

Full Mission Simulation of a Rotorcraft Unmanned Aerial Vehicle for Landing in a Non-Cooperative Environment

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SAE Aerospace Control and Guidance Systems Committee Meeting
March 3rd 2005 -- Salt Lake City, UT

Presentation Outline

- **PALACE program overview**
- **PALACE Integrated Simulation**
- **Autonomous Rotorcraft Project (ARP)**
- **Machine vision algorithms**
- **Results**
- **Conclusions / Future work**

PALACE Program Chart

Precision Autonomous Landing Adaptive Control Experiment

- **Purpose:**

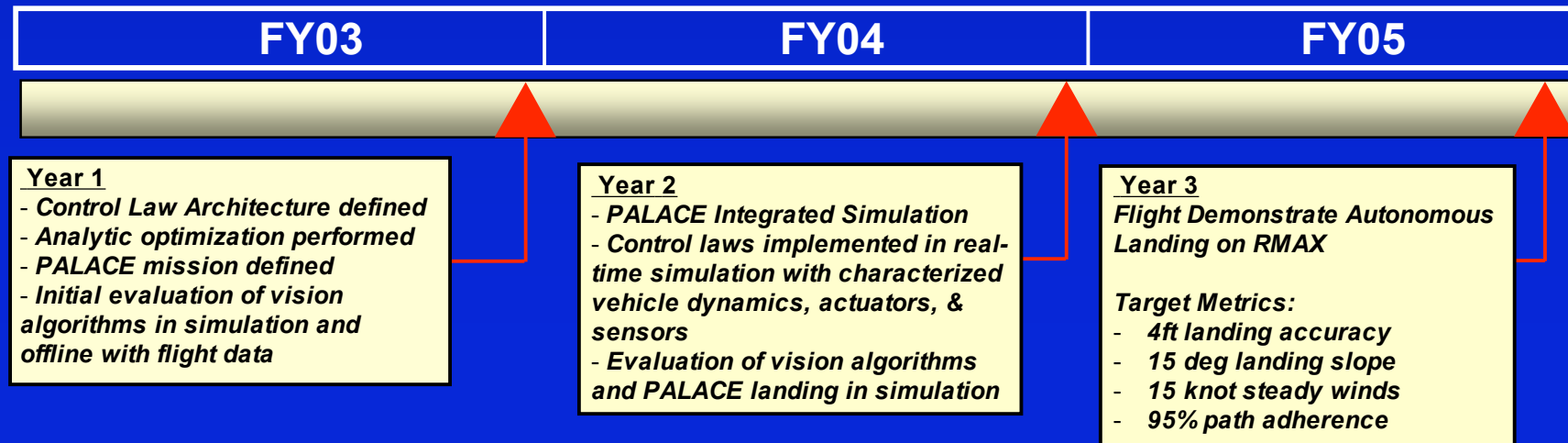
- *Autonomous precision UAV VTOL to unprepared sites in variable winds for: perch and stare surveillance, precision UAV supply delivery, recovery and FARP operations. Exploit greater portion of potential VTOL performance envelope.*

- **Product:**

- *Performance criteria, methods and flight proven adaptive control techniques for precision helicopter landing at arbitrary sites. Includes full nonlinear vehicle dynamics, control laws, sensor, & actuator models.*

- **Payoff:**

- *Reduces UAV reliance on prepared landing sites, Reduces manpower, Reduces VTOL crashes, Allows precision UAV critical supply delivery, Allows perch and stare surveillance capabilities, Provides capability for UAV FARP Ops without returning to home, Greater VTOL UAV maneuverability*



PALACE Mission

PALACE Landing Mission:

- Non-cooperative landing site
- Obstacles in landing zone
- GPS denied/occluded environment
- On-board intelligent decision making
- Agile / aggressive maneuvering

4. Arrival at Landing Zone:

- Survey of landing zone at 500 feet
- Rapid spiral descent to 100 feet
- Fuzzy logic decision making - heading

5. Vision Based Descent and Landing:

- Stereo cameras and laser range finder
- Stereo machine vision elevation mapping
- Safe landing area determination (JPL)
- Machine vision feature tracking (JPL)
- Pseudo-GPS feedback for navigation

1. Pre-flight Mission Planning:

- Define full PALACE mission
- Specify intermediate way points
- Specify location of landing zone

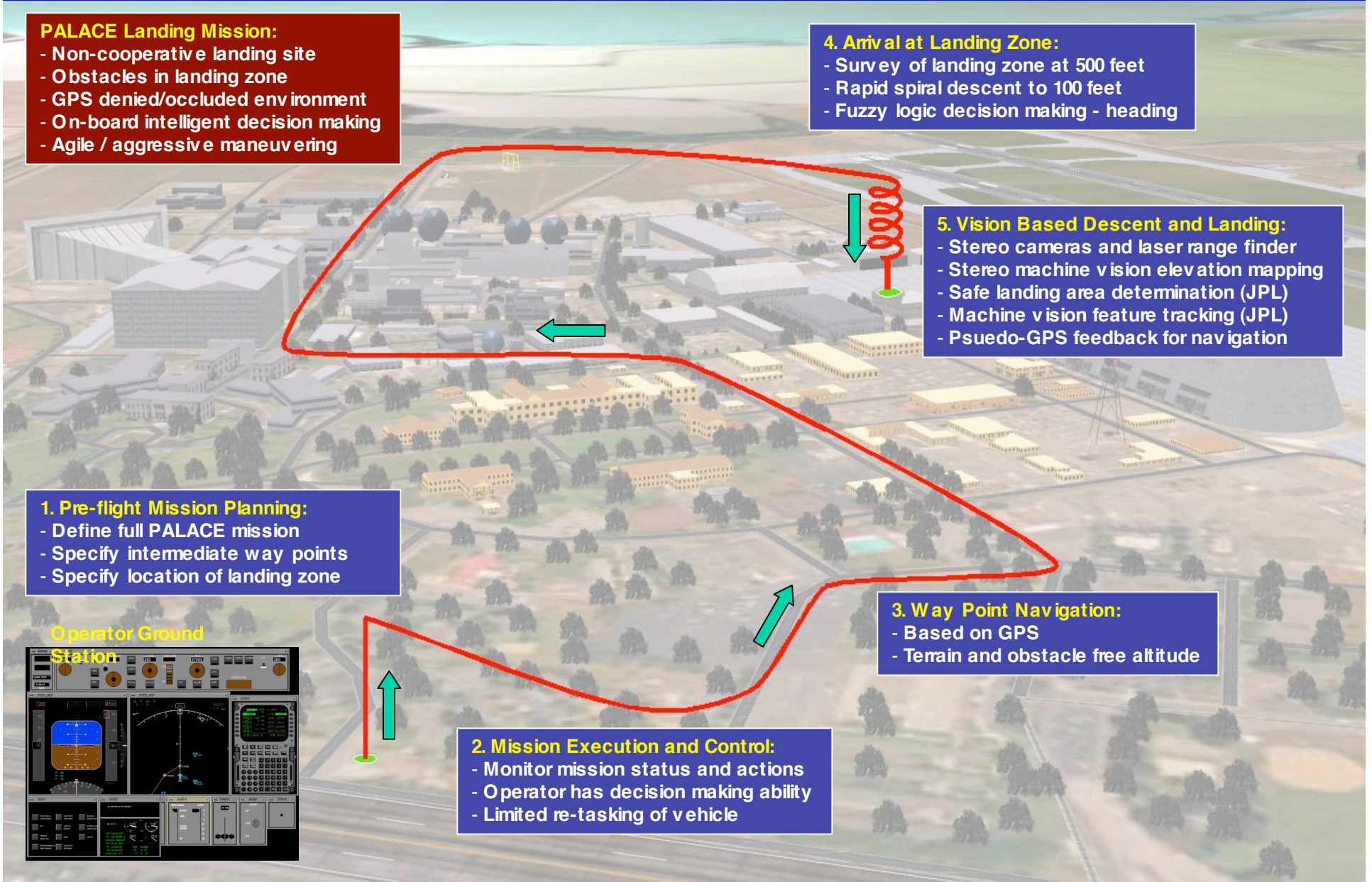
3. Way Point Navigation:

- Based on GPS
- Terrain and obstacle free altitude

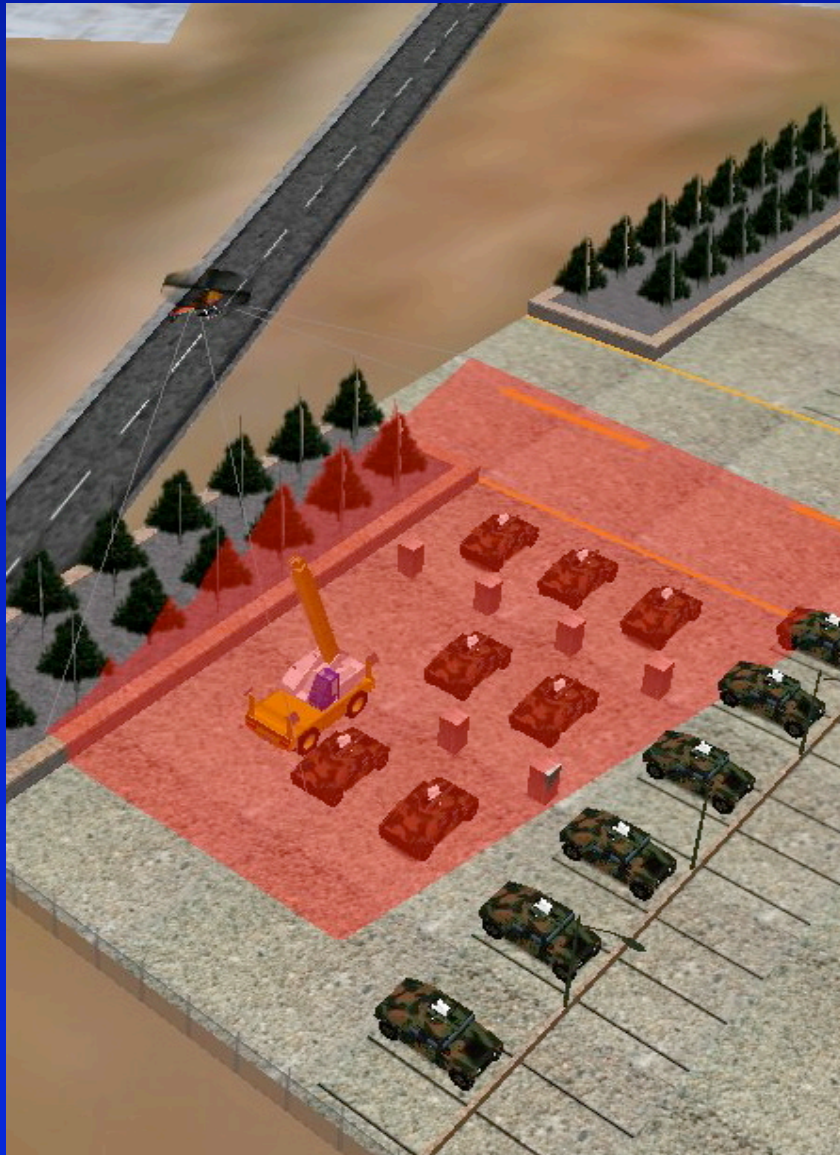
2. Mission Execution and Control:

- Monitor mission status and actions
- Operator has decision making ability
- Limited re-tasking of vehicle

Operator Ground Station



PALACE Landing Procedure



GPS

Arrival at landing zone

Determine optimum heading
for landing

Determination of landing point
at 100 feet (SLAD)

MPE

Switch to MPE navigation for
way point control

Descend 20 feet along
glideslope under MPE

Validate landing point /
determine new landing point

Descent to 10 feet along
glideslope under MPE

DR

Switch to Dead Reckoning for
way point control

Final landing under DR position
estimation

PALACE Landing Video

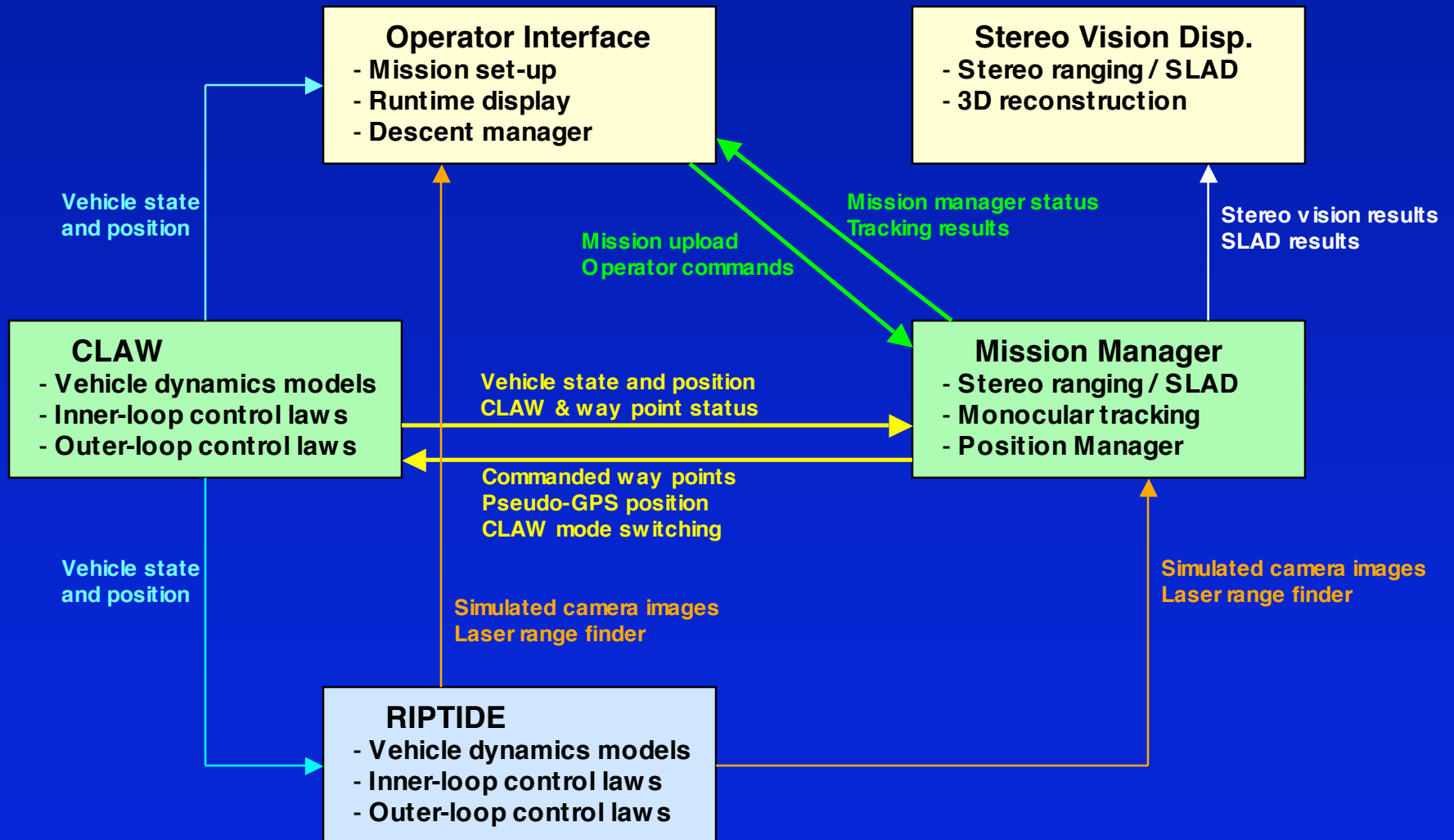


PALACE Integrated Simulation

Functions of Integrated Simulation:

- **Provide an environment for the development, integration and demonstration of the machine vision landing technologies**
- **Quantify and optimize the performance of the machine vision algorithms in realistic landing scenario**
- **Identify limitations and failure modes and refine the autonomous landing procedure to mitigate these**
- **Provide a level of risk reduction for the flight experiments and demonstrations**

Integrated Simulation Architecture



Mission Set-up Operator Interface

The interface is divided into several sections:

- Review and Save:** Contains instructions for reviewing the mission profile, saving, printing, and flying the mission.
- Mission Header:** Shows the current mission status and selected options: Takeoff Location, Landing Area, Waypoint Markers, Rally Point, and Review and Save.
- Map:** Displays an aerial view of the mission area with a pink line connecting waypoints. The waypoints are labeled with their coordinates and parameters:
 - Waypoint 01 (Green): 46632 N, 83944 E, 150m/20kts
 - Waypoint 02 (Red): 46213 N, 83741 E
 - Waypoint 03 (Blue): 46777 N, 84385 E, 150m/25kts
 - Waypoint 04 (Blue): 46230 N, 84524 E, 150m/30kts
 - Waypoint 05 (Green): 45936 N, 84091 E, 100m Circle
 - Waypoint 06 (Blue): 45944 N, 84466 E, 150m/30kts
 - Waypoint 07 (Blue): 45483 N, 84466 E, 150m/30kts
- Right Panel:** Includes a Photo dropdown menu, navigation buttons (Home, Back, Forward, Up, Down), Zoom in/out buttons, and a Hide Tags button.
- Mission Profile:** A text-based summary of the mission parameters:

```
The mission profile appears below:
Operator: Colin Theodore
Mission: Example
Operation Area: Moffett

Launch: N 36,4168
       E -122,064
Elevation: 100,0 meters
Initial Climb To: 100,0 meter
Initial Speed To: 100,0 knots

Waypoint 01
Fly Through Waypoint
N 36,418
E -122,059
Altitude: 0,0 meters
Speed To Waypoint: 0,0 knots
Continue Req'd: No

Waypoint 02
Fly Through Waypoint
N 36,418
E -122,059
Altitude: 150,0 meters
Speed To Waypoint: 25,0 knot
Continue Req'd: No

Waypoint 03
Fly Through Waypoint
N 36,4131
E -122,057
Altitude: 150,0 meters
Speed To Waypoint: 30,0 knot
Continue Req'd: No
```
- Bottom Buttons:** SAVE, PRINT, and FLY buttons.

Mission Runtime Operator Interface

The interface features a top navigation bar with menu items: AV Controls, Camera Controls, Display Controls, Mission Profile, and Help. A Warning indicator is present, along with PAUSE and ABORT buttons.

Air Vehicle Performance

ALT	VSI	HDG	SPEED
8888	000 ▲	000	222... 000 ... 333
0000 Feet	000	000	knots
5555	000	000	Lat-Long ▲
MODE			RUN TIME
CLIMBING			0hrs 00min
LAT-LONG			
00° 00' N 000° 00' W			

Mode Control

ENROUTE NAVIGATION

01	WPT	02
Command Req'd	TYPE	FlyThrough
00,000	ALT (ft)	1,000
000	HDG (deg)	030
000	SPD (kts)	040
N 000 00 000	GPS	N 000 00 000
W 000 00 000		W 000 00 000

Proceed to Next Wpt.

OPTIONS

Moving Map

ARC MAP

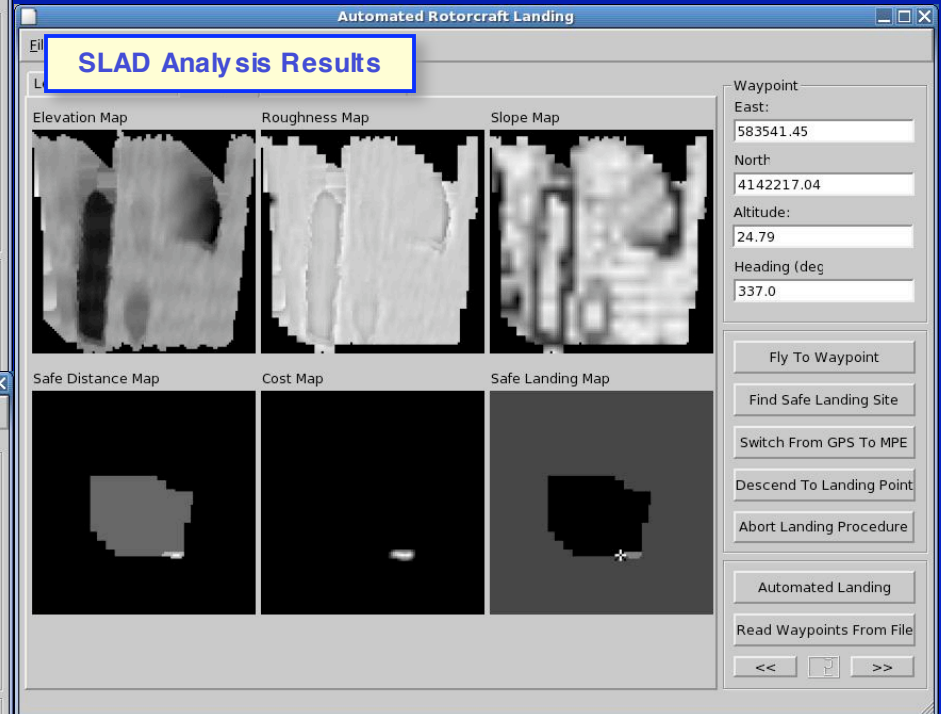
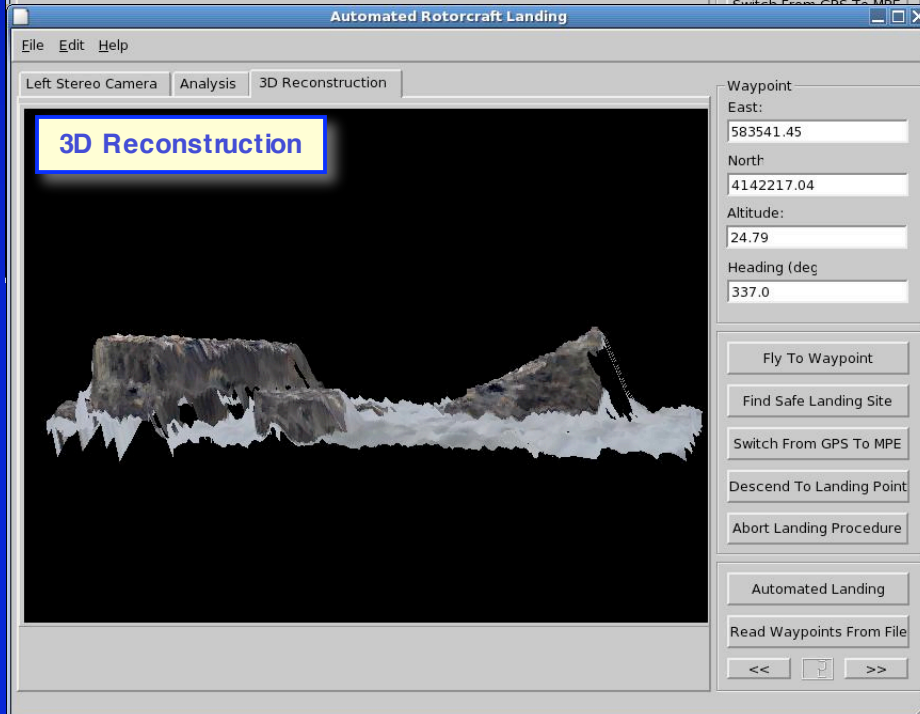
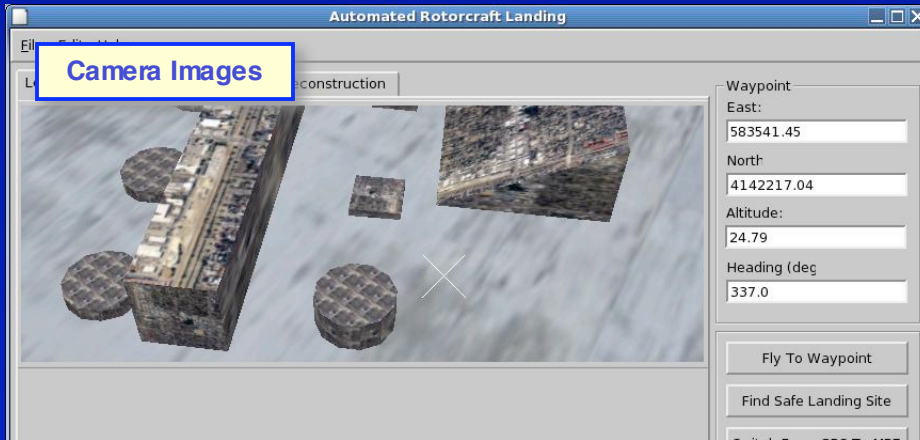
Camera View

Descent Manager

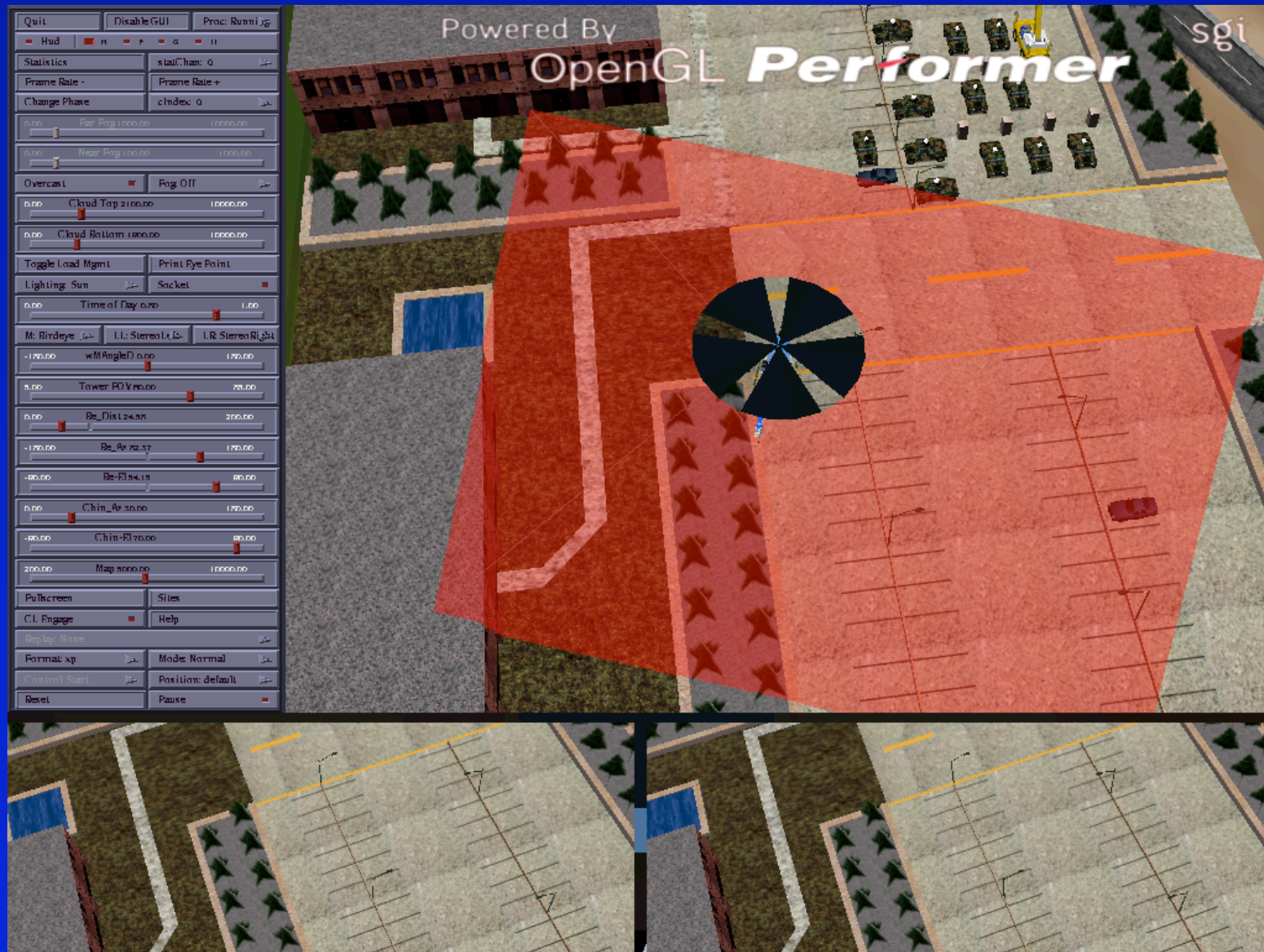
Landing Site (+) Coordinates	
N 123.45.6789	
W 23.45.6789	

ABORT Descent | Continue Descent

Stereo Vision Display



RIPTIDE Simulation Environment



Autonomous Rotorcraft Project (ARP)

Yamaha RMAX helicopter:

- 184 lbs GW, 65 lbs payload
- One hour endurance
- 3 m rotor diameter



Laser rangefinder(s)

Avionics payload and stub wing

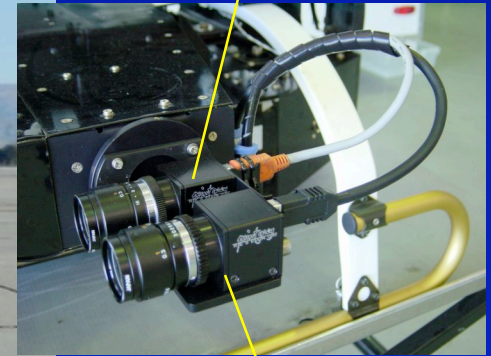
Autonomous Rotorcraft Project (ARP)

Point Grey Research
Flea - Firewire camera

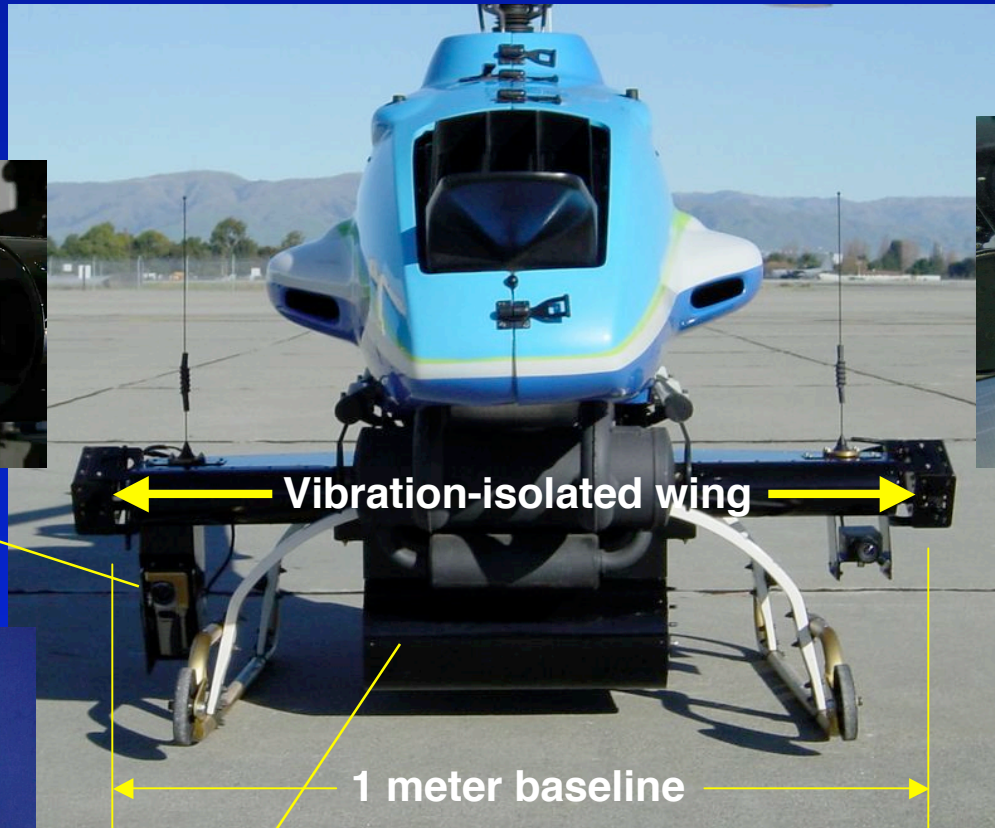


Camcorder

Point Grey Research
Flea - Firewire camera

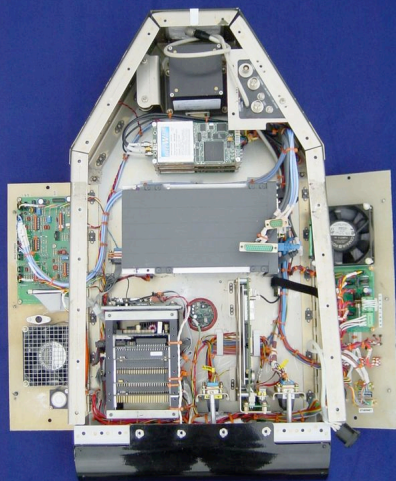


Color Unibrain
Fire - i400 camera



Avionics Payload:

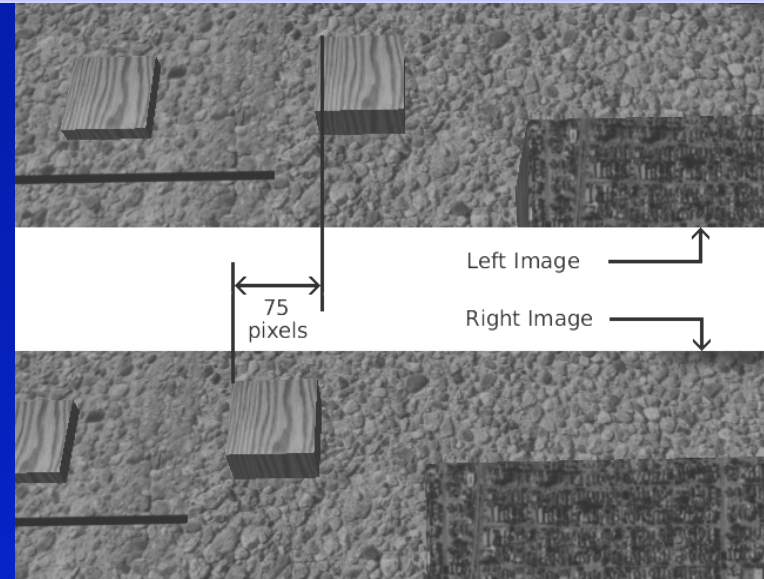
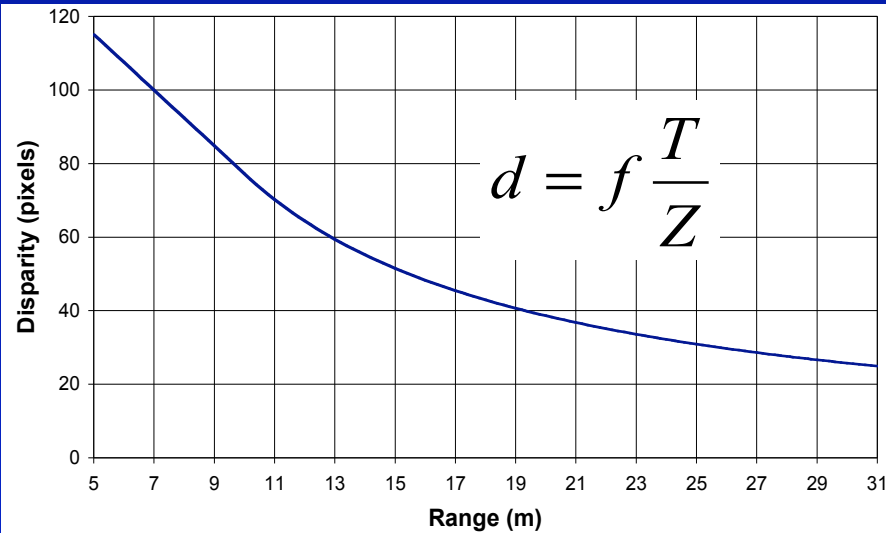
- Crossbow AHRS IMU
- PC104+ flight control computer
- Compact PCI vision computer with 802.11b
- Sonar, Ashtech DGPS



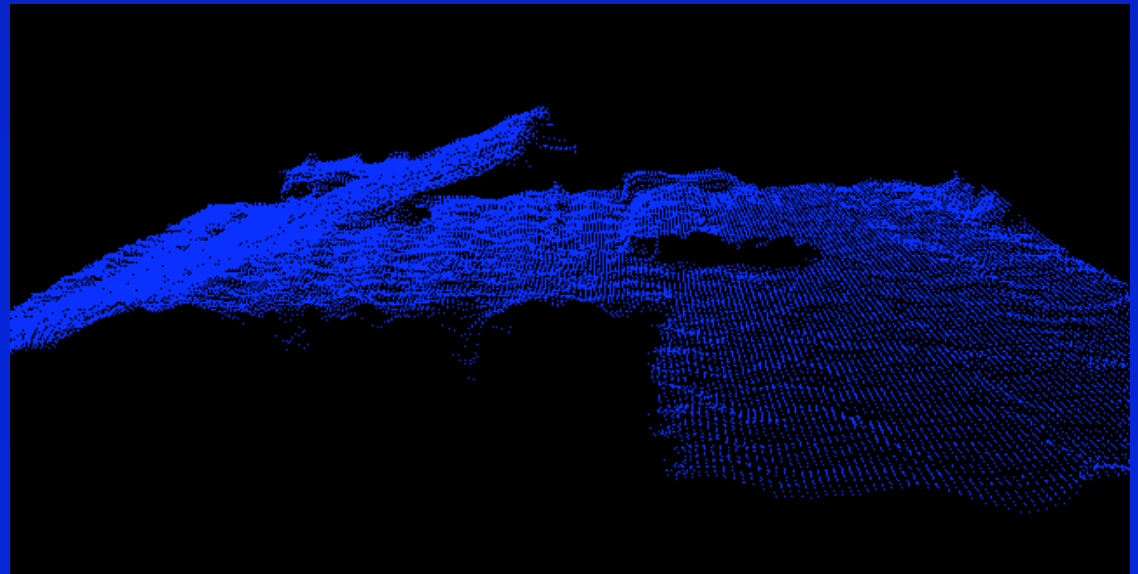
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Stereo Ranging



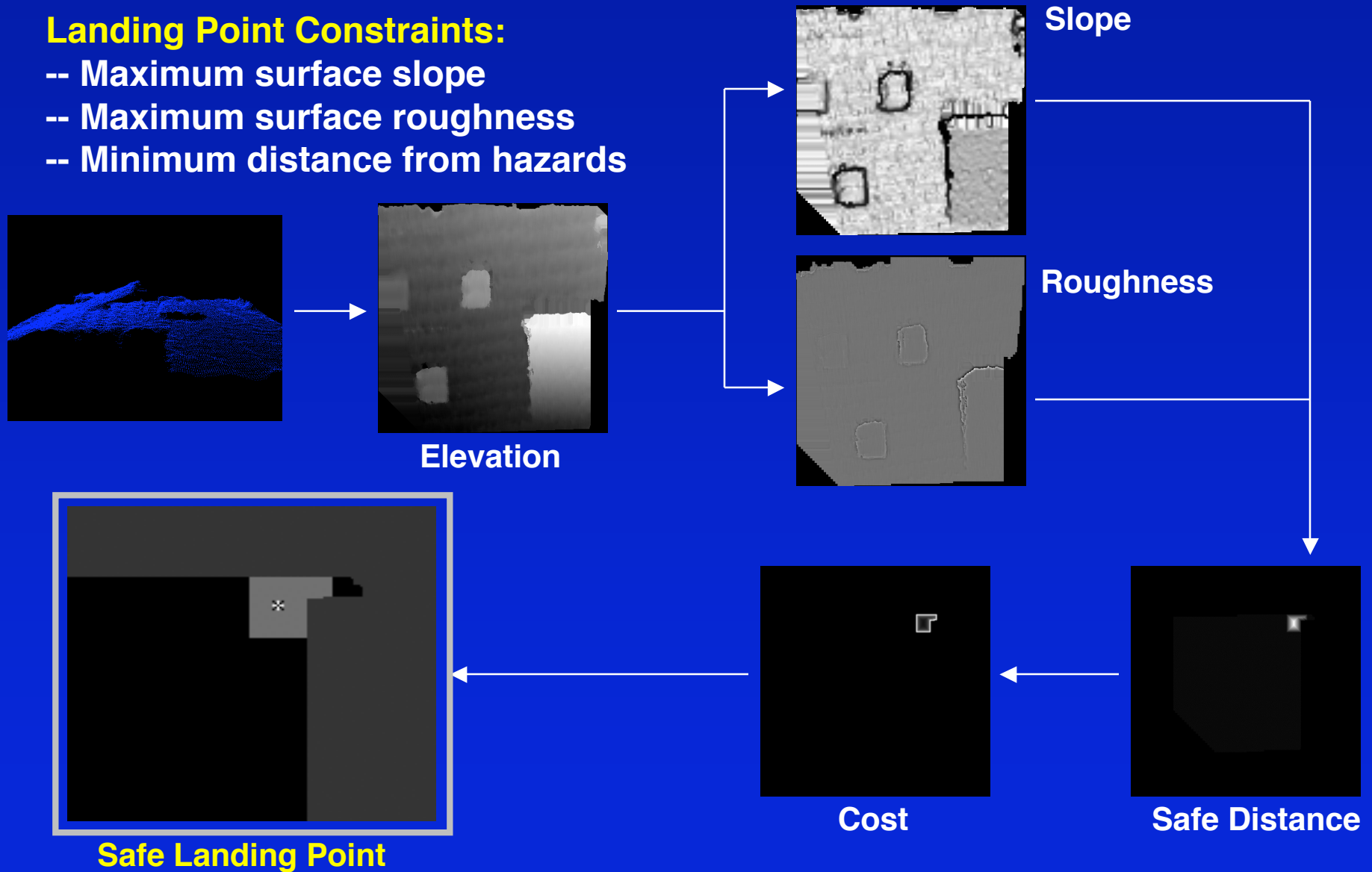
Stereo baseline (T) = 1 meter
Focal length (f) = 772.5 pixels



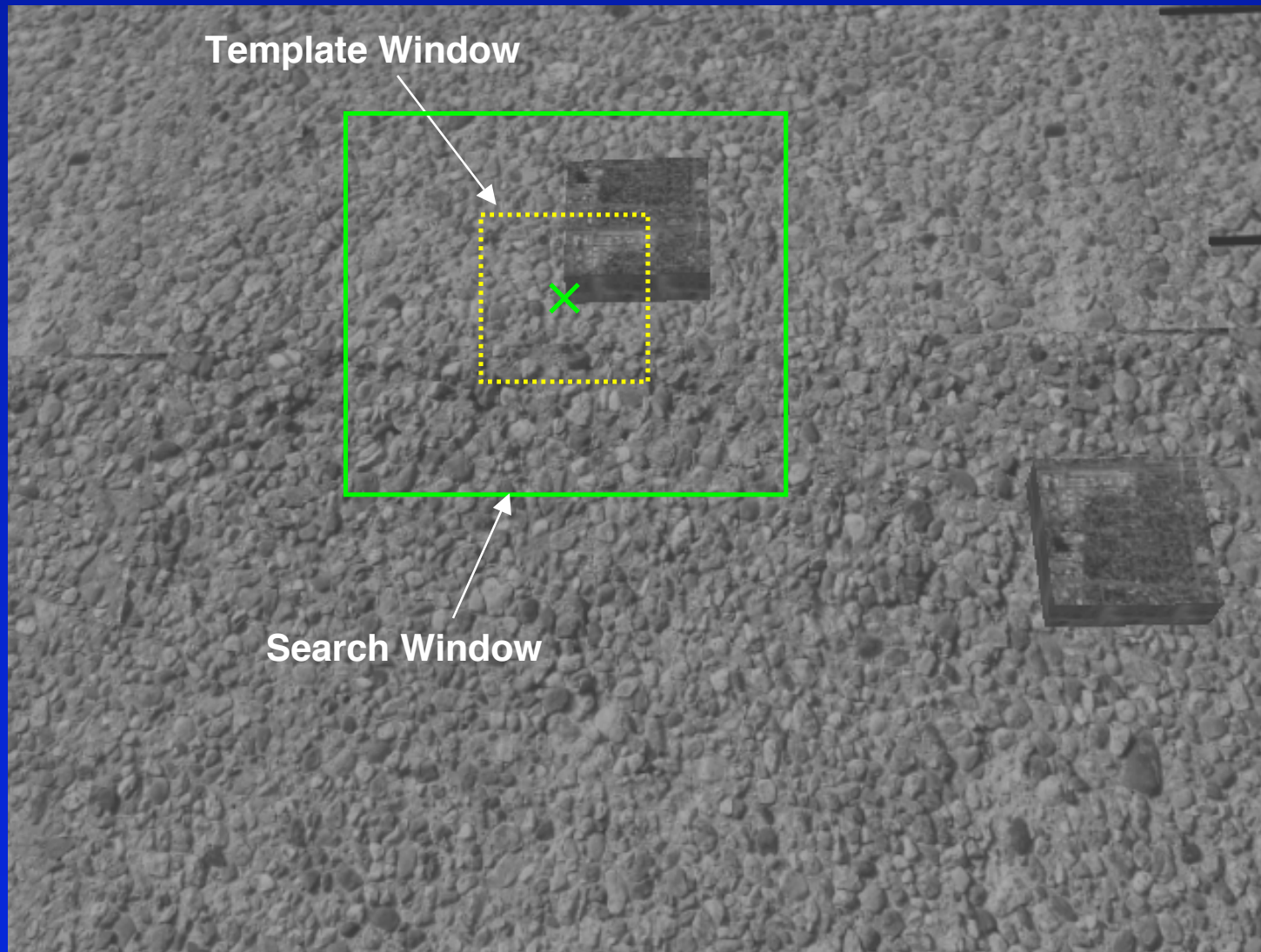
Safe Landing Area Determination (SLAD)

Landing Point Constraints:

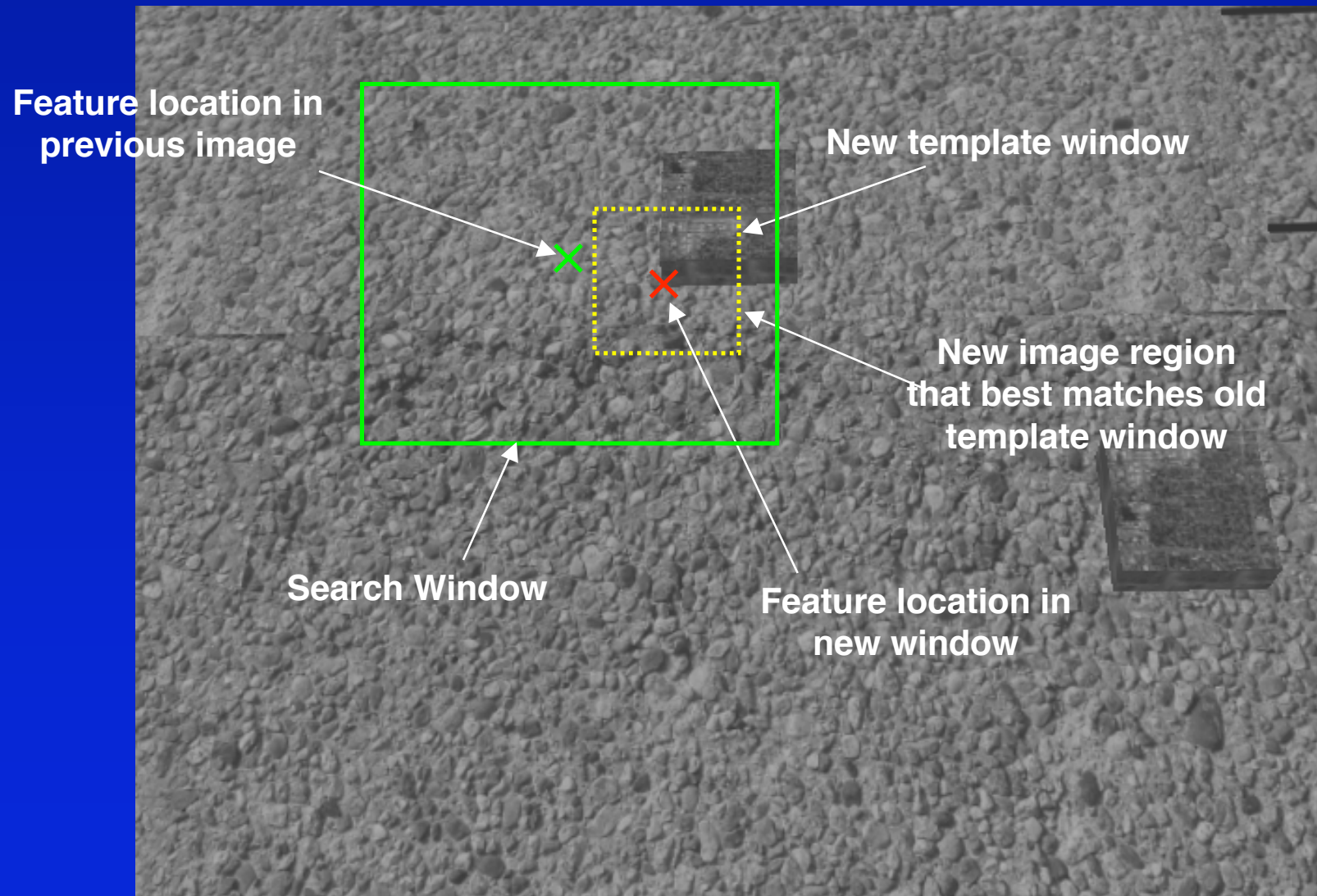
- Maximum surface slope
- Maximum surface roughness
- Minimum distance from hazards



Monocular Feature Tracking



Monocular Feature Tracking

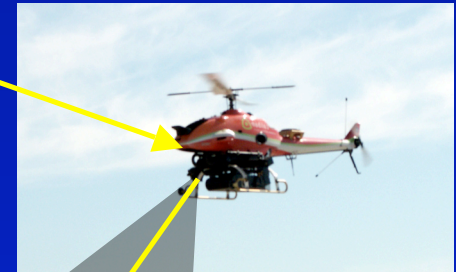


Monocular Position Estimation (MPE)

MPE Initialization:

GPS + MPE = Estimated position of landing point

GPS



MPE

Landing Point



Monocular Position Estimation (MPE)

Subsequent Frames:

Pseudo-GPS estimate = Landing point – MPE



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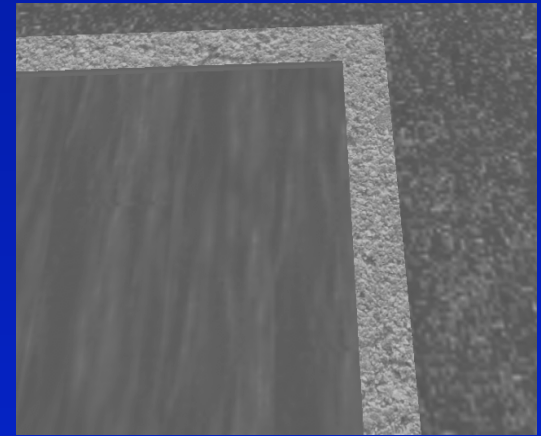
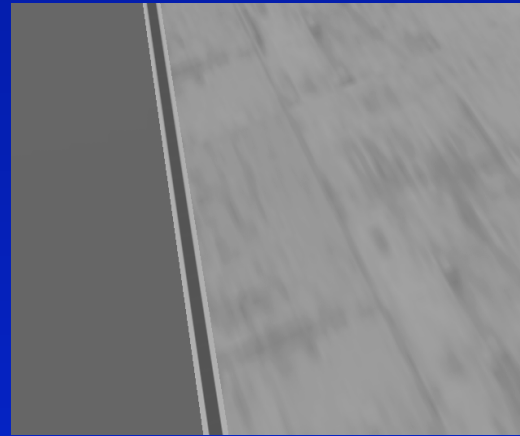
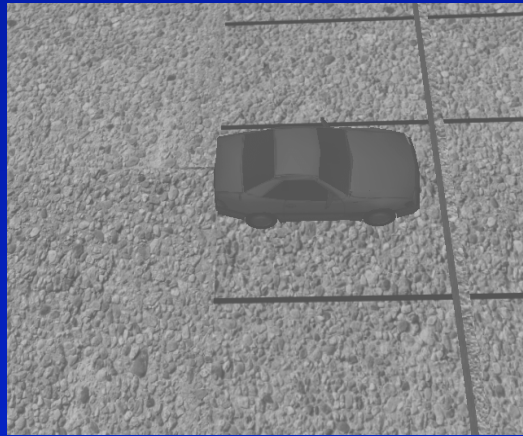
Stereo Ranging Results

Stereo Ranging Performance Evaluation:

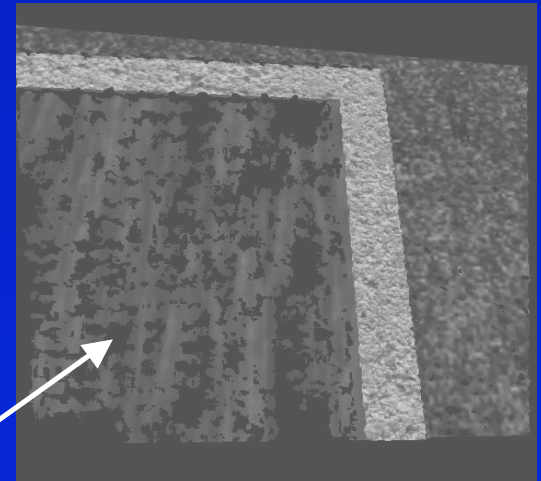
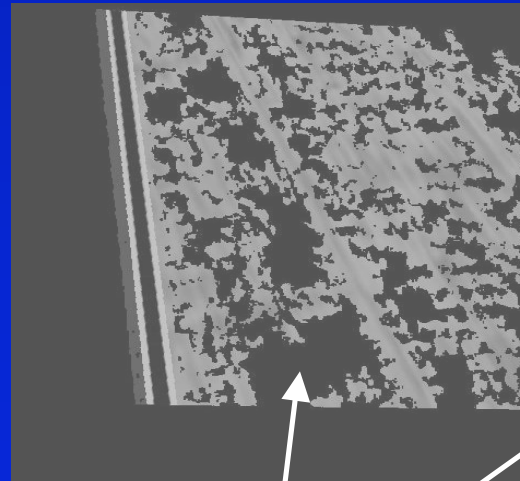
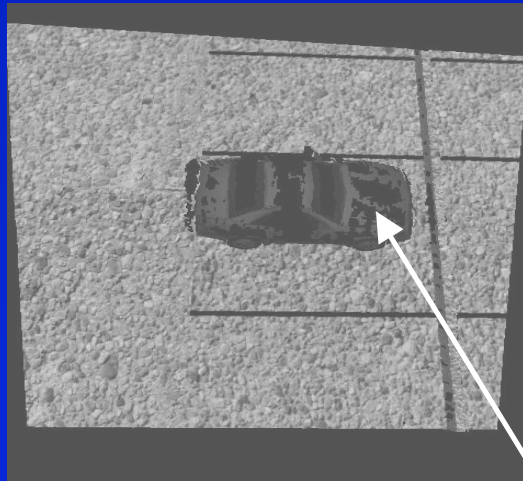
- Effect of image texture
- Range map accuracy
- Effect of image reduction
 - Processing time required
- Range map resolution

Effect of Image Texture

Left Camera Image
(Simulation)



Range Map
(Image Overlaid)

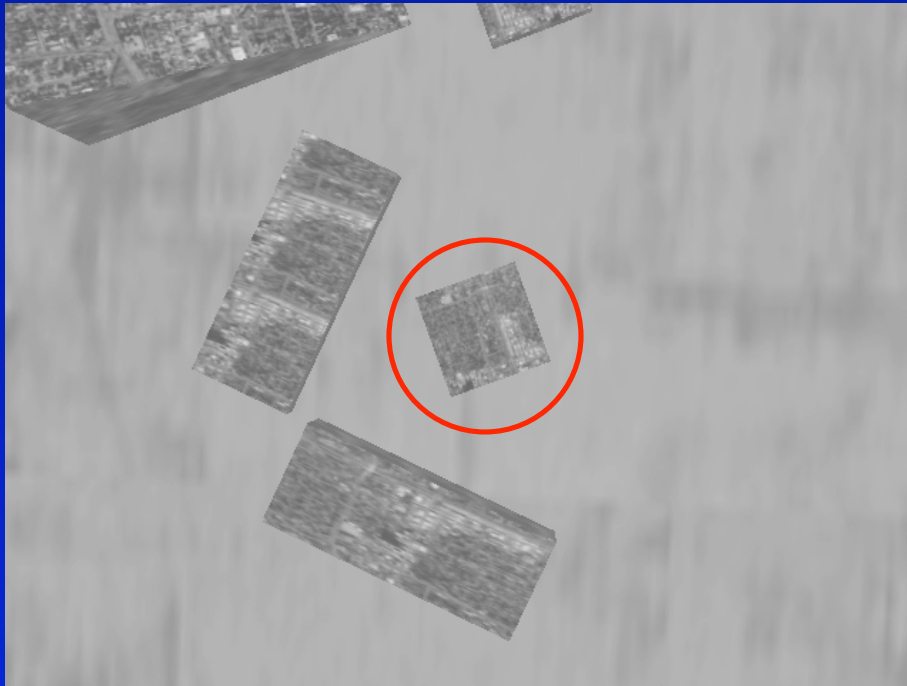


'Holes' in range maps due to lack of image texture

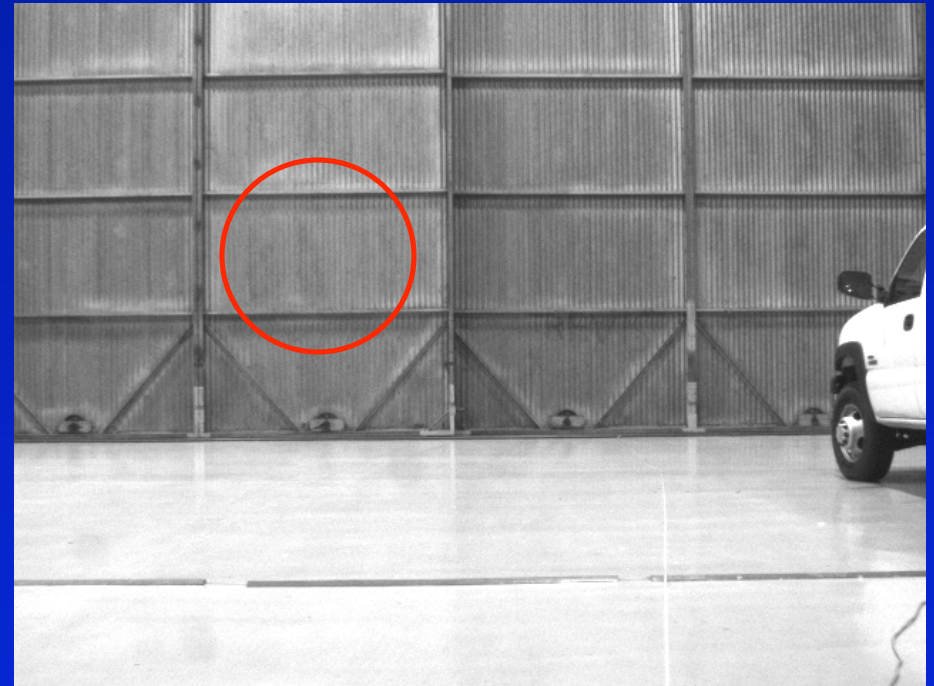
Range Map Accuracy



Simulation Camera Image

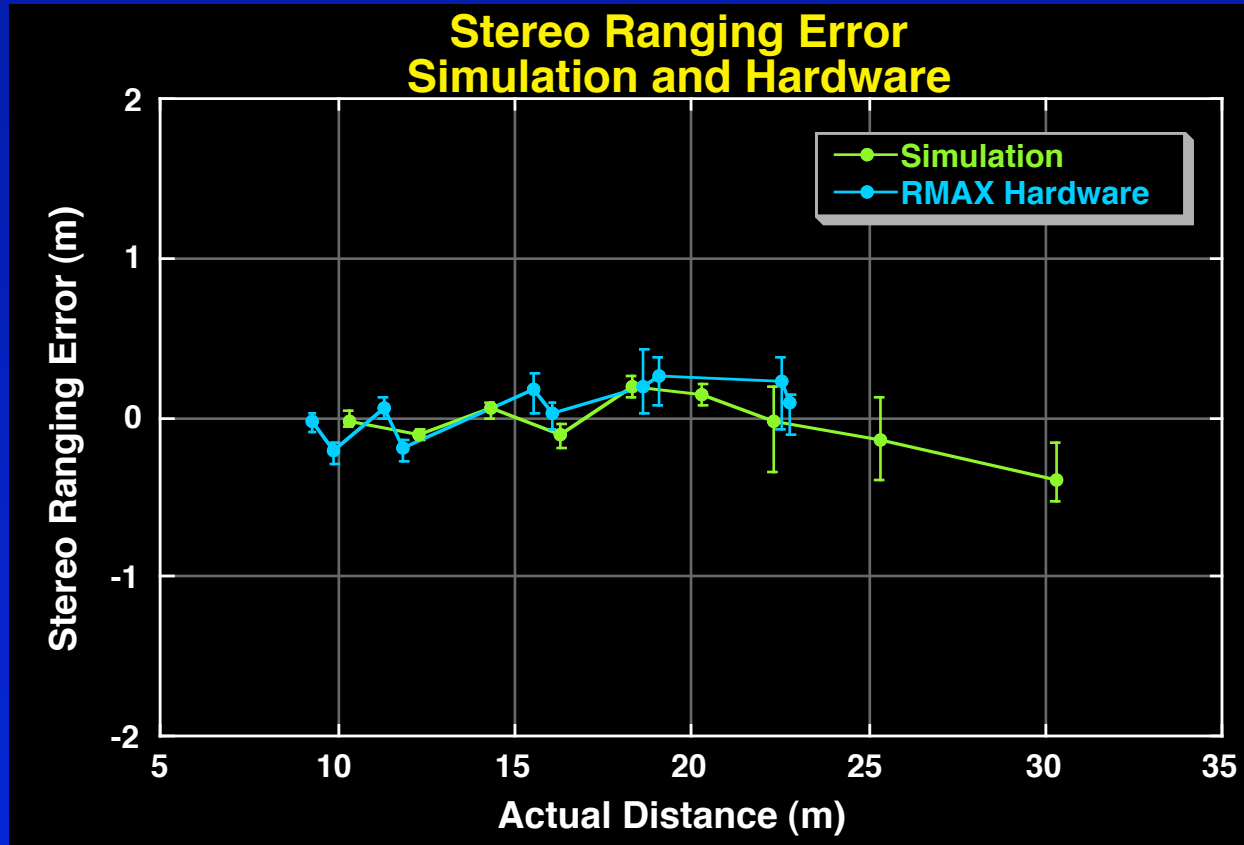


RMAX Camera Image



- Cameras perpendicular to surface -- 1 meter baseline
- Stereo ranging distances -- 10 to 30 meters

Range Map Accuracy



- Simulation ranging error with in +/- 1.3% of actual range
- RMAX hardware ranging error within +/- 2.3% of actual range

Range Map Resolution

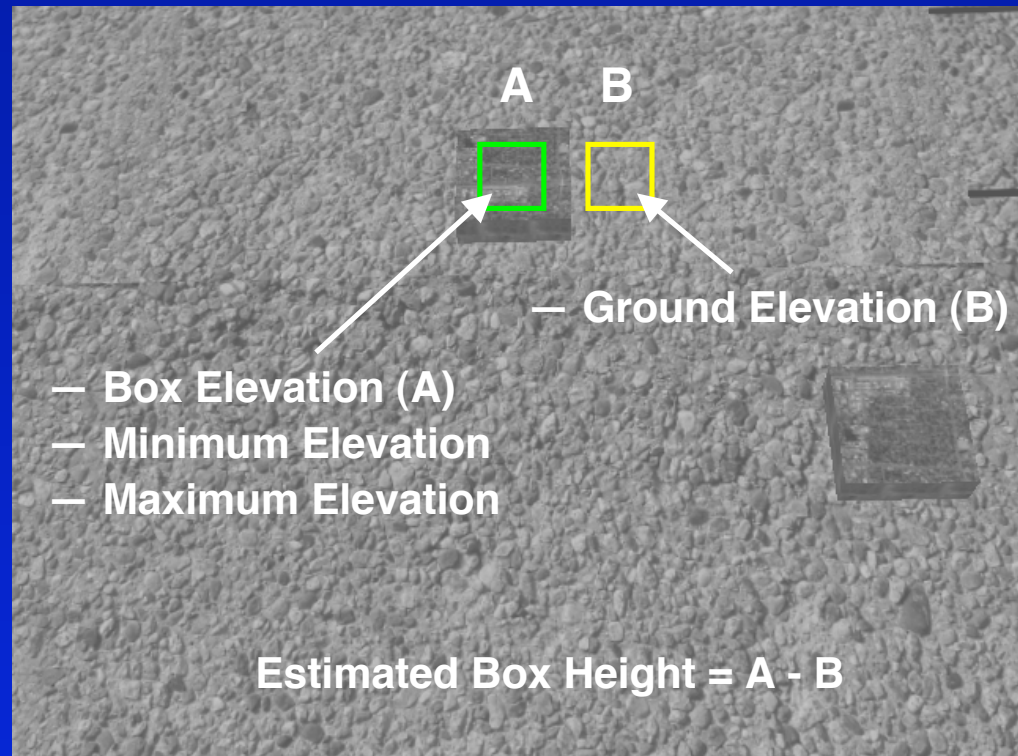
Test Parameters:

- Stereo baseline = 1 m
- Cameras = 640x480 pixels
- Camera angle = 30 deg
- Slant Range = ~12 m

Test Variables:

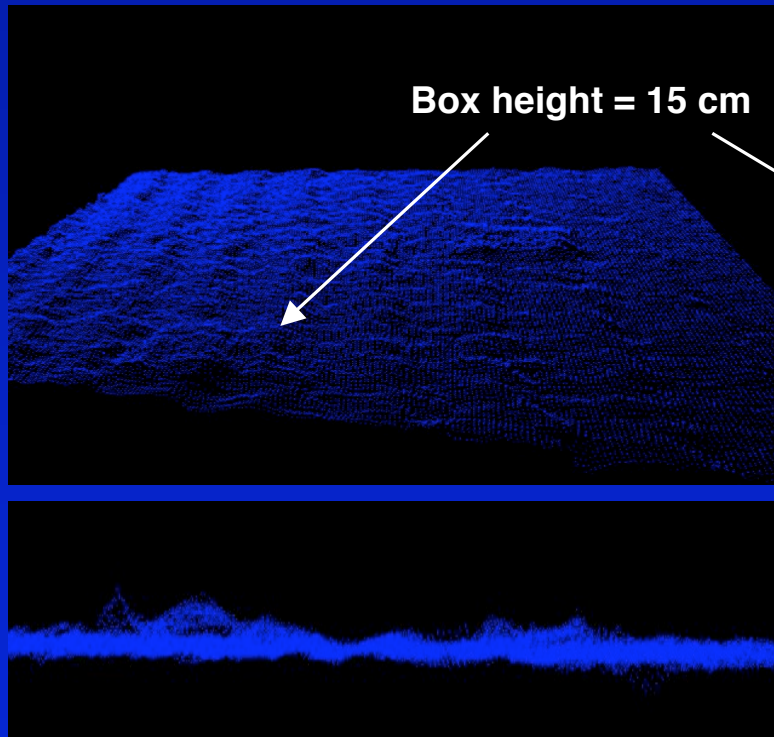
- Box height:
 - 5 to 50 cm
- Range map reduction:
 - 640x480 (full image)
 - 320x240 (50% reduction)

Box Height Tests (Simulation)



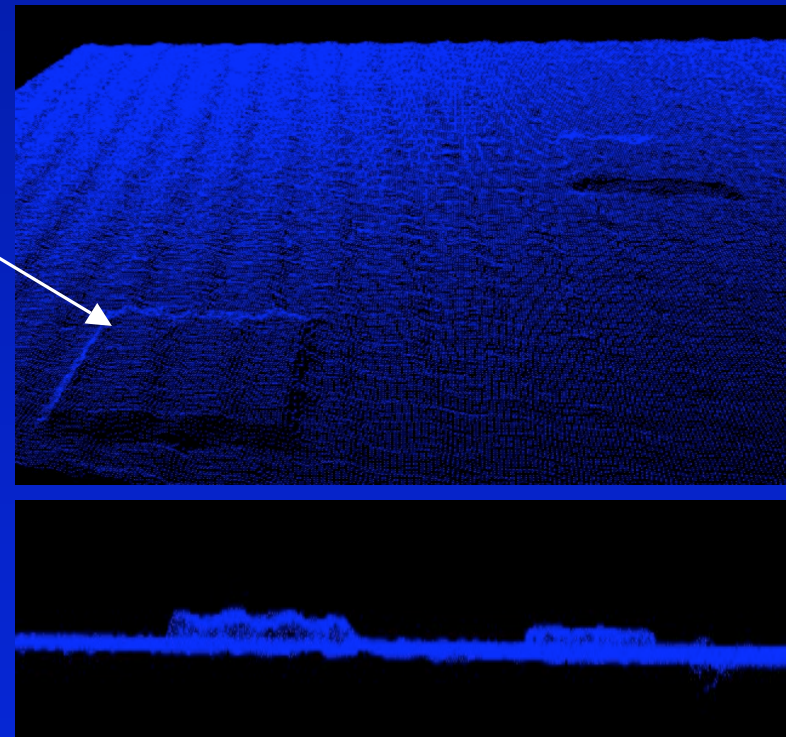
Effect of Image Reduction

50% Image Reduction
(320x240 Images)



Processing time = 2 sec

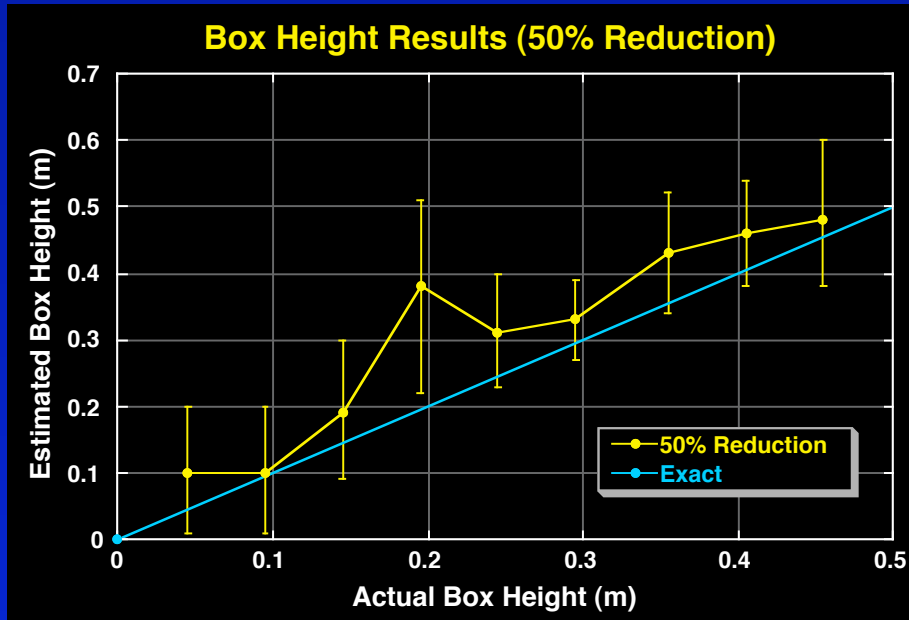
Full Image (No Reduction)
(640x480 Images)



Processing time = 6 sec

- Boxes clearly visible in full resolution images
- 3X increase in processing time with full image

Range Map Resolution



- Improved resolution with higher range map grid size
- Objects below 15cm may not be detected with 50% image reduction

SLAD Evaluations

SLAD Performance Measures:

- Rate of success in choosing safe landing site
- Number of false negatives / false positives
- Processing time

SLAD Performance Evaluations:

- Effect of number of safe landing areas
- Effect of obstacle spacing
- Effect of grid size

SLAD Constraints:

- Maximum surface slope
- Maximum surface roughness
- Minimum distance from hazards

SLAD Evaluation Set-up

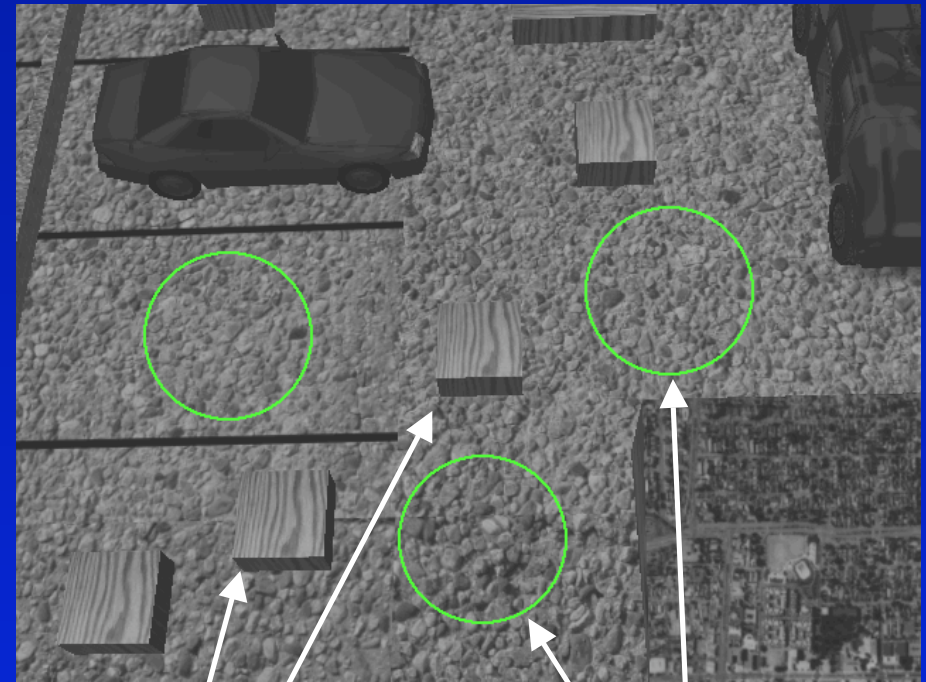
Test Parameters:

- Stereo baseline = 1 m
- Cameras = 640x480 pixels
- Camera angle = 30 deg
- Altitude = ~12 m

Test Variables:

- Number of safe landing points:
0 to 3
- Obstacle spacing (1 safe area):
90 to 110 % of constraint value
- Light Intensity:
Dim to bright in simulation
- SLAD grid size:
100x100 to 450x450
- Height above ground:
8 to 30 meters

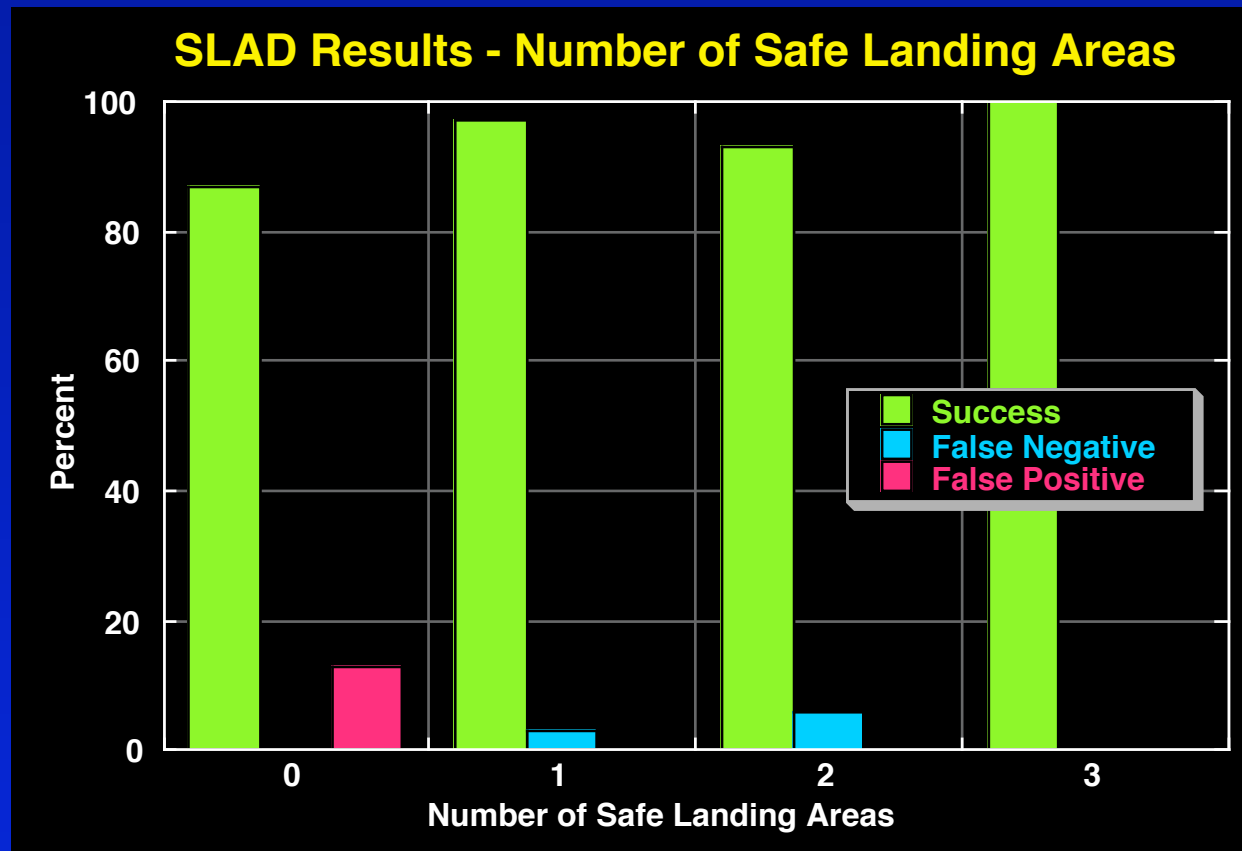
SLAD Tests (Simulation)



Movable
objects

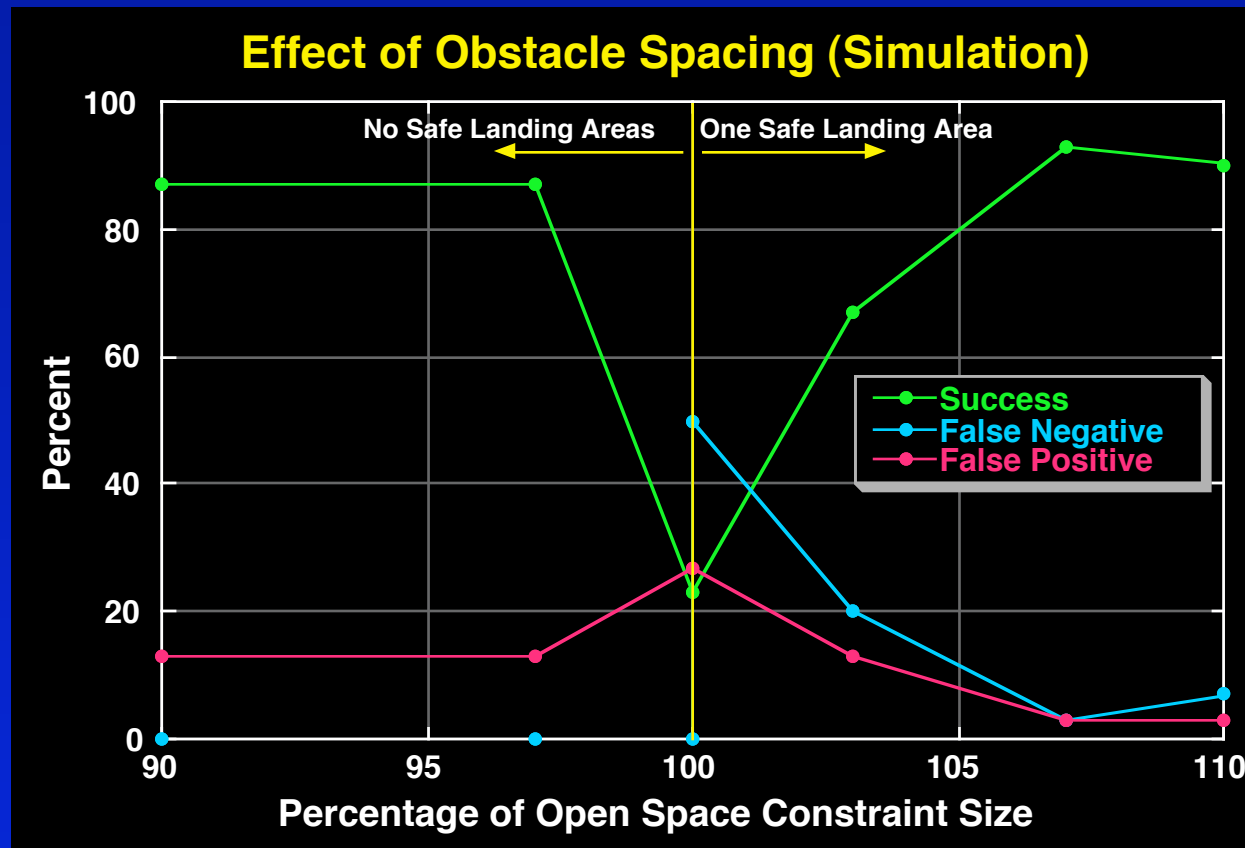
Safe landing
areas

Number of Safe Landing Areas



- > 85% success rate for all cases tested
- 10% false positives from SLAD when no safe landing points

Effect of Obstacle Spacing



Variable obstacle spacing

- Degraded performance at the open space constraint value
- Some false positive results when no safe landing site exists
- Require a margin of 5-10% for good SLAD performance

Effect of SLAD Grid Size

SLAD Success Rate versus SLAD Grid Size



Processing Time versus SLAD Grid Size



- Slight increase in SLAD processing time with SLAD grid size
- Increase SLAD performance with finer grid resolution
- 350 pixels or greater grid size required for acceptable performance

Monocular Position Estimation Results

MPE Performance Measures:

- Frame-to-frame tracking performance
- Tracking drift over tracking run of two minutes
- Processing time

MPE Evaluations:

- Effect of wind conditions
 - Wind direction, speed and turbulence level
- Effect of height above the ground
- Effect of feature tracking parameters
 - Search window size
 - Template window size

MPE Evaluation Set-up

Test Parameters:

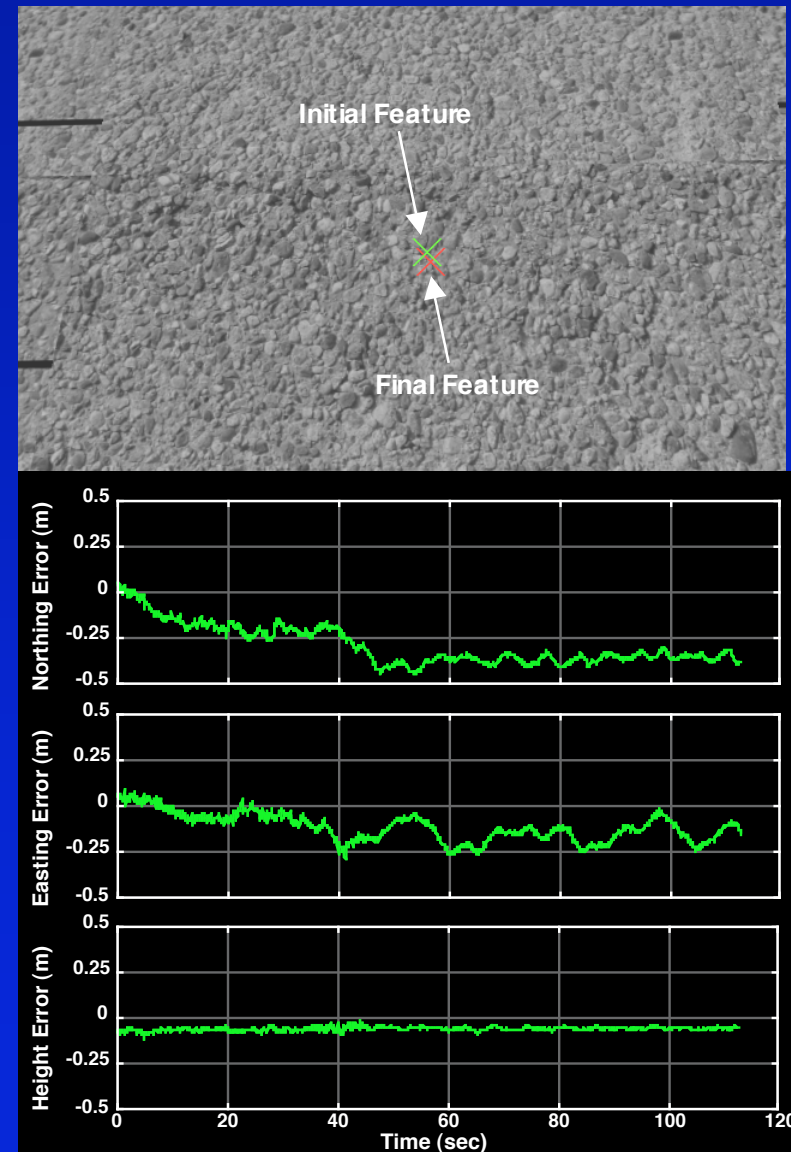
- Tests at each condition = 5
- Tracking test = 2 minutes
- Camera angle = 30 deg
- Altitude = ~12 m

Test Metrics:

- Minimum tracking coherence
- Number of times coherence < 0.6
- Maximum position estimation drift
- Number of instabilities

Test Variables:

- Wind direction, speed, turbulence
- Height above ground
- Search window size
- Template window size



Effect of Wind Conditions

Wind Conditions:

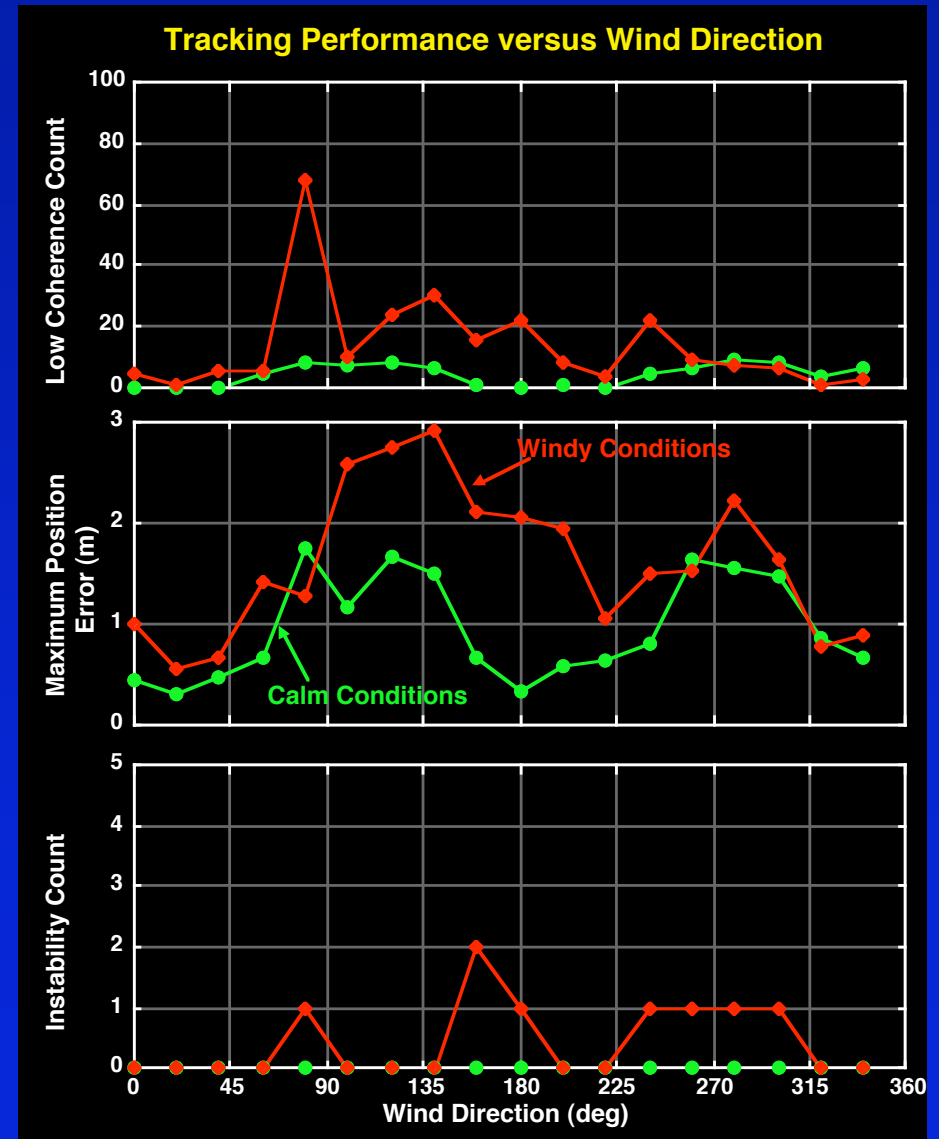
— Calm

Wind speed = 2 ft/sec
Low Turbulence

— Windy

Wind speed = 14 ft/sec
High Turbulence

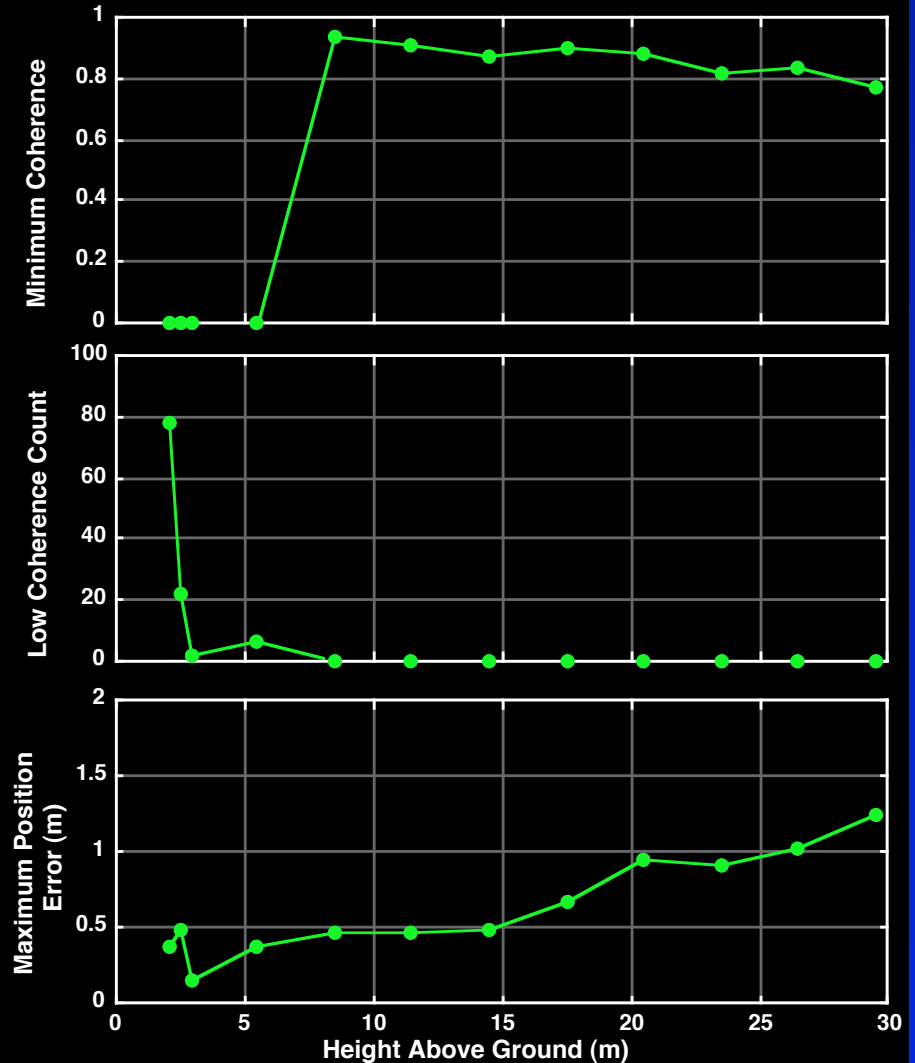
- Best performance achieved with heading of 0 deg
- Good performance under calm conditions at 180 degrees
- Instabilities indicate inability to track features



Effect of Height Above Ground

- Performance degrades below about 6 meters
- Tracking becomes unreliable under about 3 meters
- Larger position error at high altitudes due to decreased resolution

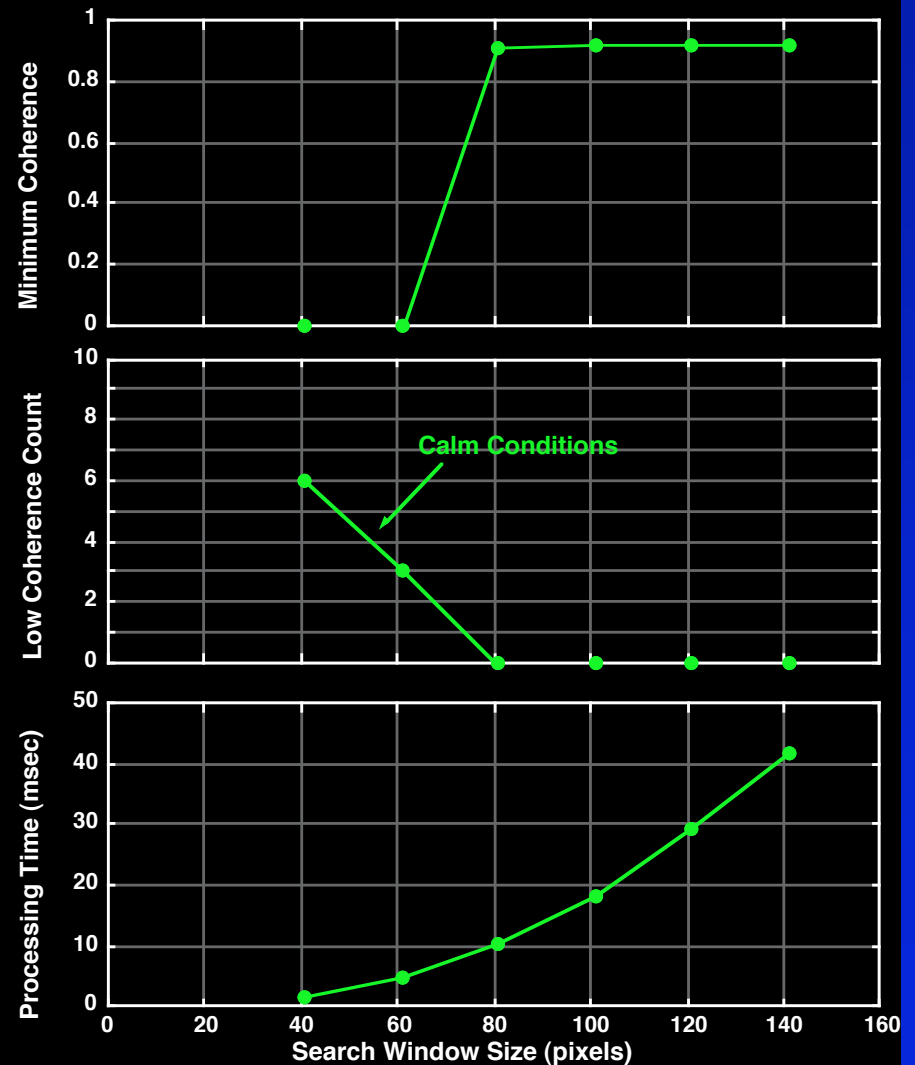
Tracking Performance versus Altitude (Calm Conditions)



Effect of Search Window Size

- No performance gain for window sizes > 80 pixels
- Significant increase in processing time for larger window sizes
- Optimum window size 60 - 80 for calm conditions

Tracking Performance versus Search Window Size



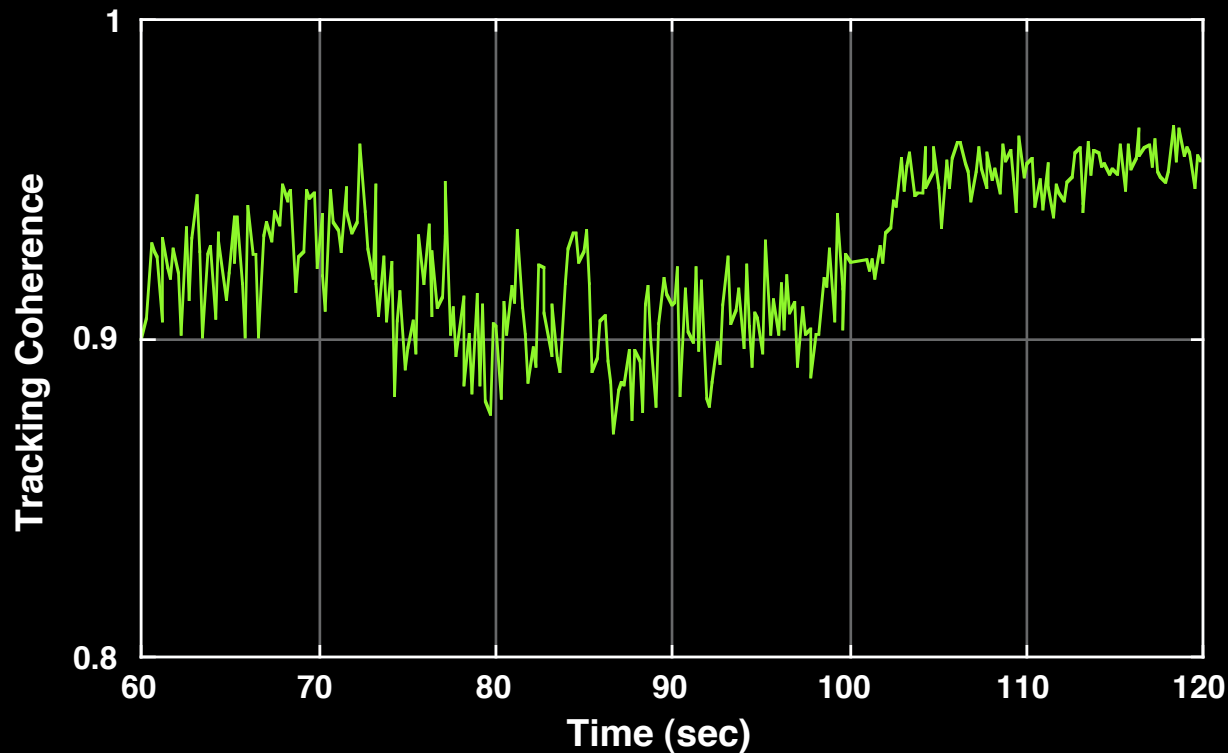
RMAX Feature Tracking Video

Open-loop tracking - No vision feedback



RMAX Feature Tracking Performance

Tracking Coherence (RMAX Flight Data)



- Real-time feature tracking on-board the RMAX during descent
- jpeg images and tracking data transmitted to the ground station
- Good tracking performance during descent based on coherence

Conclusions

- **Vision based approach --> successful autonomous landing in simulation**
- **Simulation provided a basis for evaluation of the vision algorithms in a realistic landing scenario**
- **Overall performance in flight should be similar to performance observed in simulation**
- **Performance of vision algorithms must be optimized based on available processing power**

Future Work



- Integration of mission manager landing procedure and JPL vision algorithms in RMAX hardware
- Validation of performance of vision algorithms in flight
- Examine the anomalies in some stereo-ranging / SLAD results
- Optimize the performance of the machine vision algorithms on the RMAX hardware
- **Fully-autonomous landing using RMAX hardware**

