An Experimental Evaluation of 3D Mapping with an Autonomous Helicopter

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Outline

- 3D Mapping and its Significance
- Problems with Current Mapping Methods
- Structure from Motion (SFM)
- SFM Mapping with an Autonomous Helicopter
- Path Planning Algorithm for Aerial Photography
- Data, Results, and Conclusions
- Future Work
- Questions

3D Mapping

- 3D mapping is the process of creating a three dimensional model of a surface (**DTM** or **DSM**).
- These models are useful for **terrain analysis**, **geological surveying**, tracking **soil erosion**, **rock wall stability**, etc.
- Compare models over time to track geological changes

How are 3D maps created?

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Current Large-Scale Mapping Techniques

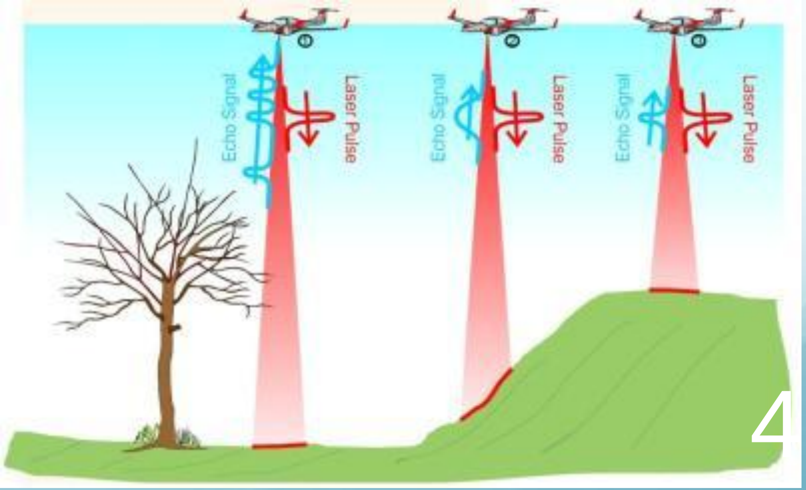
Manual Surveying

- Accurate distance measurements between two points
- Total Station & DGPS

Picture courtesy of Spiller USA

LiDAR

- **L**i**g**ht **D**etection **A**nd **R**anging
- Accurate distance measurements using laser pulses



Picture courtesy of Riegl LiDAR

Problems with Current Techniques

Manual Surveying

- Requires multiple people
- Resolution of map depends on data point grid size

LiDAR

- Expensive

How can we improve terrain mapping?

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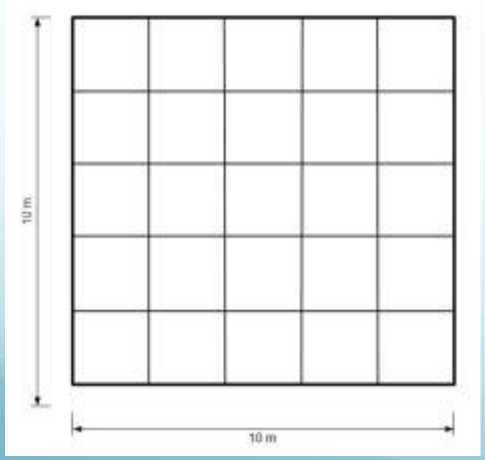
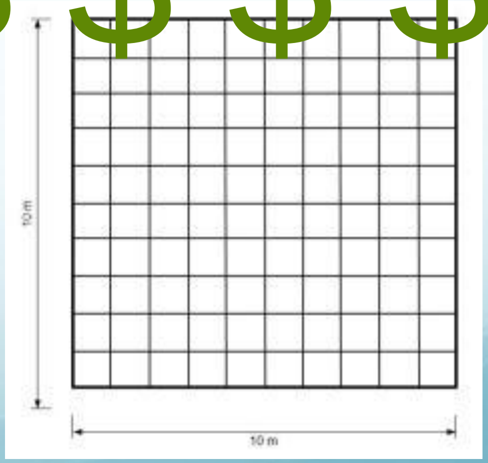


2m resolution of 10x10m area

Doubling the resolution for manual surveying

→ Large increase in number of data points



1m resolution of 10x10m area

Improving Large-Scale Terrain Mapping

- Faster
- Higher Resolution
- More Cost Efficient
- Efficient Implementation

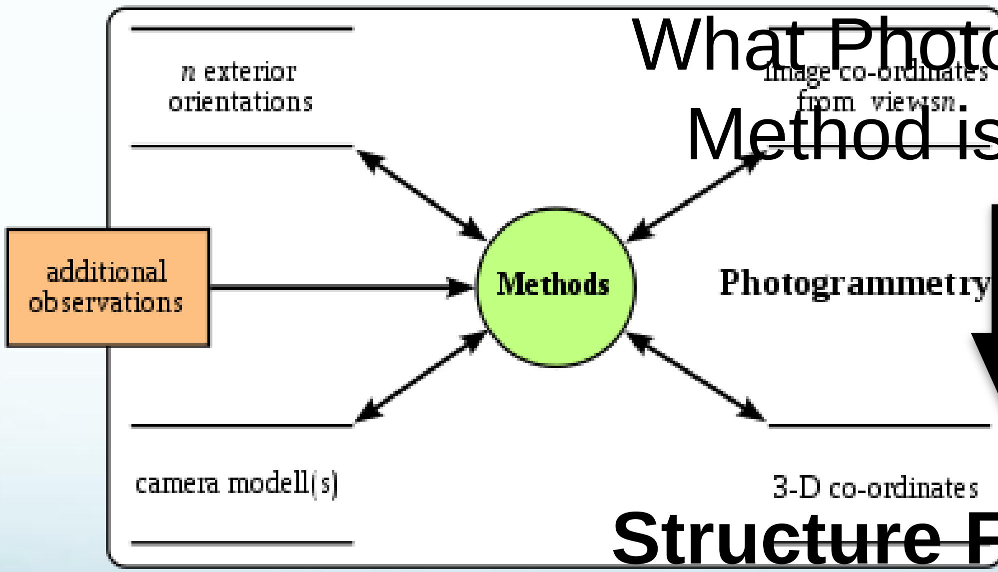
Do this without sacrificing accuracy

What methods facilitate this?

Photogrammetry

- Using techniques from multiple disciplines, infer geometric data from photographs

What Photogrammetric Method is Suitable?

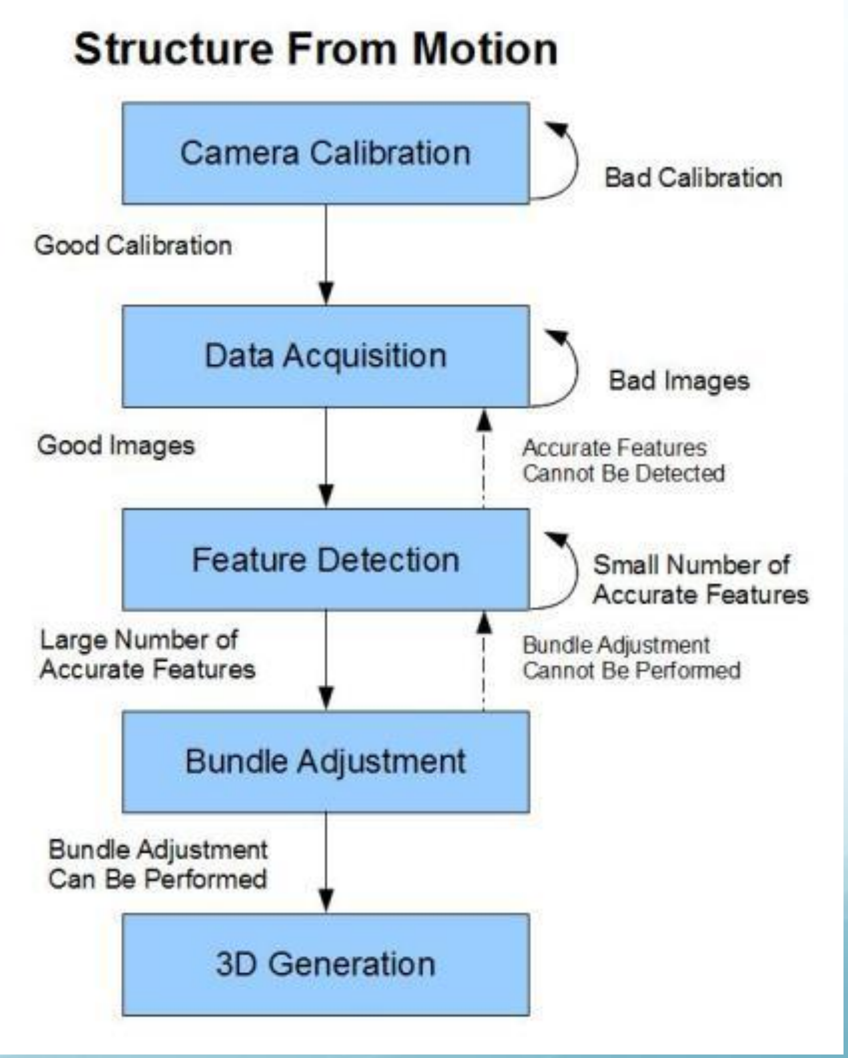


Structure From Motion

Photogrammetric data model designed by George Wiora [1]

Structure From Motion

1. Calibrate Camera
2. Take two pictures which have some overlap
3. Find points which are in both images
4. Determine how these points have changed between images
5. Create a 3D model and 'drape' the images over the model



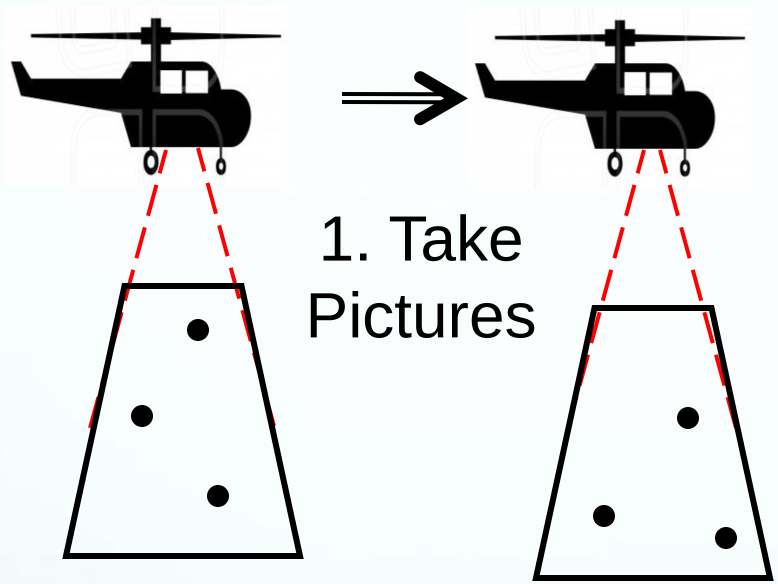
Structure From Motion Suited for UAVs

- Small, lightweight equipment
  - LiDAR devices are large and heavy
  - Stereo vision requires large baseline – impractical for UAVs

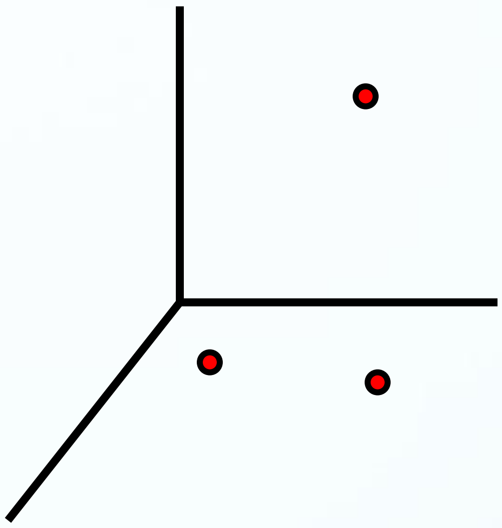
- Low price
  - LiDAR extremely expensive

- Software Options
  - Commercial – **3DM Analyst**, Leica, Socet
  - Open Source – Bundler, Photosynth, PMVS

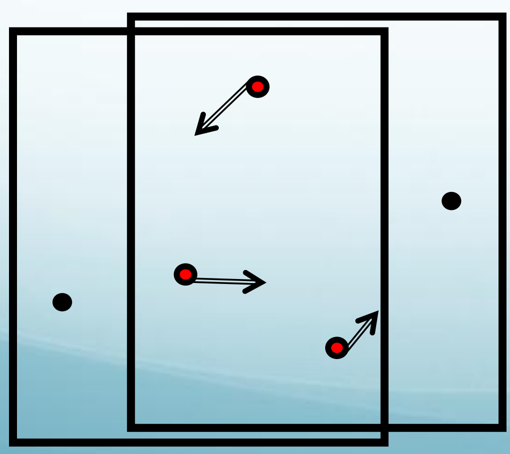
Structure From Motion with UAVs



1. Take Pictures

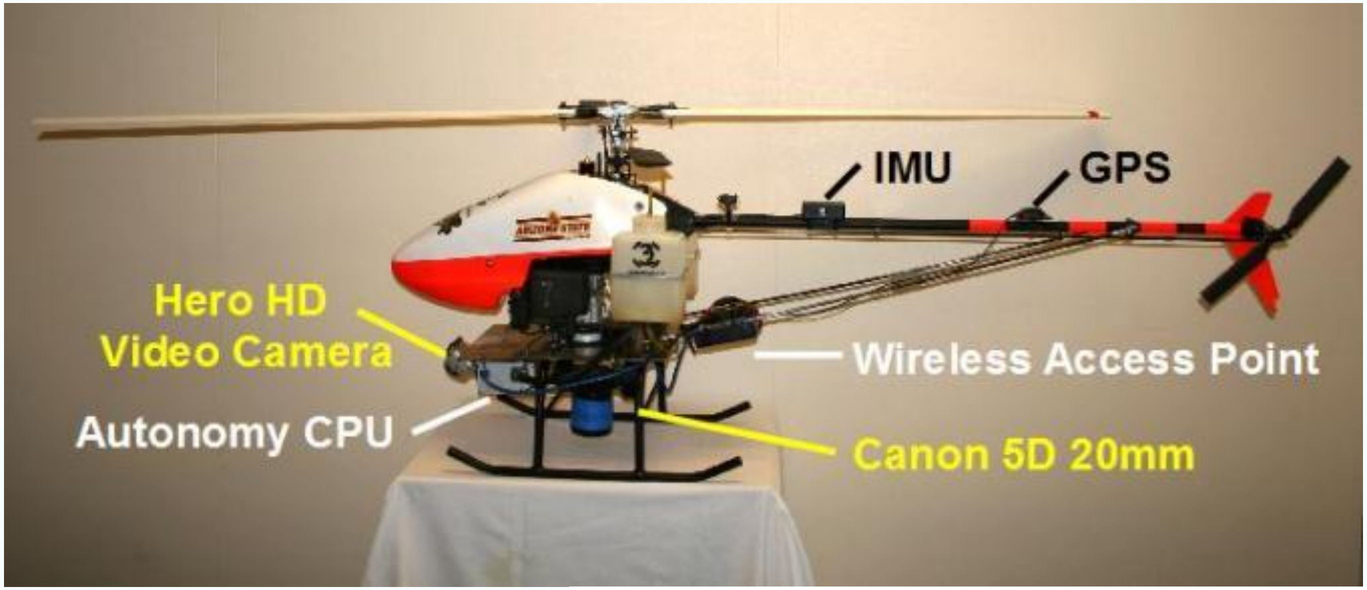


3. Generate 3D Data



2. Identify points and how they have moved in picture overlap

Integrating UAVs and Structure From Motion



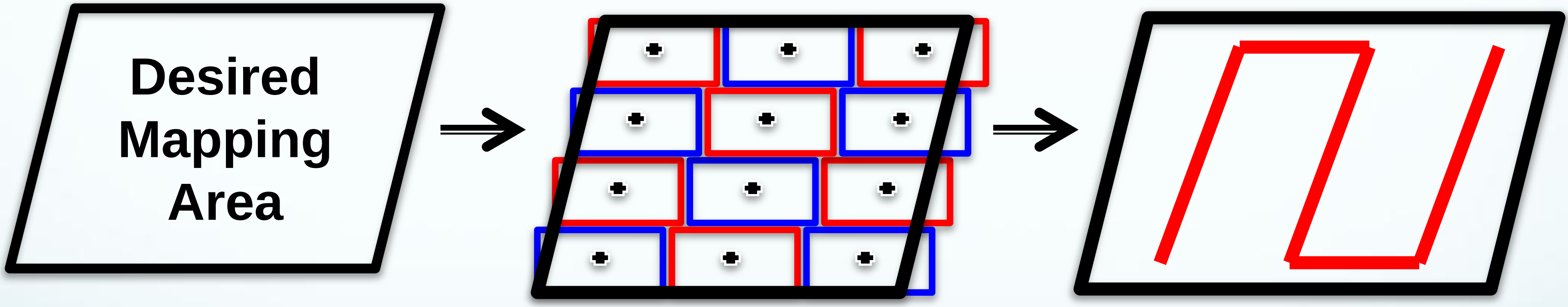
Rotomotion SR-30 UAV
- Based off X-cell Spectra-G RC Heli

Item	Specification
Length	1638 mm
Width	355 mm
Height	622 mm
Main Rotor Diameter	1981 mm
Tail Rotor Diameter	337 mm
Engine	2.4 HP 2 stroke gasoline
Maximum Speed	11 mps [40 kph] (AFCS regulated)
Endurance	$1\frac{1}{2}$ Hours
Payload	7 kg With Fuel
Telemetry	802.11-based, 800m, LOS range
Waypoint Accuracy	±3m (with good GPS reception)
Altitude Hold Accuracy	±5m (with good GPS reception)

Where do we fly?

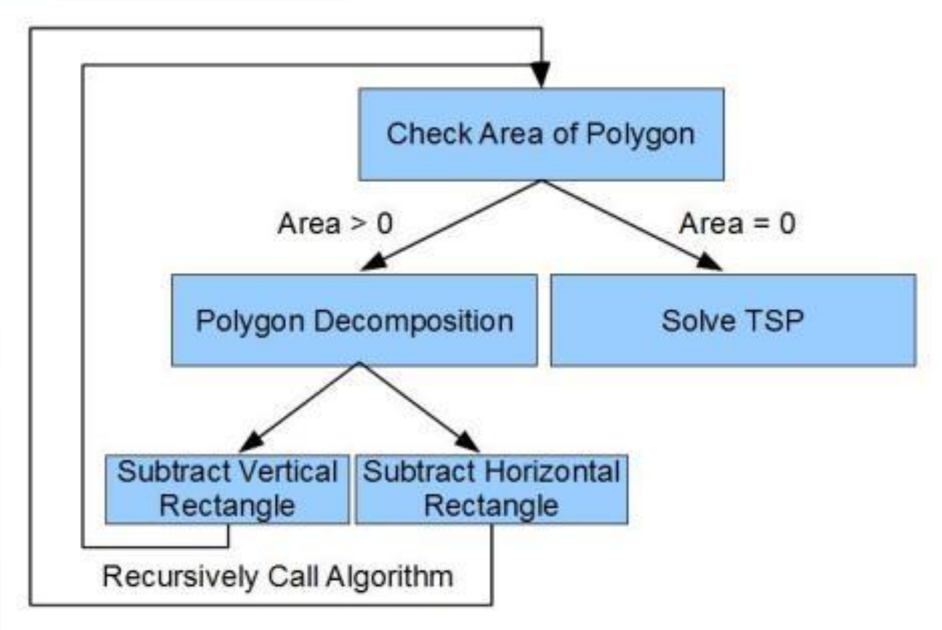
Flight Path Optimization

- Cover mapping area with rectangles
  - Polygon Decomposition Problem
    - transform polygon into finite set of smaller polygons



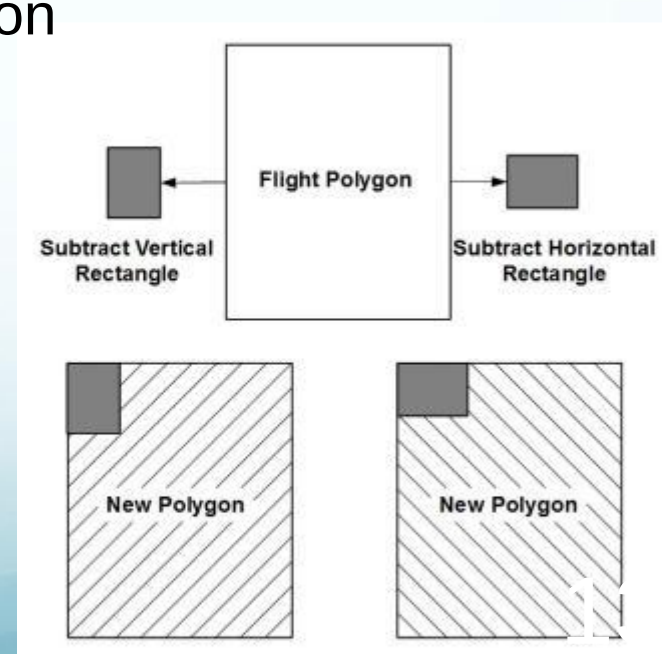
- Generate the shortest path
  - i.e. Traveling Salesman Problem (TSP)
    - How can we visit a set of locations in the shortest path possible

Polygon Decomposition



1. Check Area of Polygon
   Area = 0 move to TSP
   Area > 0 decompose

2. Subtract vertical and horizontal rectangles from polygon



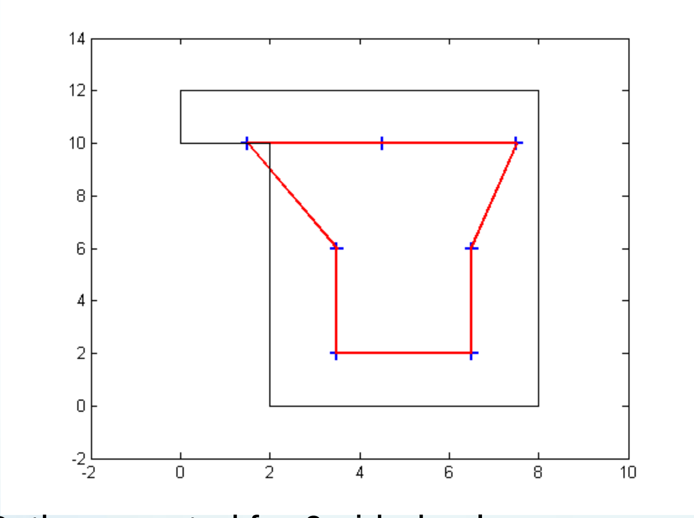
3. Recursively call algorithm with 2 new polygons

4. Return Decomposition pattern with the least image waste

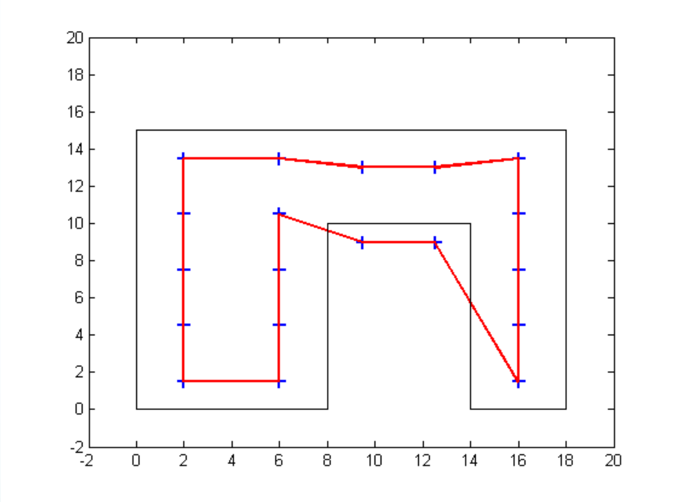
-Image waste is ground image area which does not lie in desired mapping region

Flight Path Generation

- Generate shortest path using Euclidean TSP solver



Path generated for 6-sided polygon

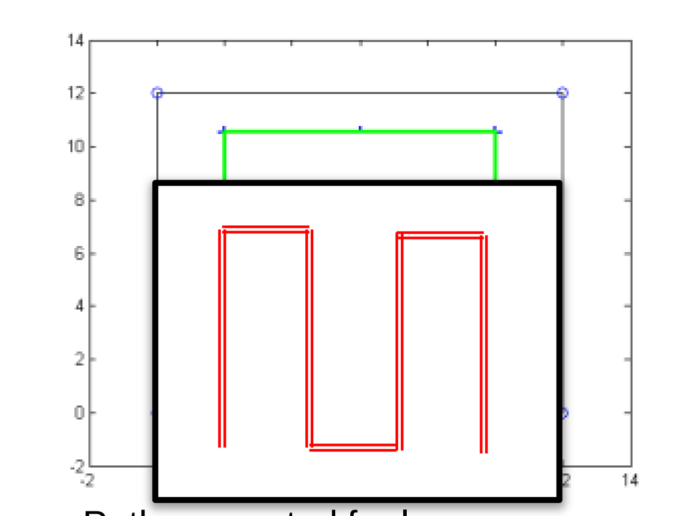


Path generated for U-shaped polygon

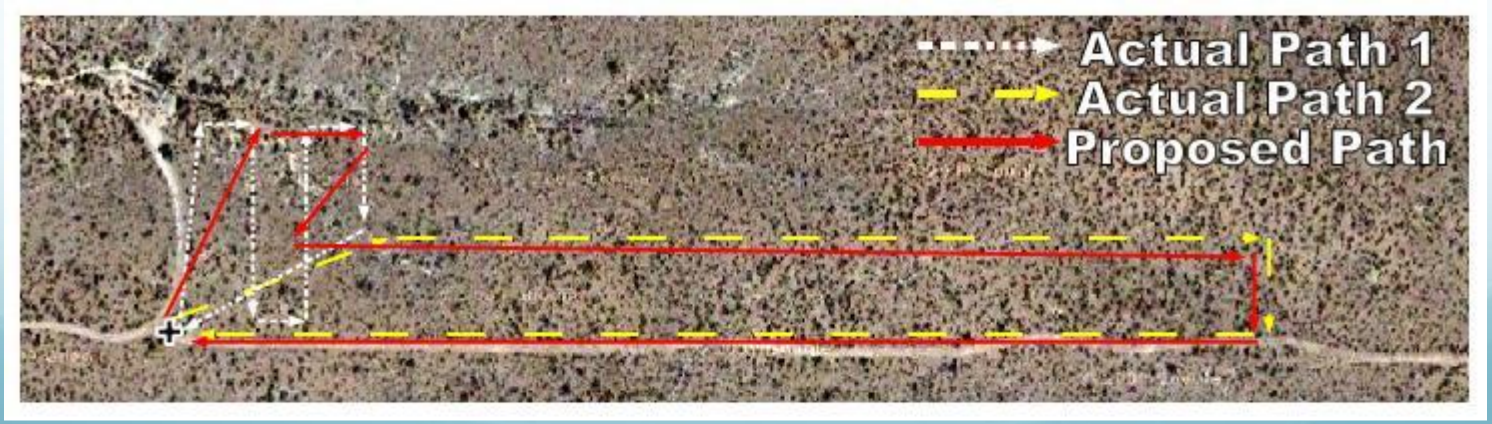
Euclidean TSP appropriate for helicopters → No cost for turning

Algorithm Results

- Paths were generated for a random selection of polygons
- These paths were compared to manually generated paths
- Proposed paths were of equal or lesser distance than manual paths, but often less intuitive



Path generated for large square
Intuitive Lawn Mower Pattern



Actual flight paths compared to proposed flight path

Evaluating SFM Mapping

1. Ground based testing in man-made environments
    - camera calibration, accuracy analysis

2. Ground based testing in natural environments
    - establish that SFM process is working correctly
    - identify problems and sources of error

3. Airborne testing in natural environments
    - evaluate UAV based SFM mapping

Ground Based Testing in Man-Made Environments

Original picture taken at Phoenix Rock Gym

Original picture with common features identified
- Red dots indicate features

3D model generated from pictures

- 10m x 15m area modeled with Canon 5d – 20mm lens
- Images taken from 15m away
- Estimated resolution of 0.5cm

Resolution and Accuracy

Resolution Estimate (GSD)

$$g_x = \frac{2h}{r_x}\cot^{-1}\left(\frac{\theta_x}{2}\right)$$

where:
h = AGL flying altitude
r_x, r_y = horizontal, vertical camera resolution (pixels)
g_x, g_y = desired horizontal, vertical ground sample distance (m)
θ_x = horizontal field of view

Error Estimate

$$\sigma_{plan} = \sigma_{pixel}\gamma\frac{d}{f} \qquad \sigma_{depth} = \sigma_{plan}\frac{d}{b}$$

$$\sigma_{total} = \sqrt{2\sigma_{plan}{}^2 + \sigma_{depth}{}^2}$$

where:
σ_{plan} = planimetric accuracy (parallel to image plane)
σ_{pixel} = estimated pixel accuracy
σ_{depth} = depth accuracy (perpendicular to image plane)
γ = pixel size
d = target distance
f = focal length
b = base distance

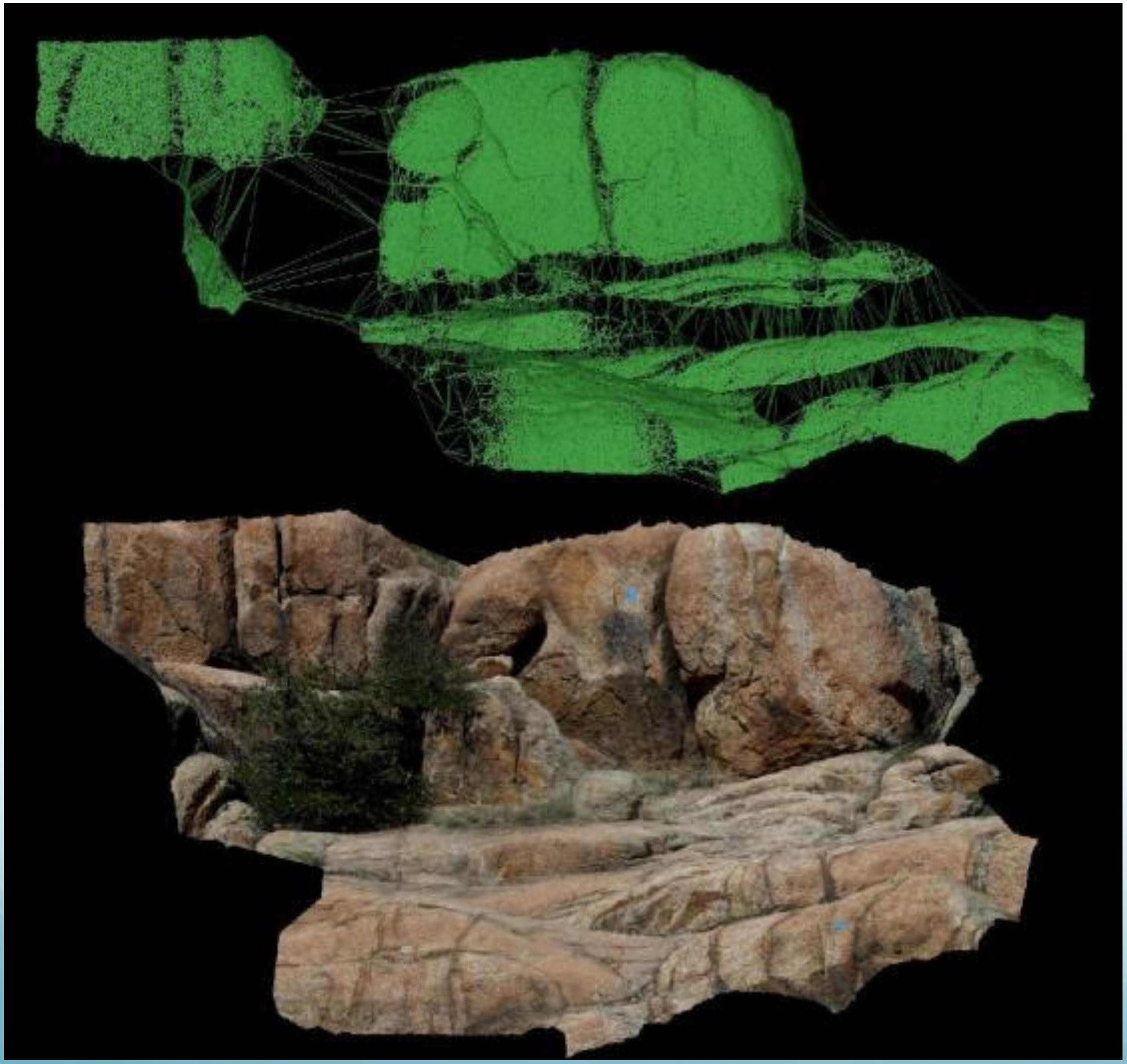
Actual Error

Measurement	Measured Distance (m)	Model Measurement (m)	Difference (cm)	Percent Error
1	1.321	1.320	-0.08	0.06
2	1.791	1.790	-0.07	0.04
3	2.057	2.080	+2.26	1.10
4	2.159	2.170	+1.10	0.51
5	2.210	2.210	+0.02	0.01
6	2.565	2.560	-0.54	0.21
7	2.756	2.740	-1.59	0.58
8	2.775	2.780	+0.51	0.18
9	2.908	2.920	+1.17	0.40
10	4.115	4.120	+0.52	0.13
11	4.204	4.220	+1.63	0.39
12	4.470	4.460	-1.04	0.23
13	5.334	5.340	+0.60	0.11
14	5.867	5.910	+4.26	0.73
15	6.166	6.200	+3.41	0.55
16	6.515	6.520	+0.49	0.08
17	7.252	7.270	+1.83	0.25

Measurements from ground based testing in man-made environments

Estimated Error = 0.30 cm
Mean Error = 1.12cm
Standard Deviation = 1.50cm
Max Error = 4.26cm

Ground Based Testing in Natural Environments



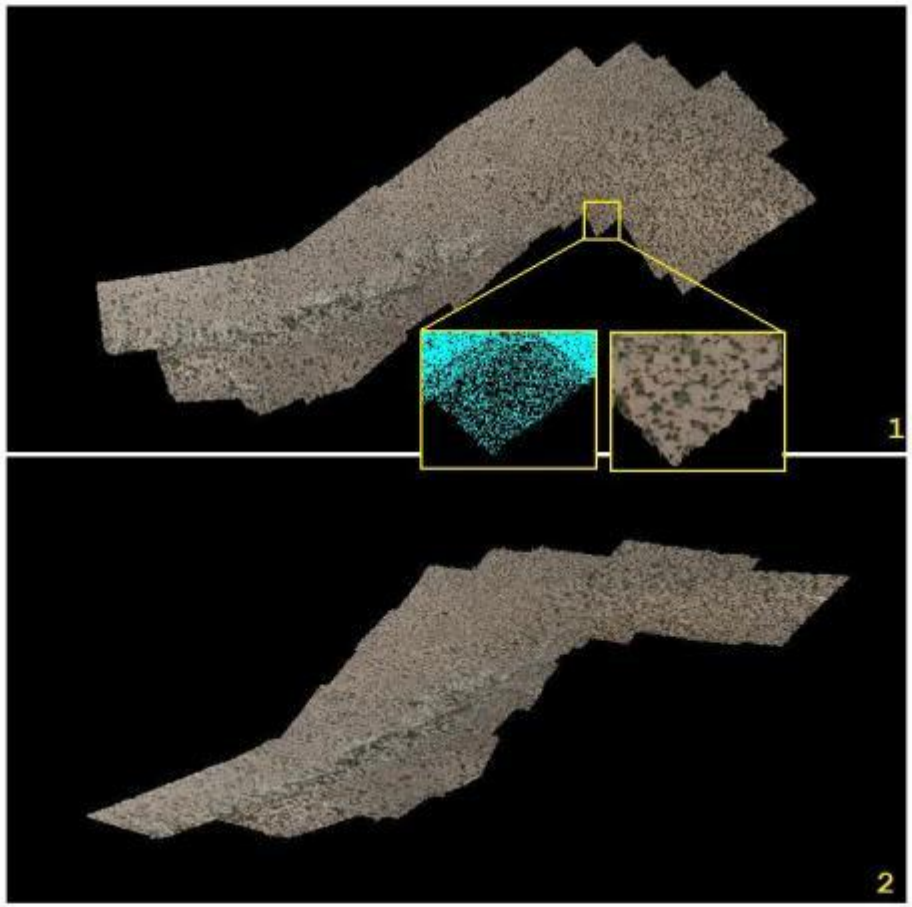
Model of boulderous terrain in Granite Dells – Prescott, Arizona

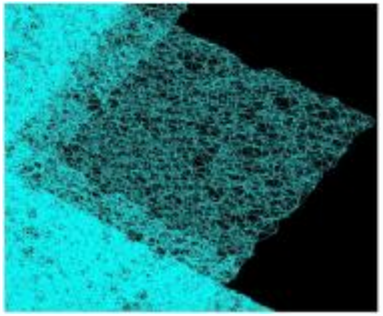
3D wire-frame model

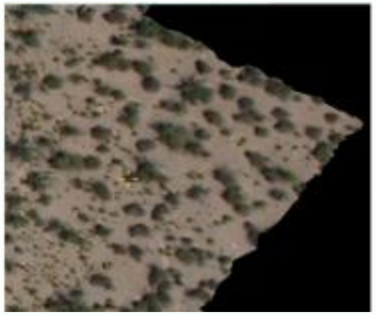
- 20m x 15m area modeled with Canon Rebel T1i – 20mm lens
- Images taken from 25m away
- Estimated resolution of 1.0cm

3D model with images draped

Airborne Testing in Natural Environments







- 400m x 50m area modeled with Canon Rebel t1i – 20mm lens
- Images taken from a maximum height of 75m
- Estimated resolution of 1.24cm

Las Cruces, New Mexico

Conclusions

- Small, affordable equipment

  → viable integration with UAVs

- High accuracy, high resolution models
- Automated flight path generation

  → less preparation time for large flight areas

- Large-scale terrain mapping available to more institutions

Future Work

- Detailed accuracy analysis
  - Compare our models with USGS models
- Feature tracking combined with 3D mapping
  - Identify moving objects (people, cars, etc.) which decrease map accuracy
- Multi-vehicle based mapping
  - Using multiple planes or helicopters can we create more accurate maps?
- Improve path planning algorithm
  - TSP solvers which weight turns – for fixed wing UAVs
  - Include kinematic constraints in TSP solver

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Thank You!

Questions

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