Designing Noise-minimal Rotorcraft Trajectories

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Outline

- Motivation and Objectives
- Technical Background
  - Rotorcraft Noise and Noise Simulation
  - Trajectory Optimization
- Summary of Approach
  - Constraint Model
  - Cost Function
  - Search
- Experiments
- Summary and Future Work

Project Goal

- Promote the use of rotorcrafts for commercial transportation
- Apply state of the art AI techniques to design rotorcraft approach trajectories that minimize ground noise.
- Why AI?
  - Difficult for pilots to predict accurately the impact of their decisions on noise
  - Too many variables: helicopter model, BVI, ground conformation, wind, comfort
- Use robust noise predictor to evaluate candidate trajectories
  - Prediction used to define cost function.

Noise

- ***Noise*** is "unwanted sound"
  - A *subjective* quantity
- ***Sound*** is any pressure variation a human ear can detect
  - An *objective* quantity
- The **decibel** scale matches the way our ear and brain "auditory system" interprets sound pressures
  - *We "hear" in decibels.*
- **Sound Exposure Level (SEL)** is a measure of the total "noisiness" of an event, that takes duration into account
  - FAA considers a 1.5 dB the minimum *significant* change

Rotorcraft Noise

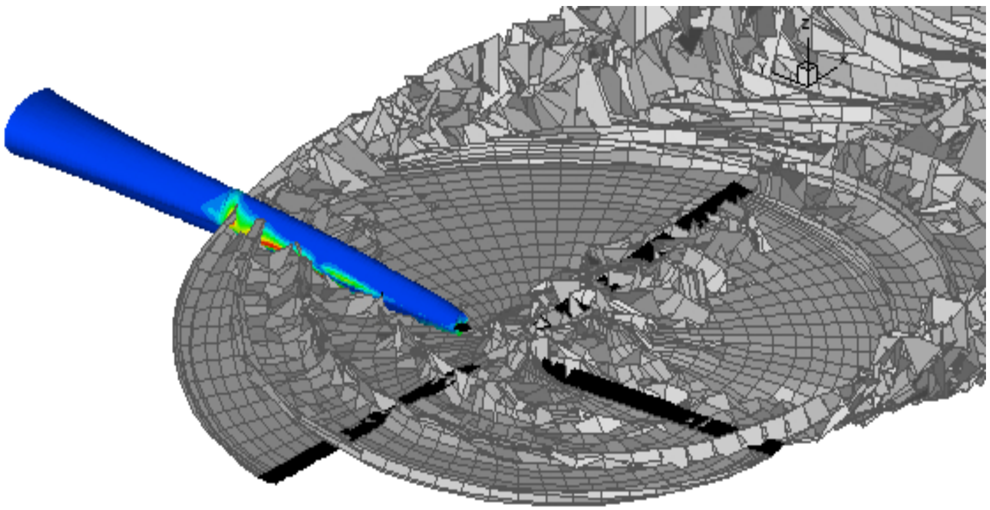
- Rotorcraft tend to have **strong impulsive and directional characteristics** compared to fixed wing aircraft.
- Noise levels can vary significantly depending on **vehicle design and flight condition.**
- For low speed descent, **where *Blade Vortex Interaction (BVI*)** noise may be present, noise levels can be 10-20dB higher than for flight conditions where BVI noise is not present.
- **Propagation** effects of source noise dependent on **atmospheric and terrain conditions.**
- Therefore, characterizing ground noise exposure is hard!

Rotorcraft Noise Sources

- Main rotor
- Tail rotor
- Engine
- Drive system

- Blade Vortex Interaction (BVI): modulation of sound by the relatively slow-turning main rotor.

- Happens when one blade interacts with the vortex of the previous blade.



Rotorcraft Noise Model (RNM)

- RNM is a simulation program that
  - **models** sound **propagation** through the **atmosphere**
  - **predicts noise levels** on flat **ground** or varying terrain.

- Purpose
  - Aid assessment of low noise terminal area operation procedures for rotorcrafts;
  - Improve rotorcraft modeling capabilities

RNM: Input

Input parameters:

- Identity of the rotorcraft
- Dimension and resolution of a grid (region of interest)
- Particular points of interest (if desired)
- A flight trajectory (3D location, velocity and orientation)

Example of RNM input file

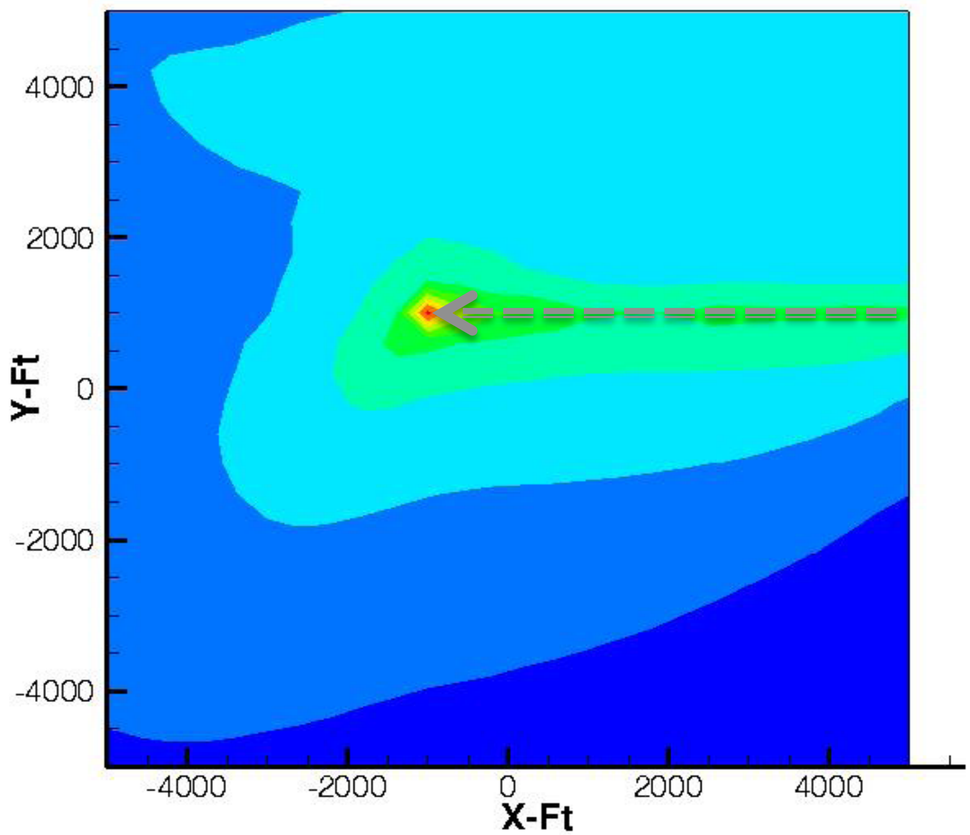
```
DIAGNOSTICS
COMPUTEPOI
COMPUTEPLT
QSAM1
SETUP PARA
200 200 500
-1000 -1000 5
3000 1000
60 30000 10000 0.0
CH146
1
0.00  0.00  0.00
0
0
ONE TRACK
rnmAnalysis
2
0.0  0.0  1249.3280028431807  0.00  0.00  90.0  0.00  0.00  0.00  90.0
2000.0  0.0  750.6719971568193  0.00  0.00  90.0  0.00  0.00  0.00  90.0
END
```

RNM: output

- Sound is analytically propagated through the atmosphere to the ground.

- RNM currently accounts for
  - Spherical spreading
  - Atmospheric absorption
  - Ground reflection and attenuation
  - Doppler shifts
  - Different ground terrains
  - Effects of wind and temperature
  - Multiple noise sources (main rotor, tail rotor, engine, etc.)

- RNM produces contour plots: graphical representation of ground noise exposure using a number of noise metrics over the designated grid



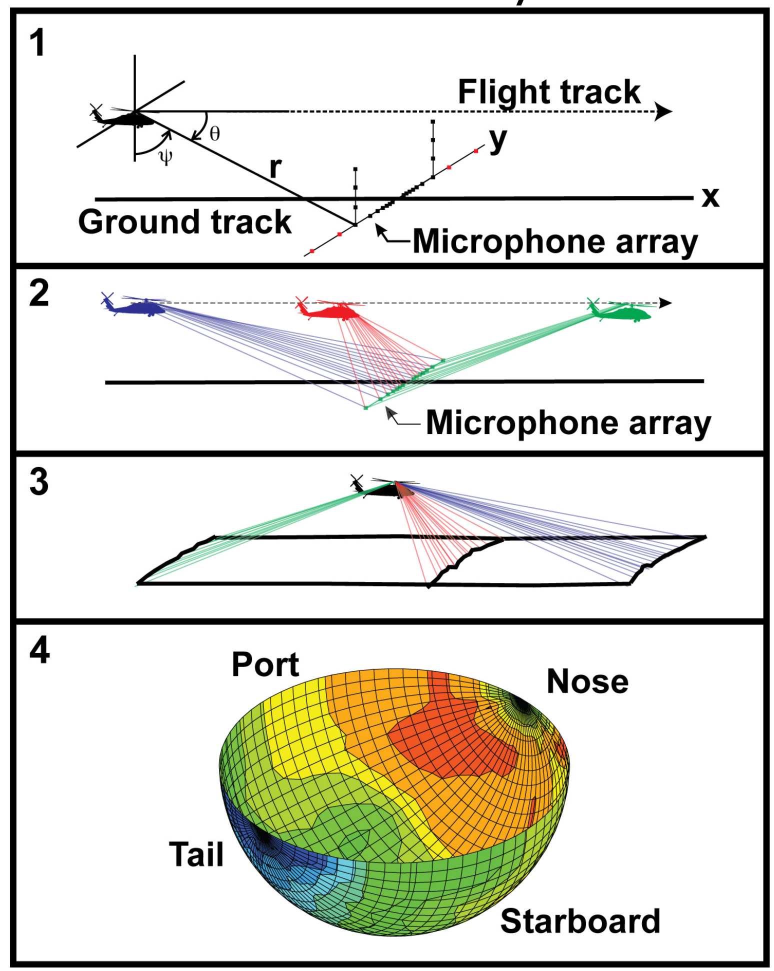
SEL values

How does RNM work

*courtesy E. Greenwood

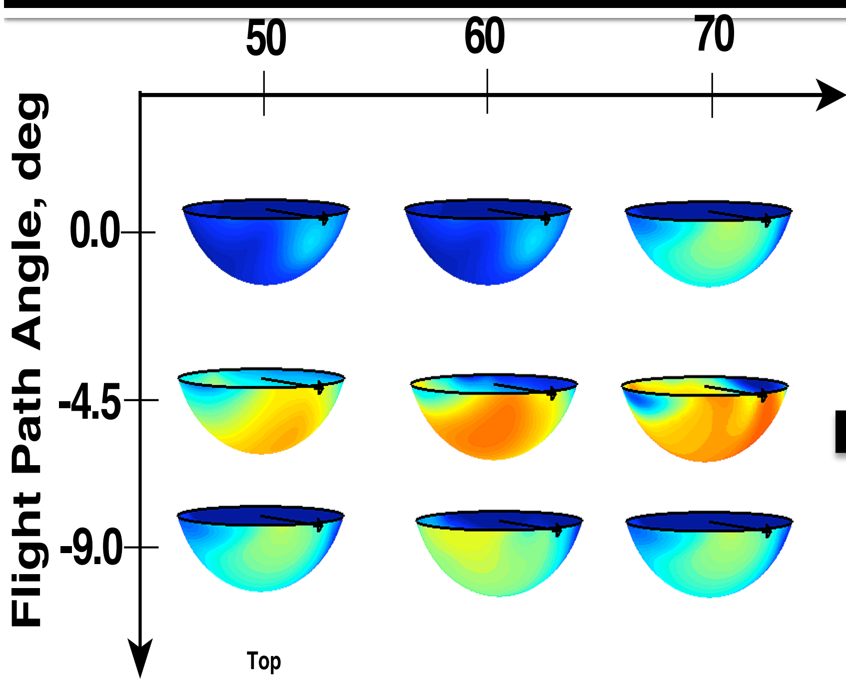
- RNMs prediction are based on sound **hemispheres** summarizing test results

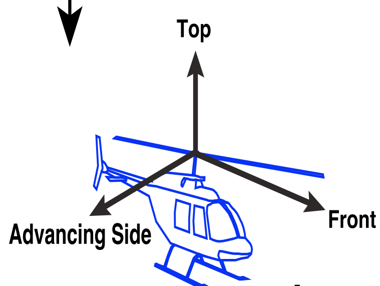
- Helicopter maintains steady flight condition throughout measurement
- Observation angles of microphones shift during flyover
- Single “compact” source of emission assumed (typically main rotor hub)
- Measurements resolved to surface of hemisphere

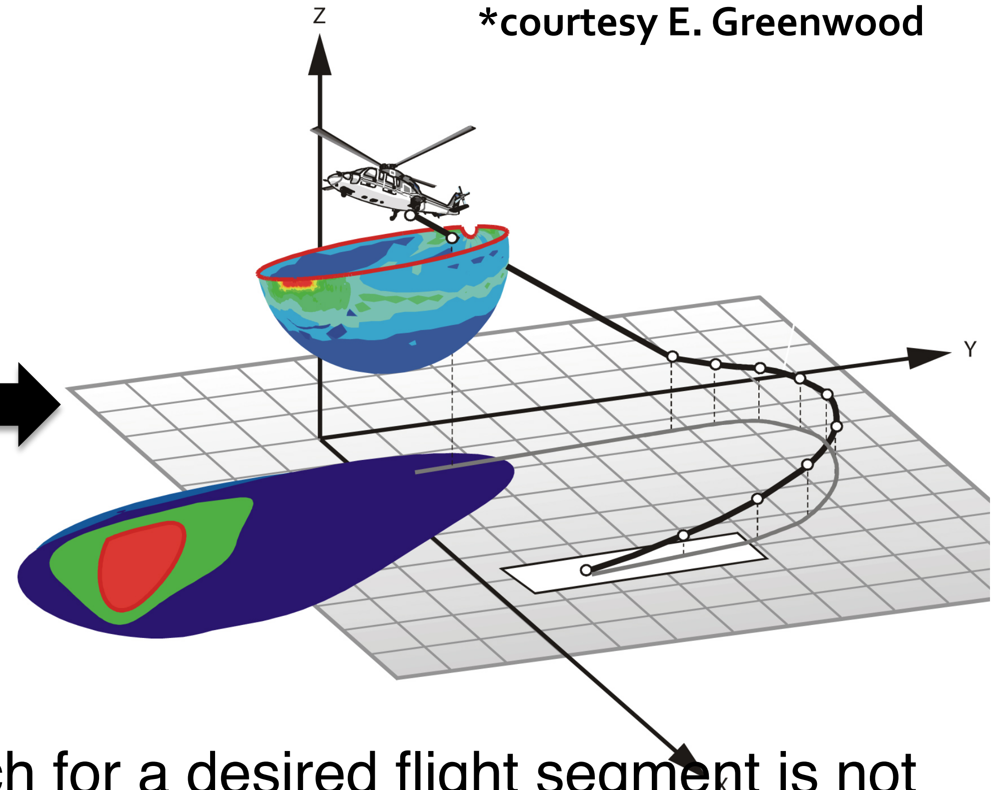


RNM uses Semi-spheres to Generate Ground Contour Maps

*courtesy E. Greenwood

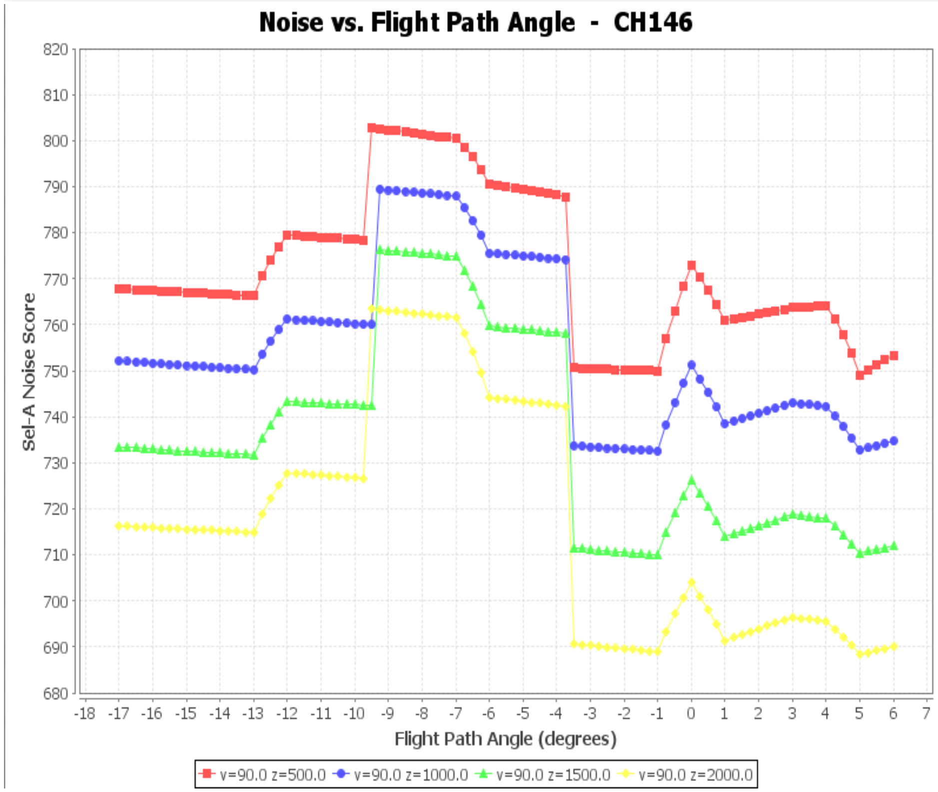


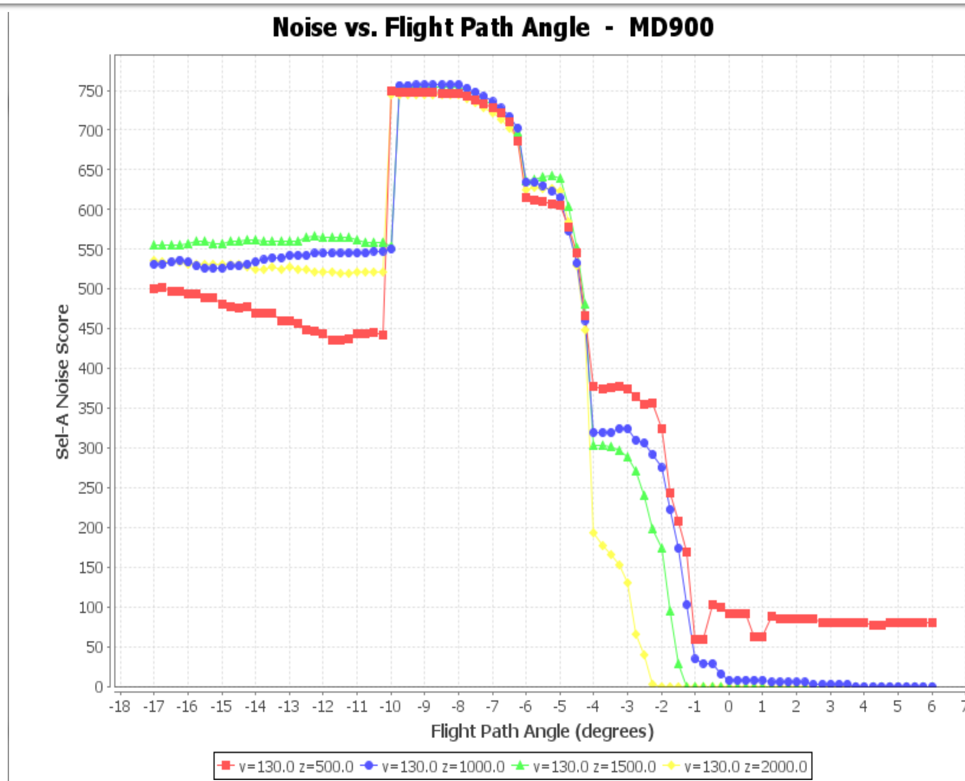




If an exact match for a desired flight segment is not found in the database of hemispheres, a new hemisphere is generated by interpolating the noise levels on the surface of the hemisphere between known values of airspeed and flight path angle.

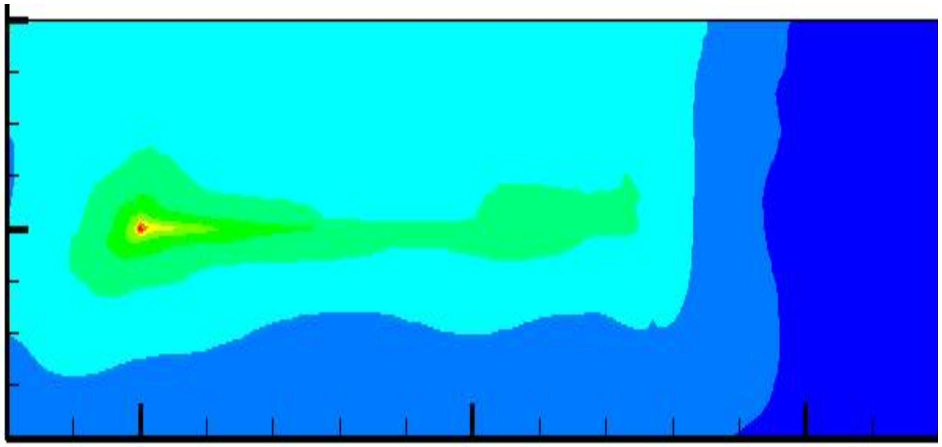
RNM simulation of BVI

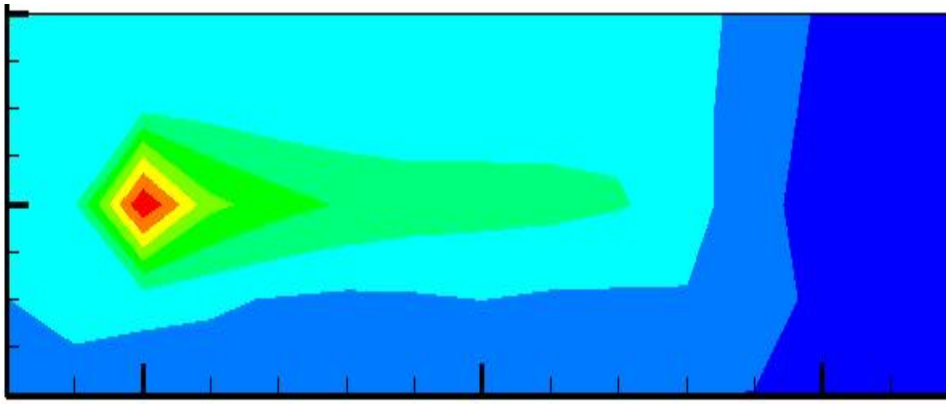




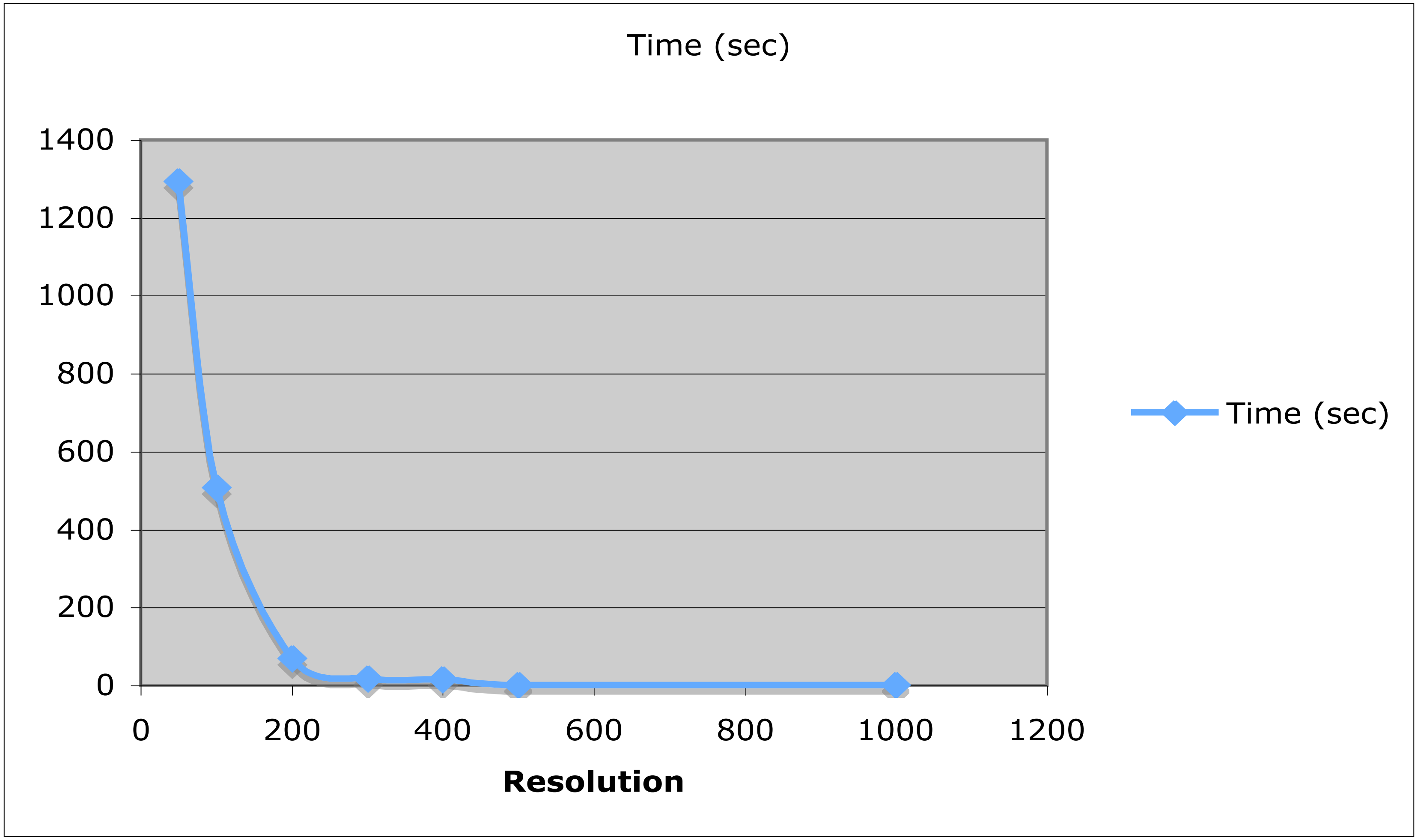
Data Resolution

- Data resolution is the distance between any two grid points
- RNM predicts ground noise at each point
- Higher resolution means
  - more accurate predictions, but
  - longer computation time





Performance/Resolution Tradeoff

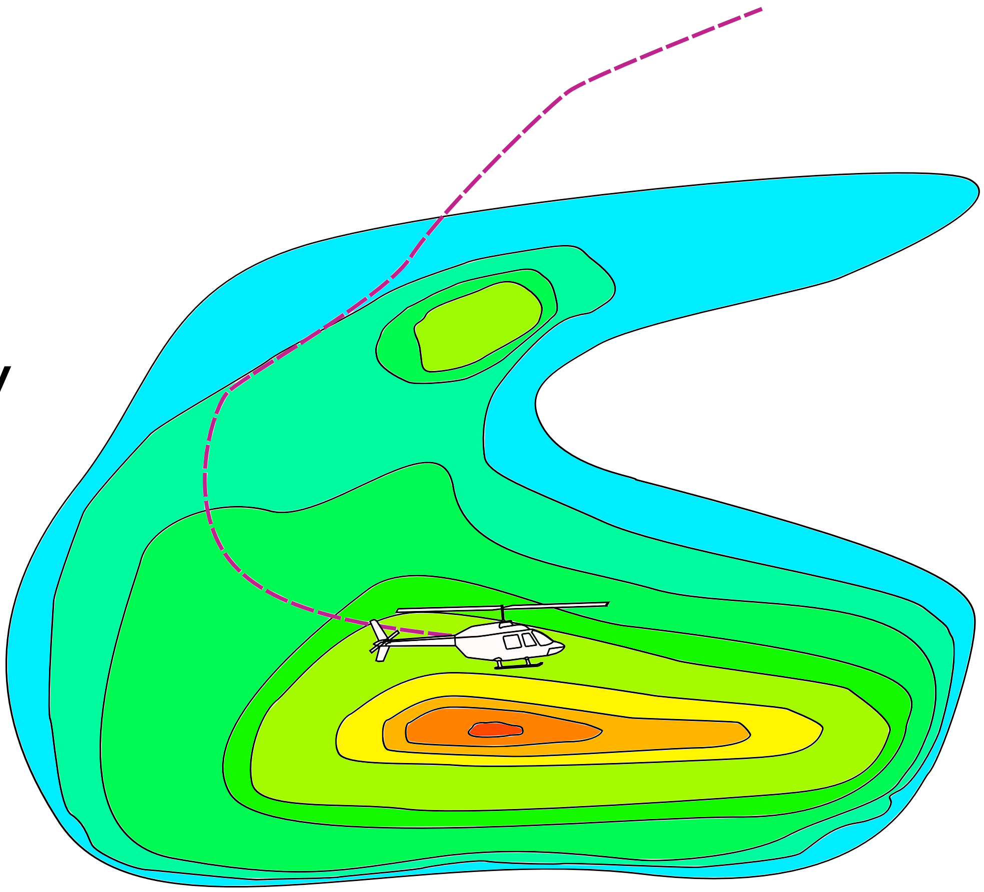


Trajectory Optimization

- Problem is to **find a sequence of control actions** for that **minimizes a *performance function***.
  - Example performance functions pertain to time, radar exposure, fuel, and noise.
- System dynamics are described by
  - Variables **z =[y,u],** where y are state variables and u are control variables.
  - State equations Á **= f(y(t),u(t),t)** describing the dynamics of the system.
  - Initial and terminal conditions.
  - Bounding constraints on state and control variables.
- Standard approaches for solving trajectory optimization problems are based either on methods of **optimal control** or on approximations to optimal control based on **non-linear programming**
- Recently**, sample methods** have evolved as the optimizers of choice

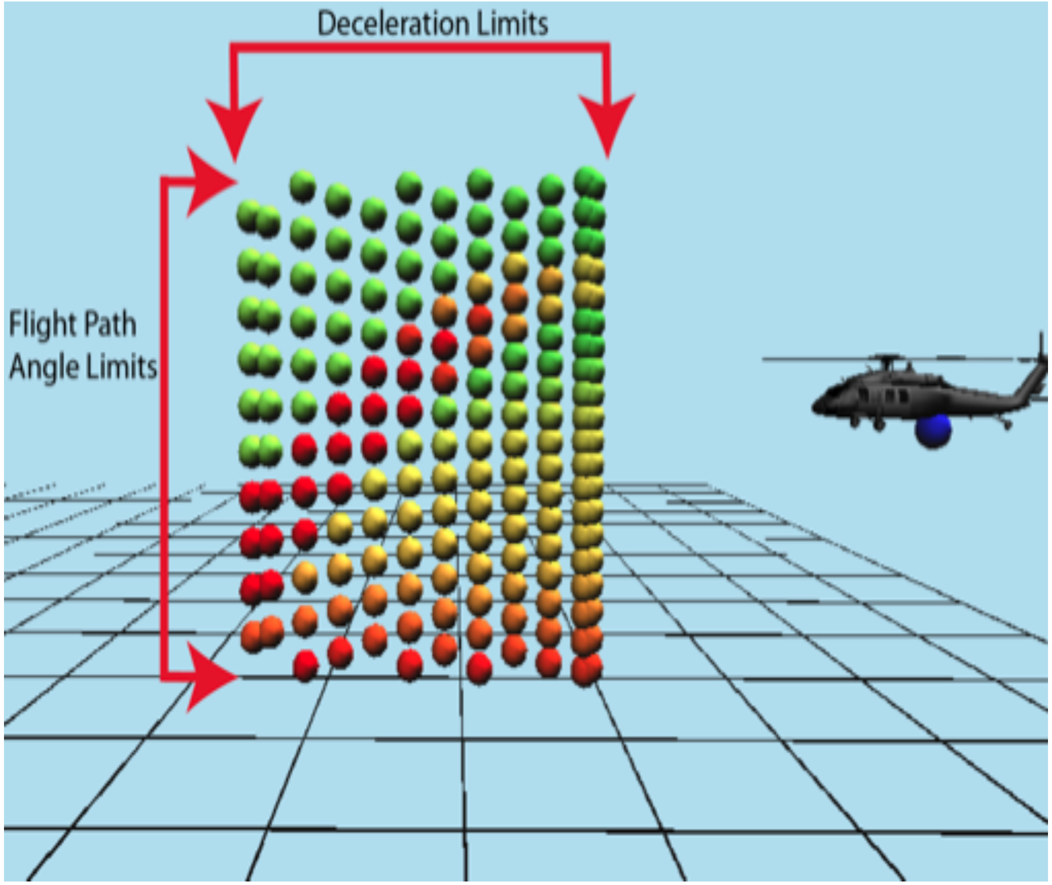
Overview of Approach

- Discrete optimization approach to planning involving **grids.**
- **Vehicle model** of position and attitude
- **State transition** model that incorporates **constraints on safety and comfort.**
- **Noise cost function** that aggregates data from RNM
- **Discretization of search space** for allowing solutions at different resolutions
- Empirical **comparison of A* with Stochastic Local Search**

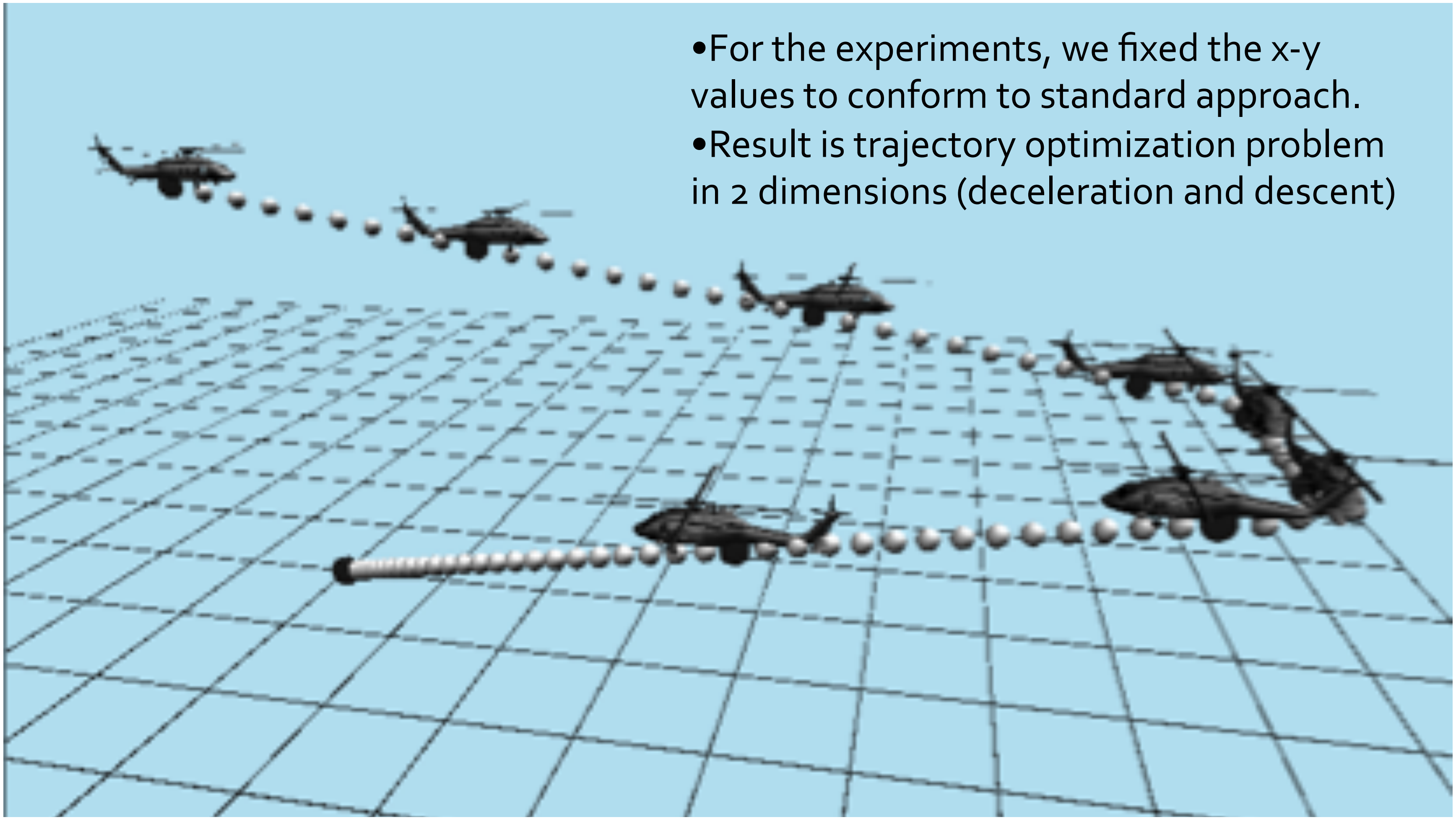


Discrete State and Control Spaces

- **State space** is a grid of points in **3D** space.
- **Action space** is **2D** grid of changes in velocity or altitude
- Limits imposed by **constraints** on deceleration and rate of descent.
- A **solution trajectory** is a sequence of state and action pairs
- Single start and end state.

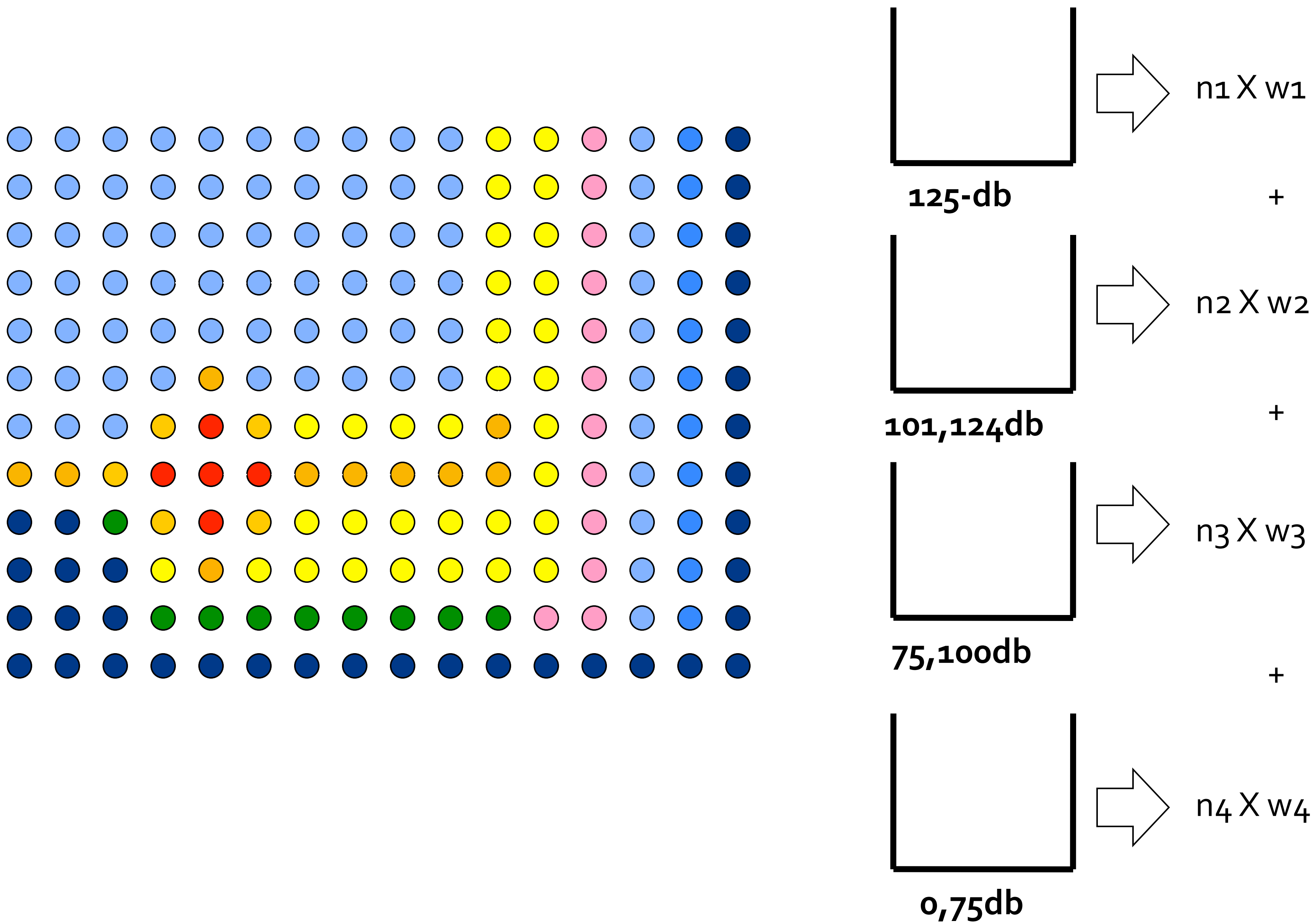


Reduction of Search Space



- For the experiments, we fixed the x-y values to conform to standard approach.
- Result is trajectory optimization problem in 2 dimensions (deceleration and descent)

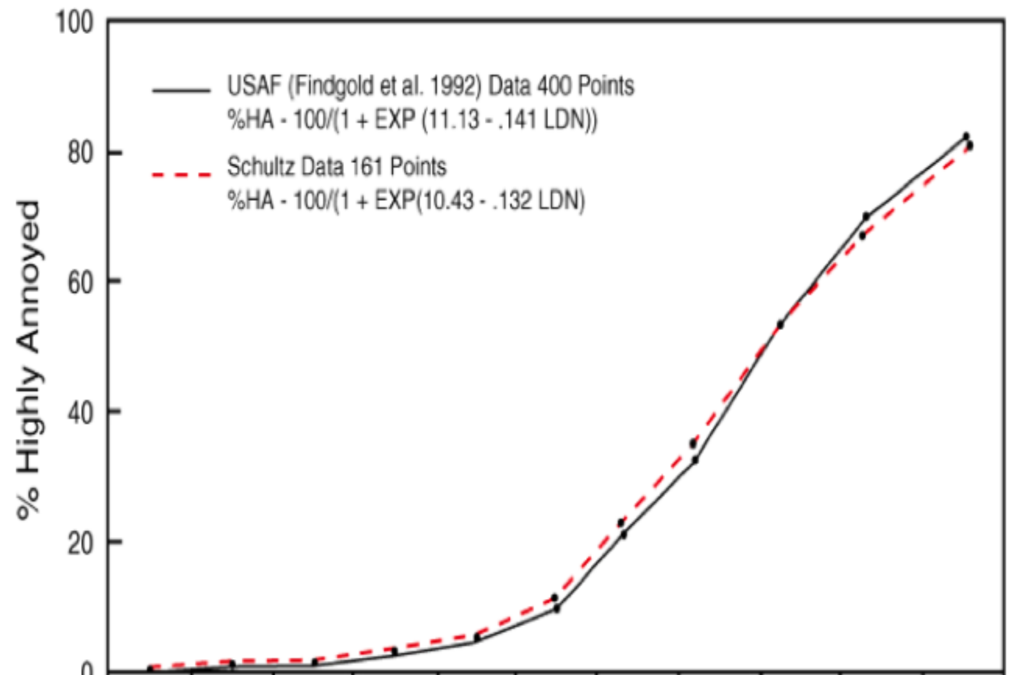
Binning Cost Function



Assigning Weights

Based on two independent sets of experiments associating dB levels with annoyance.

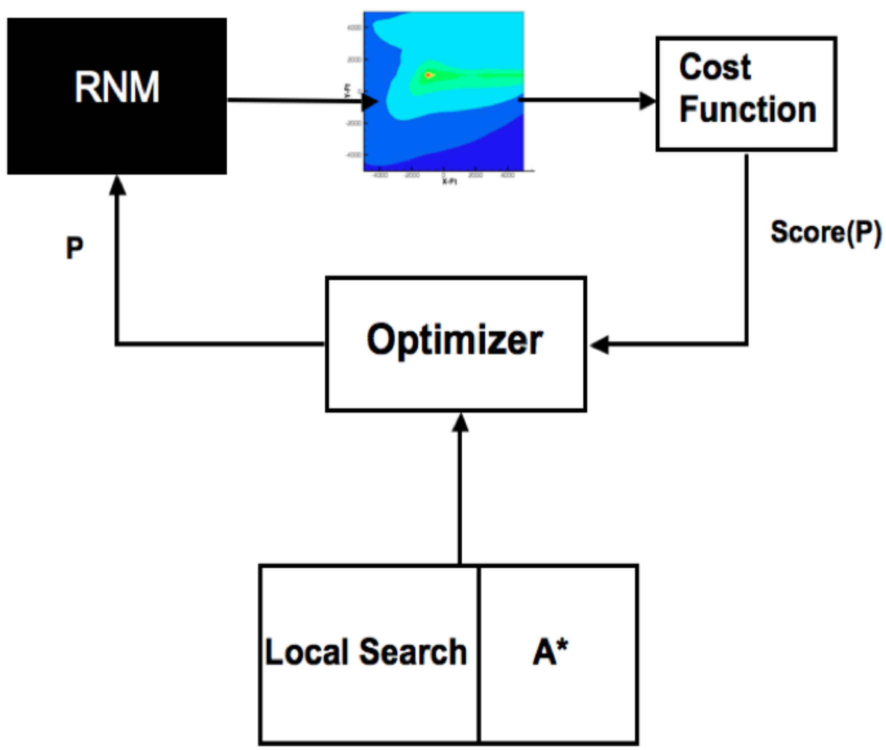
Weights were based on curve in graph.



Day - Night Average Sound Level in dB		40	45	50	55	60	65	70	75	80	85	100
Calculated % HA Points	USAF	0.41	0.831	1.66	3.31	6.48	12.29	22.1	36.47	53.74	70.16	82.64
	SCHULTZ	0.576	1.11	2.12	4.03	7.52	13.59	23.32	37.05	53.25	68.78	81

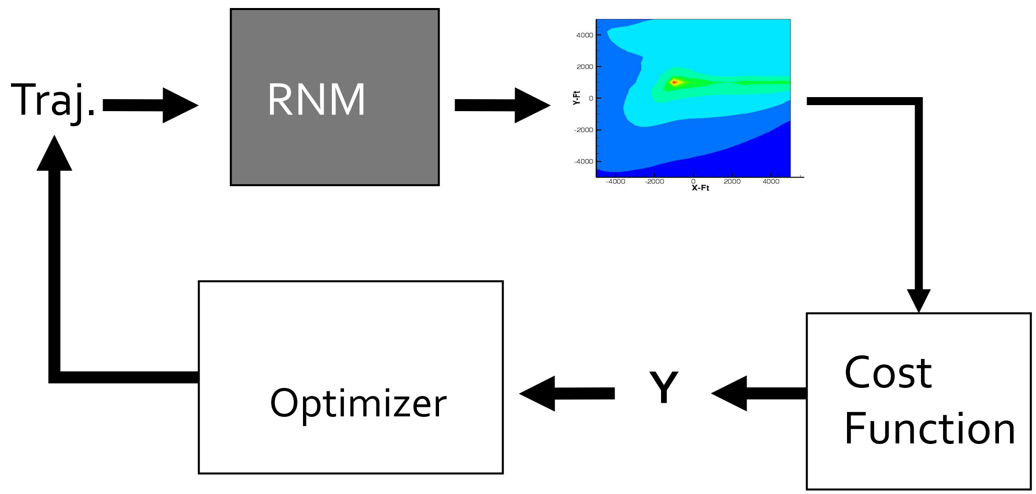
Systems Approach

- Separate search and evaluation phase
- Search phase uses either A* or SLS to generate solution
- Evaluation phase consists of run of RNM and evaluation using BIN cost function.



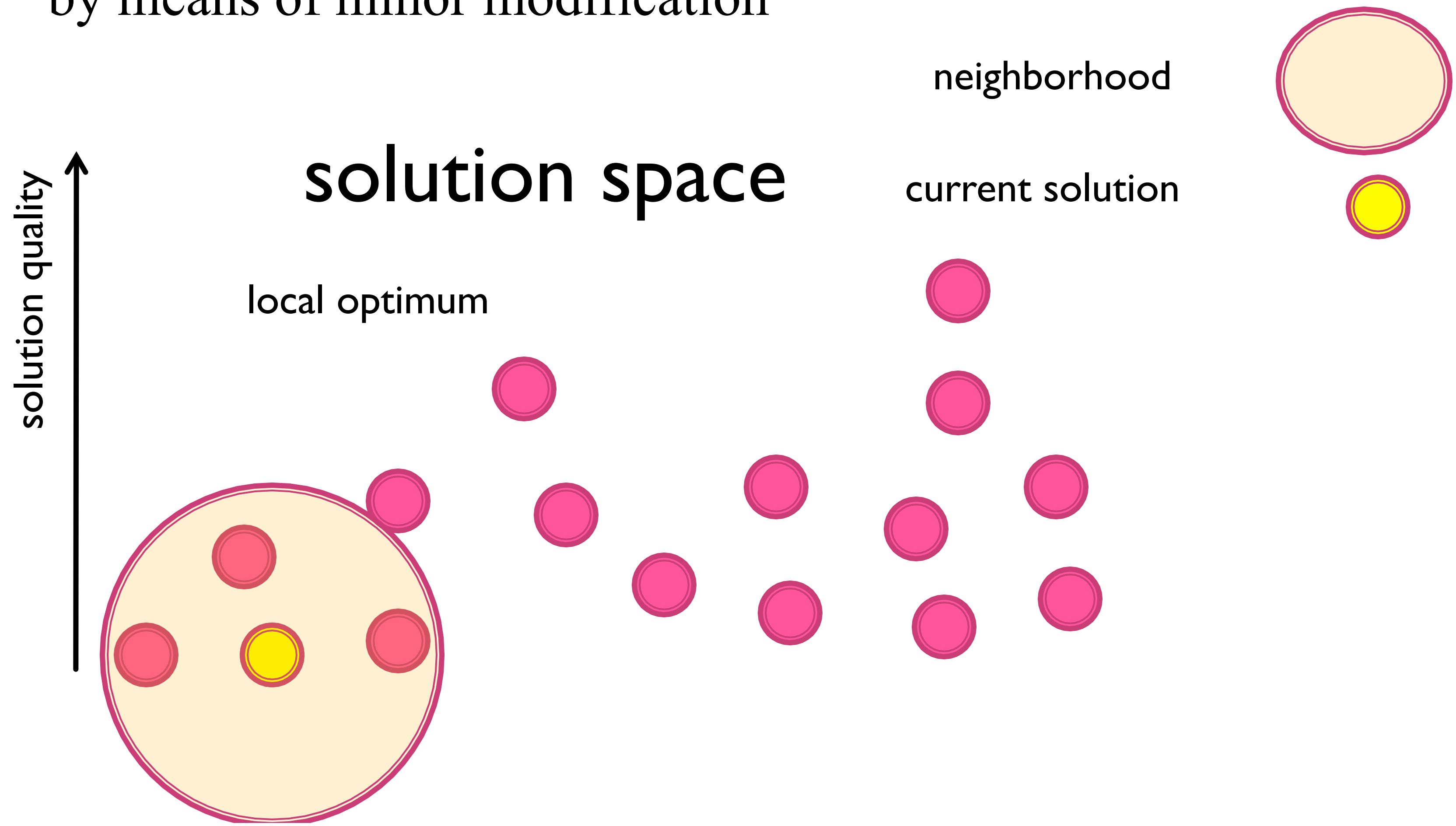
Overview of Noise Optimization Approach

- Local Stochastic Search
  - Allows for large exploration of search space with little knowledge of what is being optimized
- Uses RNM as evaluator of candidate solutions
- Randomly generated initial solutions
- Cost functions based on aggregation of predicted noise levels



Local search

Given an optimization problem and the search space of its solutions, start from an initial start position and improve iteratively by means of minor modification

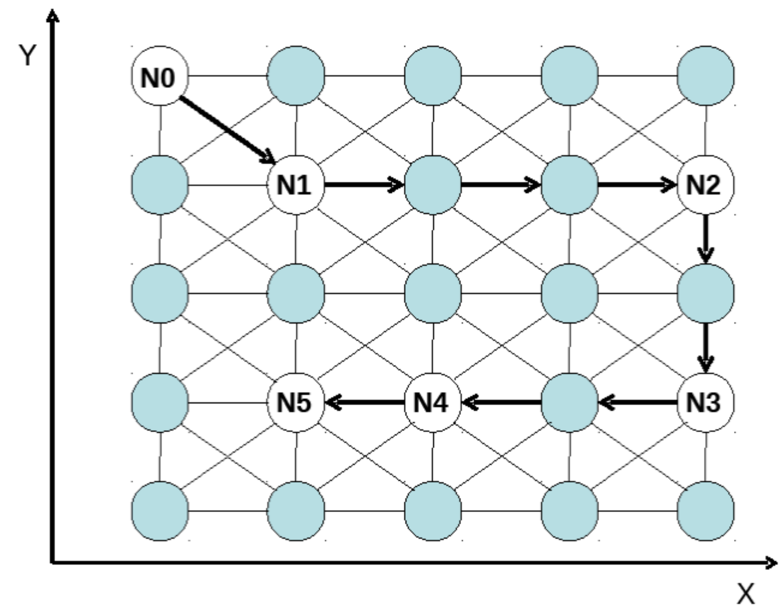


Applying local search to noise minimization

- **Search space:**

all possible "box" landing trajectories
Suggested by pilot as typical approache

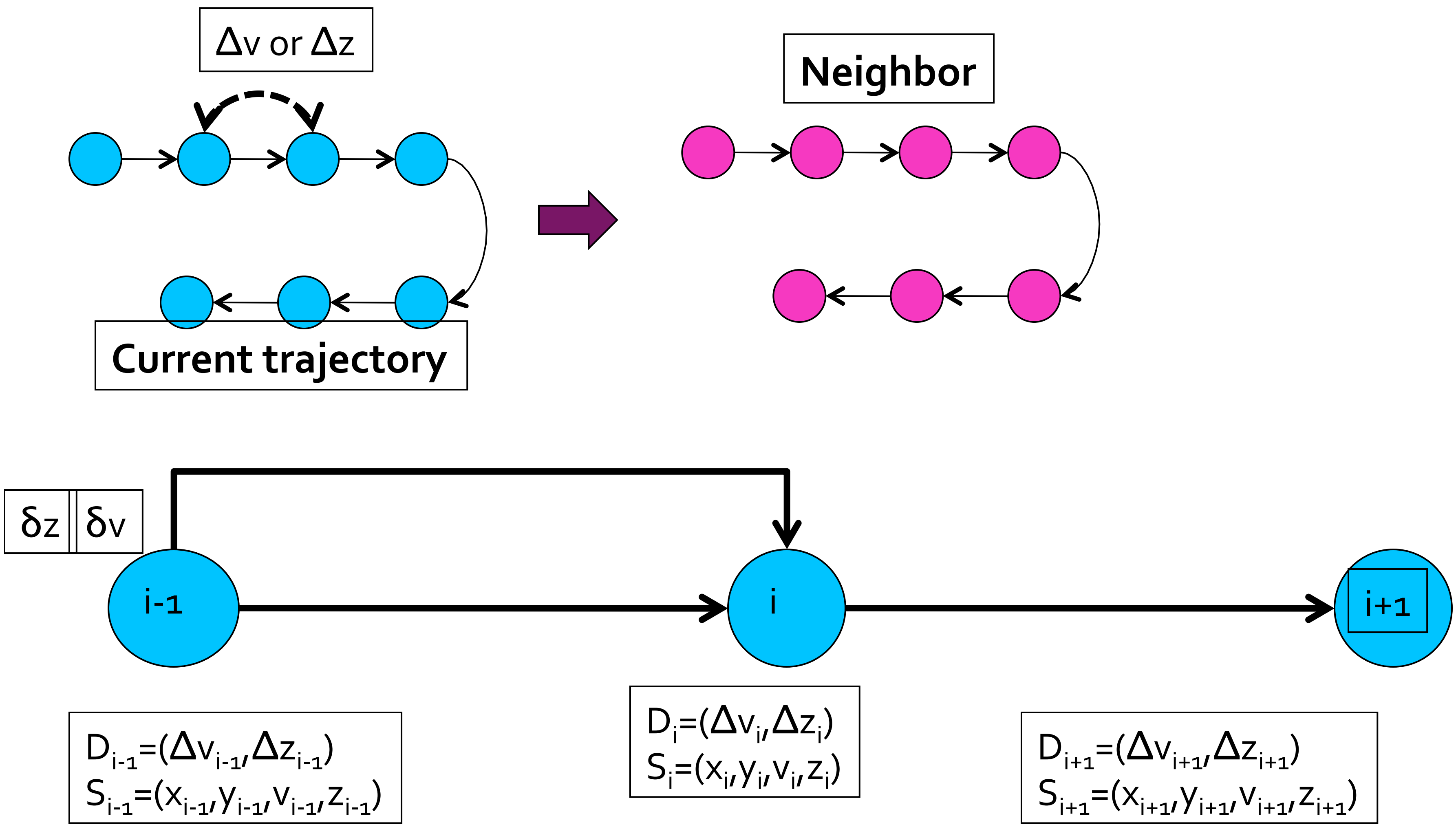
A trajectory is a sequence of
state-action pairs called nodes



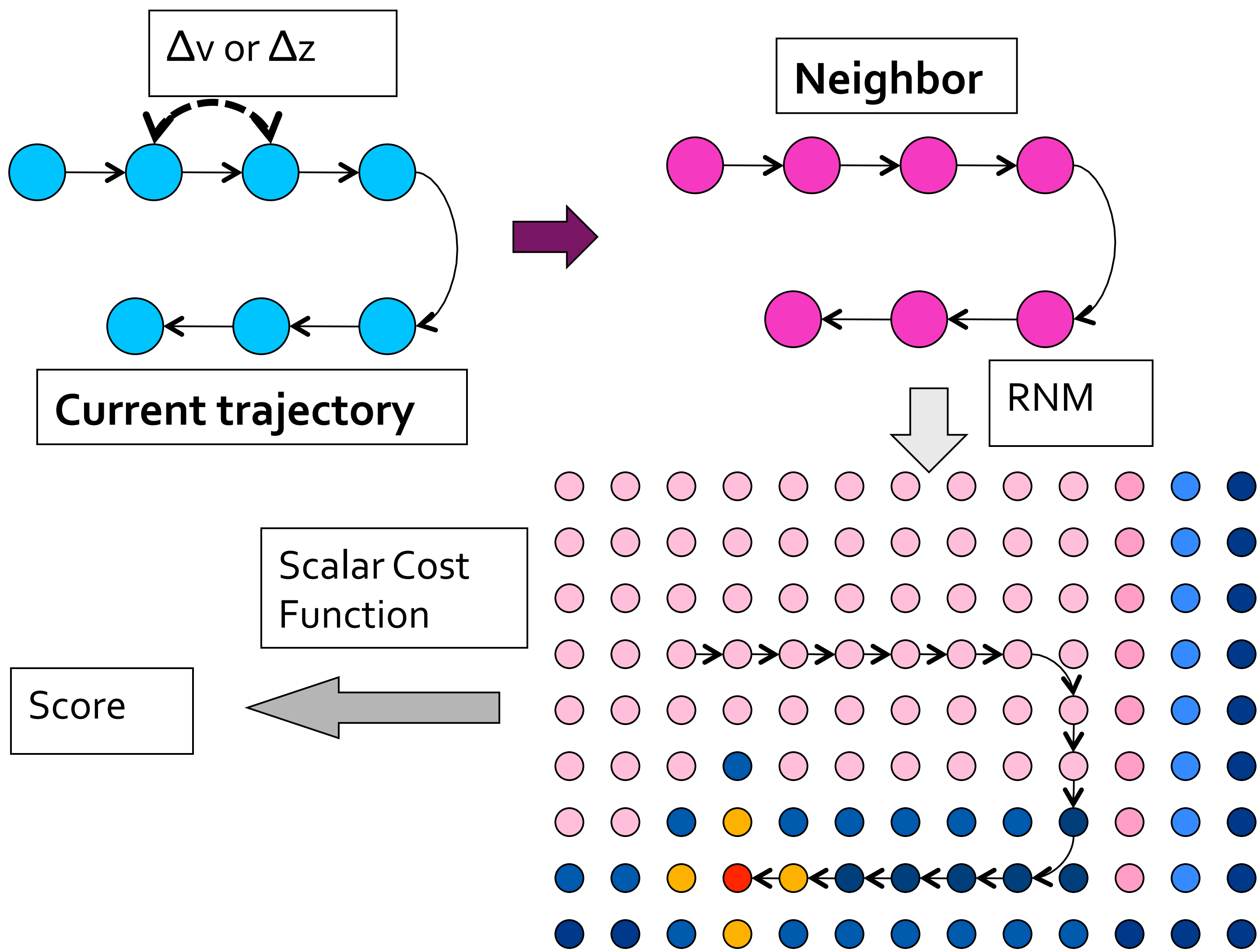
- **Neighborhood of a box trajectory T:**

Set of trajectories obtained from T by
picking any two nodes and transferring quantities of
deceleration or decent from one to the other

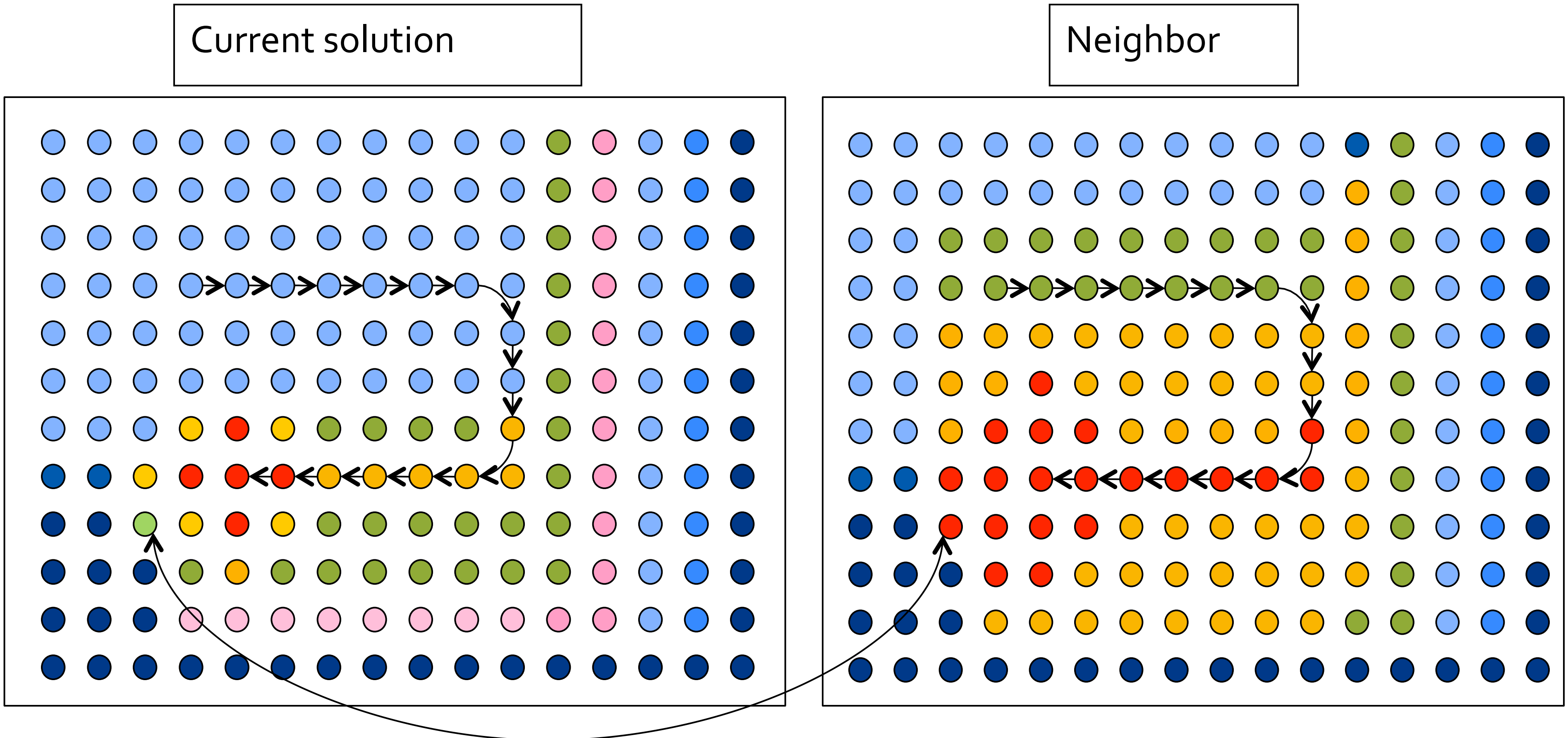
Stochastic Local search for TNOP



Local search



Significant Difference Function

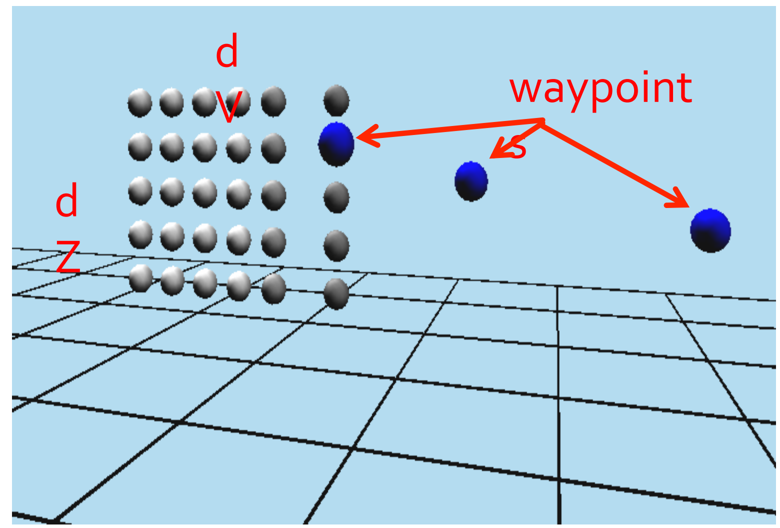


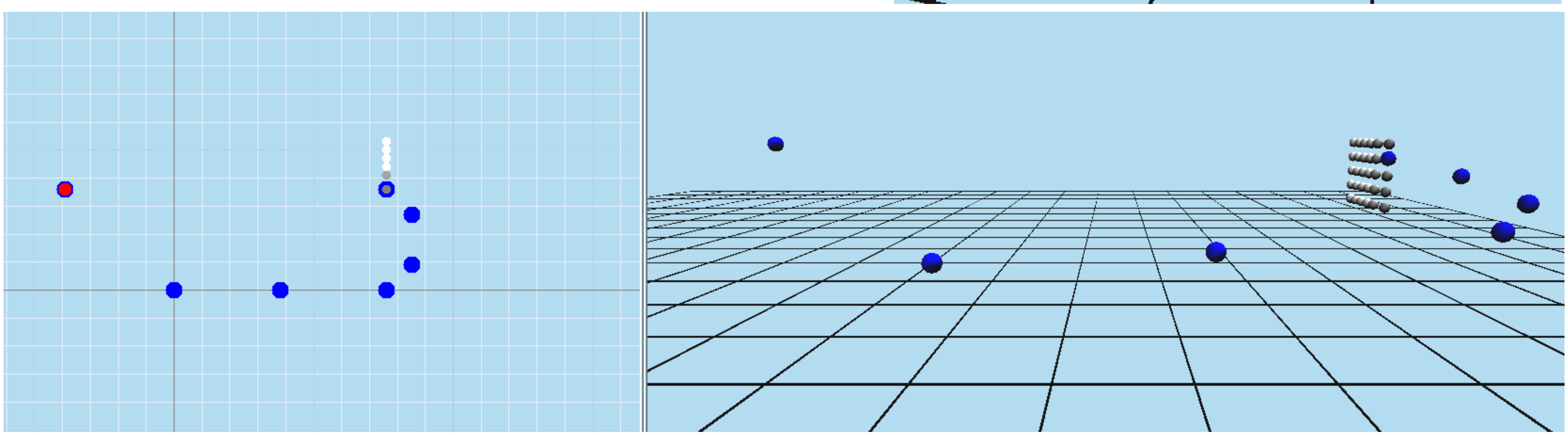
Score= number of points where neighbor is significantly more quiet – number of points where it is significantly more loud

Significantly → ≥ 1.5 dB

A*

- Complete best-first search algorithm based on incremental expansion of solution guided by heuristic estimation function.
- Heuristic estimate of cost-to-go: *fly high and slow to goal*.
    - Flying slow to goal state without descending
    - Empirically shown to be admissible
- Aggregating cost is problematic because noise of path is not a simple aggregation of path segments.





Constraints on Dynamics

- Conditions that make a trajectory suitable to fly
  - Angle of descent between 0 and 12 degrees
  - Deceleration between 0 and 0.1 gs
- A trajectory is flyable if it satisfies all the deceleration and angle-of-decent constraints along its path.
- Enforced by neighborhood function

Experiments

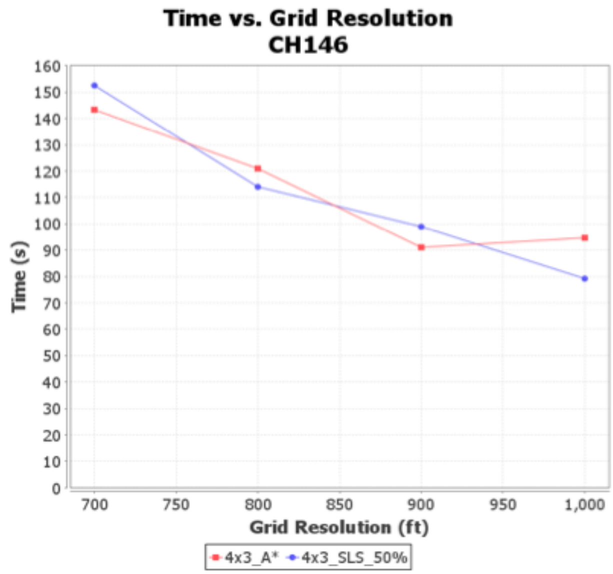
- Primary goal is to demonstrate potential for improvements to standard approaches followed by pilots
  - Provide inputs to acoustic field tests
  - Comparison of solutions with ’standard operations’
- Comparisons of A* with SLS with respect to:
  - Quality and run time performance
  - Effects of varying grid resolution

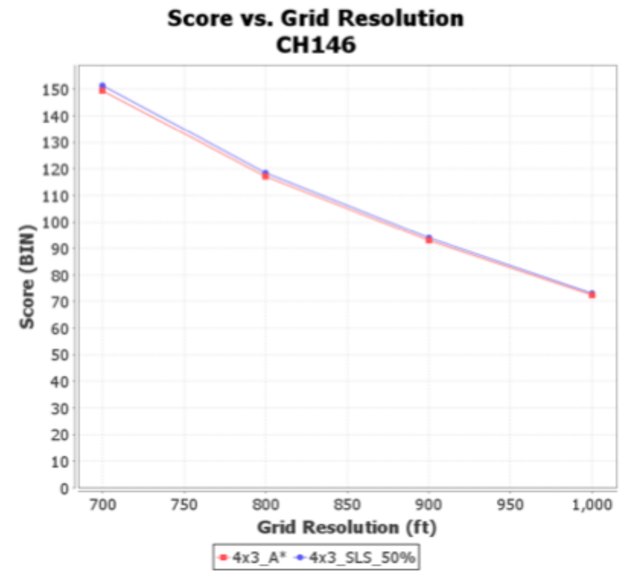
Parameter settings

- SLS algorithm has tunable parameters to adjust the
  - randomness of search
  - depth of search
- Additional parameters are used to adjust
  - Grid resolution (number of data points)
  - Search resolution (number of control actions)

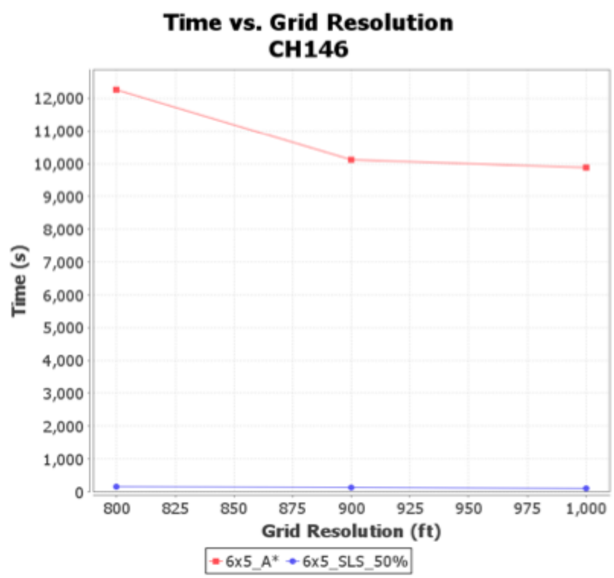
SLS v A*: Varying Grid Resolution

Low Search Res



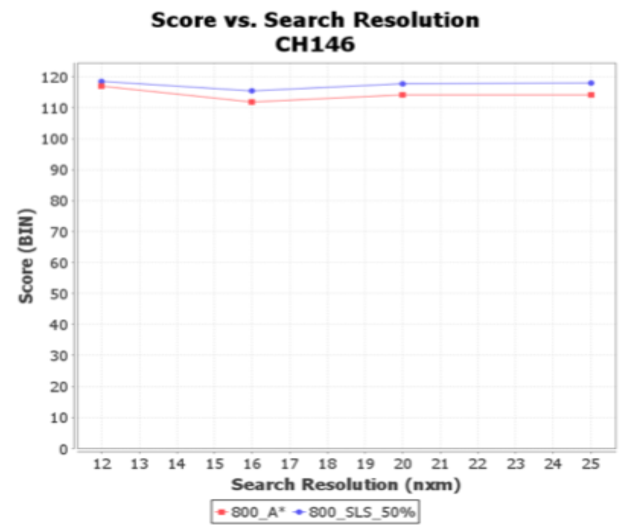


High Search Res

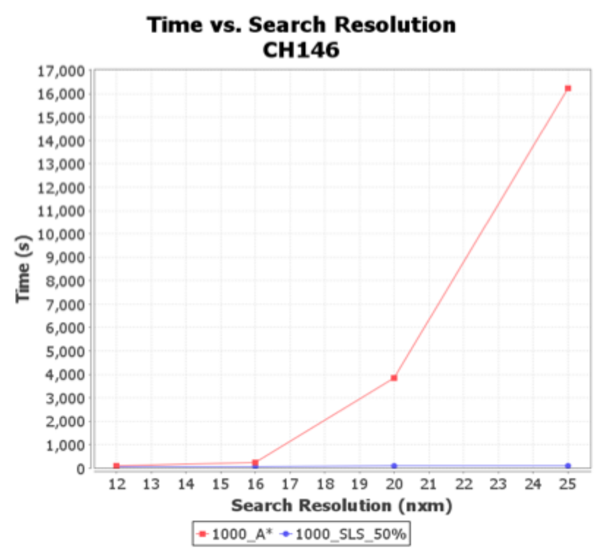


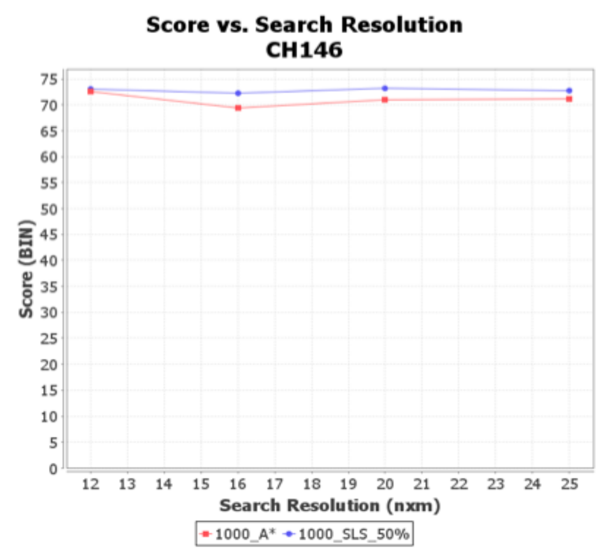
SLS v A*: Varying Search Resolution

Low Grid Res



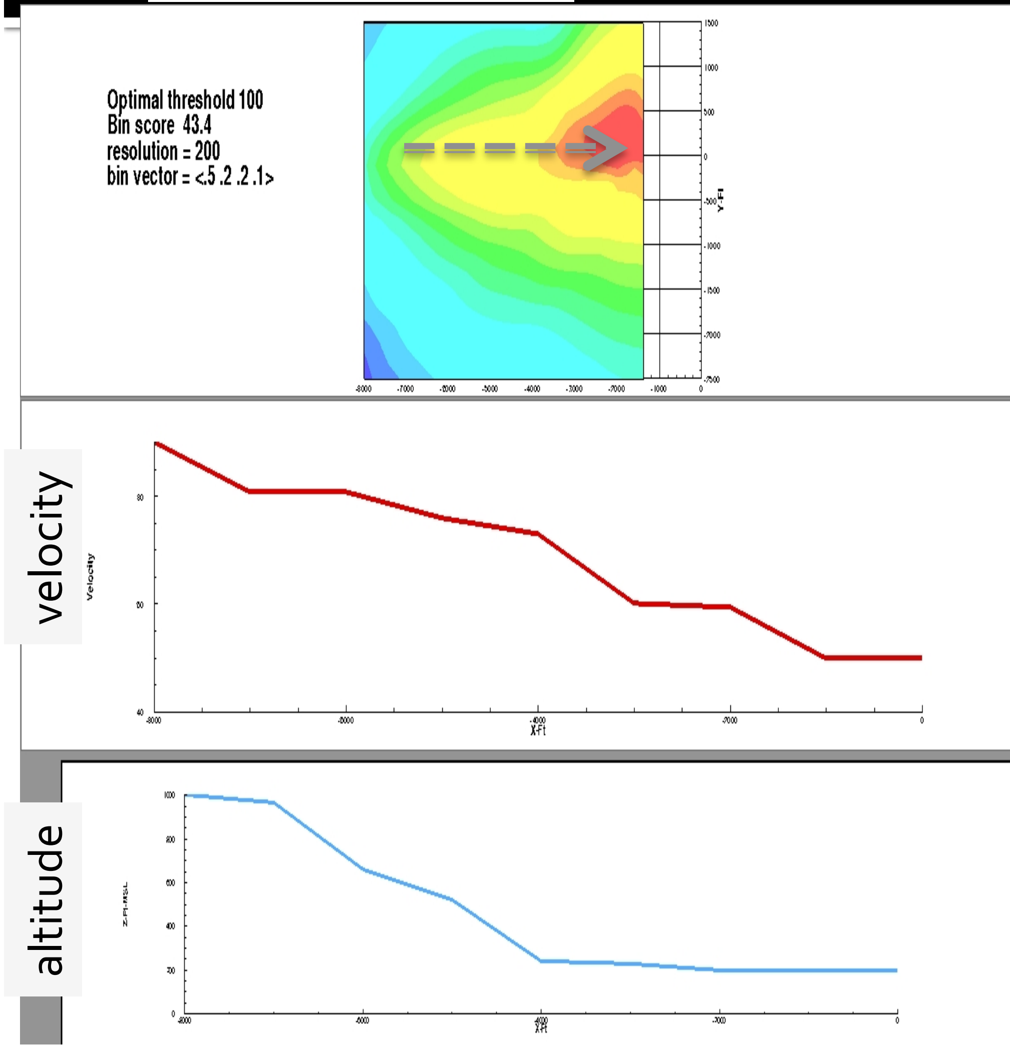
High Grid Res





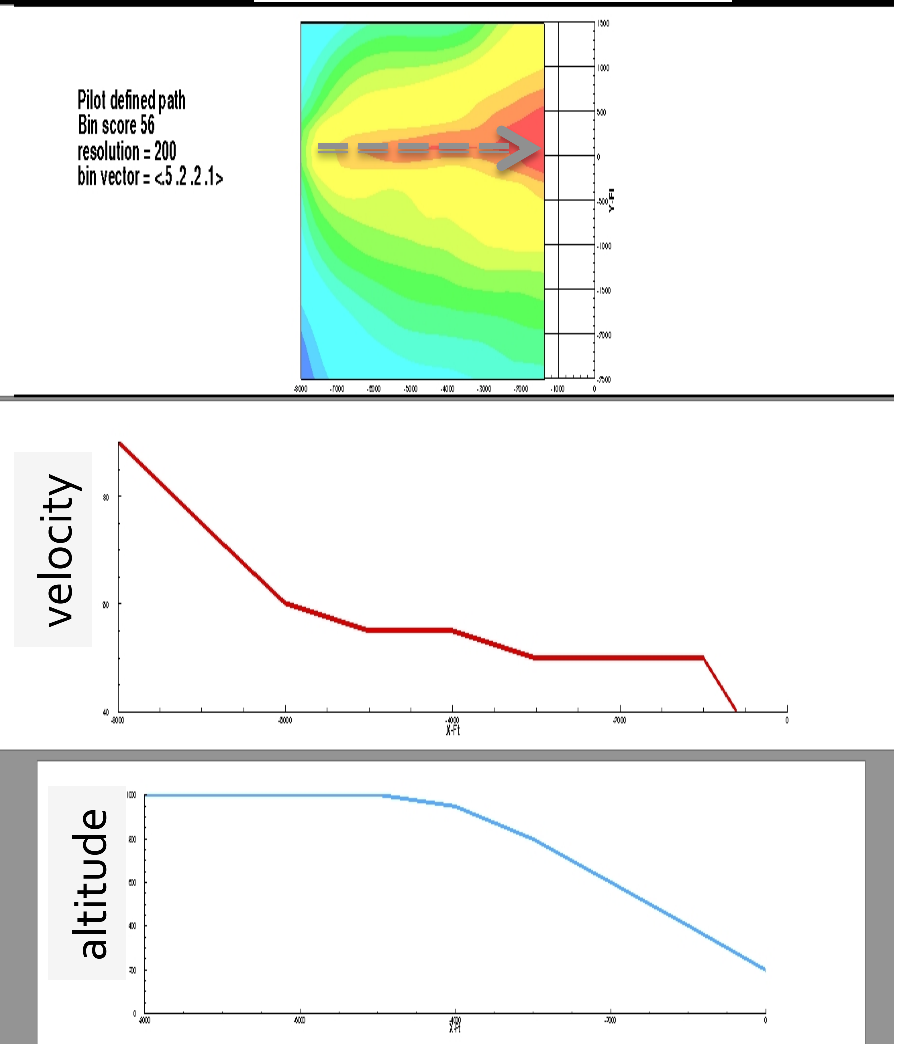
Optimal trajectory vs standard practice

AI-suggested Path



Feet to landing point

Pilot-suggested Path

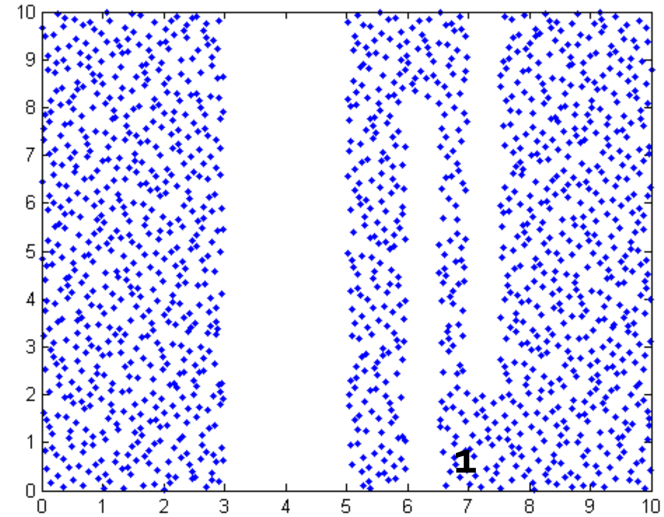


Feet to landing point

Future work: sampled based planners

- Rapidly-exploring Random Trees
- Probabilistic Road Maps:

1. Sampling
   - 4-d space (x,y,z,v,h) with heading
2. Linking
   - Flyability constraints
3. Weighting
   - Bin function score
4. Shortest Path



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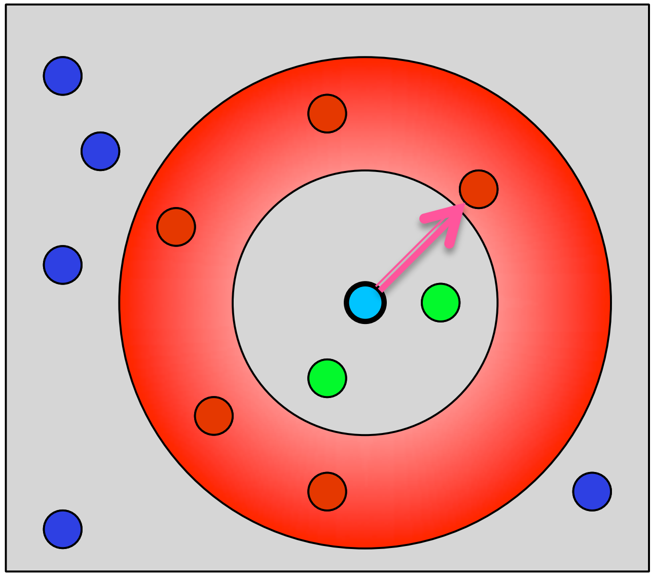

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Future work: RNM surrogate

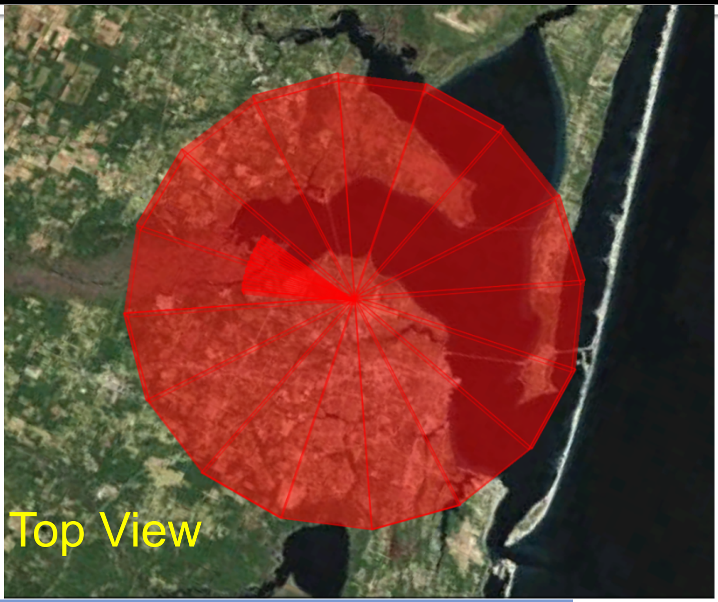
- Running RNM is the heaviest part of computation
- Bypass RNM with an ML-based surrogate that will predict the value of the cost function

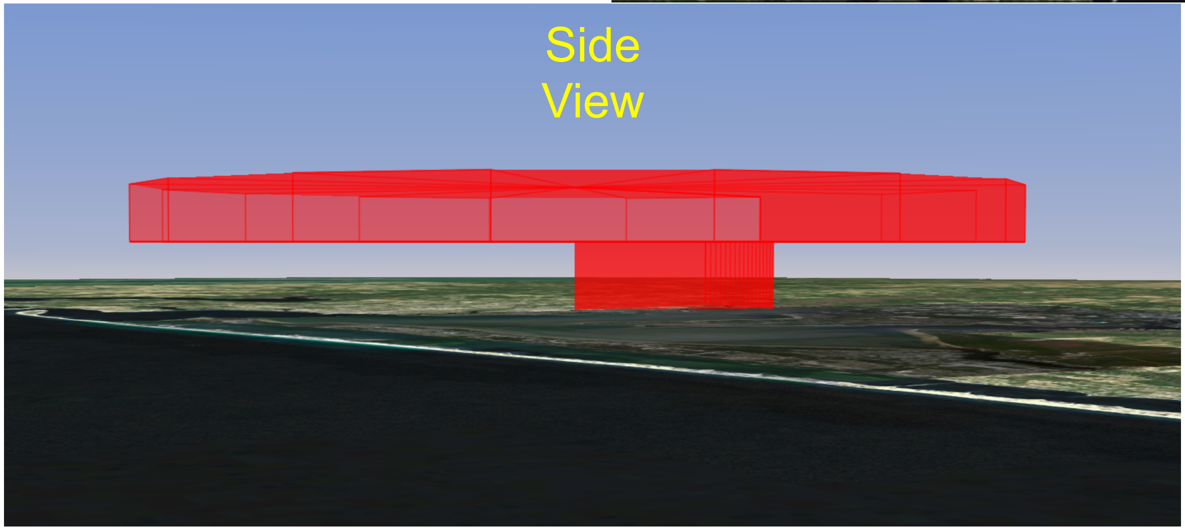
Future Work: Incorporating Land Usage

- Imported GIS data
- Weight contour plots according to land usage

Future Work: Airspace

- Incorporate airspace constraints, such as Class C airspace and approach corridors for active runways





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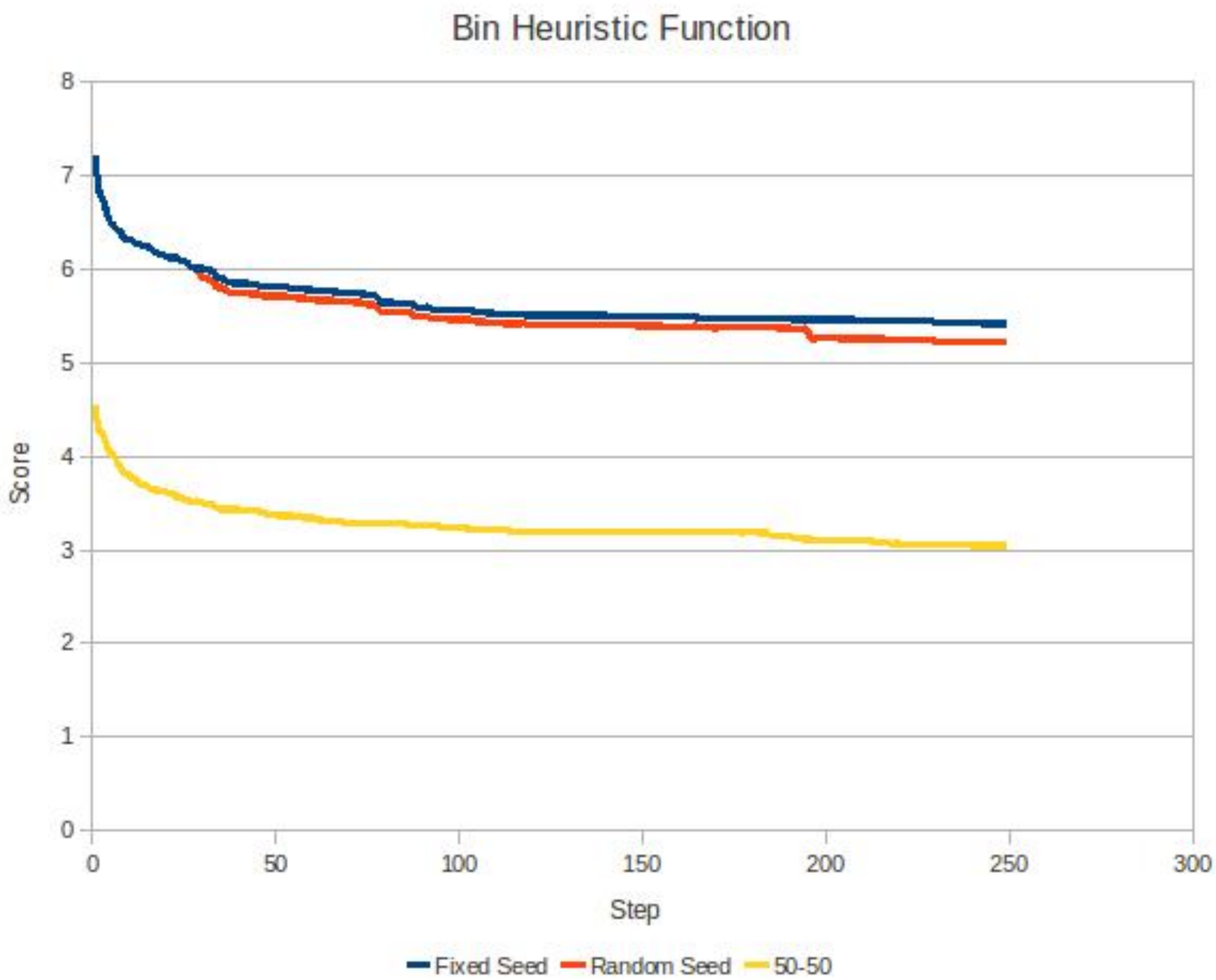
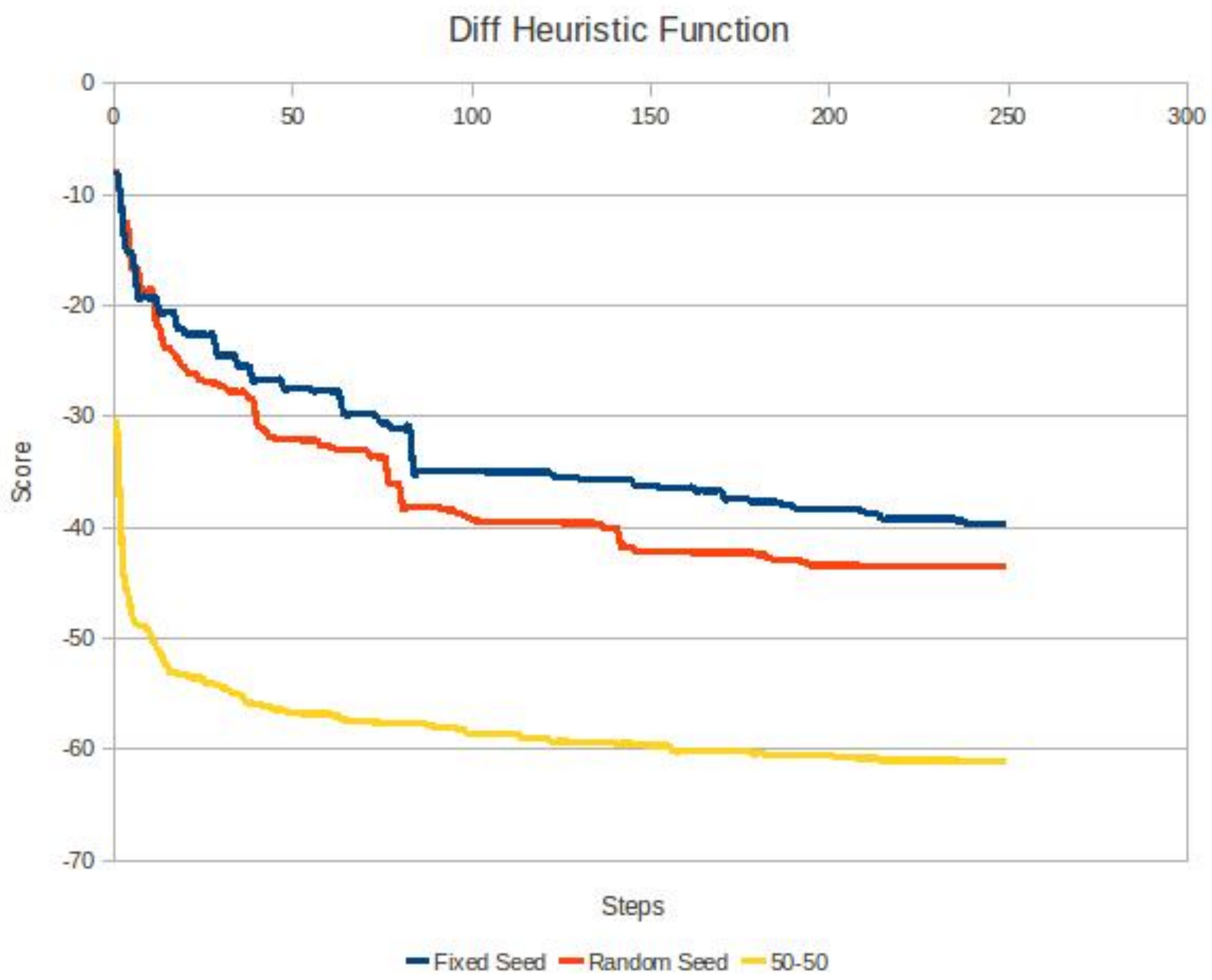
Tested algorithms

- **Fixed seed**
  - Starts from a fixed trajectory suggested by pilots
  - Picks random neighbor if neighborhood is empty
- **Random seed**
  - Starts from a fixed trajectory suggested by pilots
  - Picks random trajectory if neighborhood is empty
- **50-50**
  - Random start
  - 50% of the time picks a random solution
- Runtime behavior, average on 200 runs

Experimental results: Bin function

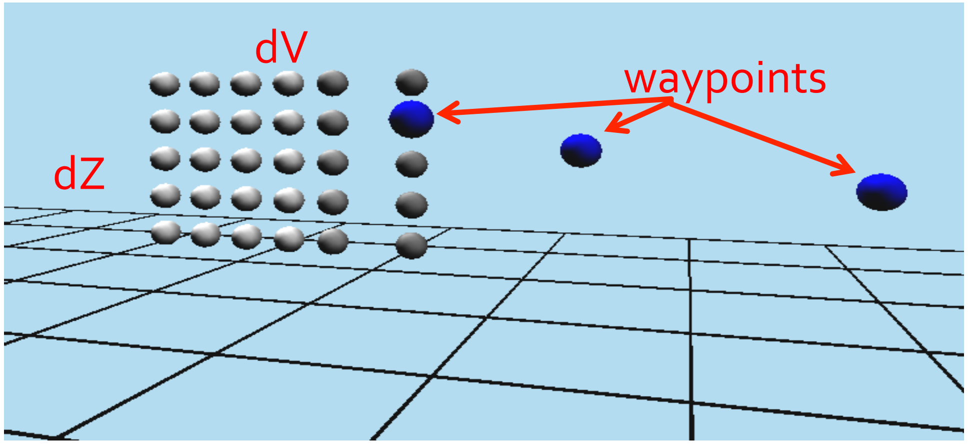


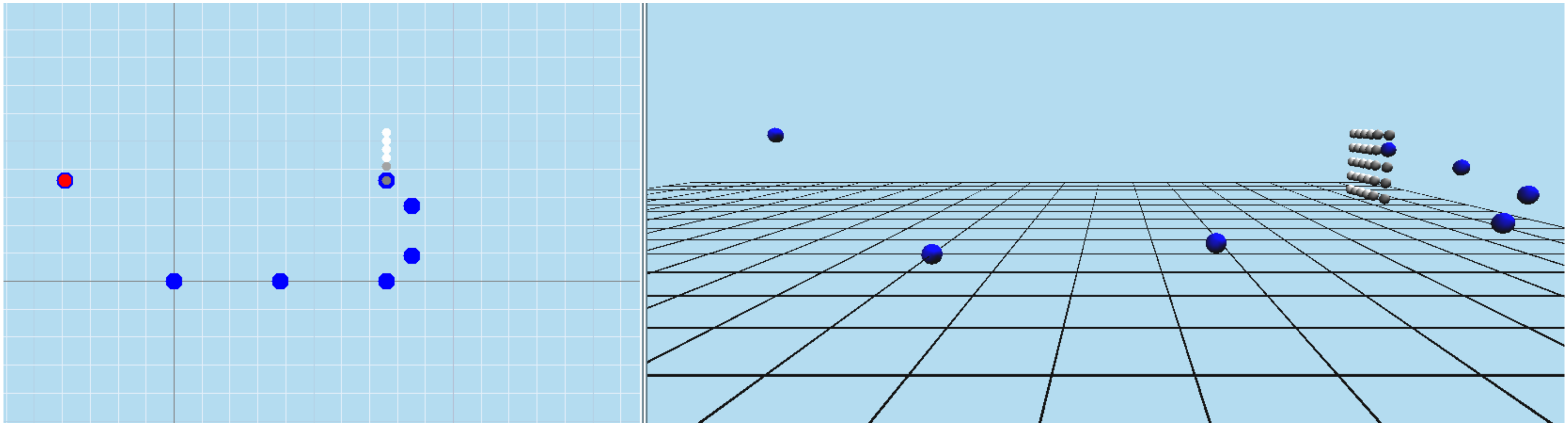
Exeperimental results: Diff function



Future work: path planning

- Path Planning techniques
- A*





Successfull research, growing team..

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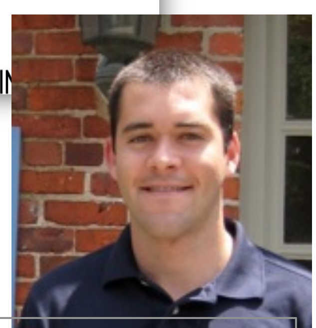
Tom Eskridge



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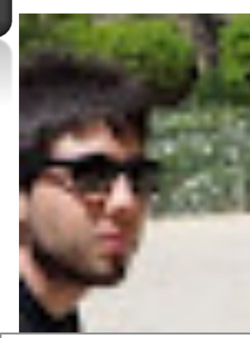
Riccardo Ferro



Riccardo Tesselli