Development of a “where-to-land” decision function for an expert piloting system (EPS) for piloted and autonomous air vehicles (Phase I Results)

NASA Aeronautics Research Mission Directorate (ARMD)
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Outline

- Background
- Innovations
- Technical approach
- Phase I results
- Development process and next steps

Background - EPS

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- What is an "expert piloting system" (EPS)?
  - Autonomous system which is able to pilot vehicles with the ability of an expert human pilot
- Previous state of the art
  - Systems exist which are able to pilot aircraft from takeoff to landing automatically… in normal situations
- Technical Challenges with an EPS
  - The ability to adapt to unknown and potentially emergency situations is difficult for an autonomous system to do
  - Additionally, traditional certification for these adaptable system is difficult, if not impossible

Background – An EPS function

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- One of the most critical decisions made in an emergency is where to land.
  - Can an alternate airport be used?
  - Are there any off runway landing sites?
  - Is ditching required?
- Expert human pilots are always "training" for such a scenario

Innovations – Automate WTL function

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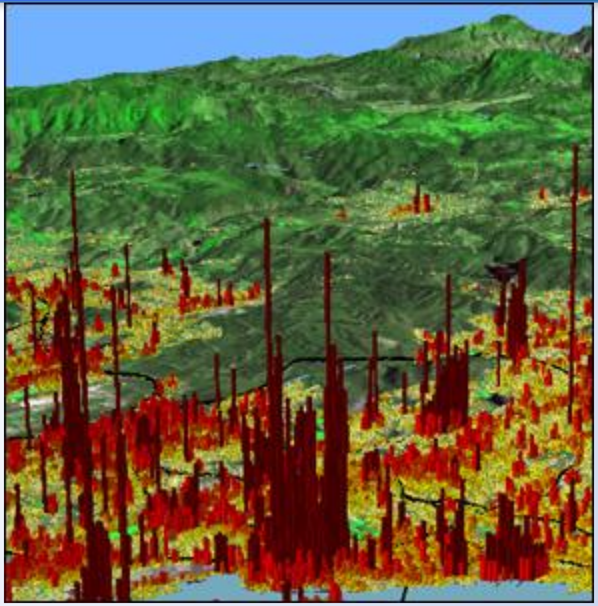

LA Basin - Credit: ONL LandScan USA

- Why?? All pilots, aircraft, and situations are not created equal.
- With new computing hardware, geographical information systems data, and machine learning algorithms these decisions can now be made by automated systems.
- Mixed criticality strategies may provide a path to certification

Innovations – WTL function

Autonomous decision process

Sense Need → Decide → Actuate

- Sense Need– Determine need for emergency landing and what type of landing (Health monitoring, vehicle state)
- Decide – Minimize the potential loss for the chosen landing selection (**Where to land decision function algorithms**)
- Actuate – Perform landing in location selected (Auto landing system, route planning, adaptive control)

Technical Approach

Target scenarios

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Landing Category	Description	Notes
Land as soon as practical	Land at nearest airfield	Currently available determination of nearest airfield available in current GPS systems
Land as soon as possible	Land when/where probability of zero loss is greater than 80% (for instance)	Category may change into land immediately if conditions for acceptable landing site are not found. Preplanning activities should limit this possibility.
Land immediately	Minimize combined expected loss in the immediate area	Preplanning activities should limit expected loss to a predefined limit.
Crash smartly (UAV only)	Minimize loss on the ground only	Failure conditions on inexpensive UAVs may always call for this landing category

- Nearest airfield algorithms currently exist.
- WTL decision function development targets emergencies scenarios which require:
  - land as soon as possible
  - land immediately
  - and crash smartly categories.
- Landing category determination comes from health monitoring function (what type of fault, aircraft state, etc)

Decision function objective

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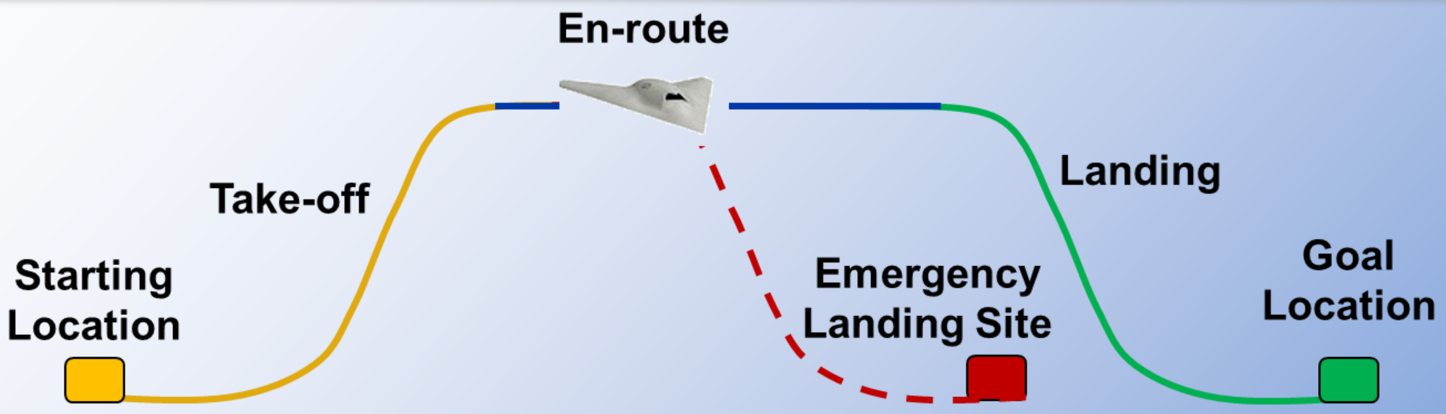

- The WTL decision function will select an emergency landing site which minimizes predicted on and off vehicle losses given:
  - the emergency landing category
  - aircraft state
  - aircraft capabilities
  - geographical and population data

Decision function components

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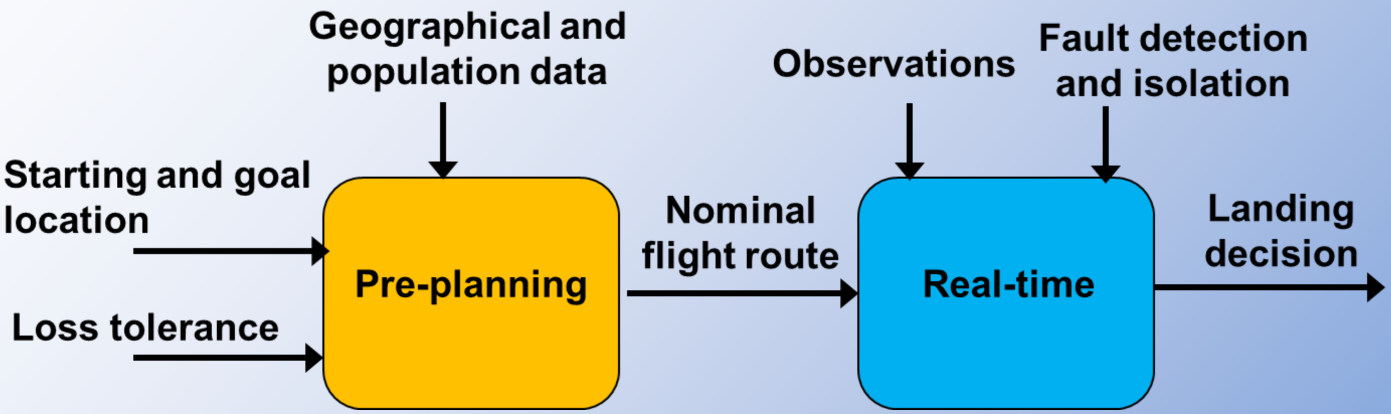

- Pre-planning – Plan flight routes with bound on expected loss using a priori information
- Real-time – Optimize landing decisions along flight route based upon real-time observations

Emergency landing model

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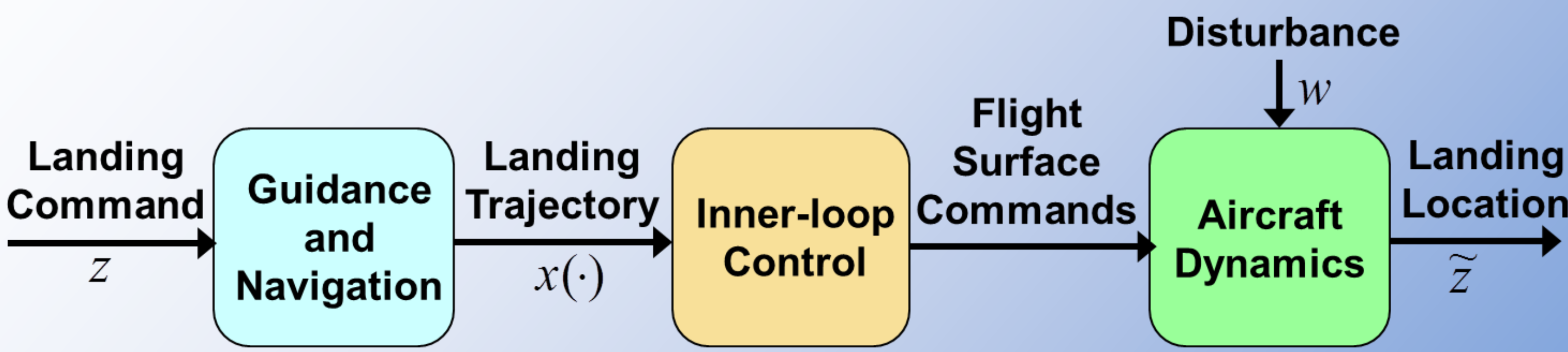

- Upon detection of fault, emergency landing system computes a landing command $z \in R^m$
  - Position, velocity, orientation at landing
- This command is passed to guidance and navigation to compute a landing trajectory
- Landing trajectory is then passed to inner-loop control to generate control commands
- Disturbances (e.g. wind and tracking errors) results in perturbed actual landing configuration $\tilde{z} \in R^m$

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Loss model

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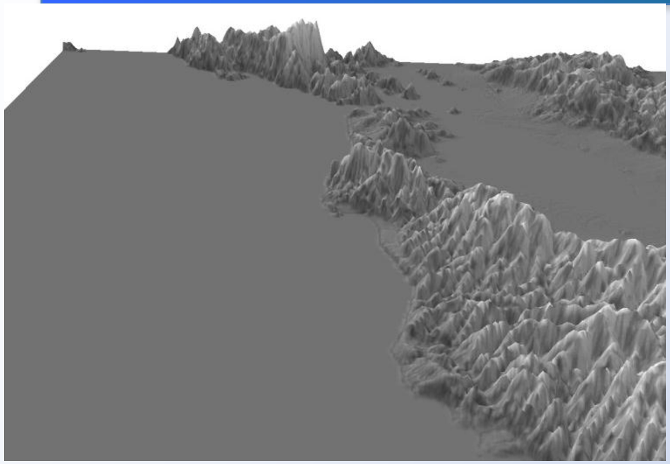
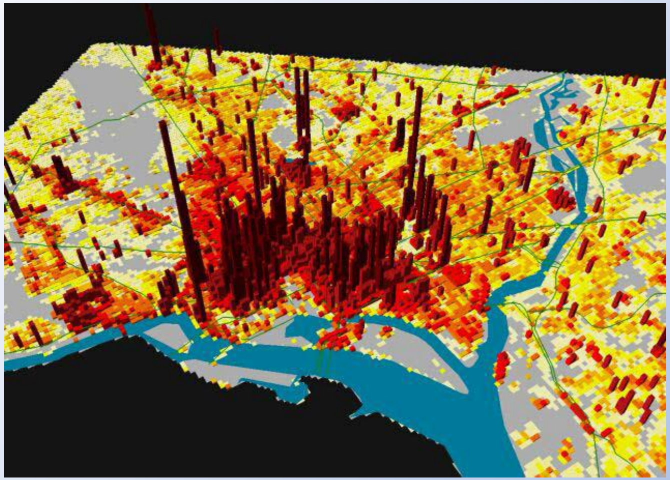


Credit: USGS NED



Credit: ONL LandScan USA

Two sources of loss

- On-vehicle loss: vehicle damage due to landing at hazardous locations (e.g. water, buildings, trees)
- Off-vehicle loss: environment damage due to landing in populated areas (e.g. residential or industrial areas)

Given potential landing sites $x_l \in R^2$, model sources of loss via two maps:

- Hazard map $H: R^2 \to \{0,1\}$
- $H(x_l) = 1$ represents hazard at location
- Constructed from geographical and terrain data
- Impact map $I: R^2 \to [0, \infty)$
- $I(x_l)$ represents environment loss at location
- Constructed from population density and land use data

Computing expected loss

- **Aggregate loss** is sum of on and off vehicle loss over emergency landing area (given a specific fault)
  - Vehicle loss incurs cost *C* if landing area contains a hazard, as defined by the hazard map H.
  - Environment loss modeled by integration of impact map
- This function is then minimized to provide the optimal landing command
- The optimal landing command is then used to provide an expected loss for each fault and compared to pre-defined maximum allowable loss to produce acceptable pre-planned flight routes.

Real-time updates of impact and hazard map

- Impact and hazard maps will be based on information which may be old and/or at too coarse a resolution to provide optimal landing locations
- Real-time updates using sensors such as cameras, radar, laser, etc provides a method to update these maps on the fly
- Real-time updates allow the system to truly act as an expert pilot would

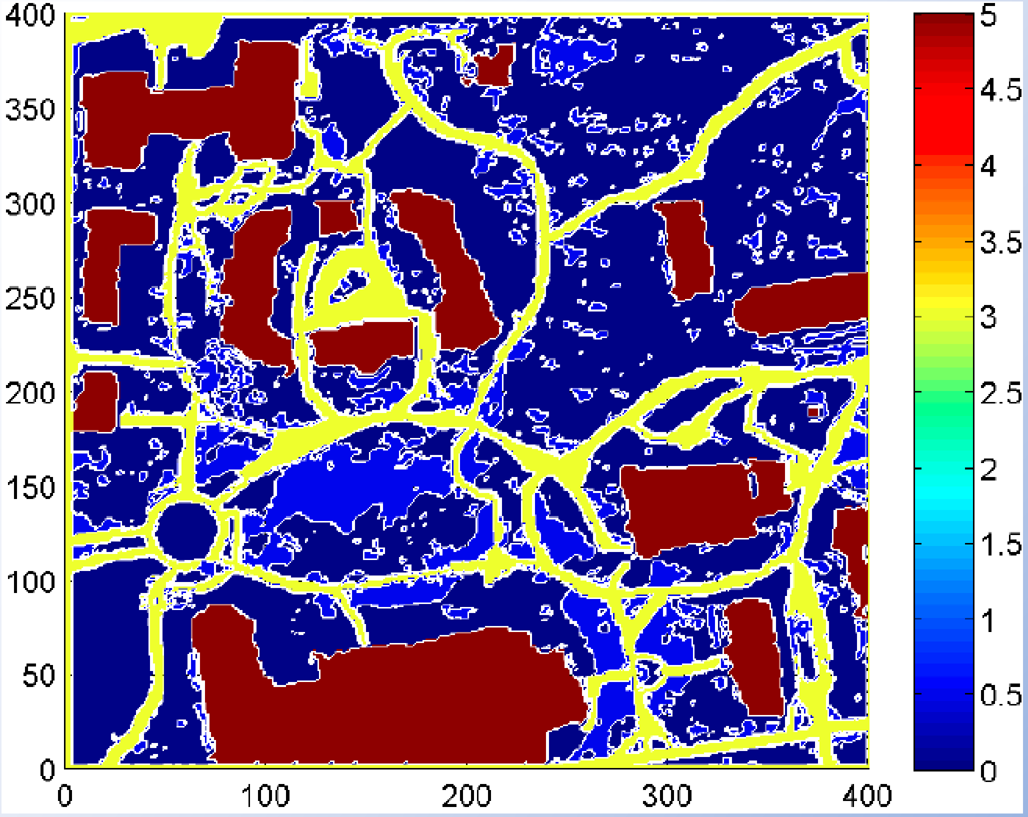
Simulation Results

Simulation scenario

Courtesy of Google Maps - ©2013 Google

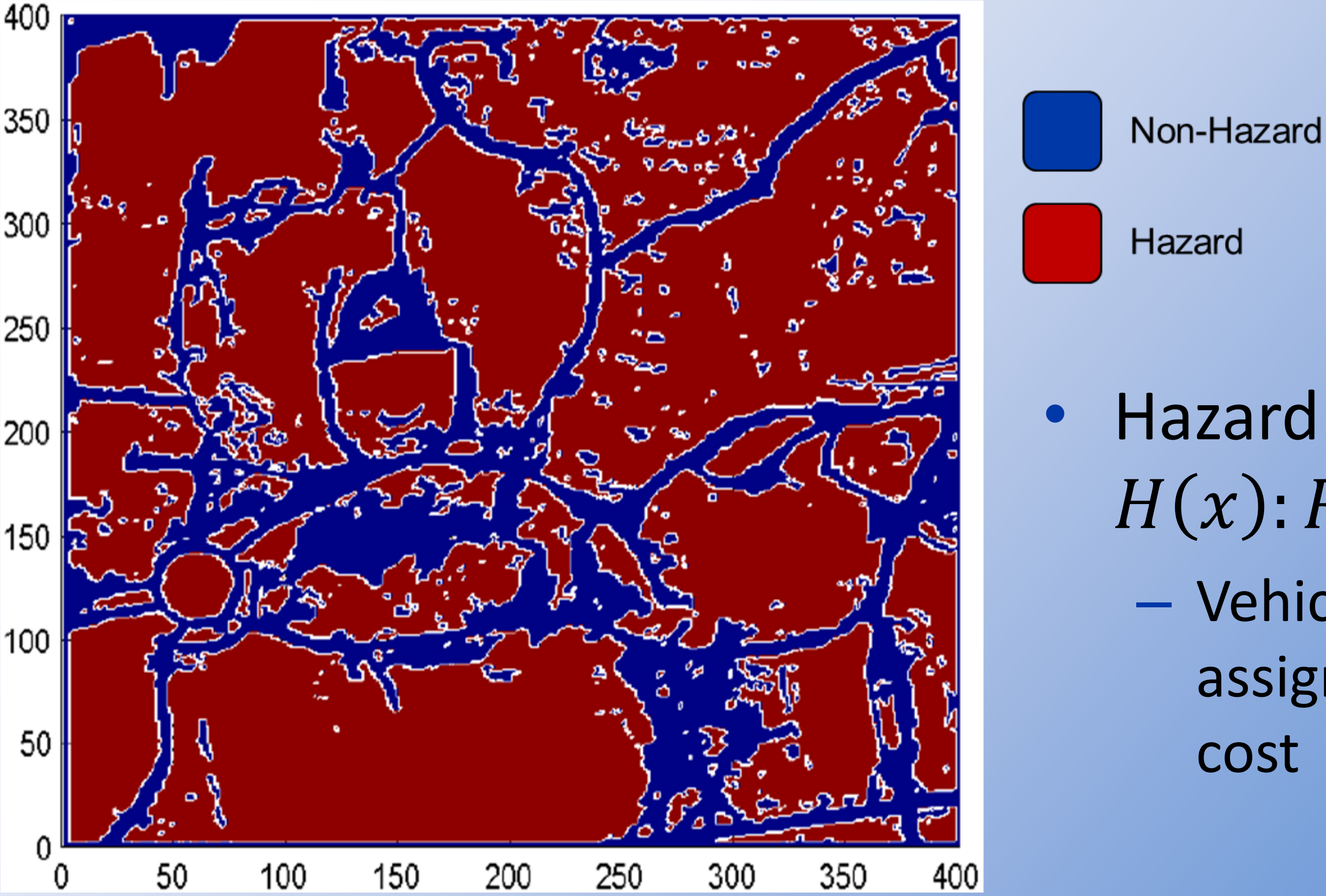
- Consider planning domain as section of UC Berkeley campus
- Assume vehicle to be quad-rotor helicopter, flying at height of 25m above ground
- Model failure mode as 10% loss of vertical thrust

Construction of impact map



- Impact map
  $I(x): R^2 \to [0,5]$
  - Buildings: 5 unit cost per 1m^2 area
  - Roads and parking lots: 3 unit cost per 1m^2 area
  - Grass: 0.5 unit cost per 1m^2 area
  - Trees: 0 unit cost per 1m^2 area

Construction of hazard map



- Hazard map
  $H(x): R^2 \rightarrow \{0,1\}$
  - Vehicle loss assigned unit cost

Aggregate losses map

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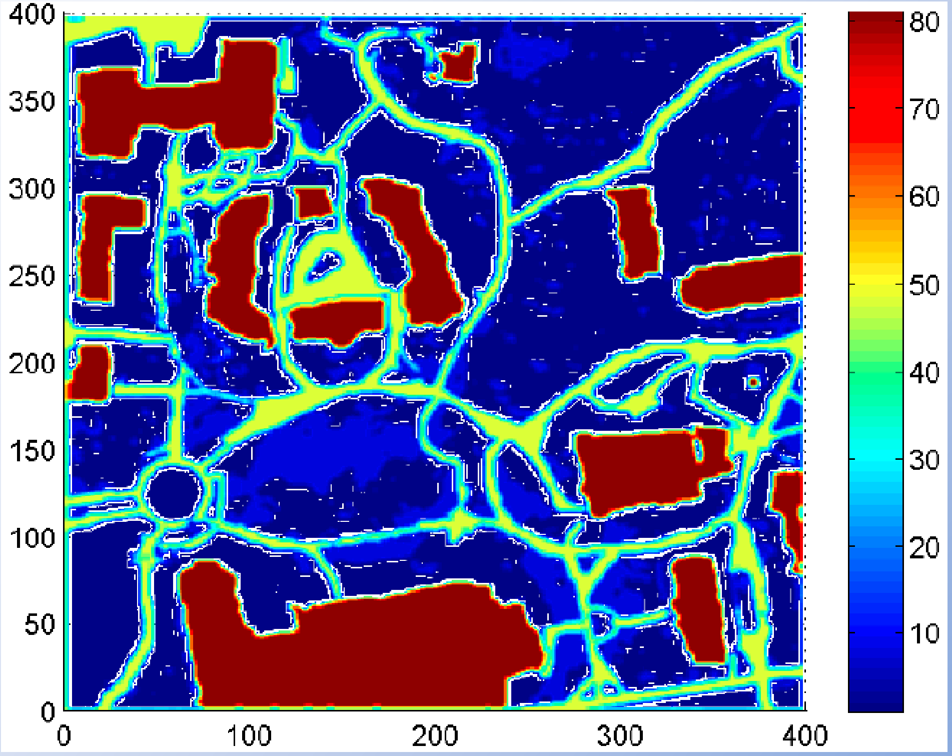

- Compute aggregate loss function as
- $l(\tilde{z}) = \int_{A(\tilde{z})} I(x)dx + \max_{x \in A(\tilde{z})} H(x)$

Minimal expected loss

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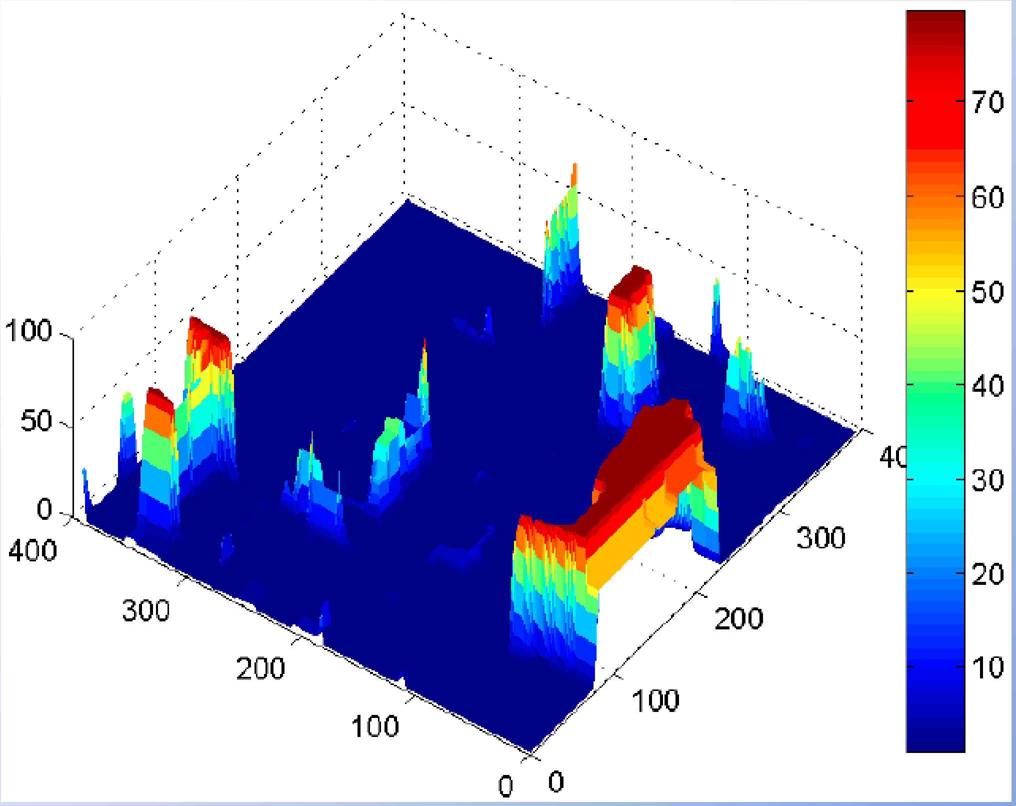

- For a fault causing a 10% loss of thrust
- At flying height of 25m

Pre-planning safe flying spaces

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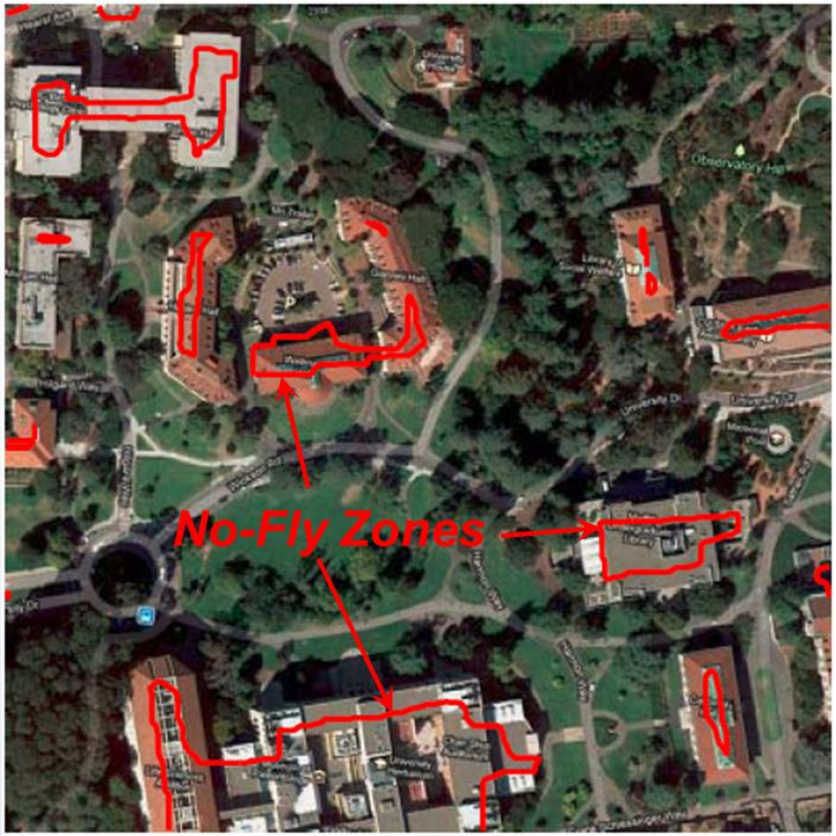

- Given tolerance on expected loss, one can threshold loss map to find safe flying space
- In this case, we consider a threshold of 8 unit cost, corresponding to landing on grass
- Note that no-fly zones mostly correspond to building tops

Flight route planning

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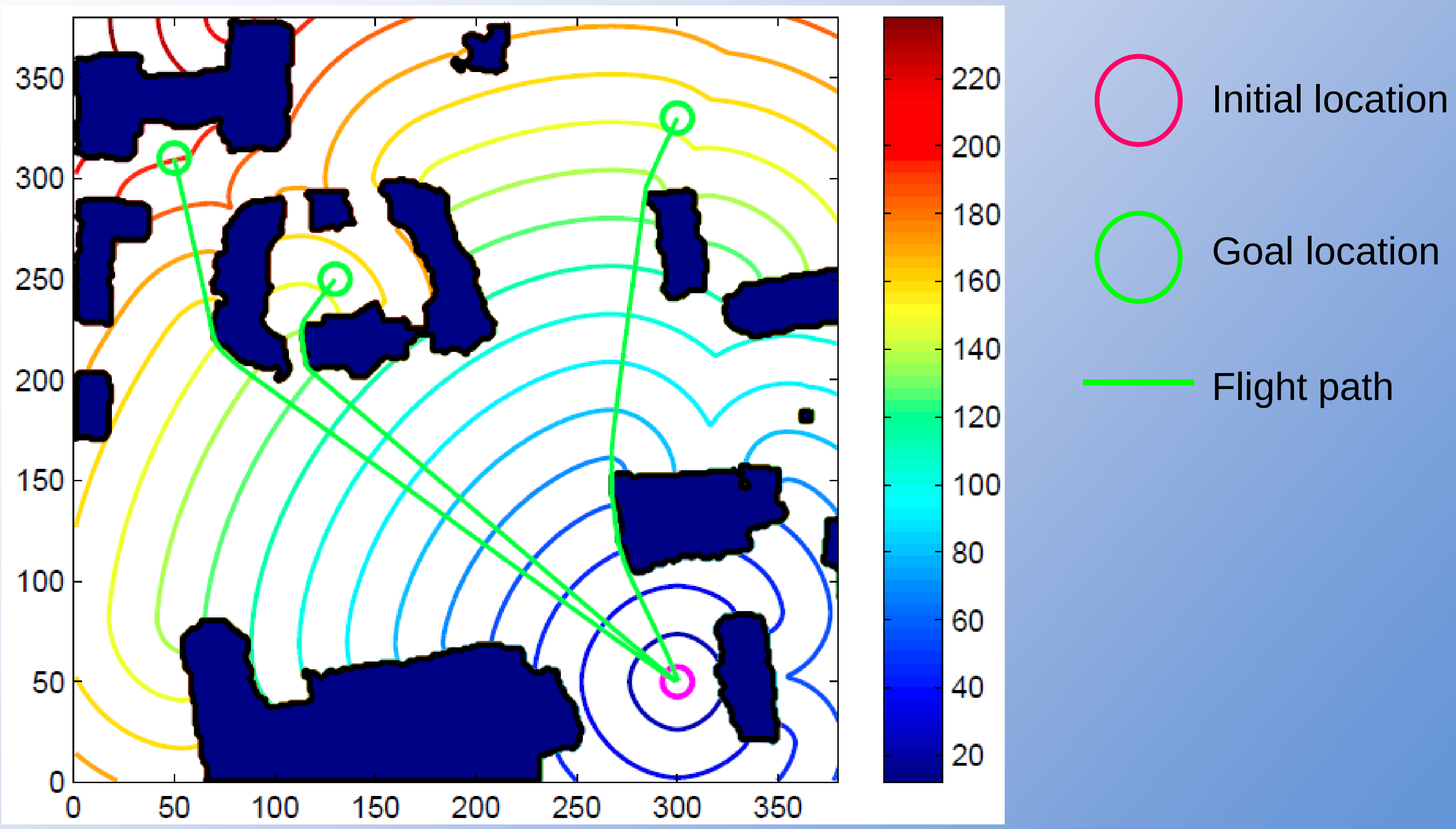
Contour Plot of Time to Reach Function



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Emergency landing simulation

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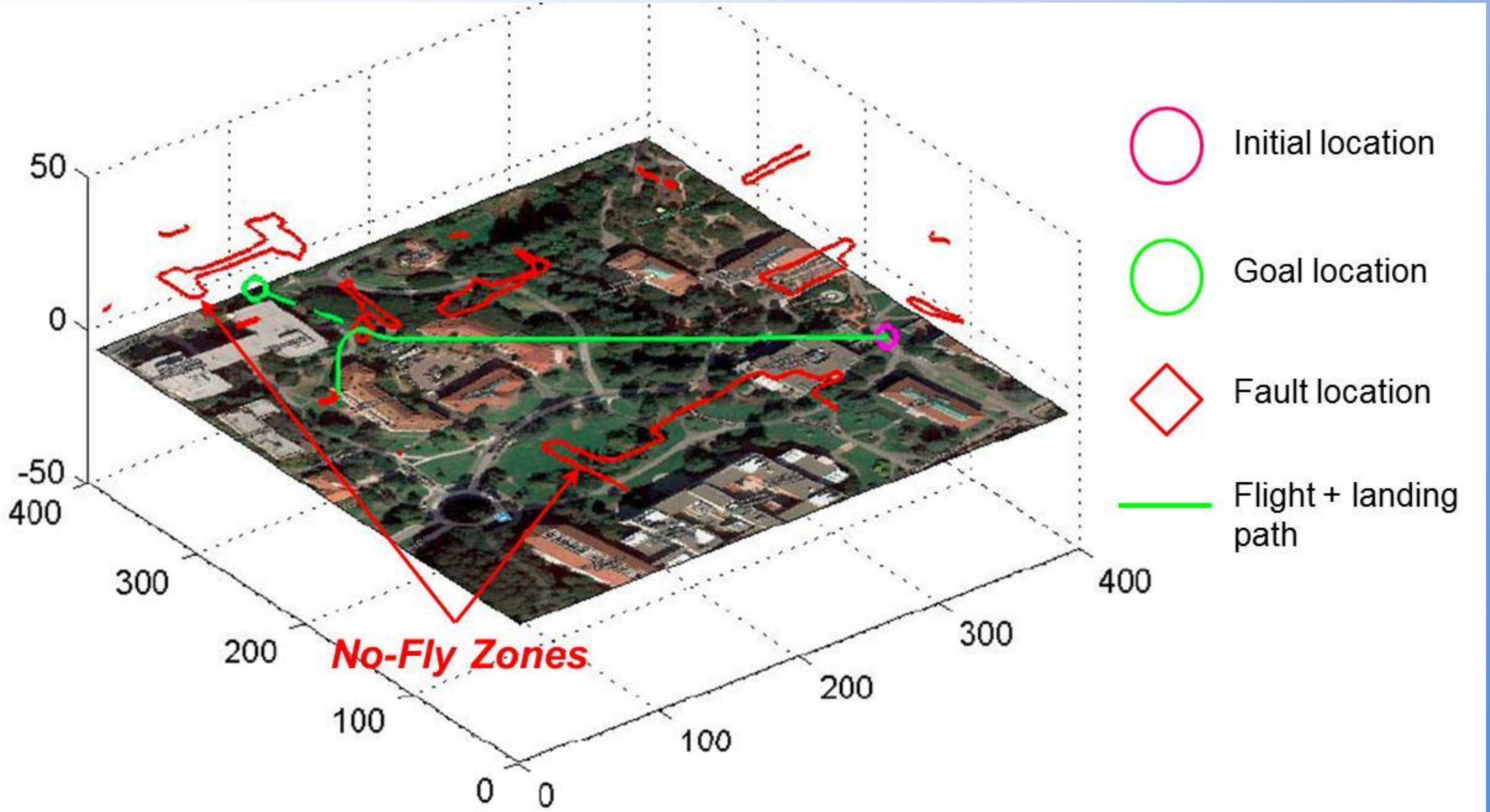

Emergency landing

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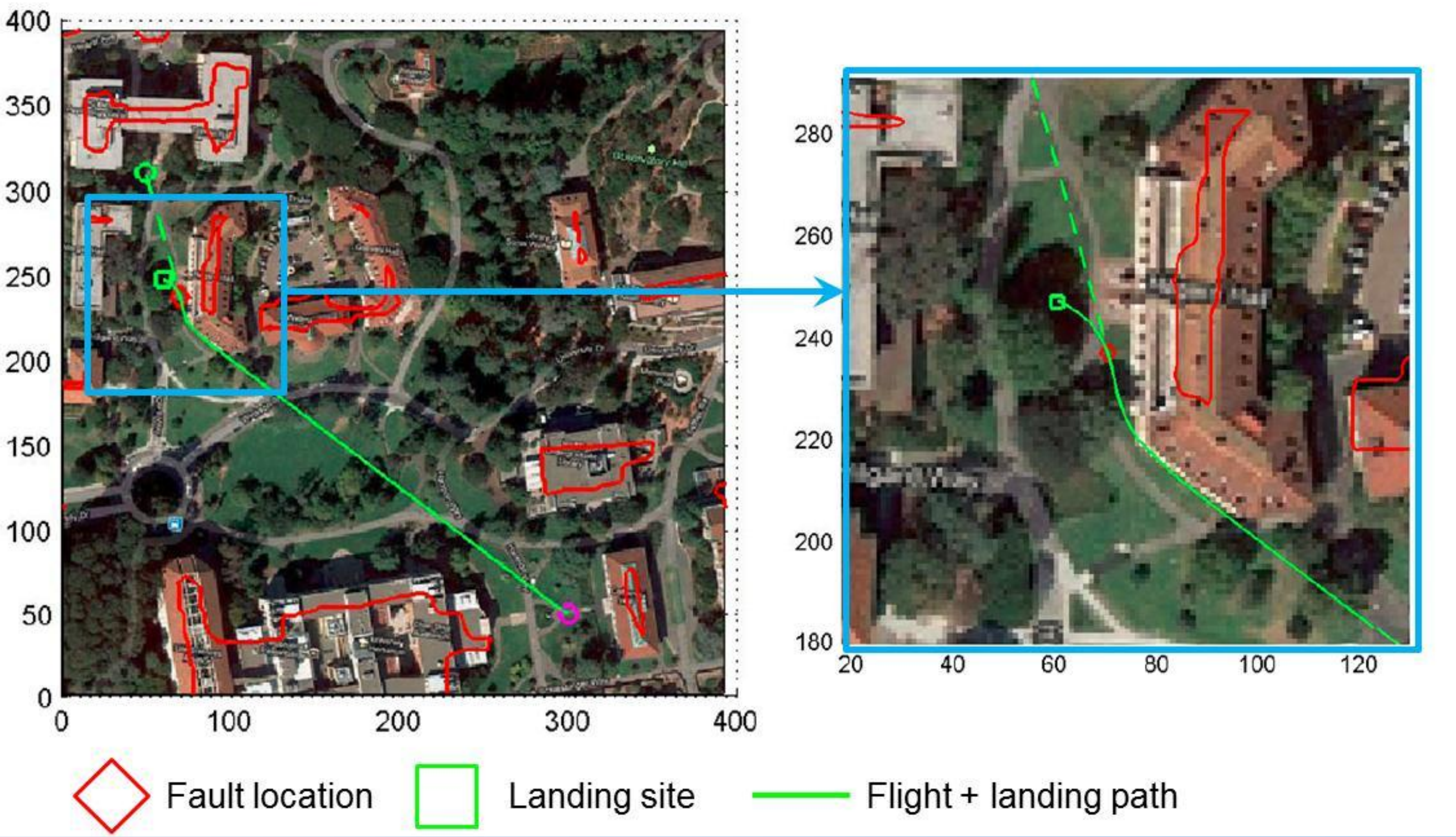
- **Overhead view of simulated emergency landing**



Real-time update simulation

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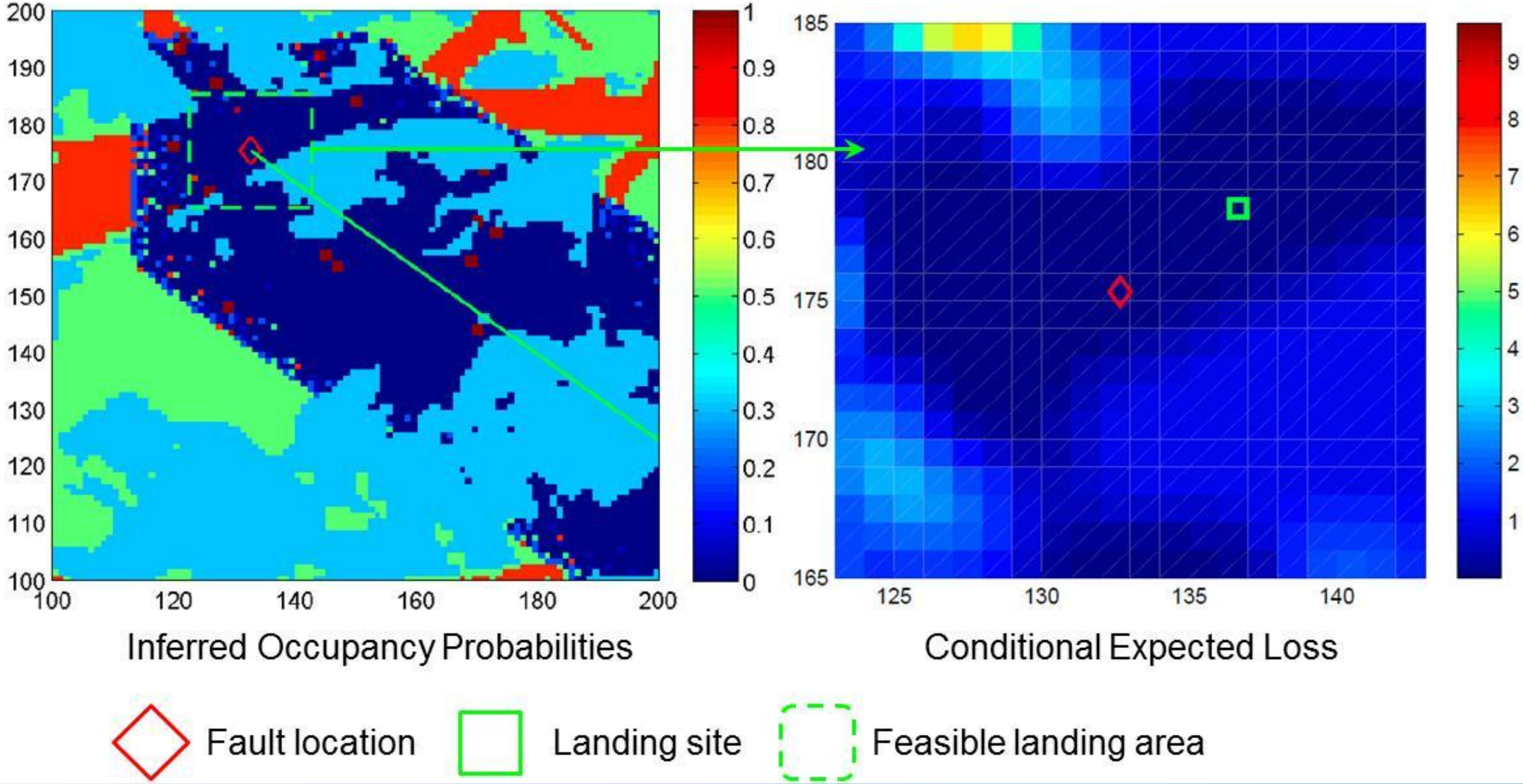
- **Using online observations, one can select landing site based upon inferred occupancy probabilities**



Flight test results

Scheduled 7/15 – 7/31

Development process and next steps

Development process and outputs

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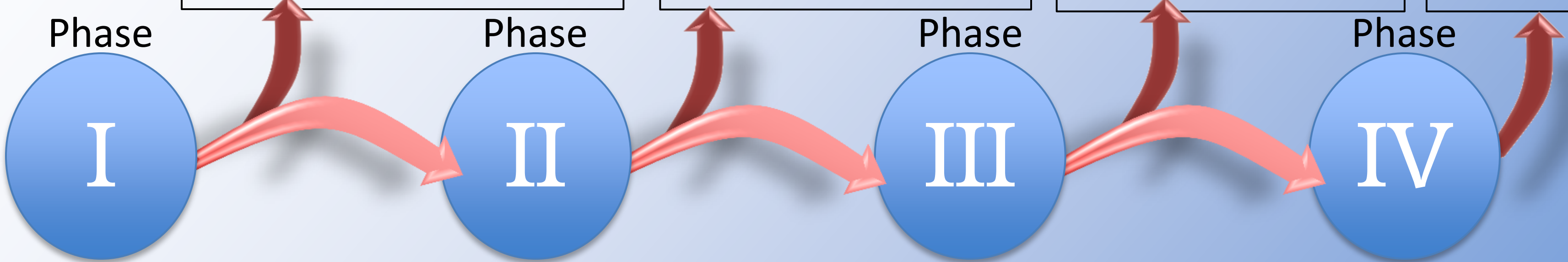
OUTPUTS

- Pre-planning and pre-computed advisory functions integrated onto GPS, electric flight bags
- Real-time updated advisory functions integrated onto glass cockpit, FMS
- Automatically initiated advisory, manually piloted system
- Fully automatic emergency landing system



Phase I

Algorithm Development

Actual:

- Geo maps

Simulated:

- Real-time Sensors
- Health monitoring
- Faults

Phase II

Real-time sensor development

Actual:

- Geo maps
- Real-time Sensors

Simulated:

- Health monitoring
- Faults

Phase III

Faults and monitoring development

Actual:

- Geo maps
- Sensors
- Health monitoring
- Faults

Phase IV

Full autopilot integration (adaptable controls??)

Immediate next steps

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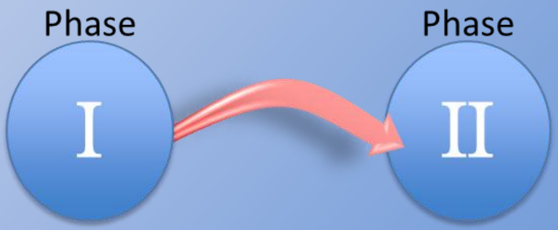
- Automatic map generation process using multiple data types
  - Processing of geographical, population, and building type information to automatically construct impact and hazard maps
- Real-time sensor development
  - Cameras, lasers
  - Computing hardware



- Online update and optimization
  - Incorporation of object detection algorithms
  - Accounting for moving objects and people
- Real-world experimentation with real-time updates
  - Selection of experiment location and hardware
  - Performing flight tests on subscale vehicles

Conclusion

- Background and project innovations
- System architecture
  - Pre-planning: Performance assurance through expected loss computation
  - Real-time update: Adaptation of landing decisions to onboard sensing
- Models and algorithms
  - Vehicle landing models
  - Generation of expected loss maps
  - Planning safe flight routes
  - Real-time optimization of landing decisions
- Simulation studies using area of UC Berkeley campus
- Development process and next steps
  - Multi-phased approach to autonomous WTL operation

Thanks… Questions