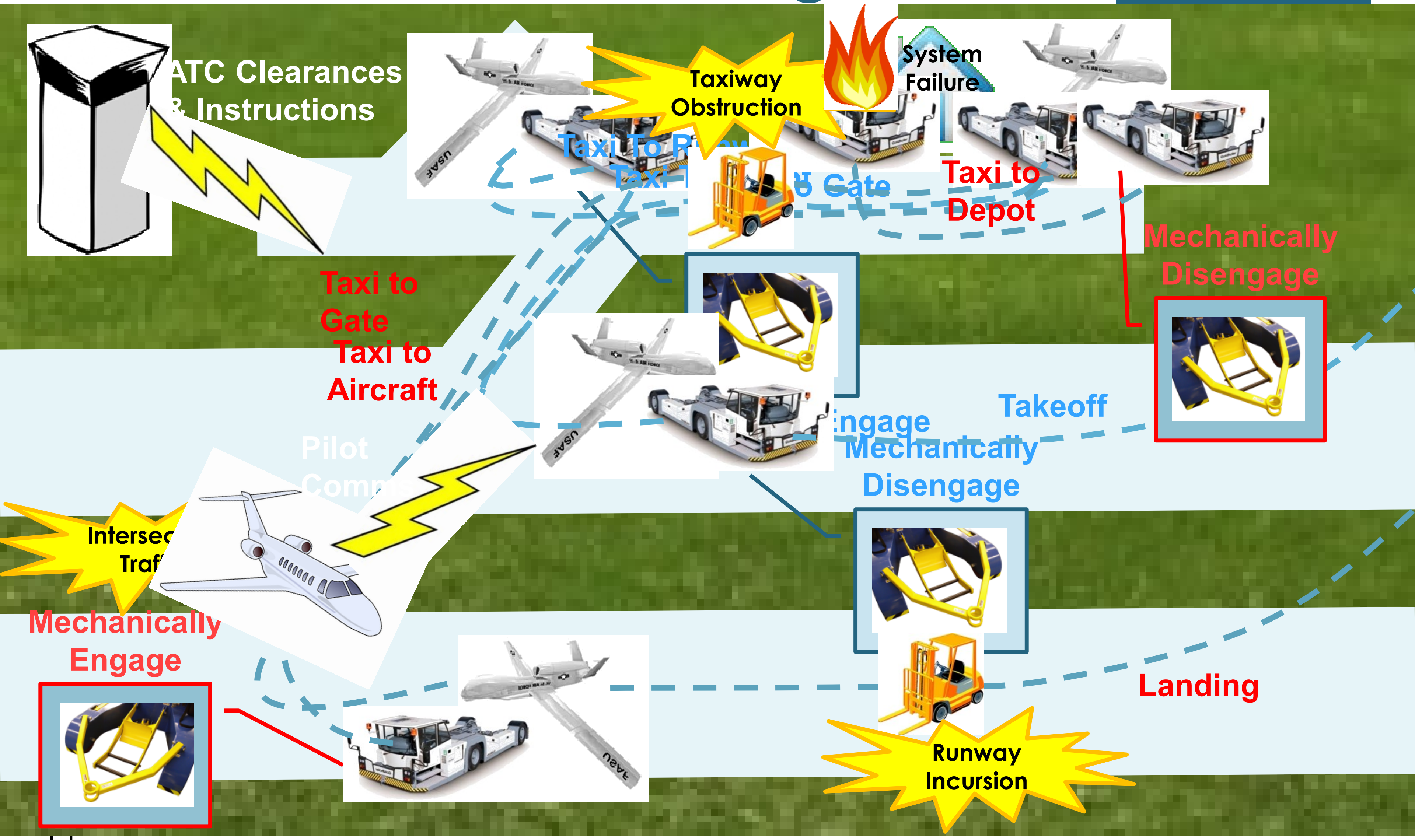
Steven E. Shladover, “The Truth about Self-driving Cars”, Scientific American, June 2016

	Human Driver Monitors Environment			System Monitors Environment		
	0 **No Automation**	**1** **Driver Assistance**	**2** **Partial Automation**	**3** **Conditional Automation**	**4** **High Automation**	**5** **Full Automation**
	The absence of any assistive features such as adaptive cruise control.	Systems that help drivers maintain speed or stay in lane but leave the driver in control.	The combination of automatic speed and steering control—for example, cruise control and lane keeping.	Automated systems that drive and monitor the environment but rely on a human driver for backup.	Automated systems that do everything—no human backup required—but only in limited circumstances.	The true electronic chauffeur: retains full vehicle control, needs no human backup and drives in all conditions.
Who steers, accelerates and decelerates	Human driver	Human driver and system	System	System	System	System
Who monitors the driving environment	Human driver	Human driver	Human driver	System	System	System
Who takes control when something goes wrong	Human driver	Human driver	Human driver	Human driver	System	System
How much driving, overall, is assisted or automated	None	Some driving modes	Some driving modes	Some driving modes	Some driving modes	All driving modes

Examples of Level 4 Autonomy for Airport Surface Logistics

- Towing/Taxiing Aircraft
- De-icing
- Baggage load/unload/transport
- Other

Example: Autonomous Taxiing



Summary of Part 1

- Surface management is a hard logistics problem.
- Driving, loading/unloading, docking/undocking are mechanical capabilities.
- Dual goals of logistics management: safety and efficiency
- Autonomous logistics requires at most level 4 autonomy.
- Cognitive skills in sensing, communication, planning and scheduling.

Part 2: Operational Architectures for Airport Operations

Requirements for Autonomous Logistics

- Safe
  - Does not run into obstacles
  - Does not endanger humans
- Minimum impact
  - Seamless part of logistics; humans don't need to change their behavior (much), but can see benefits.
- Minimal changes to infrastructure
  - Don't need to re-design whole facility; can adapt to any existing facility.
- Improves surface logistics ("intra-logistics")
  - Makes humans more effective in their jobs

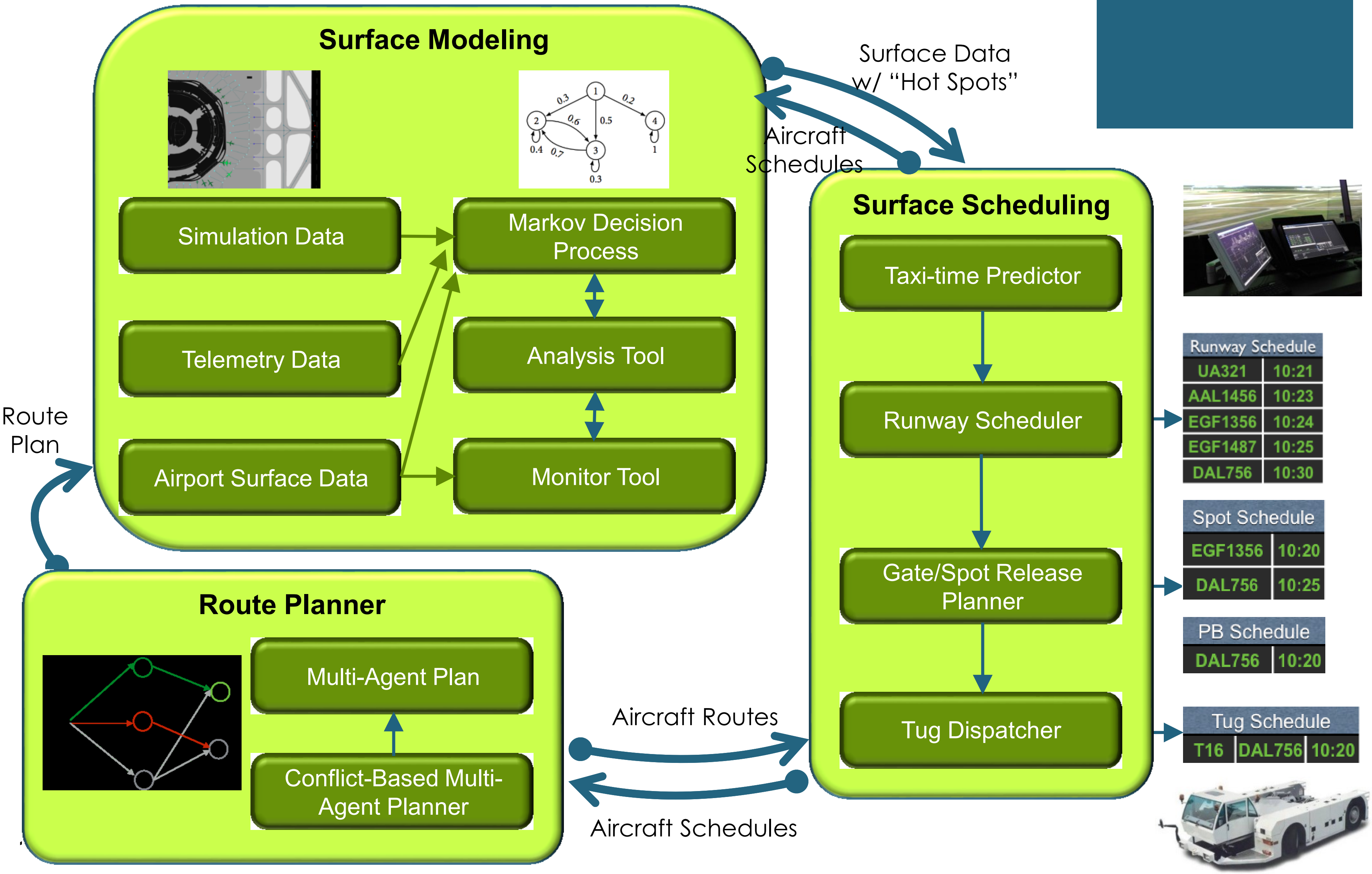
Challenges

- Technical challenges:
  - Accommodate large unpredictable variation in the environment,
  - Accommodate real time variation in the environment,
  - Achieve customer-acceptable efficiency and reliability levels,
  - Provide intrinsic safety of use and operation.
- Economic challenges:
  - Required affordability (ideally, payback within twelve months),
  - No external hidden costs to the customer,
  - Provide a robust business model.
- Social challenges:
  - If a labor replacement is involved, then the product must provide an equivalent or greater benefit to some portion of the labor pool to offset the potential job loss,
  - Must operate in a way that feels common and familiar, not foreign,
  - Must operate in a way that is perceived as completely safe,
  - Must operate in a way that is perceived as simple and not intimidating.

Logistics Activities for Airport Surface Management

- **Surveillance**: provide identification and accurate positional information on aircraft, vehicles, and obstacles within the required area.
- **Guidance**: facilities, information, and advice necessary to provide continuous, unambiguous, and reliable information to keep aircraft or vehicles on the surfaces and assigned routes intended for their use.
- **Control**: Application of measures to prevent collisions, runway incursions and to ensure safe, expeditious and efficient movement.
- **Route planning and scheduling**: The planning and assignment of routes to individual aircraft and vehicles to provide safe, expeditious, and efficient movement from its current position to its intended position.

An Operational Architecture



Part 3: Incremental Deployment of Autonomy: 4 examples

- De-icing
- Baggage routing
- Maintenance towing
- Autonomous return for TaxiBot

De-icing

Current de-icing is labor intensive and uses harsh chemicals. Automation has the potential to remove people from contact with chemicals, provide more accurate deicing, and reduce harmful chemical usage

Baggage Handling

Luggage transport is the prime delay in customer transport, timing efficiency and customer satisfaction. Perhaps the leading candidate for early implementation of autonomy on the surface.

Maintenance Towing

Super tugs are used to tow aircraft to maintenance hangars (‘dead towing ‘) by lifting and carrying the nose gear. They are faster and more agile than standard tugs.

Maintenance towing could provide a way to prove the reliability of autonomy without the ‘stress’ of piloted aircraft in heavy taxi traffic.

Autonomous TaxiBot

TaxiBot® employs full nose landing gear capture to enable tow-bar-less towing. The aircraft pilot controls the speed, brakes and steering from the gate to the runway. Current operations of the TaxiBot® utilize a safety driver on the tow vehicle. The driver provides a safety backup and also drives the TaxiBot® back from runway back to the gate.

Autonomy could replace the safety driver in these roles.

Next Steps

- Studies on human-machine teaming
- Data from current operations
- Studies on cost and impact
- Staged testing and rollout

Summary

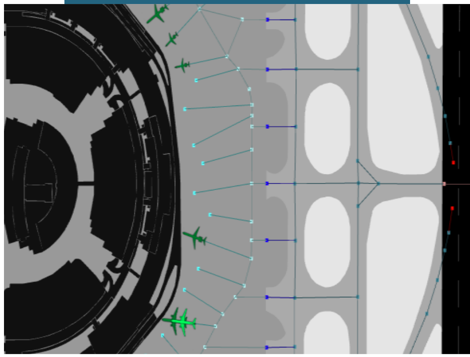
- Surface operations at hub airports is a complex logistics problem.
- Improvements in safety and efficiency can be gained through the judicious application of autonomy and automated decision support.
- Logistical tasks can be accomplished through level 4 autonomy
- Trust and acceptance requires incremental integration

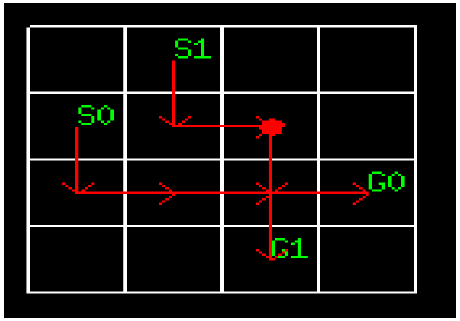
Backup

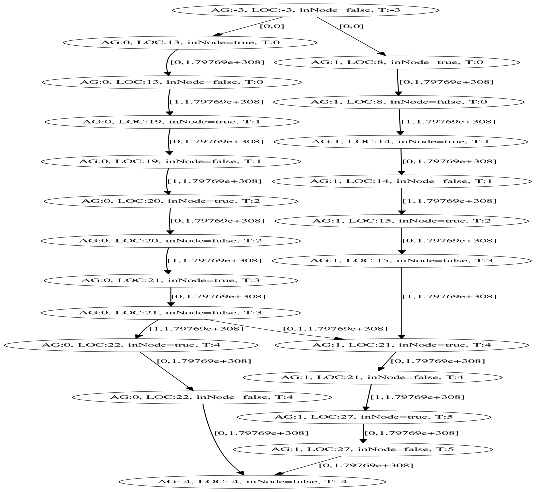
Hybrid Planning and Scheduling Approach

- Surface planning and scheduling is a centralized process, performed by a decision-support tool used by ramp controllers, or tower (ATC) operators.
  - Requires directing aircraft to their destinations in a timely manner, with the aim being to reduce the overall travel time, delays at the runway queue, and to maximize throughput.
  - Separation constraints between taxiing aircraft maintain safety (performed autonomously by the towing vehicles).

- Route planning using multi-agent path finding (MAPF) for route planning of towing vehicles.
  - MAPF seeks a set of conflict-free paths for a set of agents.
  - A discrete time planner on a grid: the output is a set of synchronized paths that assign each agent to a location at each discrete time step.
  - Temporal uncertainty in execution is addressed by generalizing solutions into STNs.







Scheduling using SARDA

- Inputs to the scheduler consist of the current snapshot of the airport, scheduled push back and arrival times for some time into the future (currently, the next 15 minutes), and constraints such as aircraft-specific parameter and separation constraints.
  - To handle uncertainty in surface dynamics, these inputs are refreshed every few seconds. To control the number of changes made to the outputs of the schedule, a freeze horizon is imposed which precludes major changes to be made to the current schedule.

- The outputs are three schedules: a runway schedule, a spot pushback schedule, and a towing vehicle schedule. The times computed by the scheduler represent each vehicle's earliest possible arrival time at each node.

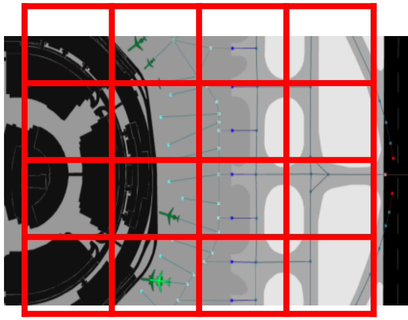
- Routes may contain separation constraint violations. To resolve such conflicts, the system contains a flow model and a network event simulator to model arrivals at nodes representing intersections, to determine the amount of time that aircraft must hold at current locations to maintain separation requirements, and to ensure other safe conditions (e.g. at intersection crossings, or to maintain wake vortex separation).

- Together, the scheduler and model approximate the taxi routings and resource utilization (gates and runways) that are most likely to be used by tower controllers.

- A towing vehicle dispatcher assigns tugs to aircraft using a simple shortest heuristic.

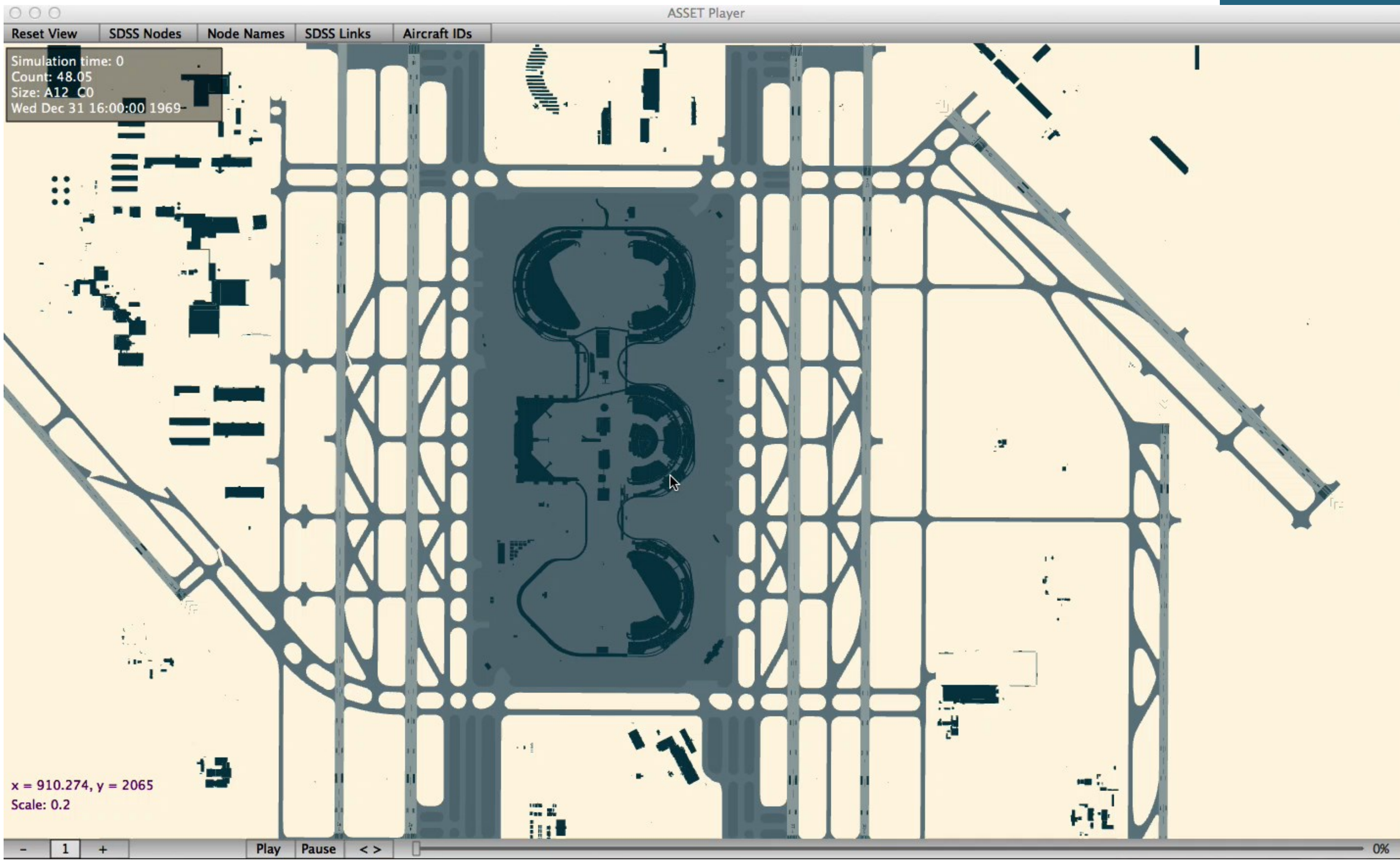
Modelling for Predictive Analysis

- To improve planning under uncertainty, a behavior model of the airport surface is inferred from telemetry data
- The model uses a grid abstraction of the surface as a basis for a Discrete Time Markov Chain (DTMC)
  - Automata with nodes representing states of the airport surface abstracted from log data and edges labeled with transition probabilities
  - Currently we use a grid abstraction of surface with values indicating number of aircraft on each grid element.
  - The generated DTMC can be visualized and analyzed automatically using a translation to the modeling formalisms of the PRISM or UPPAAL model checkers.
- Model is analyzed using temporal logic queries to obtain predictions about the likelihood that temporal constraints related to safety or efficiency will be violated.
- Can be used by human or machine planners to monitor or alter route plans.



Grid Abstraction

Fast Time Simulation



Taxiing operations current pr and limitations

- Aircraft depend on their engines or human-driven towing vehicles during departure or arrival ground operations.
  - Departure: pushback, engines-start, taxi-out, engine warm-up
  - Arrival: taxi-in, engine cool-down, shutdown.
- Possible improvement areas:
  - Efficiency in operations
    - Higher precision navigation
    - Alternative to voice communication
  - Environmental
    - Pollutants: taxiing at airports using main engines results in emissions of around **18 million tons of CO2** per year.
  - Economic: taxiing at airports using main engines is forecast to cost airlines around **$7 billion in fuel cost (2012)**
    - Fuel burn
    - Inefficient engine operations in idle setting
    - Break wear increase during stop and go taxiing
    - Risk of foreign object damage due to engine suction
- Technologies are currently being developed for *Engines-off-taxiing*.
  - Taxibot, Electric taxi, ‘operational towing’.

1. Aircraft Engines not Optimized for Ground Operations

- For the taxi out phase of departures, the pilot either simply releases the brakes to start moving or applies additional breakaway thrust. Afterwards, the produced thrust of all engines, even in idle, is sufficient to slightly accelerate the aircraft once it is moving.

- “Although using the thrust of the main engines…seems to be a smart double use, there are problems associated with this procedure. Most obvious is the highly inefficient operating point of the engines in idle thrust setting, which leads to relatively high fuel consumption and pollutant emissions. The permanent thrust requires the pilot to regularly slow down the aircraft which results in increased break wear. Moreover, due to the pull of the engine suction there is the risk of foreign object damage as long as the engines are running.” (Wollenheit and Muehlhausen, 2013)