

Autonomous Mapping of Abandoned Underground Mines with UAVs



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Acknowledgements



Mining engineering

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Technology trends in mining
MINExpo International review
NIOSH automation partnership

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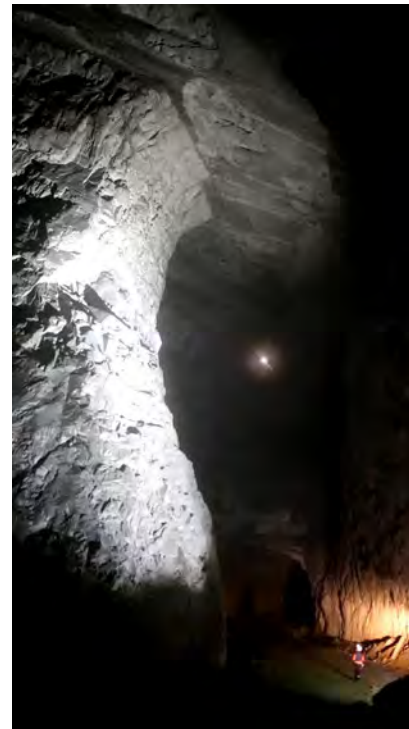
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me.smenet.org

Outline

- 1) Background & Motivation
- 2) Project Goals
- 3) UAV Development
- 4) Case Studies
- 5) Conclusions



Motivation



Background – Stone Pillar Collapses

- Low width-to-height ratios, irregular shapes & geologic features can be problematic
- Difficult to monitor pillars in old works due to limited access
- As-mined assessment of pillars is needed
- 5 significant pillar collapses in stone mines between 2015 – 2021
- Is there a safe method to remotely map and monitor underground pillars?



← Source: MSHA →




Source: 1057 News


SAFETY ALERT

Stone Mine Massive Pillar Collapses

Four massive pillar collapses have occurred in limestone mines since October 2020



Width-to-Height Ratio
Example: 30/50 = 0.6



Be Alert for Spalling and Hourglassing

Air Blast From Massive Pillar Collapse

Causes of Massive Pillar Collapses:

- Slender pillars are susceptible to sudden failure
- Benching can create these tall, thin pillars (width-to-height ratio <0.8)
- Collapses can occur in old and recently benched areas

What are the Dangers?



- Air Blasts
- Ground Falls
- Surface Sinkholes
- Loss of Mine Access

Address Potential for Future Massive Pillar Collapses:

- Properly design pillars for benching (width-to-height ratio >0.8 and assess pillar stability)
- Maintain planned dimensions
- Account for pillar raveling or blasting overbreak
- Assess geologic features in the pillar

Identify At-Risk Areas:

- Recognize signs, such as spalling and hourglassing, that may indicate a pillar is overstressed
- Assess benched areas and verify pillar dimensions
- Evaluate potential air blast pathways
 - Reduce exposure of miners to airpaths
 - Protect mine infrastructure


For more information:
www.msha.gov/PillarInitiative


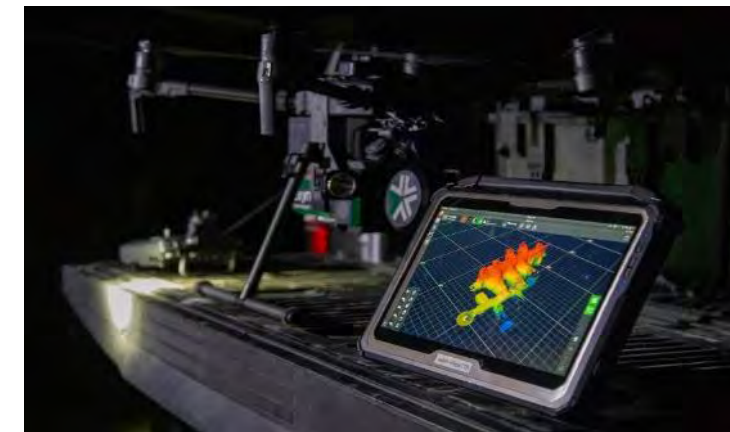
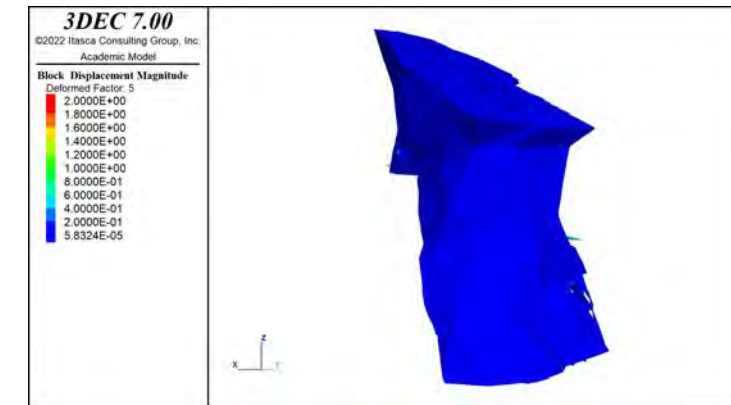
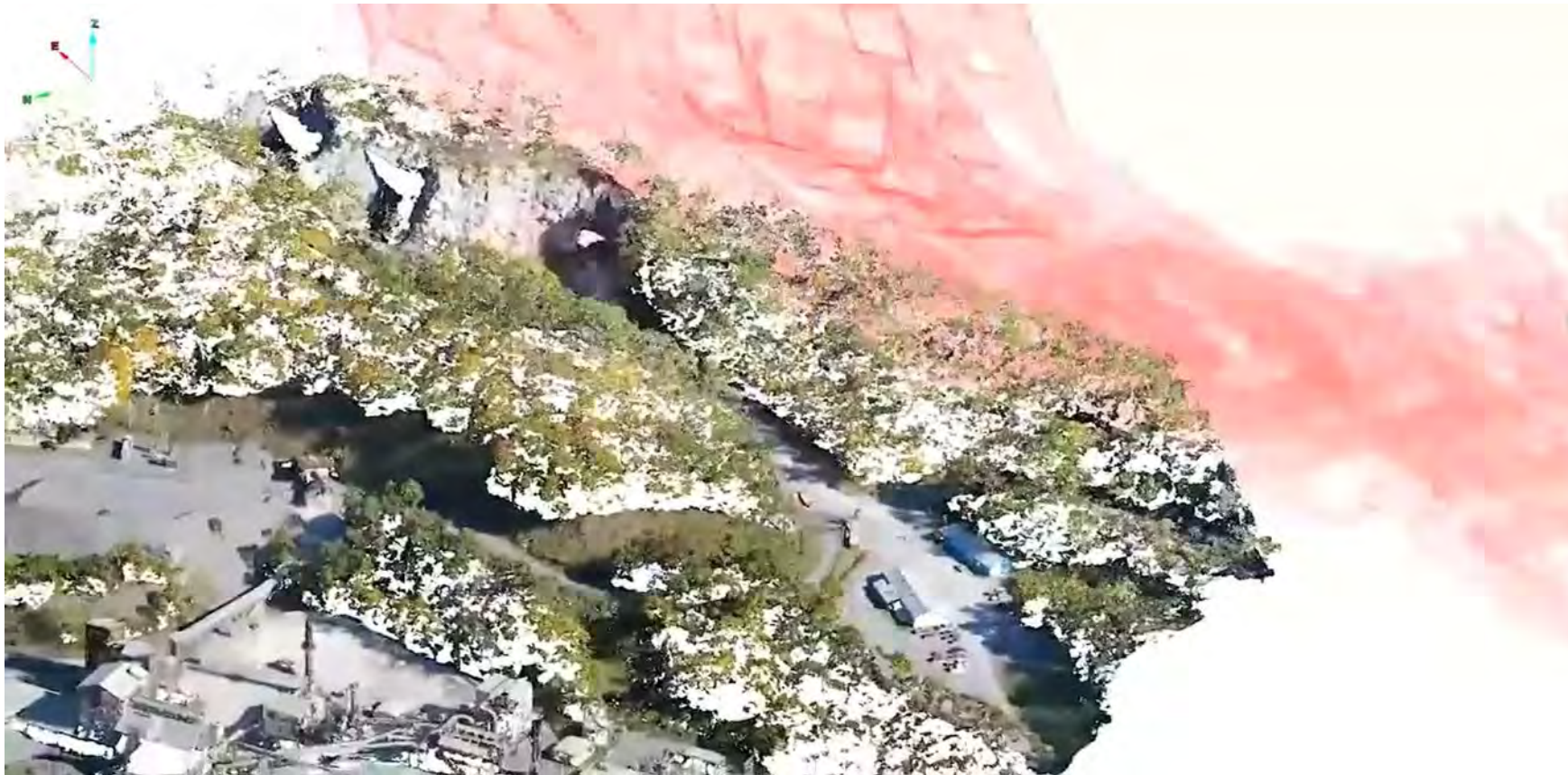
Traditional Surveying

- Proven, Precise
..but time consuming, few points
- Places surveyor at risk to potential ground falls, slip/trip hazards
- Limitations due to accessibility

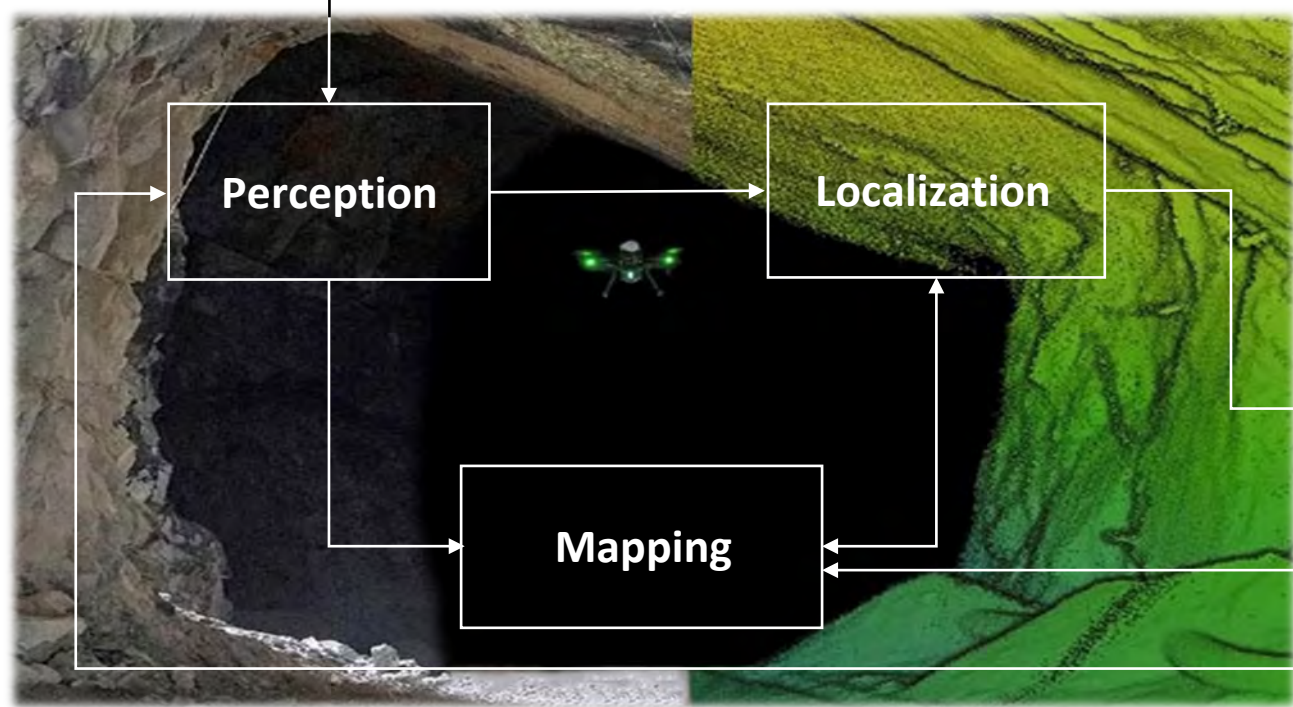


Project Goals

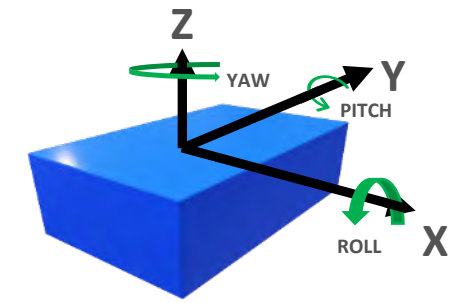
- #1: Drone-based mapping beyond visual line of sight (BVLOS) in GPS-denied u/g mines
- #2: Capture quality data to use for geotechnical & numerical analysis



UAV Multi Sensor Fusion

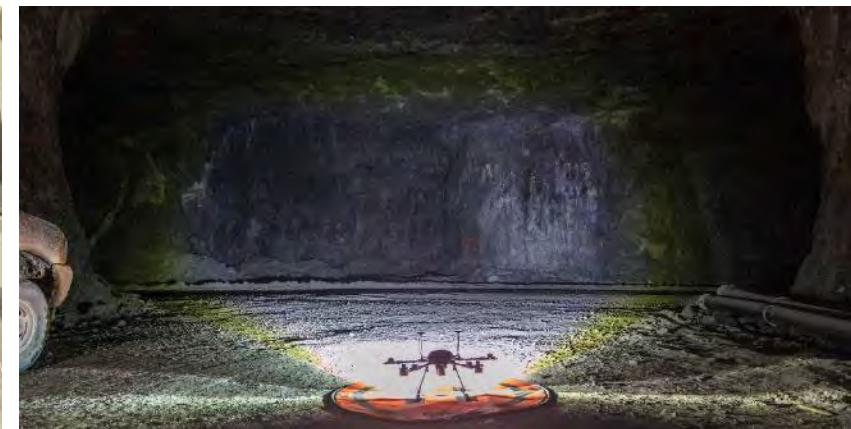
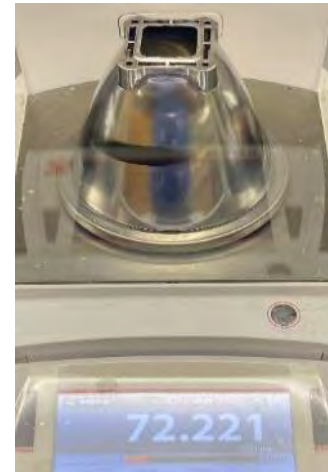


Path / Motion Planning
 $p(x_{0:T}, m \mid z_{1:T}, u_{1:T})$

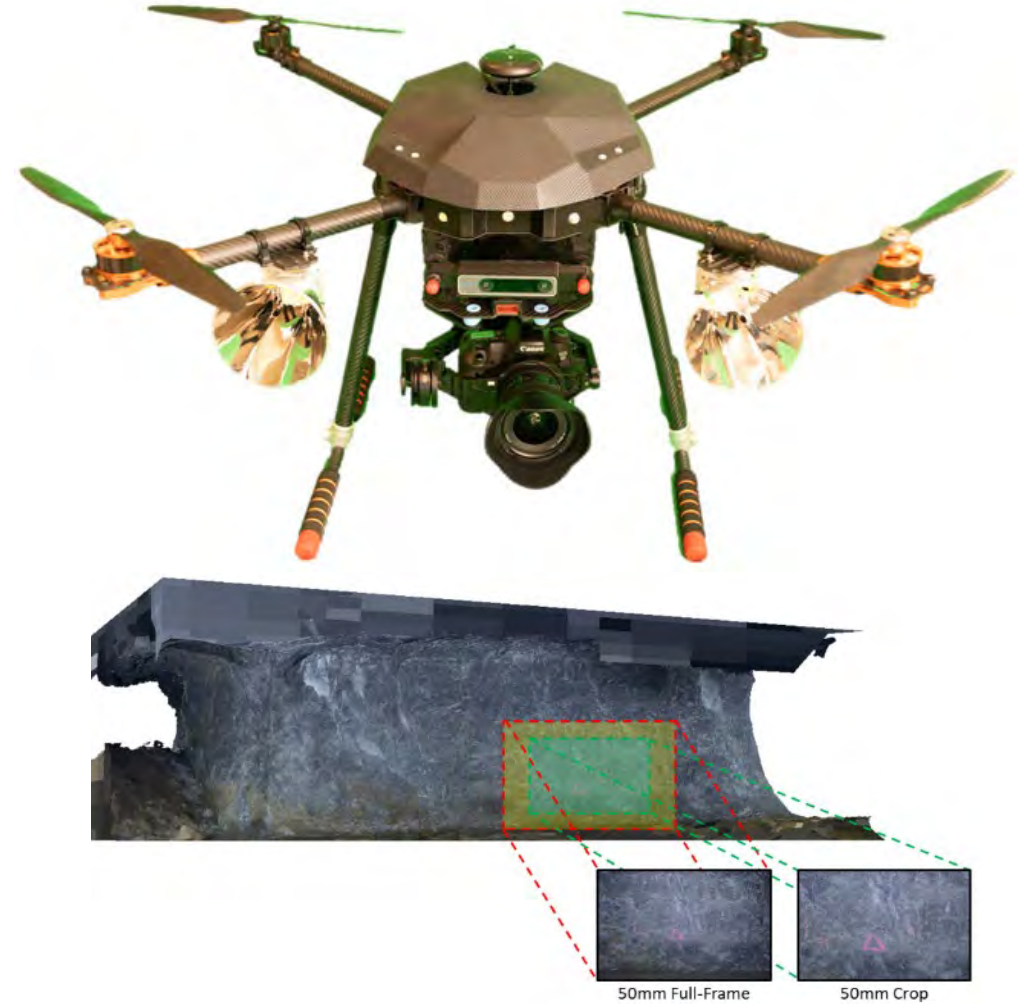
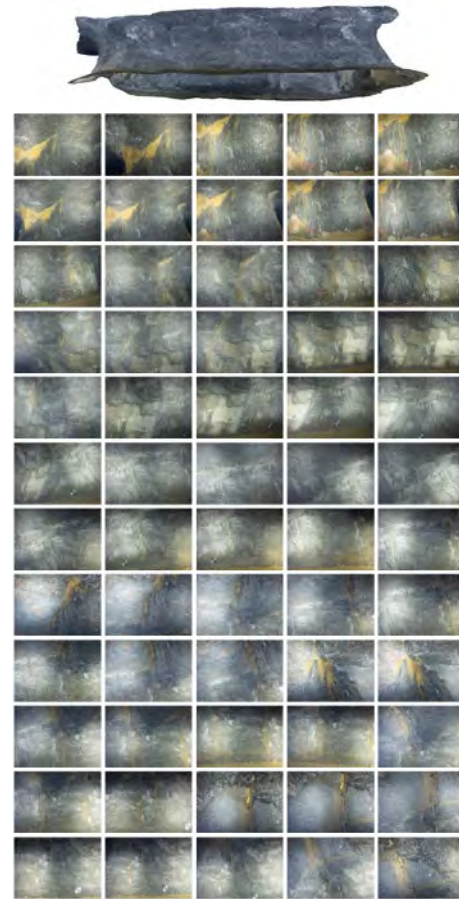


Control

Onboard Lighting Development



Camera Design



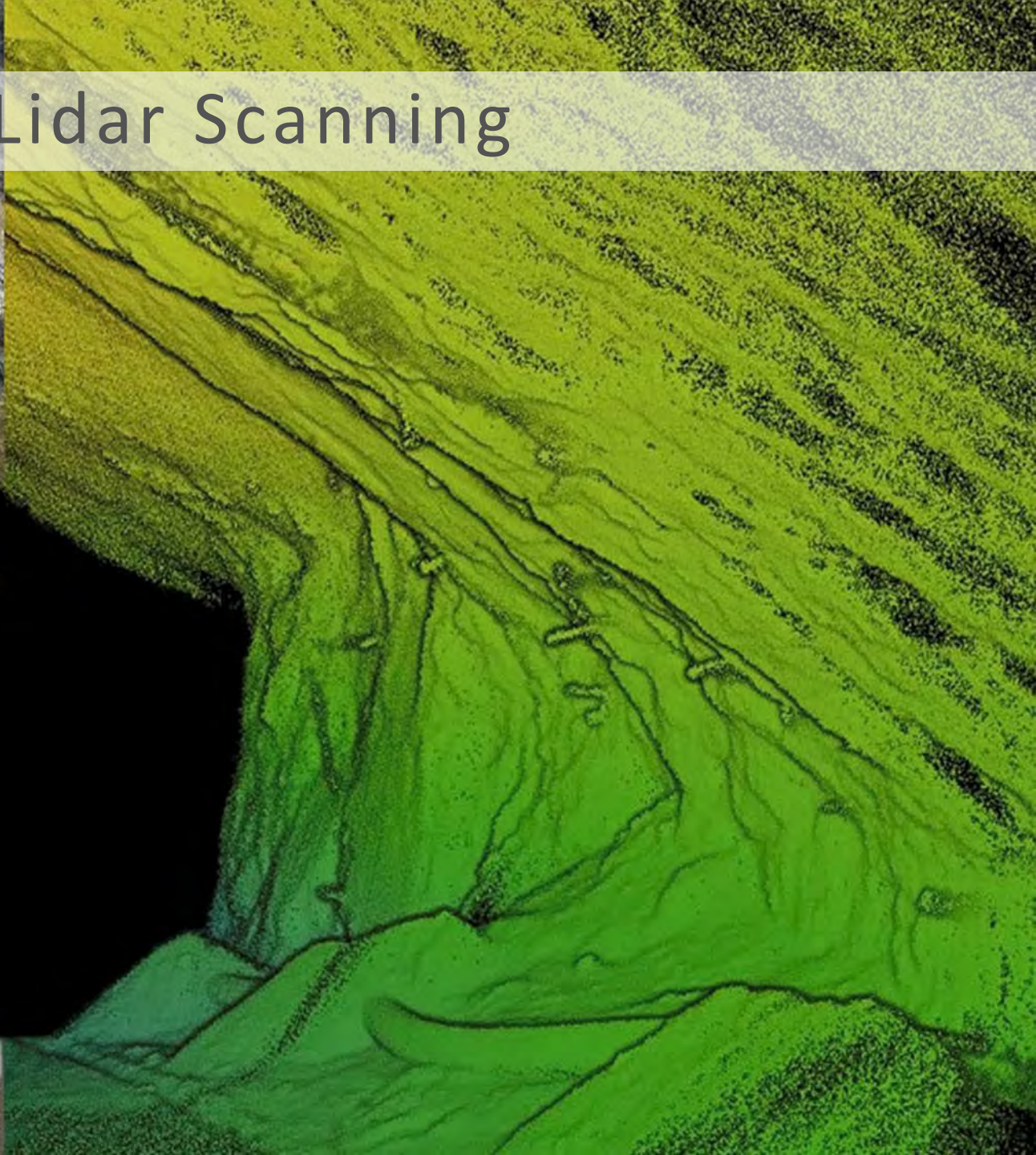


AUTONOMOUS UAV's



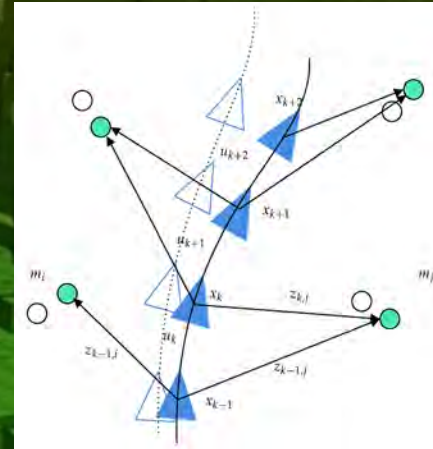
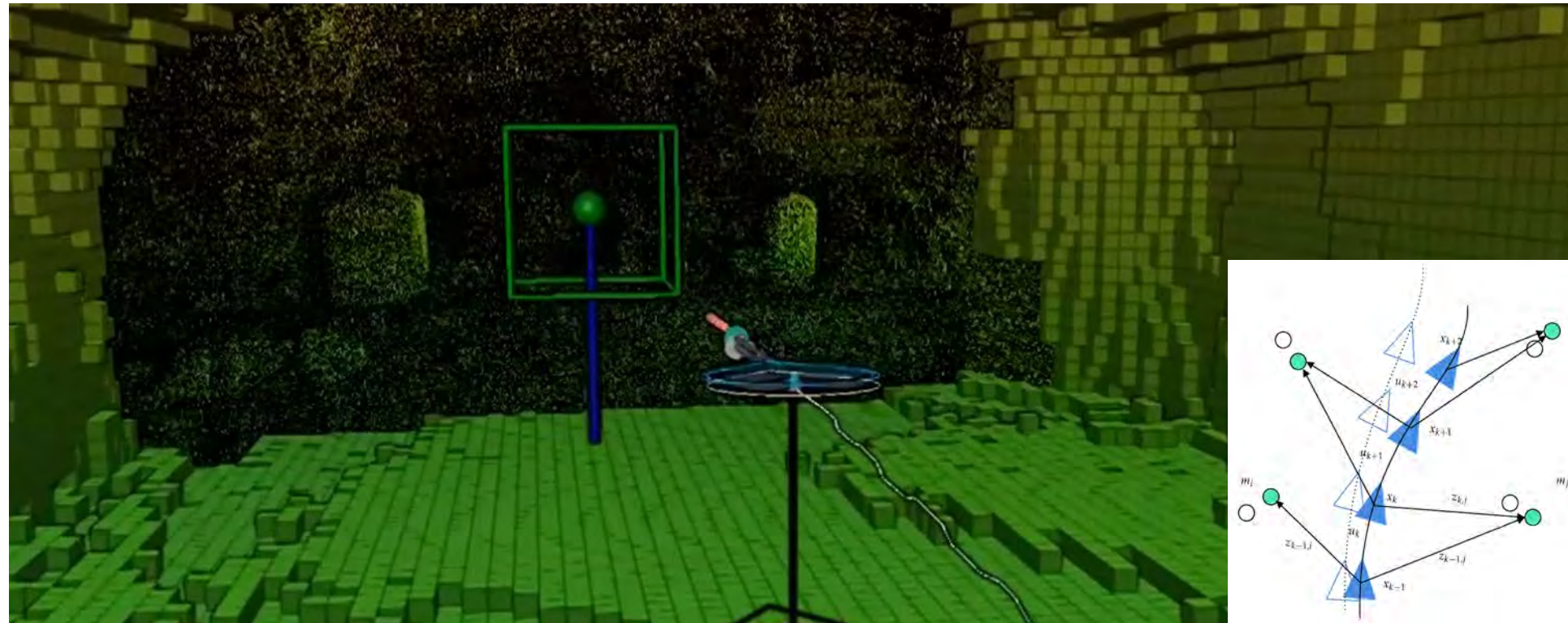
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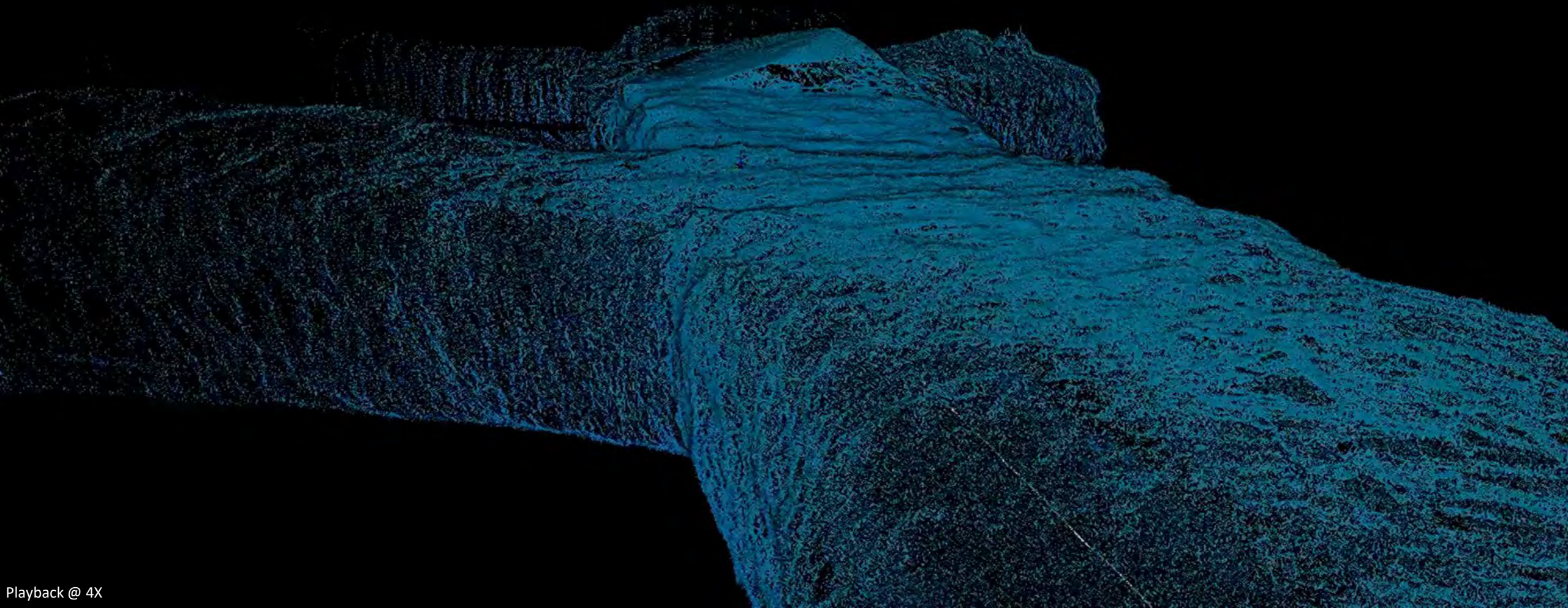
Drone-based Lidar Scanning



Simultaneous Localization and Mapping

- **SLAM** - algorithm to map an environment while keeping track of the object's location within
- **Occupancy grid** - generated to simplify localization & reduce onboard processing req'd





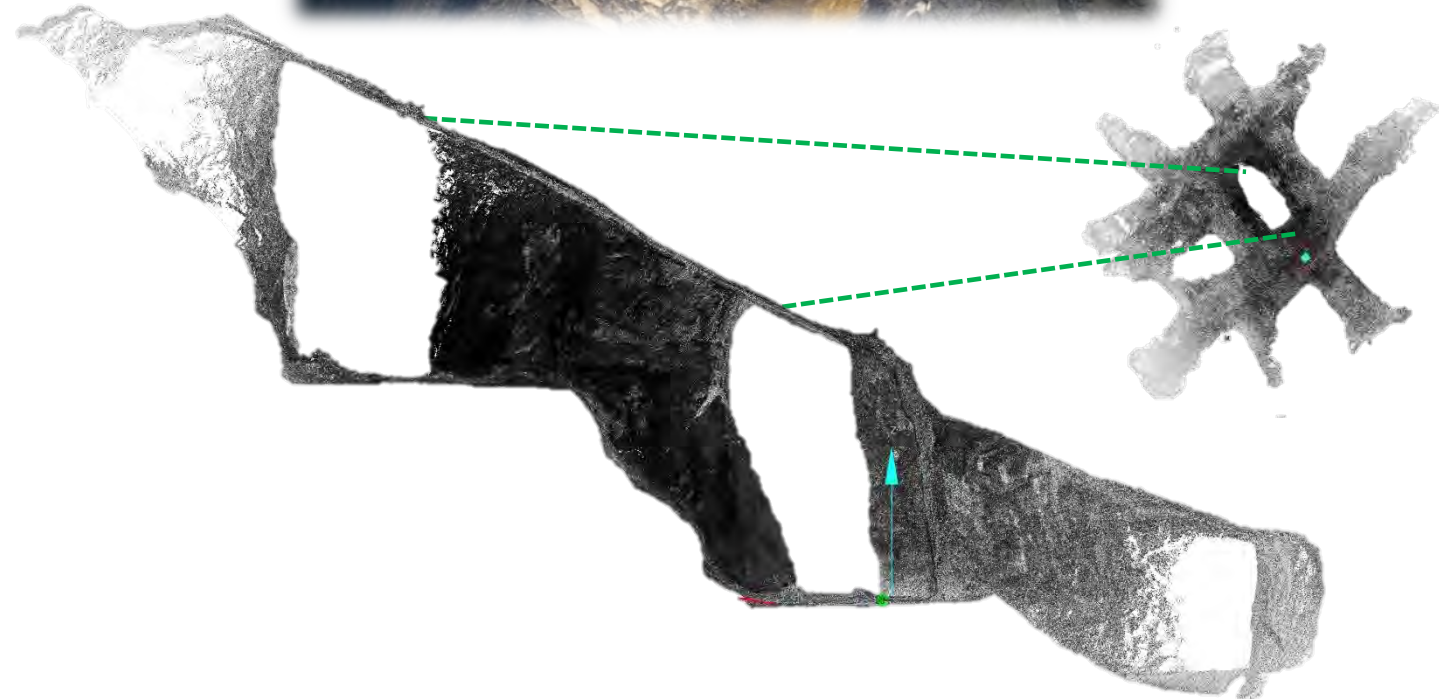
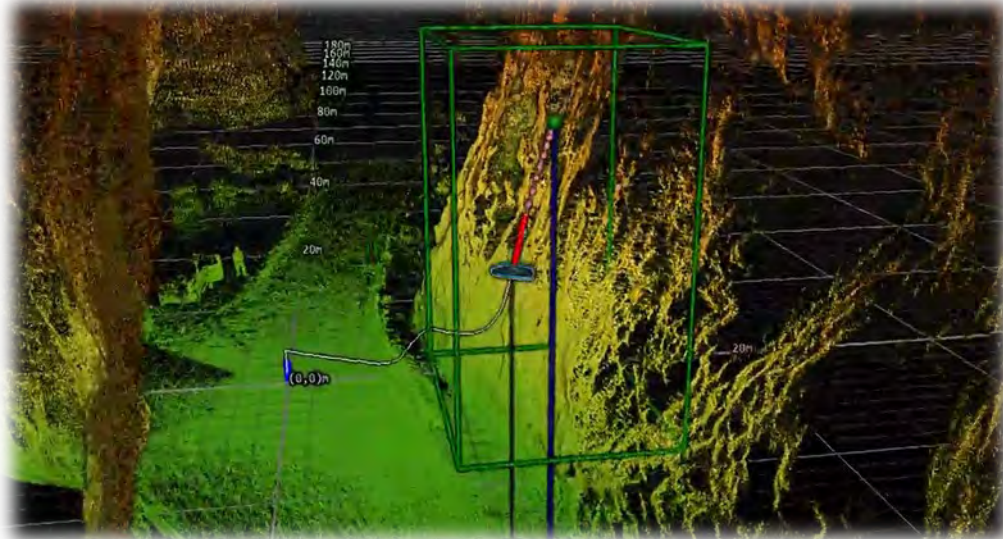
Case Study #1: Benched Mine Pillar (30m height)



Drone-based Mapping of a 30m Benched Pillar

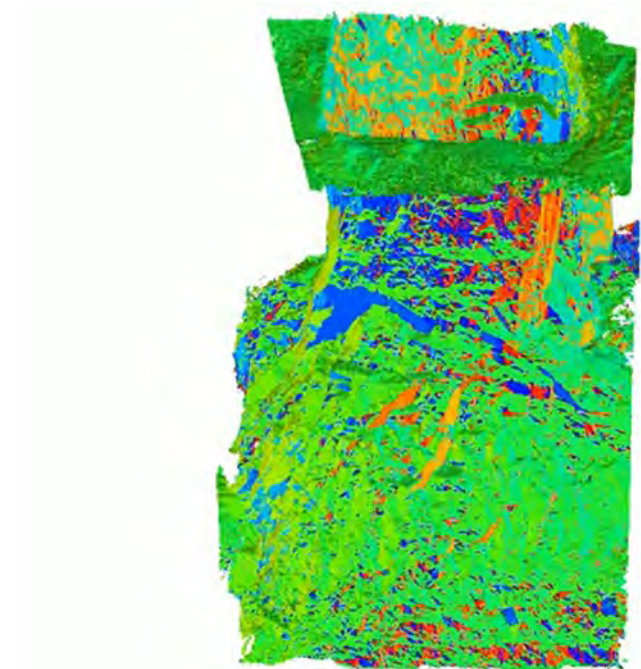
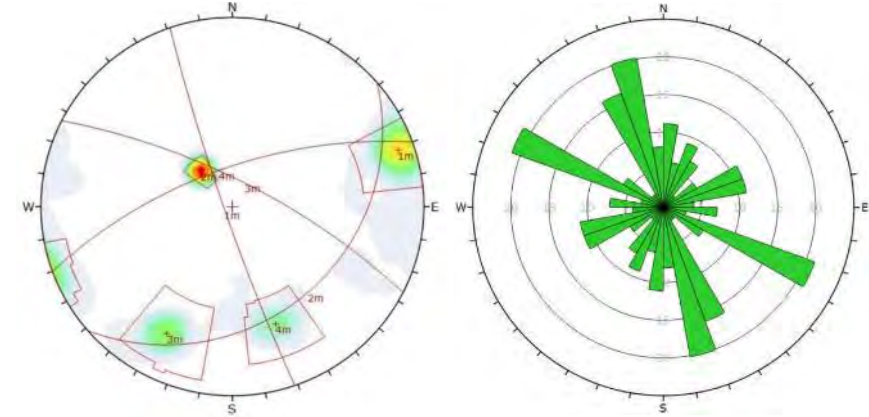


Drone-based Mapping of a 30m Benched Pillar



Geotechnical Mapping

- Orientation & Dip + Dip Direction
- Color by dip & strike
- Map Discontinuities
- Stereonets & Rosette Diagrams



Case Study #2: Abandoned U/G Mine Workings



Mapping Abandoned Mine Areas w/ Autonomous Drones

- 500-acre surface limestone cement operation
- ~23 miles of historic underground mining
- 100' thick high calcium deposit dipping 23°



Surface Model

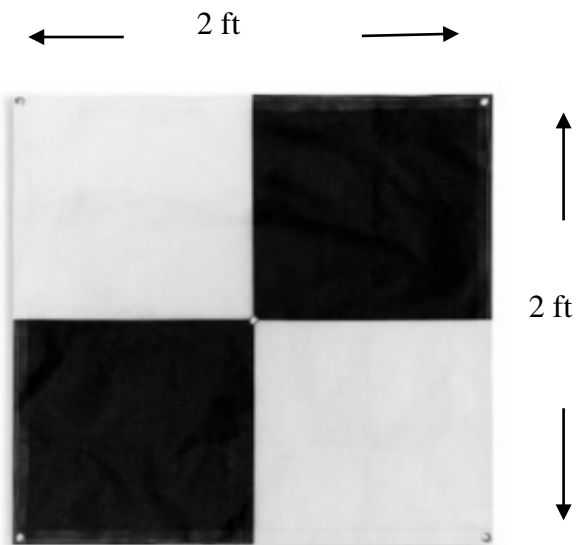


Highwall Model



Georeferencing & Scaling

- Retroreflective survey targets for lidar
- 2' x 2' Aerial Ground Control Point Targets
- Survey in for best alignment & global reference



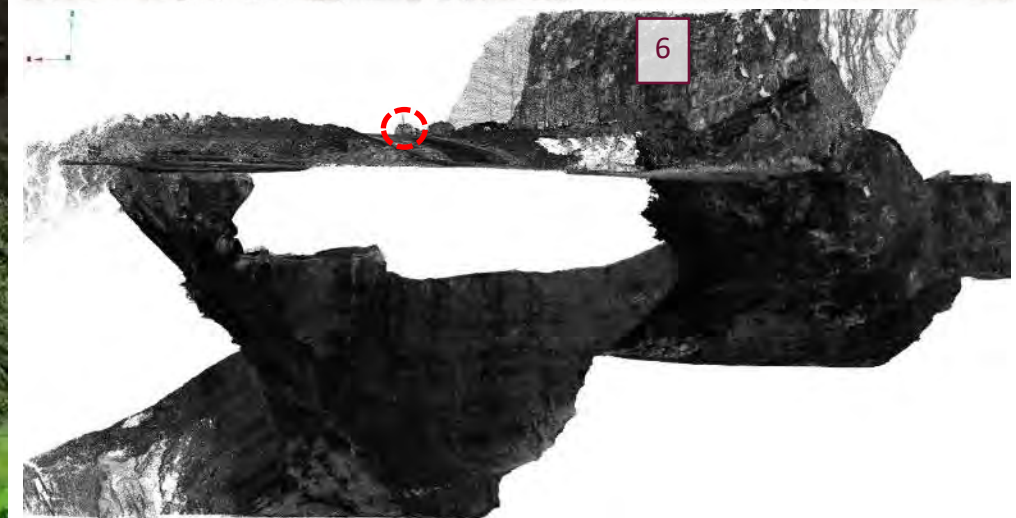
Underground Drone Survey Access Points



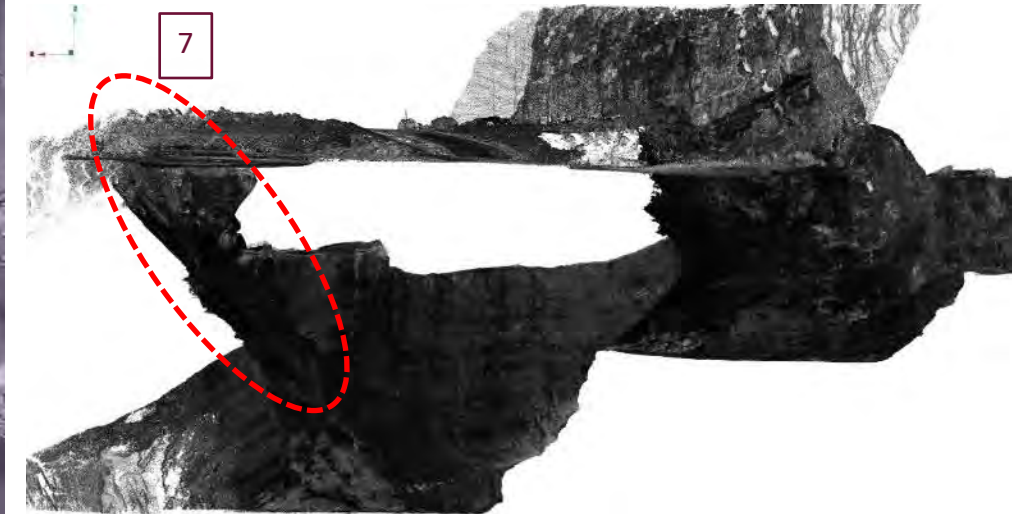
Underground Mapping from Highwall



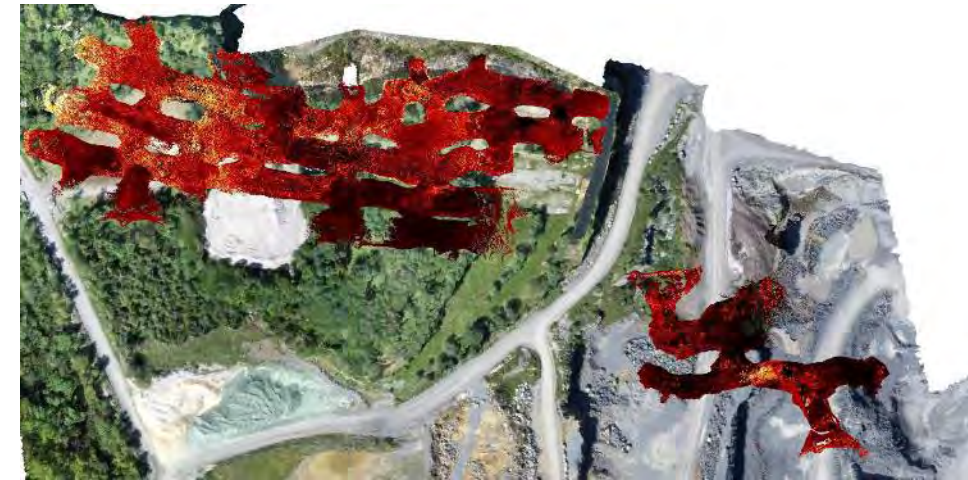
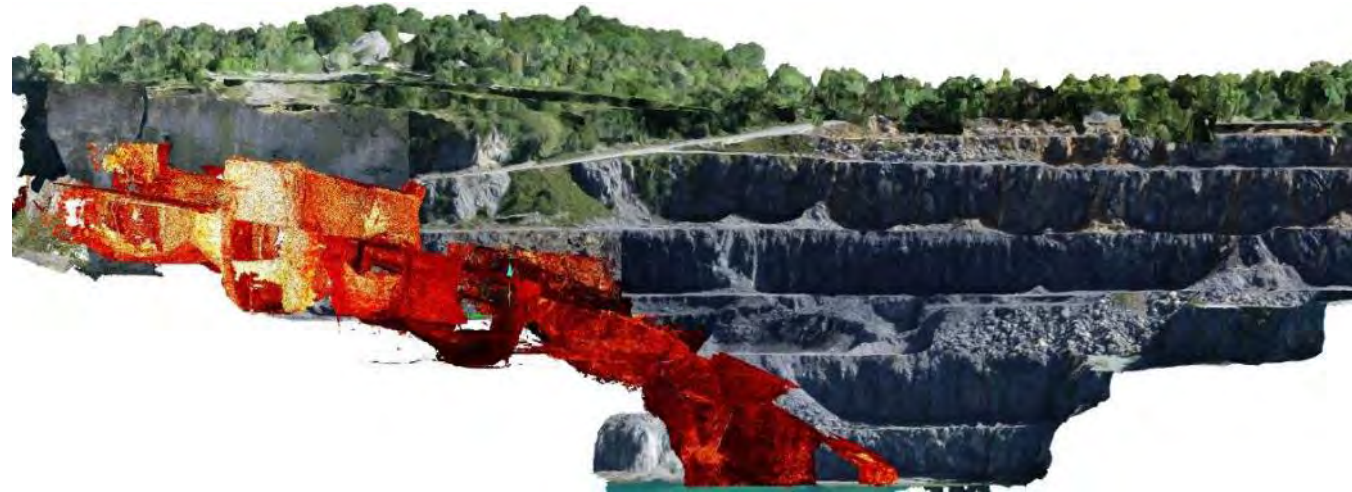
Underground Mapping from Pit



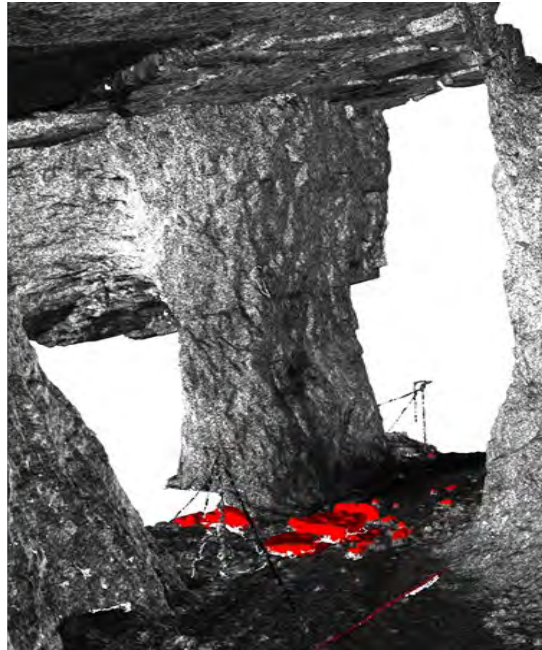
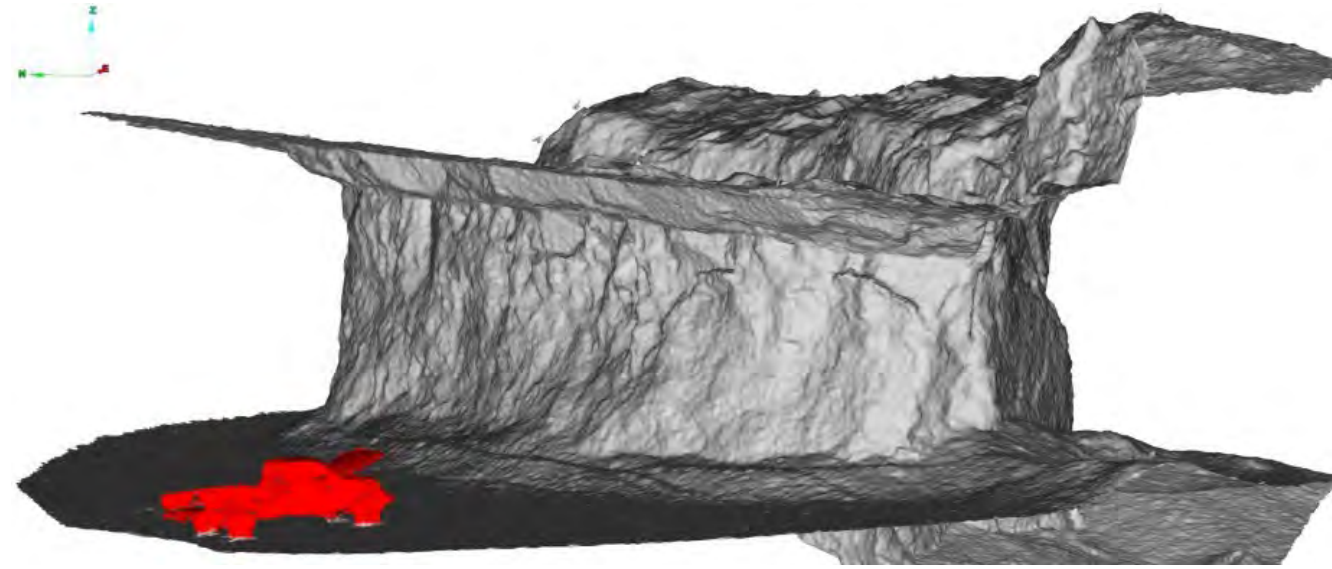
Underground Mapping from In-Pit Opening



Pit Cross Sections & Top View



Hazard Identification from Scans



Conclusions

- Mitigation of risk & reduced personnel exposure
- Faster data collection
- Improved visualization & modelling
- Remote geotechnical analysis
- Facilitate inspections in difficult or previously inaccessible areas



