Certifiable Autonomous Flight Management for Unmanned Aircraft Systems

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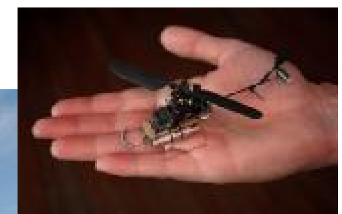
Unmanned Aircraft Systems (UAS)

Tempest Storm Chaser (UC)

Endurance Fuel Cell (UM)



Micro Air Vehicle

Information + Transport (Computers vs. Cars?)

- Surveillance Ops
  - Emergency Support → *Homeland security, natural disasters, accidents*
  - Multi-user Data Collection → *News/events, traffic, maps, science (e.g., meteorology)*
  - Single-user Data Collection → *Personal UAS for area inspection/site surveillance*
- Support Ops
  - Communication/data relay
  - Payload drop → *Sensor tag, courier service, airborne deployment*
  - Airborne refuel/recharge
- Transport
  - Cargo (large transport) → *FedEx, UPS*
  - Passenger → *Pilotless airlines?*

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Dissenting Commentary…

- Aircraft automation *leads*, not lags, level of automation found in other vehicle platforms

- My talk is more about onboard automation than air traffic control
  - It is the [decentralized] onboard automation that will make the [centralized] air traffic management problem "easier"

- My perspective is that we can achieve autonomy such that humans WILL NOT NEED to be "in the loop" during emergency, and that this will be *safer*

Introduction

- Motivation:
  - UAS can fly at *substantially* reduced cost, emissions, noise
  - *Autonomous* aircraft require less infrastructure
  - Pilots may have no better (or less) relevant information than the automation **à** automation can be more "certain" of its decisions than can human pilots **à** autonomous FMS can be *safer*
- Objective: This presentation overviews requirements, challenges, & progress toward ***certifiable*** (trusted) and ***autonomous*** UAS Flight Management Systems (FMS)
- Outline:
  - Requirements & challenges for ***safe*** UAS FMS
  - Loss-of-control avoidance via "adaptive" FMS
  - Case study: Adaptive FMS applied to US Airways Flight 1549
  - Wanted: ***UAS in the NAS (National Airspace System)***

UAS Safety: Setting the Context

- International Civil Aviation Organization (ICAO) Definition:
  - ***Safety*** *is the state in which the risk of harm to persons or of property damage is reduced to, and maintained at or below an acceptable level through a continuing process of hazard identification and risk management.*

- UAS loss does not necessarily imply risk of harm to persons or of damage to property
  - A UAS can crash but remain *safe* throughout the event

- UAS objective: Maintain acceptable levels of risk to high-value [manned or unmanned] aircraft and civilians/structures on the ground

Certifiable Autonomous FMS == Safe FMS

- UAS and manned aircraft must obey Federal Aviation Regulations (FARs) at all times to ensure safety, predictability, and acceptance
  - Published procedures & checklists can be programmed
  - Autopilots can generate and follow flight plans
  - Datalinks can communicate with air traffic control
- UAS must sense-and-avoid other aircraft
  - Position broadcasting equipment (e.g., ADS-B) will become standard for all aircraft; "sense-and-avoid" systems are under development
- In extremity (e.g., damage/failure), UAS must be able to "declare an emergency" then prioritize minimizing risk of harm to people and property

Commonly Observed UAS Issues

- UAS are designed to be managed from a ground control station
- Loss of Communication Link
  - Lost link requires safe default operation, including sense and avoid
  - Confusion over controlling entity and compromised operator situational awareness can result
- UAS Component Failures
  - Powerplant, flight control, and communications equipment failures are prominent causes of UAS incidents.
  - Lower-cost components result in lower reliability.
- *A UAS FMS with the ability to autonomously & safely manage* ***lost link*** *and* ***failure/damage*** *situations will address both of these concerns*
  - *This translates to a UAS FMS that avoids "loss-of-control" and that respects the FARs at all times*

MQ-8 Fire Scout (Aug. 2010)

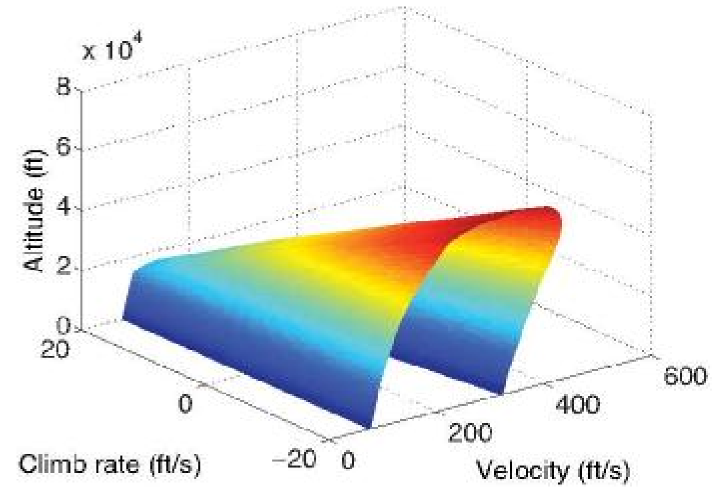
- *Fire Scout breached the National Capitol Region airspace after traveling 32km (20nm) in the wrong direction. Ground operators lost contact about 75min after takeoff. The UAS is programmed to return to base in such situations, but the aircraft instead veered northwest, away from the base. After shifting to another ground control station, the Fire Scout operator restored control.*

- Multiple causal factors have been identified:
  - Lost link initiated the chain of events
  - Software anomaly prevented mode shift → "return to base"
  - Operator sent a command improperly (procedural error was a contributing factor)
- Fortunate circumstances
  - No collision occurred
  - The link was eventually restored
  - The autopilot software maintained positive control

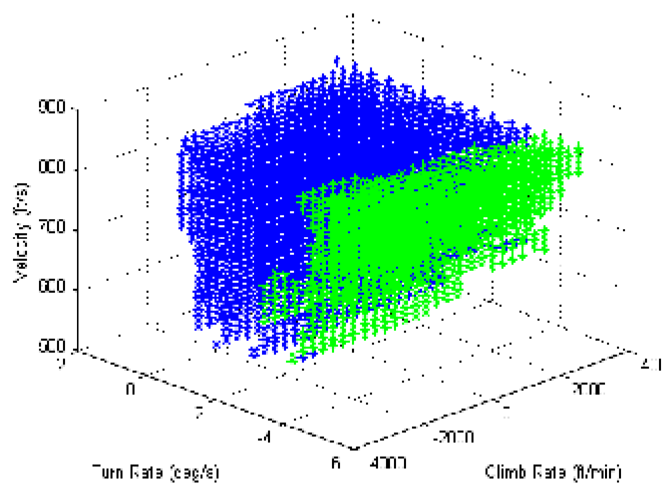
- ***"Certified" (Validated & Verified) Autonomous FMS***
  - ***Lost link would not compromise the vehicle's mission or safe operation status***
  - ***Safety-critical software will require a high level of validation/verification, and will need to earn our "trust"***

Our Focus: Avoid Loss-of-control (LOC)

- Loss of control is the leading cause of aviation accidents, manned and unmanned
- Loss of control occurs when an aircraft departs its “safe” operating envelope
- Flight envelope has traditionally been defined based on performance limits and stall using “simple” linearized models
- Aerodynamic stall is not a limit for a capable controller – *controllability* & *stabilizability* are better metrics



Traditional Flight Envelope Example [MCC10].



Damaged Transport Flight Envelope (Green = stable, Blue = stabilizable)

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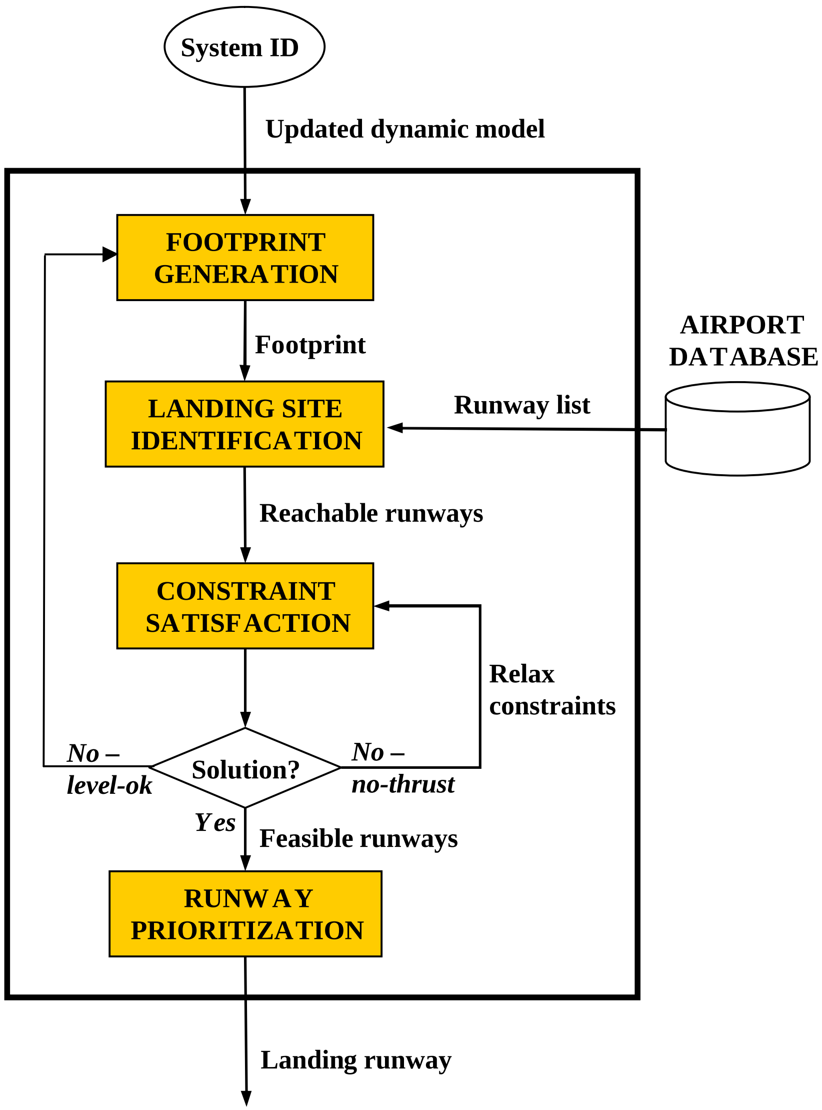
LOC Avoidance with Damage/Failures

- When experiencing damage/failures, controllers must first identify and then remain within the full set of stabilizable flight states
- For UAS or manned aircraft, safety suggests "controlled" flight to a nearby landing site
- Algorithms must be real-time; situational awareness should be maximized (for ATM, UAS operators, and other aircraft)
  - Provided solutions should be intuitive (e.g., trim-states to waypoints)
- Failure can occur anywhere
  - Physical space & flight envelope space
  - If not sensed, reduced flight capabilities must be *discovered*
    - Not necessarily through comprehensive exploration, and not presumed from a single local approximation
- Once envelope is sufficiently known:
  - Select a landing site, then plan a *feasible trajectory* to that site

Landing Site Selection
(autonomy, not automation)



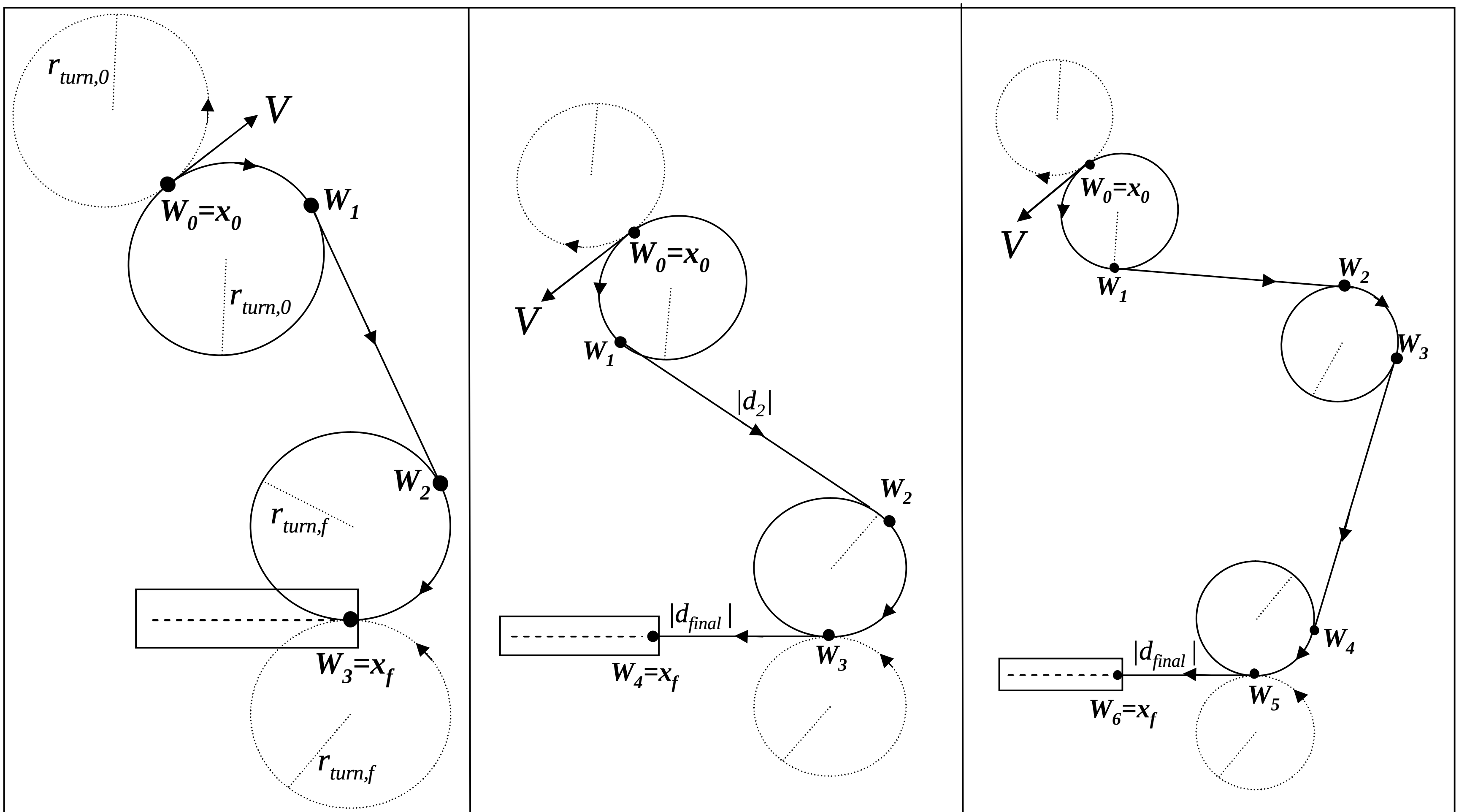
$$U = \sum_i C_i \cdot w_i =$$

$$C_1 \cdot \frac{r_l}{r_{l,\max}} + C_2 \cdot \frac{r_w}{r_{w,\max}} + C_3 \cdot I +$$

$$C_4 \cdot \frac{\left(w_{c,\max} - w_c\right)}{\left(w_{c,\max} - w_{c,\min}\right)} +$$

$$C_5 \cdot S + C_6 \cdot f + C_7 \cdot \left(\frac{d}{d_{\max}}\right)$$

Real-time Flight Planning: Augmented 3-D Dubins Paths



Worst-case Dubins Trajectory

Direct/Extended Final Trajectory

S-turn (High Altitude) Trajectory

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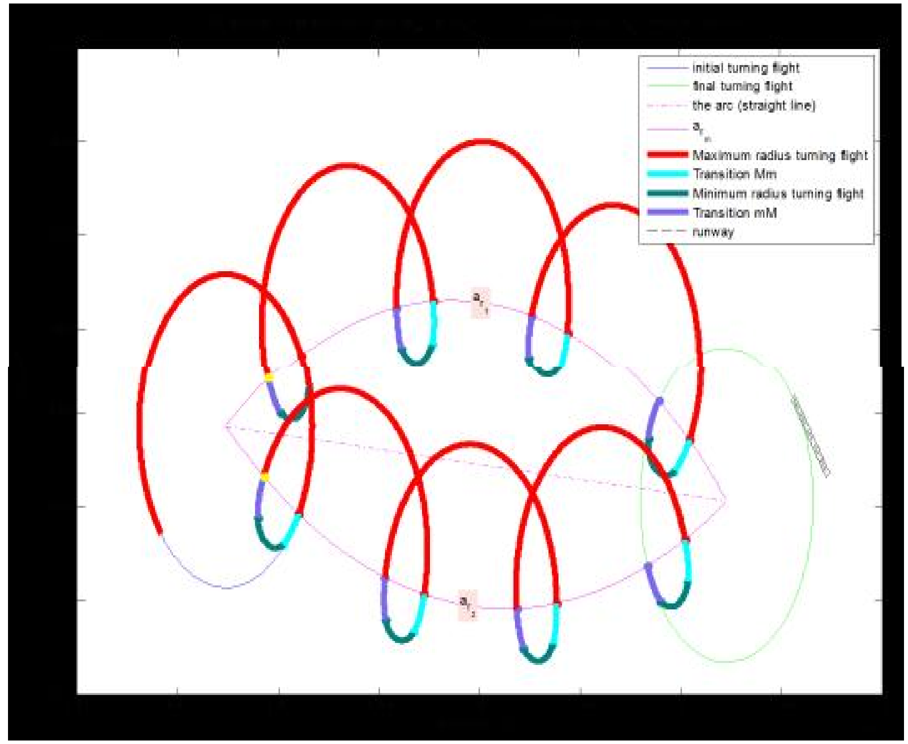
Turning Dubins Vehicle (TDV)

- Dubins solutions possible when envelope enables straight and turning flight at a gentle descent
- TDV trajectories handle case where straight flight is not possible
- Progress to-date
  - Analytic proof that minimum/maximum radius sequence is minimum-distance
  - Adjust reference circle radius to connect final and landing states, including heading
  - Proof that analytic solution is comprehensive, including transitions

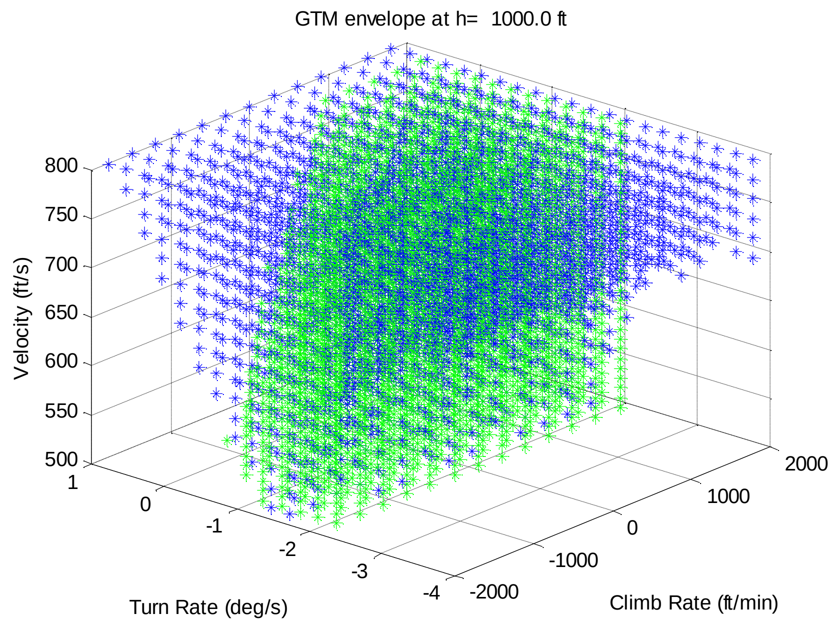


Trim State (Envelope) Discovery

- Dynamics of a damaged aircraft are not known immediately post-incident.

- Achievable trim states and flight envelope boundaries must be *discovered* while the aircraft is flying.

- We integrate multiple local approximations of the envelope to “learn” a sufficient set for landing



Actual envelope (blue);
local envelope prediction (green)

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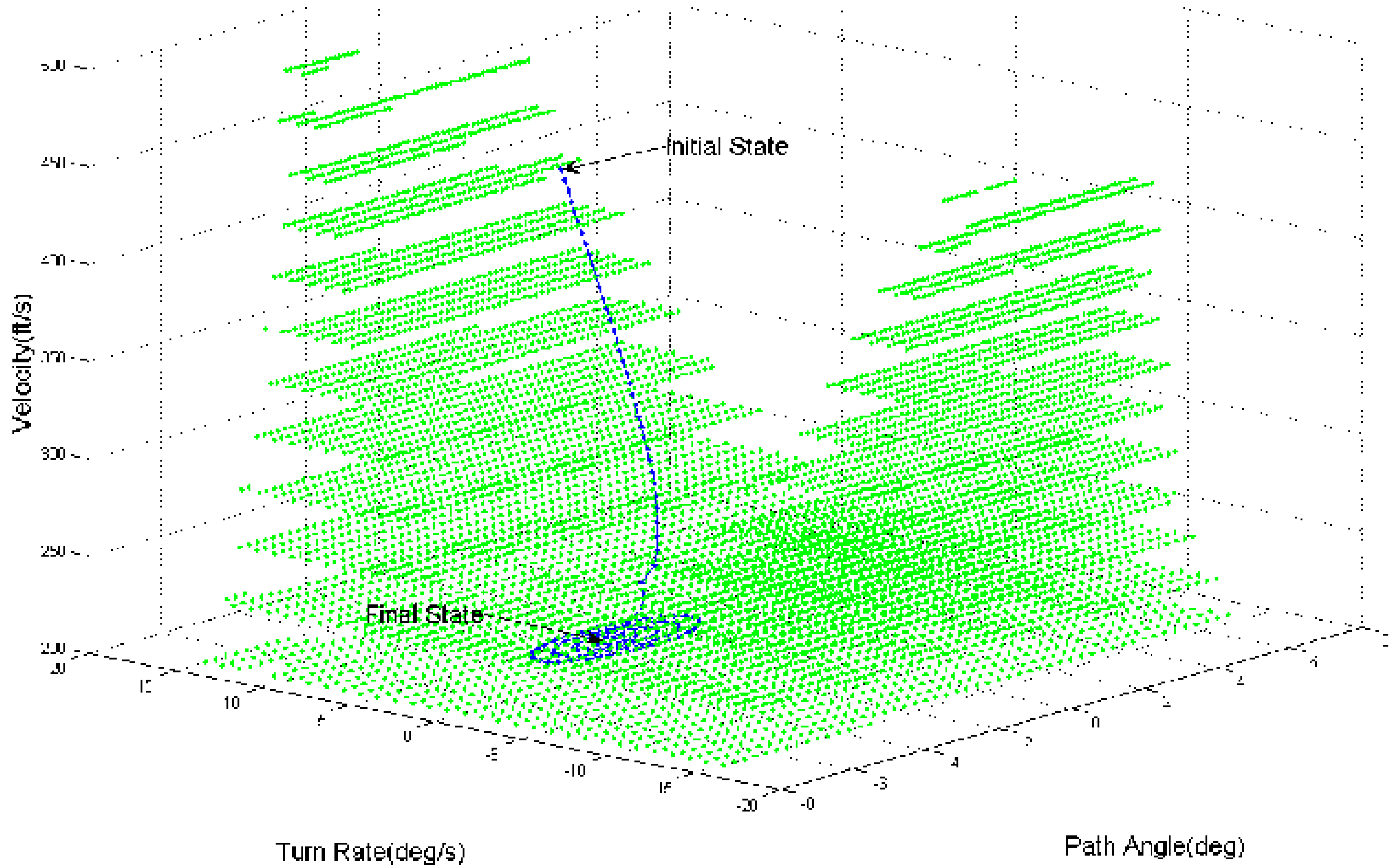
Trim State Discovery: Guidance

- Initial approach: 3-D potential field path planner + ‘bug’ algorithm to follow edge of envelope at boundaries
- Path planner operates in ***trim state space*** $\dot{\psi}, \gamma, V$ rather than physical space
- Goal: Ideal final approach trim state and local turn rate neighborhood
- Physical space provides constraints (e.g., terrain)
- Ongoing: Formal modeling of constraints and multi-objective costs; extension to a nonlinear programming optimization protocol to provide optimal baseline for comparison (NLP *not* real-time)

Trim State Discovery Example

- F-16 with aileron jam at 10°
- Initial state: $\dot{\psi} = 15.5°, \gamma = 2.9°, V = 400 \text{ ft/sec}, h = 10000 \text{ ft}$
- Goal state: $\dot{\psi} = 0, \gamma = -3°, V < 250 \text{ ft/sec}$



[Autonomous] Emergency Flight Management: A Case Study

- On Jan. 15, 2009: US Airways Flight 1549 departed from LaGuardia
- Approximately 2 minutes into the flight, the aircraft encountered a flock of Canadian geese.
- Birds were ingested into both engines, resulting in failure of both (loss-of-thrust)
- The pilot, Captain Chelsea "Sully" Sullenberger, guided the aircraft into the Hudson River
- There was no loss of life or major injury

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Flight 1549 Questions…

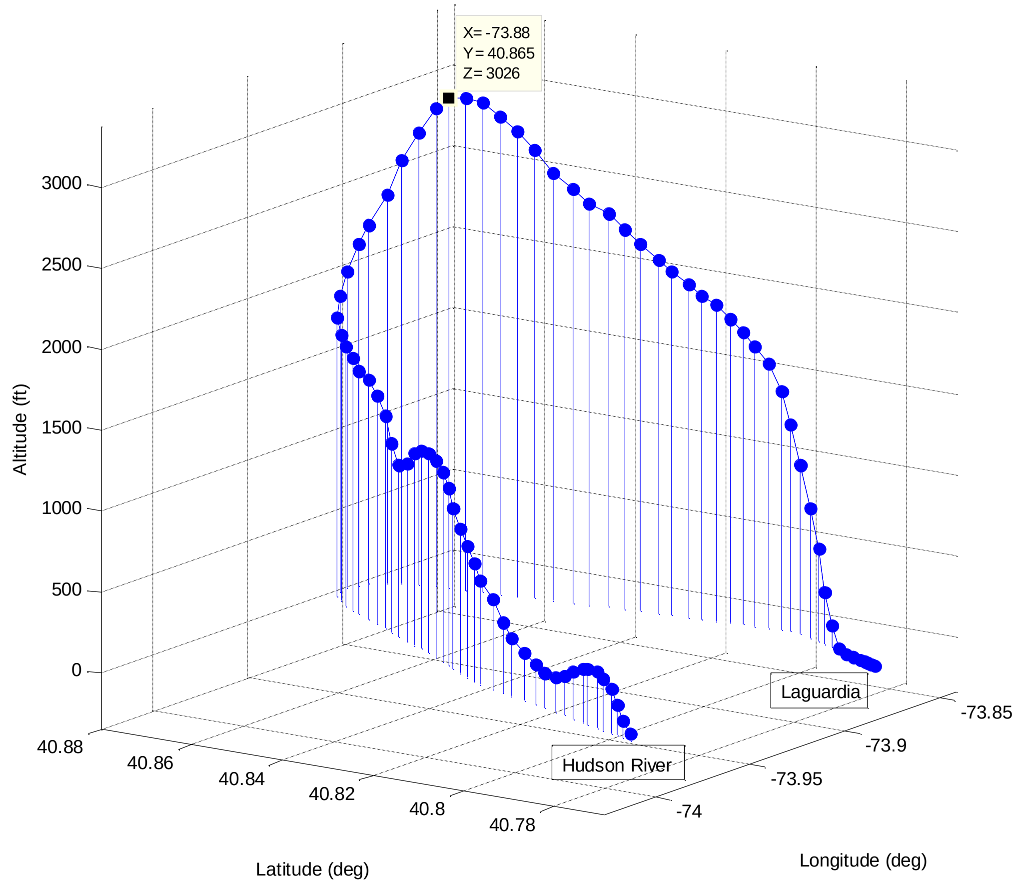
- What if an adaptive/emergency flight planning decision had been available for Flight 1549?
  - Was a runway landing feasible?
  - What time constraints were present?

- Would our C-based adaptive flight planner successfully generate solutions for the Flight 1549 situation without modification (except for A320 glide parameters)?

- What are the implications of these results?

Flight 1549 3-D Flight Profile

- Actual Flight 1549 trajectory shown
- Labeled point is where our analysis begins
- Previous point is maximum altitude (3046')
- GPS points recorded every 4 sec
- Our cases: (t+4) (labeled), (t+8), (t+12)
  - Subsequent points cannot reach runway



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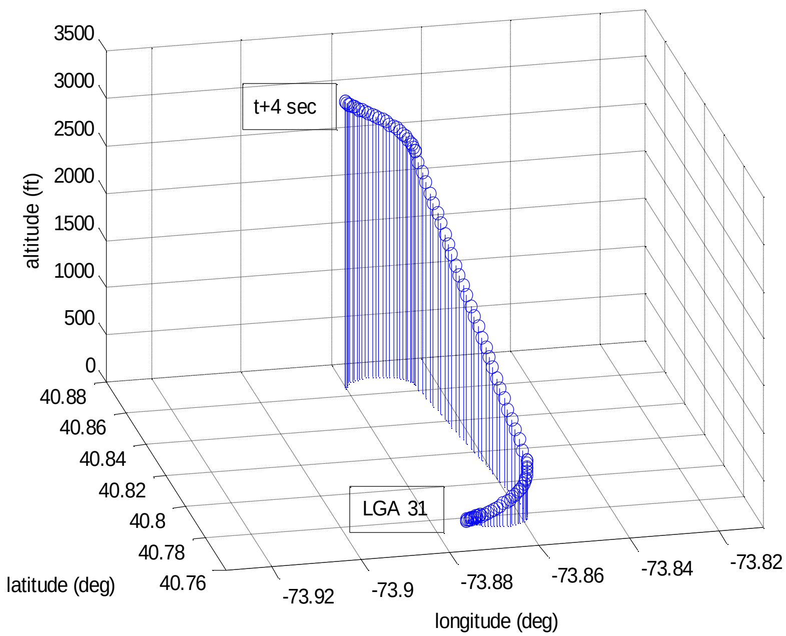
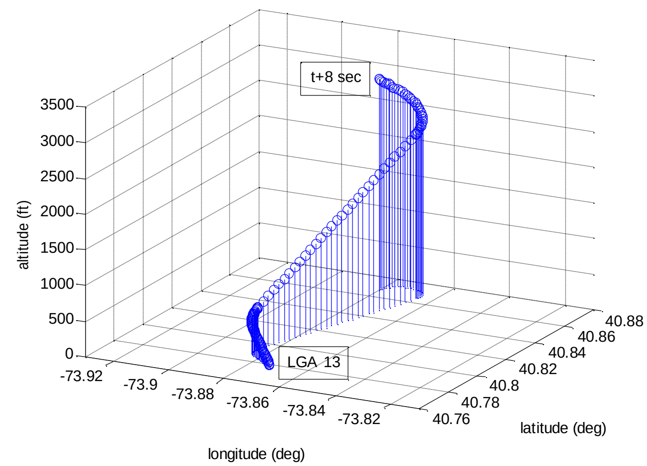
Emergency Flight Planning Results

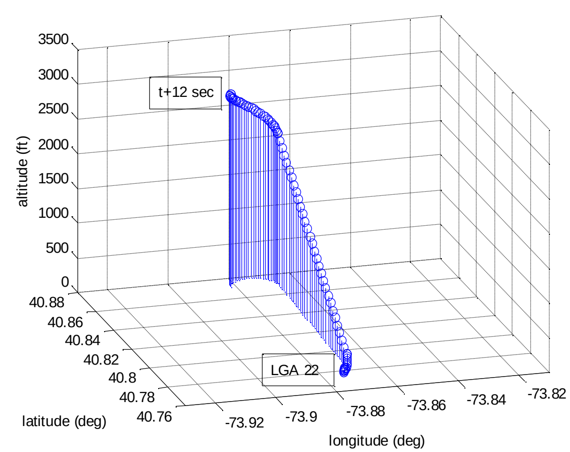
- Footprint analysis indicated LaGuardia (LGA) runways were reachable
- Fast response was critical to success
  - After t+12 sec, LGA was not reachable



LGA 31 preferred (headwind)



At t+8, LGA 31 was no longer reachable; LGA 13 was selected instead



At t+12, only LGA 22 was reachable

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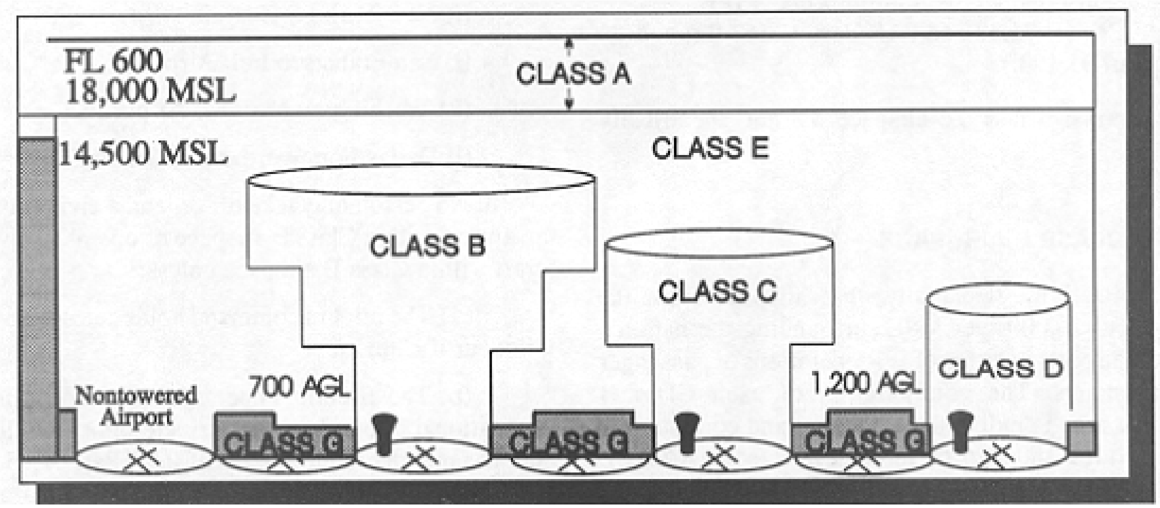
Flight 1549: Answering the Questions

- Our baseline emergency flight planner indeed found a landing trajectory to LGA
  - Identified solutions were consistent with NTSB analyses & pilot-flown simulations
- The Flight 1549 pilot made sound decisions, but a pilot with less skill (and luck) might not be as successful
- If an AFP solution had been presented nearly-immediately after the loss-of-thrust event, the pilot would have known of this option and likely executed it with confidence

Wanted: UAS in the NAS

- NextGen focuses on transport operations, passenger and cargo
  - NAS-related standards/R&D targets "enroute" (Class A) and "terminal area" (primarily Class B) traffic / operations
  - Recent NextGen discussion has begun to consider "large, costly" UAS
- Other business models (e.g., **surveillance**) must also be supported
- *If we build a NAS that **fully** supports UAS, they will come…*
  - *But, they must be safe, by the ICAO definition…*



(http://en.wikipedia.org/wiki/Airspace_class_(United_States))

Real risk of “Legacy Operations” Only!!!

UAS in the NAS: Additional Barriers

- Technological:
  - Acceptable risk without triply-redundant systems (for small UAS)
  - Safety certification of miniaturized, low-cost components/systems
  - Validation/verification: onboard automation, operator situational awareness/responsiveness, network-centric operations
- Psychological:
  - Fear of flying on (or being near) an aircraft with no human pilot
  - Invasion of privacy concerns
  - Pilots: Lost job, loss of comfort (coordination with a computer?)
- Legal: "Pilot error" is more palatable than "automation error"

Conclusion: Flight in NextGen & Beyond

- Levels of onboard automation will continue to increase in manned and unmanned aircraft
  - Motivation is capability, cost, and *improved* safety, not "coolness factor"

- Coordination in the future NAS will be fully-automated
  - High-speed data link; optional or no verbal communications
  - Super-density operation beyond human response capacity
  - Mixed-use operations (manned/UAS) with improved rather than compromised safety standards
  - Support for unmanned transport and information-gathering operations

- Piloted aircraft must be equipped with technologies that interface with the automated fleet
  - This doesn't necessarily represent a cost or weight problem once UAS-compatible technologies are certified

Achieving the autonomous UAS FMS goal

- Deterministic algorithms are certifiable – strive for them!
- Emergency/adaptive flight management *can* reduce risk
  - Reduced rigidity, but it's a challenge to certify "anomaly" handling
- *UAS may benefit even more from anomaly management algorithms in the context of UAS FMS*
  - ***It's not that emergencies/anomalies are impossible to handle autonomously, it's that we need to actually program & verify the automation to detect and manage them***
  - ***Published procedures translated to software are a promising start; autonomous flight management with adaptation will provide the flexibility these procedures lack***