2024 FECM/NETL SPRING R&D PROJECT REVIEW MEETING – 4/23/2024

An Autonomous Robotic Inspection System for Coal Ash and Tailings Storage Facilities (FE0032177)

University Training and Research for Fossil Energy and Carbon Management – UCR

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Co-PIs: Deniz Tuncay (Mining Eng.), Onur Avci, John Quaranta (Civil Eng.)

West Virginia University

Benjamin M. Statler College of Engineering and Mineral Resources

Team

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  - Department of Mechanical, Materials and Aerospace Engineering – WVU
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  - Department of Civil and Environmental Engineering – WVU
- **John Quaranta** – Co-PI
  - Department of Civil and Environmental Engineering – WVU
- **Berk Tulu** – Former Co-PI

Students:

- **Paulo Galvão Simplício** – PhD student
  - Mechanical Engineering
- **Feras Abla** – PhD Student
  - Civil Engineering
- **Cengiz Kaydim** – PhD Student
  - Mining Engineering
- **Mustafa Can Suner** – PhD student
  - Mining Engineering
- **Kyle Sellers** – Undergrad student (Summer 2023)
  - Mechanical Engineering

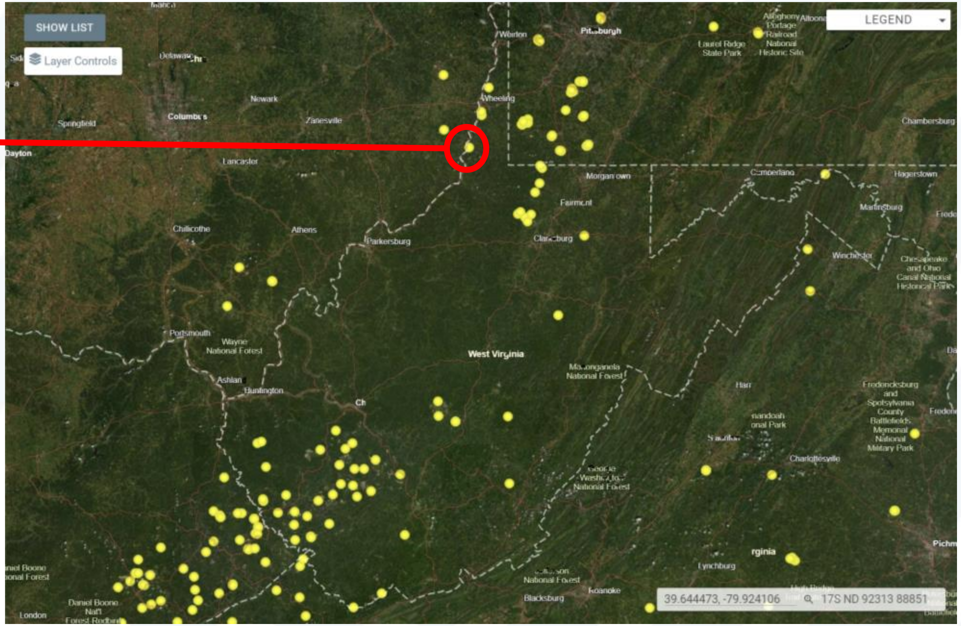
Coal Ash and Tailing Dams

- **Tailings dams, impoundments**, **slurry ponds,** or **ash ponds** are facilities that store waste by-products from coal mine and coal-fired power plants.
- The US has more than 700 coal ash ponds.
- In WV only, at least 52 impoundments[1] are classified as high hazard level
  - failure may result in loss of life, significant economic losses, and/or environmental damage.
- Ash ponds contain contaminants like mercury, cadmium, and arsenic.

Brushy Fork impoundment, WV
31,000,000 m^3 of coal waste
Image: https://appvoices.org/

[1] https://nid.usace.army.mil/

Map of dams in Northern and Central Appalachia



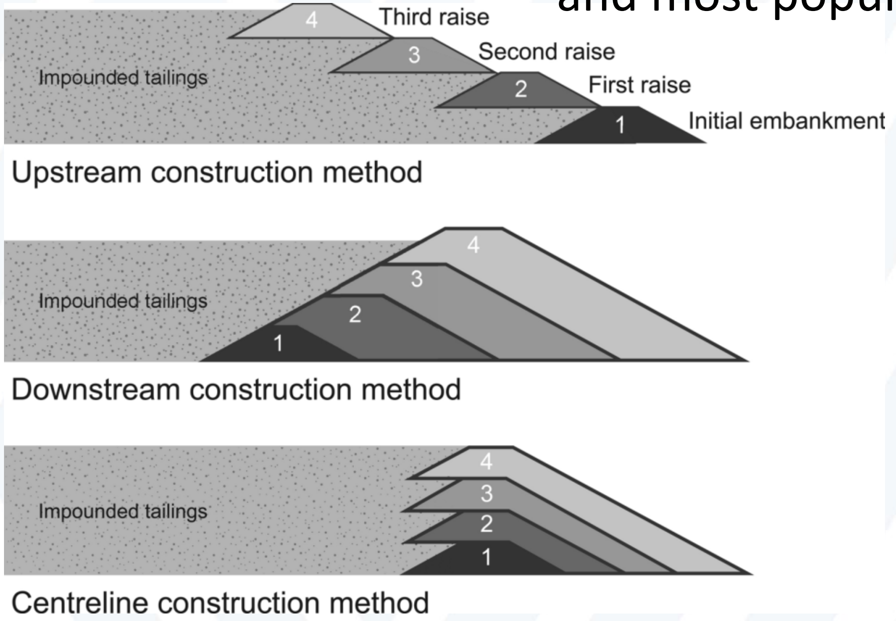
Source: US Army Corps of Engineers, National Inventory of Dams, Geographic Information System (GIS). https://nid.usace.army.mil/

Impound Construction

- Impounds are often embankment dam structures incrementally raised with the same waste they store.

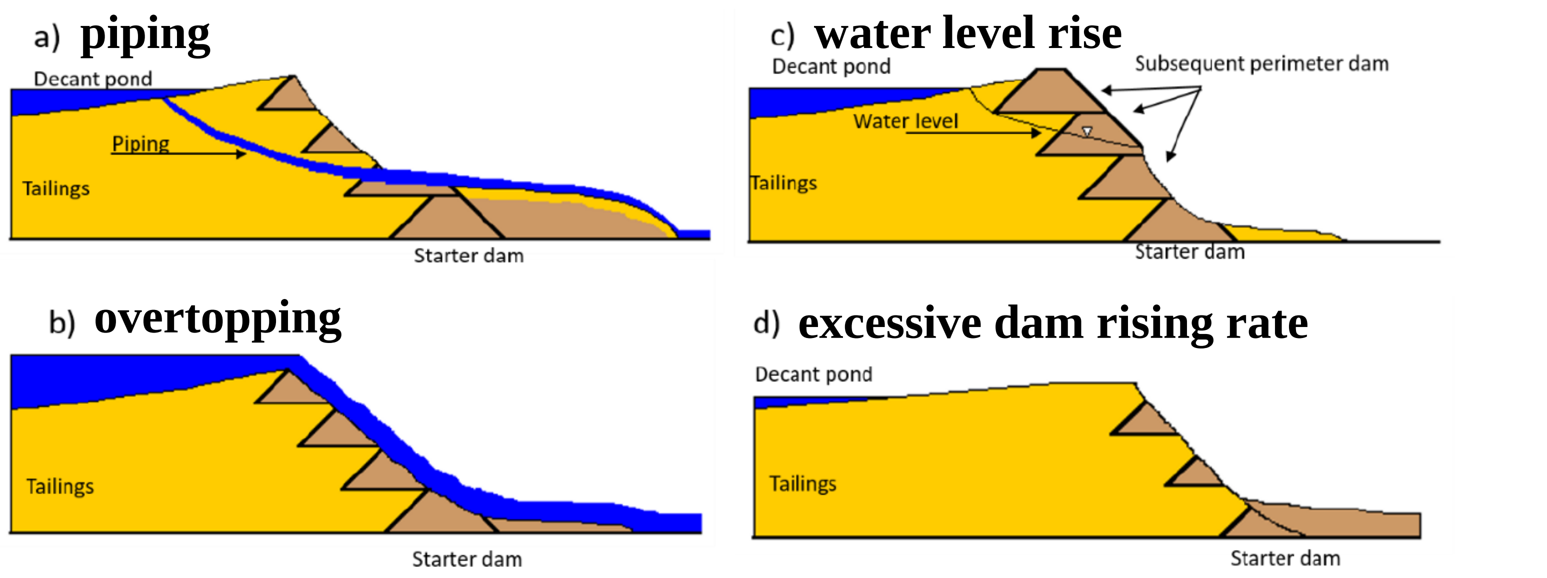
Lowest initial cost and most popular.

MSHA Handbook Series, Dam Inspection and Plan Review Handbook, Number PH21-V-6, January 2021



Lumbroso, D., Collell, M.R., Petkovsek, G. *et al.* DAMSAT: An Eye in the Sky for Monitoring Tailings Dams. *Mine Water Environ* **40**, 113–127 (2021).

Impound Liquefaction (Failure)



Pacheco, R. L. R. (2019). Static liquefaction in tailings dam and flow failure. *Madrid, SP*.

Impound Liquefaction

- Iron mining tailing dam, Brumadinho, Brazil, Jan. 2019
- 11.7 million m^3 of tailings were released
- 363 people died or are missing

https://www.youtube.com/watch?v=NK6EDKOys5E

Closer accidents

Dan River Steam Station, North Carolina, USA

Jan. 2014 - About 74,000 tons of coal ash and 27 million gallons of contaminated water flown through drainage pipe into Dan River.

https://www.nytimes.com/2014/03/01/us/coal-ash-spill-reveals-transformation-of-north-carolina-agency.html

Closer accidents

Kingston fossil plant, Harriman, Tennessee

Dec. 2008 – A retention wall failed. The wave of coal ash and mud toppled power lines, covered roads and ruptured a gas line. It damaged 12 homes, and one person had to be rescued, though no one was seriously hurt.

Image: https://www.nrdc.org/

Closer accidents

Feb. 1972 - collapse of tailings dam after heavy rain; the tailings traveled 27 km downstream, 125 people lost their lives, 500 homes were destroyed. Property and highway damage exceeded $65 million.

Image: https://www.herald-dispatch.com/

Main causes of accidents

- Clogged drains;
- Obstructed spillways;
- Settlement of the dam crest;
- Settlement and slope instability;
- Inadequate Maintenance
  - excess of vegetation, erosion, animal burrows;
- Cracking;
- Sink holes in the dam;
- Seepage.

Result in Overtopping (34% of accidents)

May result in Piping

https://damsafety.org/dam-failures

Prevention: Inspection!

Common Inspection Frequencies for High or Significant Hazard Potential Dams

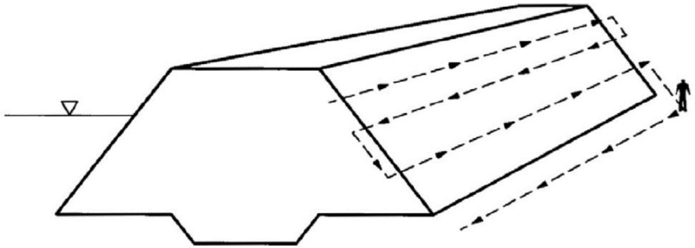
Inspection and Monitoring Category	Inspection and Monitoring Frequency
Construction inspections	Daily – Weekly
Informal inspections during operation	Daily
Normal inspections during operation	Every 7 days
Formal inspections during operation	Yearly
Extreme weather or first filling	As needed per occurrence
Seismic event	As needed, and see table below

MSHA Handbook Series, Dam Inspection and Plan Review Handbook, Number PH21-V-6, January 2021

Abandoned dams

- The long-term stability of the embankment and any seepage containment system is critical.
- To be considered abandoned, tailings dams need to be modified to ensure it is not capable of impounding water above the tailings.
- Inspection at its normal frequency should continue until the site is abandoned according to the design plan.

Suggested inspection (MSHA)

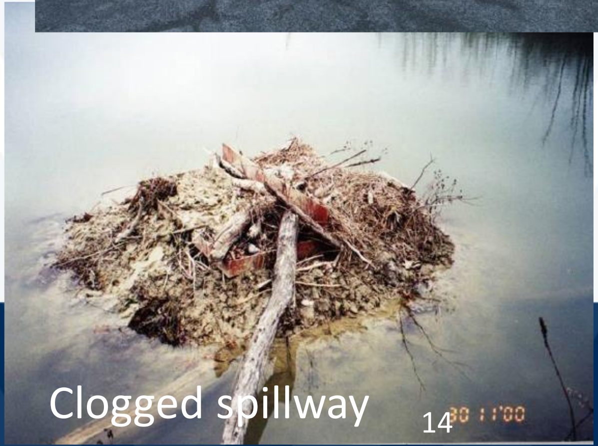


Seepage on downstream slope

Sinkhole in pool area

Crack on the crest

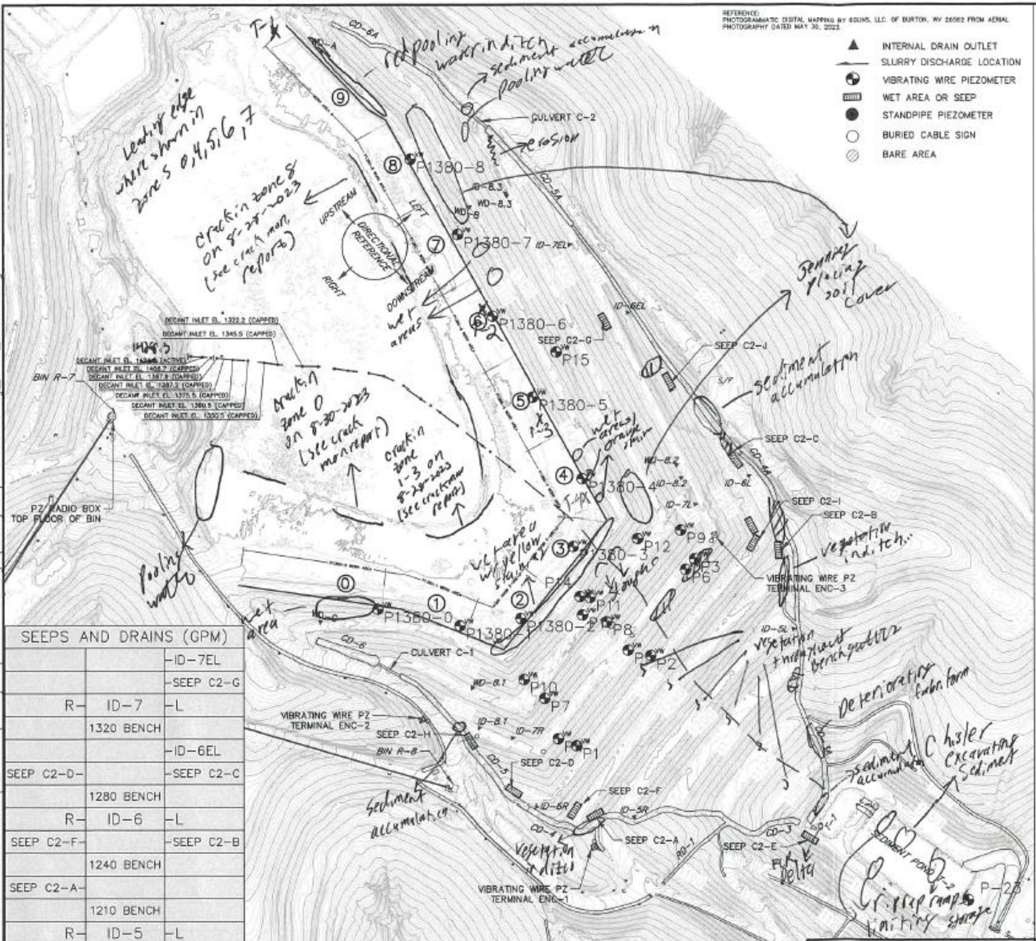
Cracks on embankment slope



Clogged spillway

MSHA Handbook Series, Dam Inspection and Plan Review Handbook, Number PH21-V-6, January 2021

Cumberland 2 Tailings Dam
Iron Senergy
Bituminous Coal Mine, Waynesburg, PA



SEEPS AND DRAINS (GPM)		
		-ID-7EL
		-SEEP C2-G
R-	ID-7	-L
	1320 BENCH	
		-ID-6EL
SEEP C2-D-		-SEEP C2-C
	1280 BENCH	
R-	ID-6	-L
SEEP C2-F-		-SEEP C2-B
	1240 BENCH	
SEEP C2-A-		
	1210 BENCH	
R-	ID-5	-L
	1170 BENCH	
	1125 BENCH	
	1080 BENCH	
SEEP C2-E-		
3" FLUME-		-DECANT

OBSERVATIONS BY: MJG

DATE: August 30, 2023
7-Day inspection

POOL ELEVATION: 1426.6

ACTIVE DECANT INLET: 1428.3

DECANTING: (NO) YES HEAD ABOVE RISER: —

SLURRY DISCHARGE: (NO) YES

PUMPING FROM IMPOUNDMENT: (NO) YES

DISCHARGE LOCATION: —

EMBANKMENT STAGE: Embankment Construction / Impoundment Elimination

MAIN EMBANKMENT ELEV: 1438 TO 1440

EASTERN EMBANKMENT ELEV: 1432 TO 1440

WORKING SURFACE	TODAY	THIS WEEK	
COMBINED REFUSE PLACEMENT:	(NO) YES	(NO) YES	
CCR PLACEMENT:	NO (YES)	NO (YES)	SHOW ON DWG.
PUSHOUT ACTIVITY:	NO (YES)	NO (YES)	SHOW ON DWG.

SURFACE CONDITIONS: (GOOD) FAIR POOR

THICK LIFTS UNCOMPACTED AREAS POORLY GRADED RUTS

DENSITY TESTS: NO (YES) PASSING: 4

FAILING:

PROCTOR SAMPLE TAKEN: P-22 DATE: 8-9-2023

DOWNSTREAM SLOPE/ABUTMENT CONDITIONS: See dwg

(INDICATE SEEPAGE AREAS, SLOUGHS, EROSION ON DRAWING)

SEDIMENT POND/SEDIMENT TRAPS:

Chisler Excavation Sediment from Sed Pond T-2

Riprap ramps limiting storage

ACTIVE MAINTENANCE/CONSTRUCTION PROJECTS:

Jenning excavating - placing soil cover on Eastern Embankment

NOTES: PHOTOS: NO (YES)

P-23 = 11.7'

T-2 Pool = 1029.9'

3" Flume = 0.09' (10gpm)

Valley UD = 11 GPM

D'APPOLONIA		IRON SENERGY	IRON CUMBERLAND, LLC
PROJECT NUMBER: 028530		DRAWN BY: MJG / DATE: 06/16/2023	COAL REFUSE DISPOSAL AREA NO. 2
FILE NAME: Weekly Inspection Drawing_2017_C3D'13.dwg		CHECKED BY: / DATE:	WEEKLY INSPECTION DRAWING
			SCALE: AS SHOWN / DRAWING NO. / REV

W:\2002\028530 - CONSTR MONITORING\REPORTS\Weekly Inspection Drawings\Weekly Inspection Drawing_2017_C3D'13.dwg

This project

MSHA recommended inspection equipment

- Note pad / Inspection form
- Weir and pipe flow charts
- Camera and extra batteries
- Calculator
- Global Positioning Unit (GPS)
- Measuring tape and 6-foot ruler
- Range finder or Abney level
- Water level indicator
- Survey ribbon
- Graduated bucket or container of known volume
- Clear container for checking clarity of flow
- Watch or timer
- Binoculars
- Handheld spotlight

Our proposed equipment

Objectives

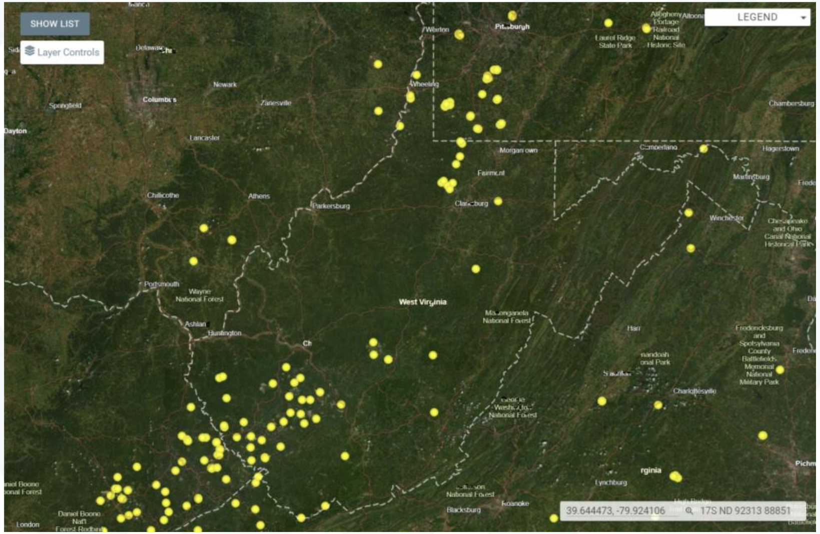
- Develop a robotic drone, equipped with several complementary sensors, that will autonomously inspect several structures of a storage facility;
- Create AI-based hazard detection algorithms that will use multispectral and georeferenced images (i.e., thermal and visual) and 3D Point Clouds to detect hazards in the storage facility structure.

Technical Approach

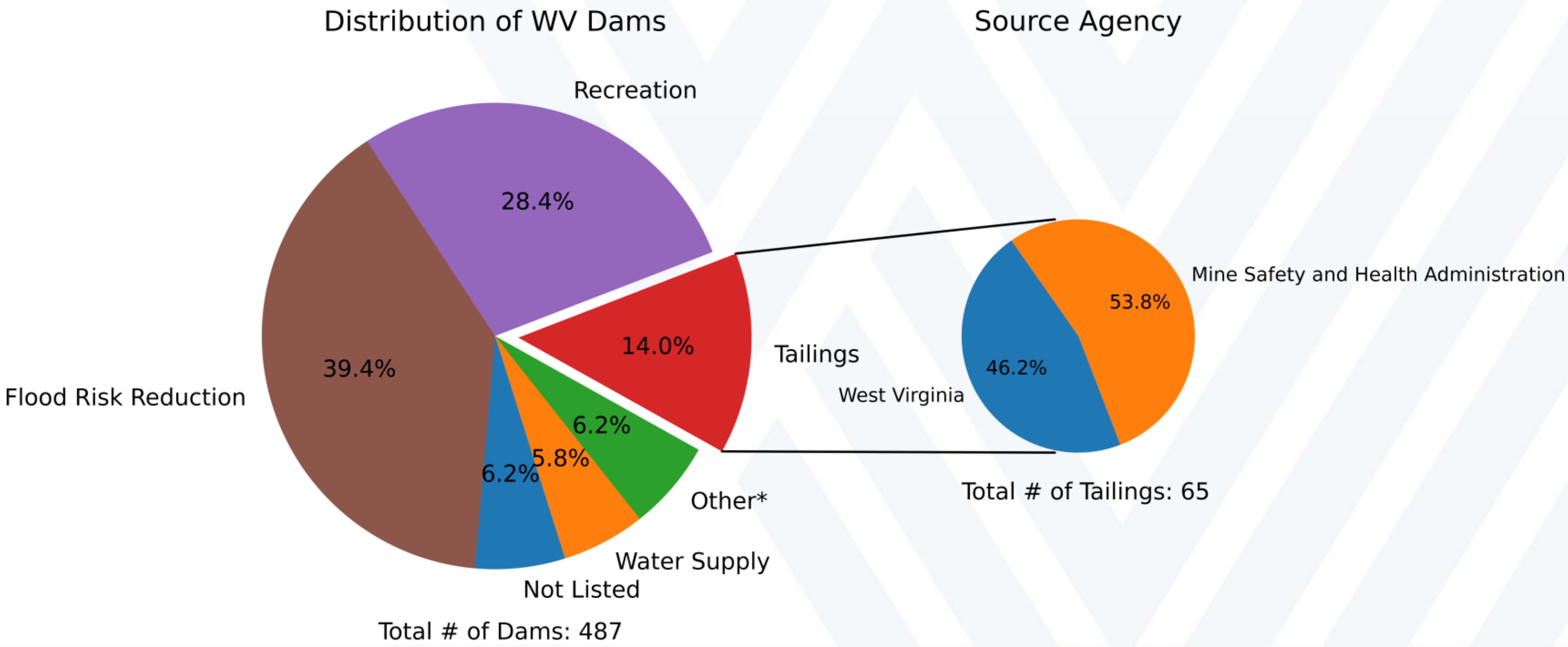
- Task 1.0 – Project Management and Planning
- Task 2.0 – Configuration assessment of coal refuse facilities and programming of autonomous inspection logics
  - 2.1 Preliminary facility configuration assessment
  - 2.2 Detailed assessment of inspection structures and locations
  - 2.3 Development of autonomous inspection logics
- Task 3.0 – Drone assembly and programming
  - 3.1 – Drone assembly
  - 3.2 – Inspection of open-channel spillways and principal spillway inlets/outlets
  - 3.3 – 3D mapping of dam's crest and slopes
  - 3.4 – Detection of leaking due to seepage through embankment slope and foundation
- Task 4.0 – Development of hazard detection software and user interface
  - 4.1 – Hazard detection
  - 4.2 – User Interface application

2.1 – Preliminary facility configuration assessment

- Database with some characteristics of coal waste facilities in WV and neighboring states.
- Source: US Army Corps of Engineers, National Inventory of Dams (NID)



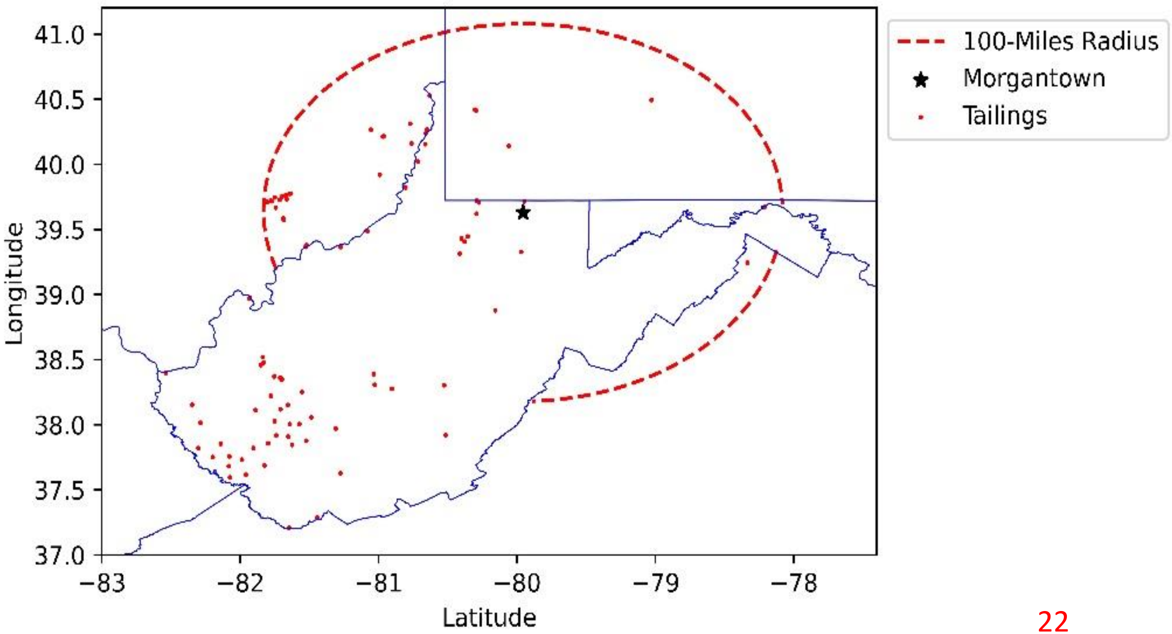
Dams in WV



Distribution of WV Dams
Recreation
28.4%
14.0%
Tailings
39.4%
Flood Risk Reduction
6.2%
5.8%
6.2%
Other*
Water Supply
Not Listed
Total # of Dams: 487
Source Agency
Mine Safety and Health Administration
53.8%
46.2%
West Virginia
Total # of Tailings: 65

Characteristics of the database

- Tailing dams in WV and 100 miles radius from Morgantown
  - 65 from WV
  - 29 from OH
  - 4 from PA
  - 1 from VA

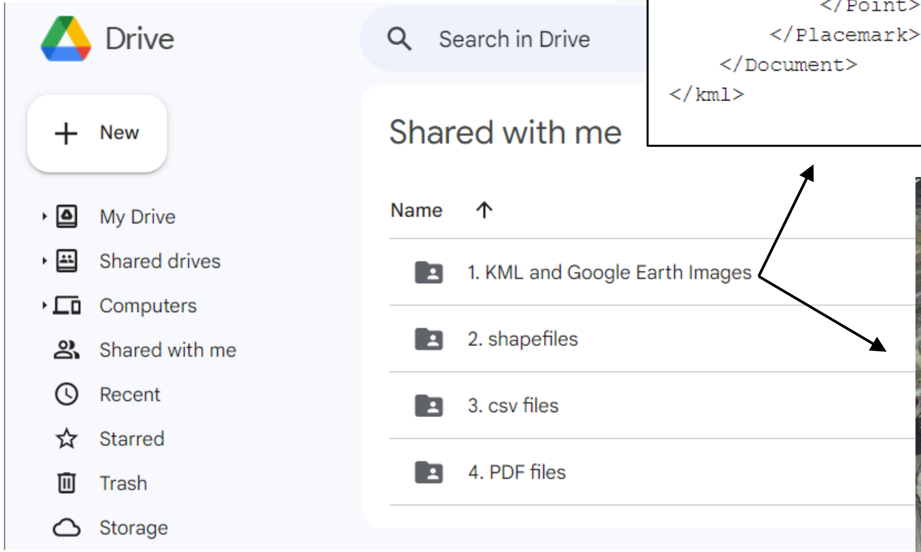


Characteristics of the database

- The database consists of
  1. Keyhole Markup Language (KML)
     - used to visualize storage facilities and their NID data on Google Earth
  2. shapefile with NID (National Inventory of Dams) data of the facilities
  3. csv files with NID data of the facilities
  4. pdf and drawing files with the imported google image
     - will be used for detailed analysis.

Characteris

```xml
<?xml version="1.0" encoding="UTF-8"?>
<kml xmlns="http://www.opengis.net/kml/2.2" xmlns:gx="http://www.google.com/kml/ext/2.2">
    <Document id="1367">
        <Placemark id="1369">
            <name>Moccasin Hollow Impoundment</name>
            <Point id="1368">
                <coordinates>-81.48611111,38.056400000000004,0.0</coordinates>
            </Point>
        </Placemark>
    </Document>
</kml>
```



2.2 –Assessment of inspection structures and locations

3.1 – Drone assembly

- Purchase, assembly, test, and initial programing of the drone.
- Ground control station (laptop)
  - Robot Operating System (ROS 2)
  - Data collection and storage
  - Motion planning and execution

Drone selection - criteria

- Required
  - Made in USA (to comply with DOE FOA)
  - Remote ID (to comply with FAA)
  - Programable by a computer with SDK (necessary for automation)
  - RGB Image (required for Dam inspection)
  - Thermal Image (required for Seepage detection)
  - Lidar (required for 3D Mapping)
- Desirable
  - NDAA & TAA compliant (to facilitate use by governmental agencies)
  - RTK (for precise positioning)
  - Easy operation (to facilitate transfer of technology)
  - Affordable (to facilitate transfer of technology)

FAA - Federal Aviation Administration
NDAA - National Defense Authorization Act
TAA - Trade Agreements Act

ANAFI USA GOV drone

- Required
  - ✓ Made in USA (to comply with DOE FOA)
  - ✓ Remote ID (to comply with FAA)
  - ✓ Programable by a computer with SDK (necessary for automation)
  - ✓ RGB Image (required for Dam inspection)
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  - ✗ Lidar (required for 3D Mapping)
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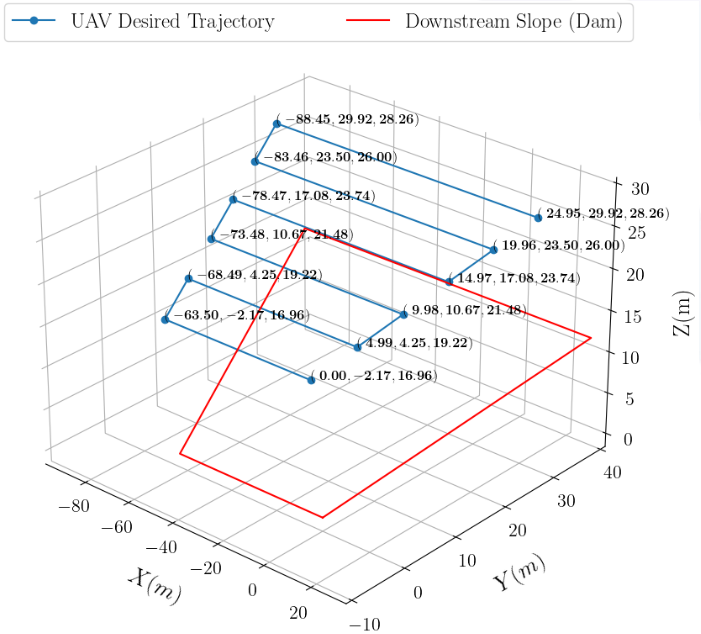
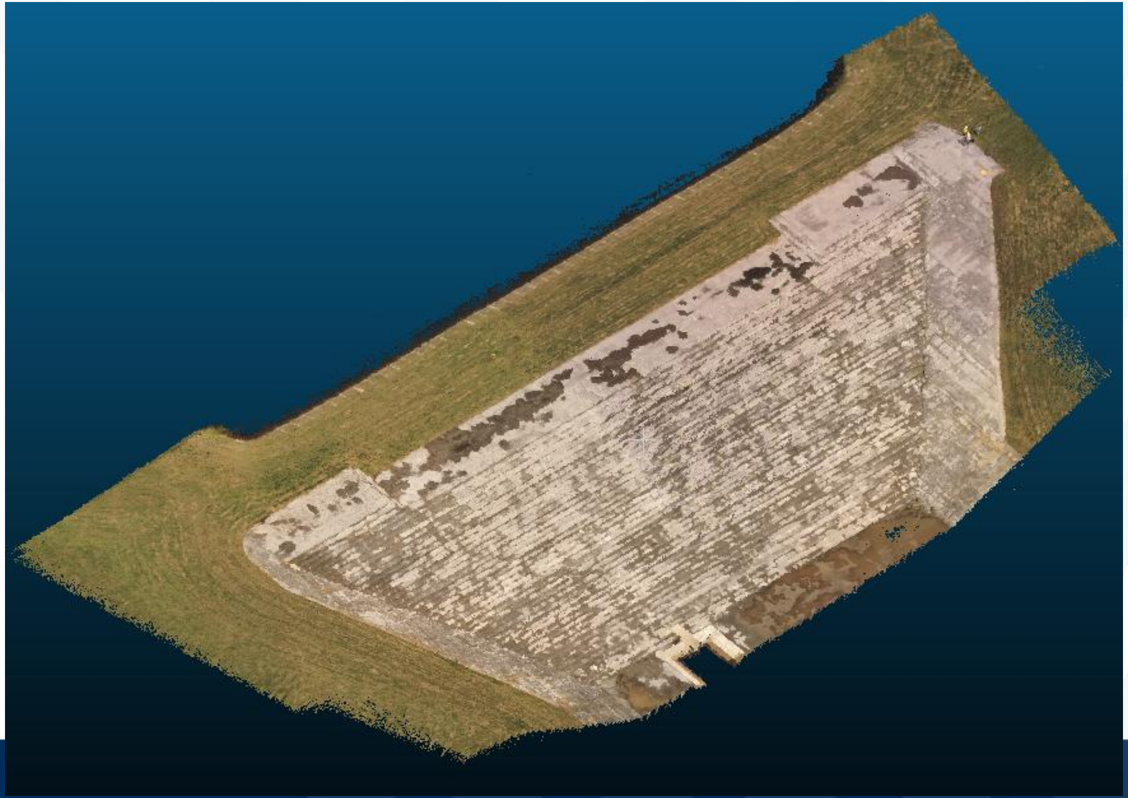
FAA - Federal Aviation Administration
NDAA - National Defense Authorization Act
TAA - Trade Agreements Act

Testing mission https://youtu.be/SuqJXi0uRdk

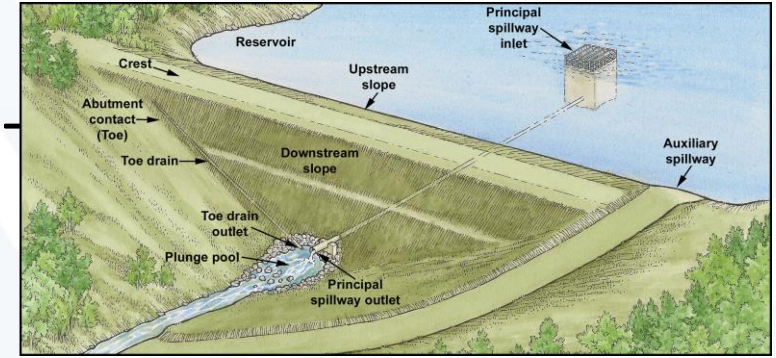
WestV


UAV Desired Trajectory
Downstream Slope (Dam)
(−88.45, 29.92, 28.26)
(−83.46, 23.50, 26.00)
(−78.47, 17.08, 23.74)
(−73.48, 10.67, 21.48)
(−68.49, 4.25, 19.22)
(−63.50, −2.17, 16.96)
(24.95, 29.92, 28.26)
(19.96, 23.50, 26.00)
(14.97, 17.08, 23.74)
(9.98, 10.67, 21.48)
(4.99, 4.25, 19.22)
(0.00, −2.17, 16.96)
X(m)
Y(m)
Z(m)

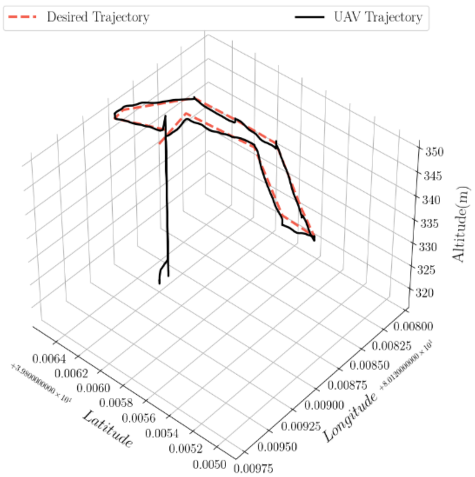


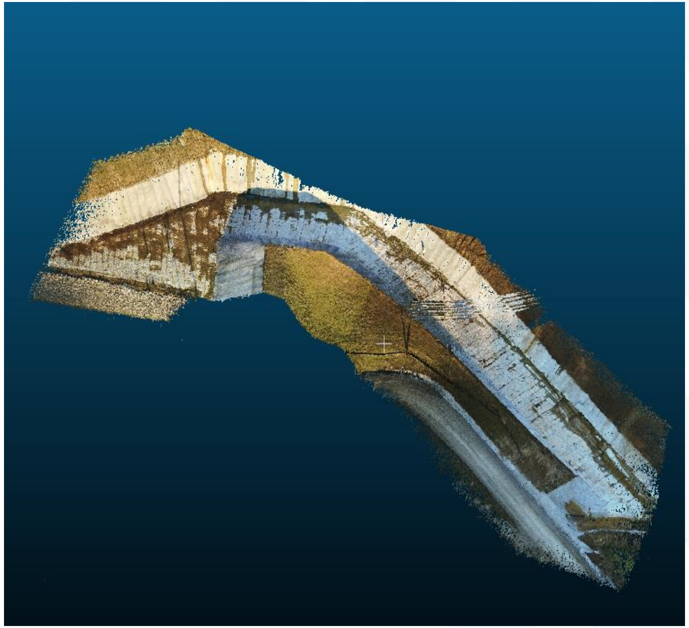
3.2 – Inspection of spillways

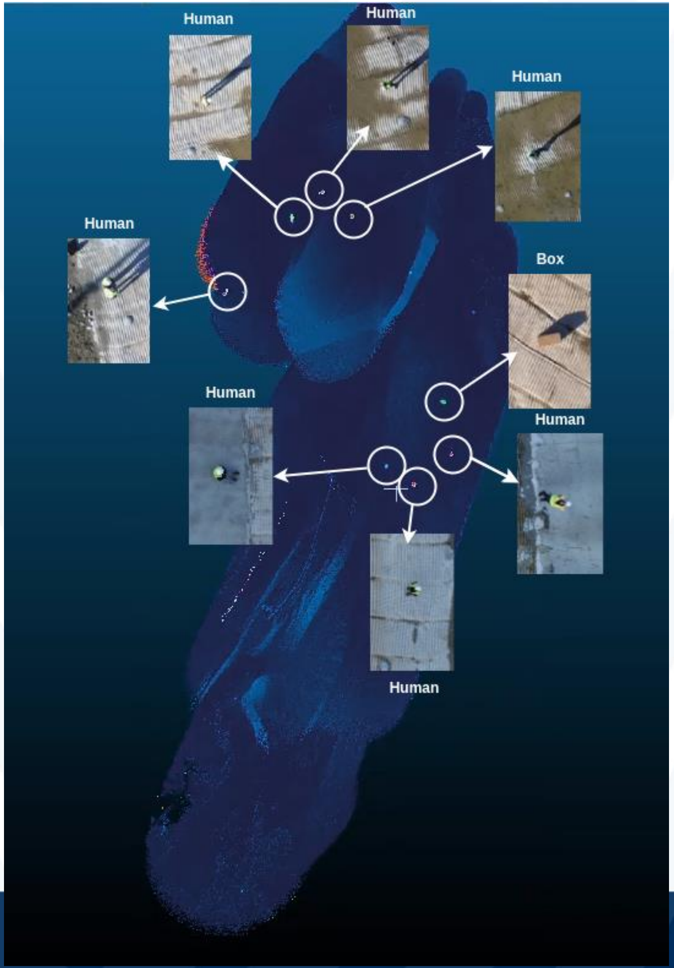
- Development of software to autonomously inspection open-channel spillways and principal spillway inlets/outlets with the drone.
- Structure position using GPS.
- Object detection using computer vision and AI.



Results https://youtu.be/gZe3Vgp2NxA


Desired Trajectory
UAV Trajectory
350
345
340
335
330
325
320
Altitude(m)
0.00800
0.00825
0.00850
0.00875
0.00900
0.00925
0.00950
0.00975
Longitude
0.0064
0.0062
0.0060
0.0058
0.0056
0.0054
0.0052
0.0050
Latitude

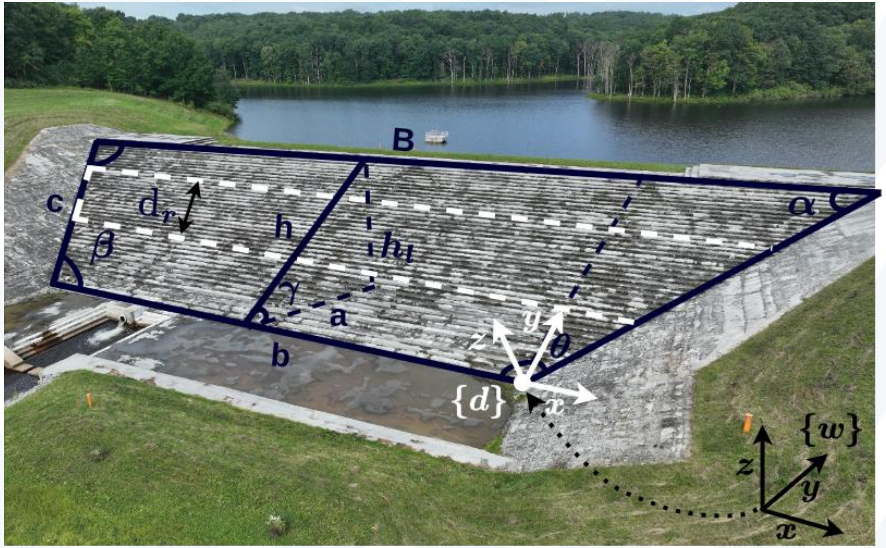



Human
Human
Human
Human
Box
Human
Human
Human

Current work

3.3 – 3D mapping of dams

- development of a software that creates tri-dimensional maps of coal waste facilities with a drone
- Focus on crest and slope
- Investigations on required resolution, optimal coverage, battery changes, etc.



Publications

- P. V. G. Simplicio, and G. A. S. Pereira, “Mission Planning for Photogrammetry-based autonomous 3D Mapping of Dams using a commercial UAV,” in *Proceedings of the International Conference on Unmanned Aircraft Systems (ICUAS’24),* Chania, Crete, Greece, June 2024, Accepted.
- B. Martinez R. Junior, P. V. G. Simplicio, and G. A. S. Pereira, “A Behavior Tree Approach for Battery-Aware Inspection of Large Structures Using Drones,” in *Proceedings of the International Conference on Unmanned Aircraft Systems (ICUAS’24)*, Chania, Crete, Greece, June 2024, Accepted.

Next steps…

3.4 – Seepage detection

- development of software to detect leaking and infiltration in the embankment slope and foundation of coal waste facilities using the drone.
- Computer vision based on thermal images.
- Investigation of the best weather, season, time of day, distance to the structure, etc.

Next steps…

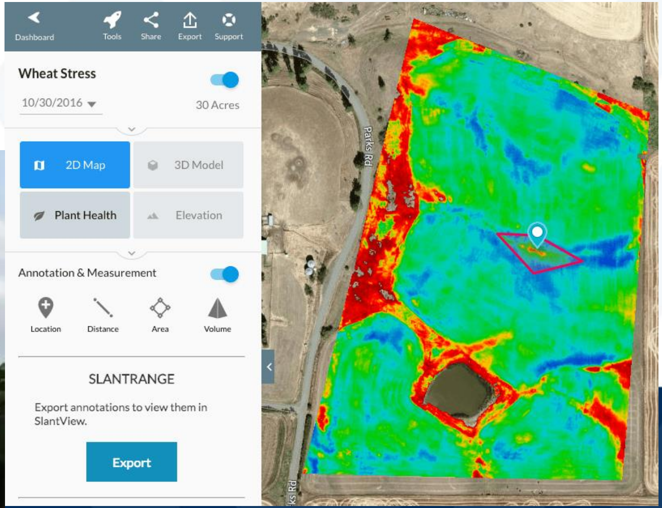
4.1 – Hazard detection

- development of algorithms for hazard detection in coal waste facilities using data collected by the drone
- AI-based software
  - Comparison of time-lapse data (images, LIDAR point clouds)
    - Erosion and crack
    - Excess of vegetation
    - Animal activity, etc

Next steps…

4.2 – User interface

- development of a user interface to facilitate drone control and hazard detection



https://www.dronedeploy.com/

Timeline

Task #	Task name	Year 1				Year 2				Year 3			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1.0	**Project Management and Planning**												
2.0	**Configuration assessment of coal refuse facilities and programming of autonomous inspection logics**												
2.1	Preliminary facility configuration assessment												
2.2	Detailed assessment of inspection structures and locations												
2.3	Development of autonomous inspection logics												
3.0	**Drone assembly and programming**												
3.1	Drone assembly												
3.2	Inspection of open-channel spillways and principal spillway inlets/outlets												
3.3	3D mapping of dam’s crest and slopes												
3.4	Detection of leaking due to seepage through embankment slope and foundation												
4.0	**Development of hazard detection software and user interface**												
4.1	Hazard detection												
4.2	User Interface application												

Project Benefits

- At least 7 students trained in multidisciplinary technology
  - 4 PhD students
  - At least 3 undergraduate students (summers 2023, 2024, 2025)
  - Recruitment focused on underrepresented groups
- Efficient methodology/technology for coal storage facility inspection
  - Reduced time of inspection
  - Increase in inspection frequency
  - Automatic logging and archiving

Project Benefits

- More efficient inspection may help prevent accidents
  - Social impact
  - Environmental impact
- Technology transfer
  - TRL 5 expected at the end of the project (Technology validated in relevant environment)
  - Stakeholders feedback and use

Acknowledgments

- This project is supported by the U.S. Department of Energy's University Training and Research for Fossil Energy and Carbon Management Program – UCR
- Thanks to
  - NETL team
  - Jason Hissam (Federal Project Manager)
  - George Kusko (Contract Specialist)
  - Xingbo Liu (Research Dean and Project advisor – WVU)
  - Kathleen Cullen (Grant administrator – WVU)
  - Office of Sponsored Programs (OSP/WVU)

Thank you!

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West Virginia University