

Autonomous Visualization and Monitoring Benchmarking for Operations and Maintenance

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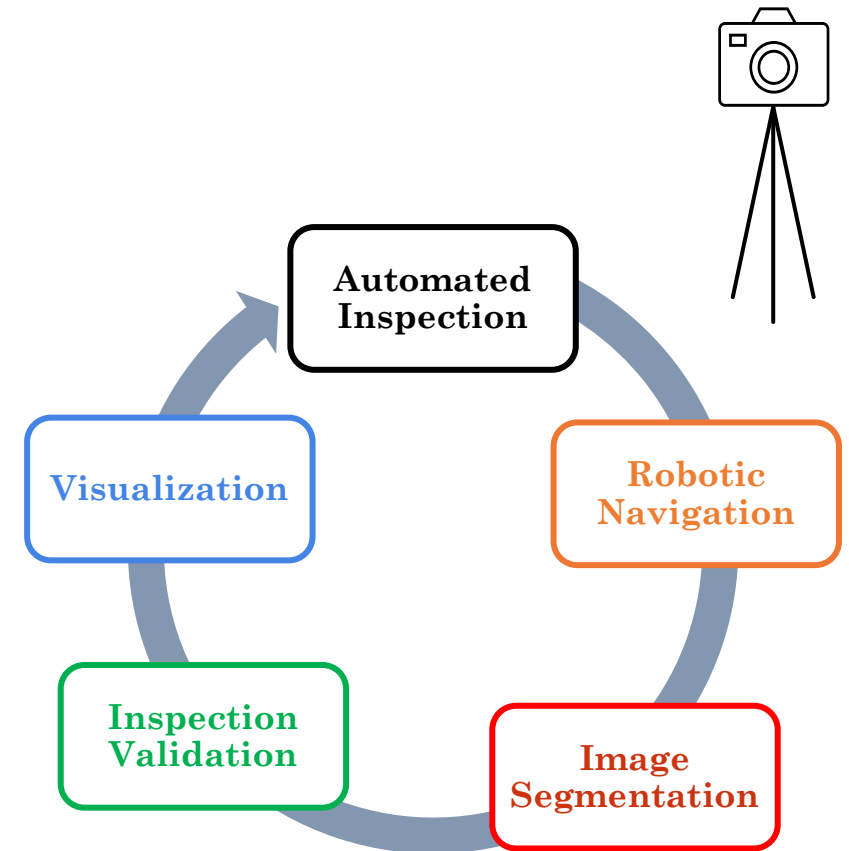
- Plants are increasingly adopting new technologies to more efficiently inspect, monitor, and maintain power plants.
- Robotics, including drones and rovers, are being tested for navigation within industrial facilities in conjunction with visualization technology
- Develop comprehensive [guidelines](#) on the implementation and capabilities of these devices



Duke Maintenance Facility



FARO Focus Scanner Mounted onto Jackal Robot



- For **Autonomous Inspection**, two major components need to be investigated to develop benchmarks

- **Robotic Navigation**

For autonomous navigation, the robot must avoid obstacles and path routes to scan critical components

- **Image Segmentation**

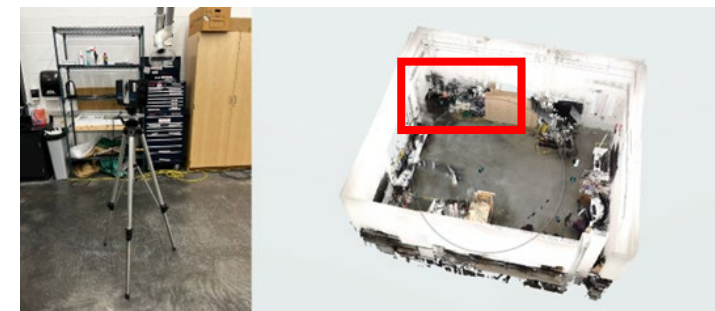
3D segmentation requires explicitly trained models and higher compute cost

- Evaluate against benchmarks to create guidelines



2D Image Segmentation

3D ?

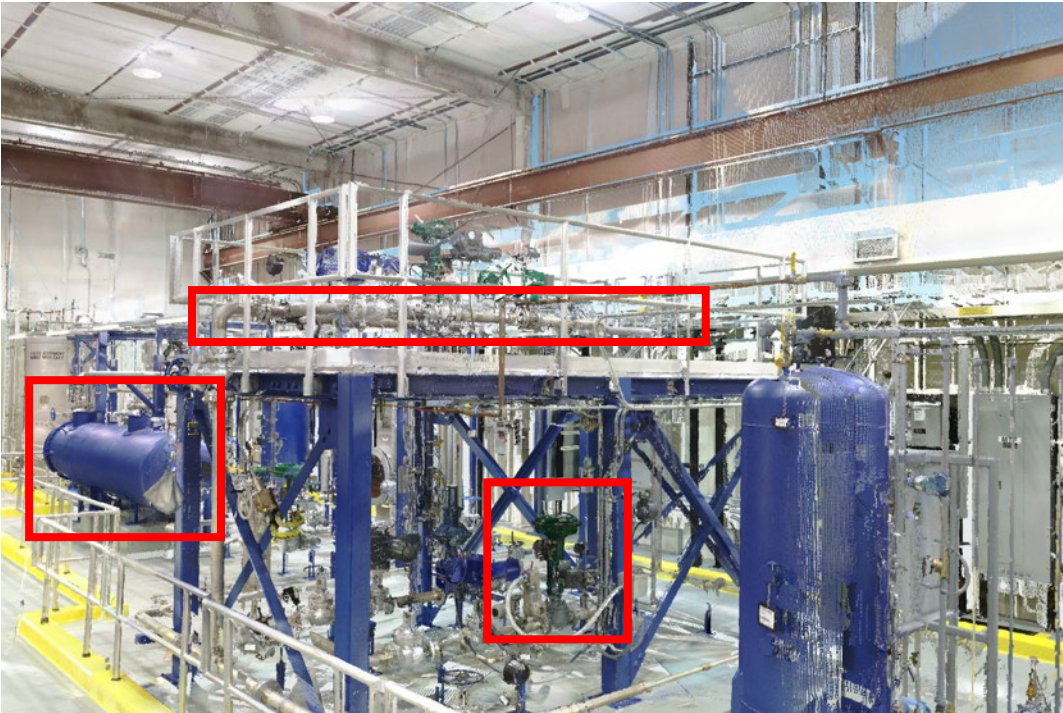


3D Cloudpoint

Object Identification

Classification	Heat Exchanger	Pipe	Valve
Label	Residual Heat Remover	Aux. Steam	Chilled Water Supply
Position Center (X, Y, Z)	[5.1,7.8,1.3]	[6.4,9.7,2.4]	[6.5,11,0.7]
Dimension (Radius)	0.62	0.1	0.14
Status	Operational	Operational	Normally Open (NO)

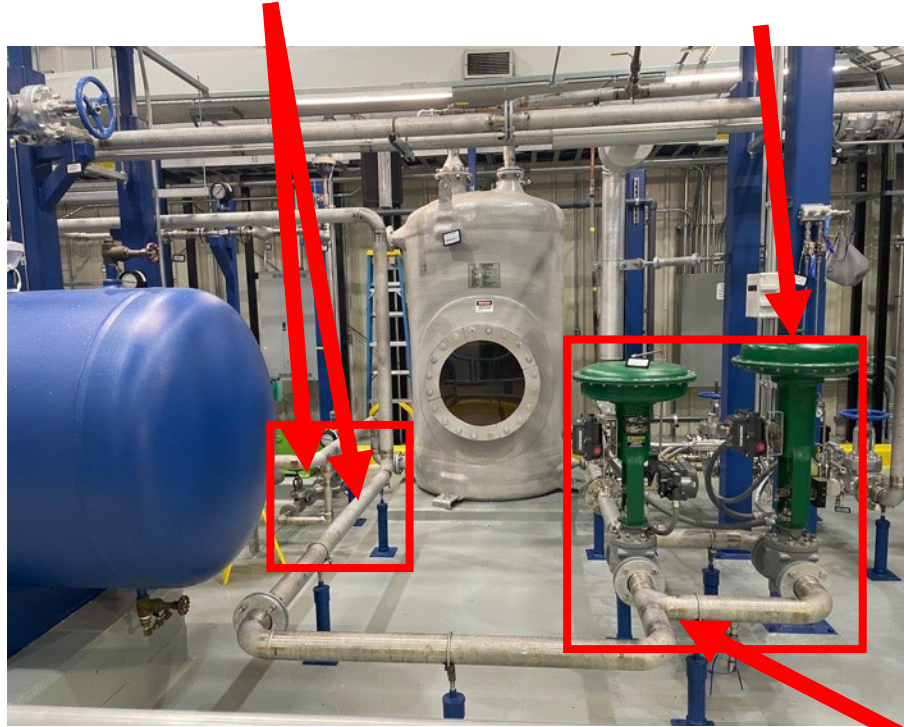
Arbitrary Table Values



Industrial Objects of Interest

Clearance Distance?

Position



Industrial Objects of Interest

Defects?

- **Considering hazards and maintenance, what is important inspectable criteria?**
 - Dimensions
 - Spatial Data (Position)
 - Change detection
 - Defect Detection (cracks, leaks, etc.)
- For autonomous and continuous evaluation, the previous/historical scans and data must be stored
- Seismic and other design basis events may disrupt operation or cause extensive damage
 - Object displacement
 - Defect generation
- In the case of severe concerns, minimize exposure or personnel risk by doing preliminary scans to **detect defects**

➤ What makes a good **3D scan**?

- Fidelity (Resolution)
- Occlusion
- Perspective
- Coverage
- **Object Reflectivity**

➤ What about Post Processing?

- Supersampling
- Gap-Filling
- Point Size
- Registration Quality



Cloudpoint Post Processing
(Supersampling, Gap-Filling)



Distortion of Objects with
Reflective Surfaces

➤ How are scans procured?

- Robotics are constantly tested in industrial environments
- Considering a known space, paths can be programmed with desired scan locations

➤ Simultaneous Localization and Mapping (SLAM)

configuration allows for collision detection and autonomous navigation to desired points

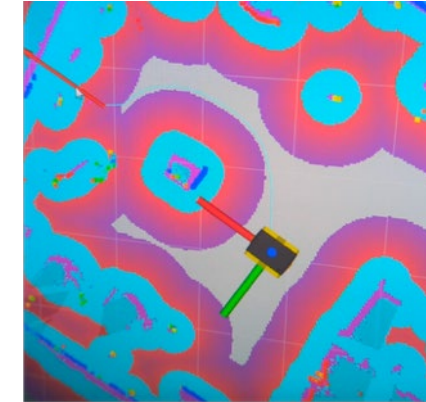
- Map area
- Designate scan locations
- Set repeatability



FARO Scanner mounted on Jackal Robot



Jackal Robot Gathering Positional Data

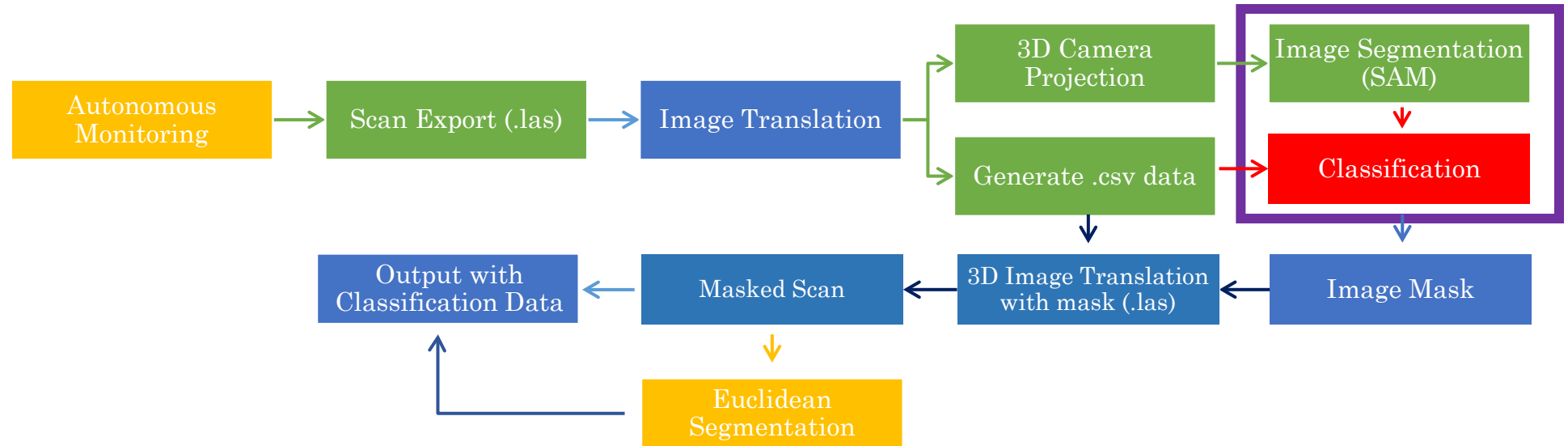


Generation of Positional Map



Positional Map of Maintenance Facility

- Our Method seeks to use the best parts of **2D and 3D visualization**
- Apply this method to benchmarks



➤ Image Segmentation from 2D

Once the image is translated from a perspective into 2D, we can use a generic (pre-trained) segmentation model. Considering multiple perspectives, and error mitigation, we can construct a 3D mask from 2D segmentation.

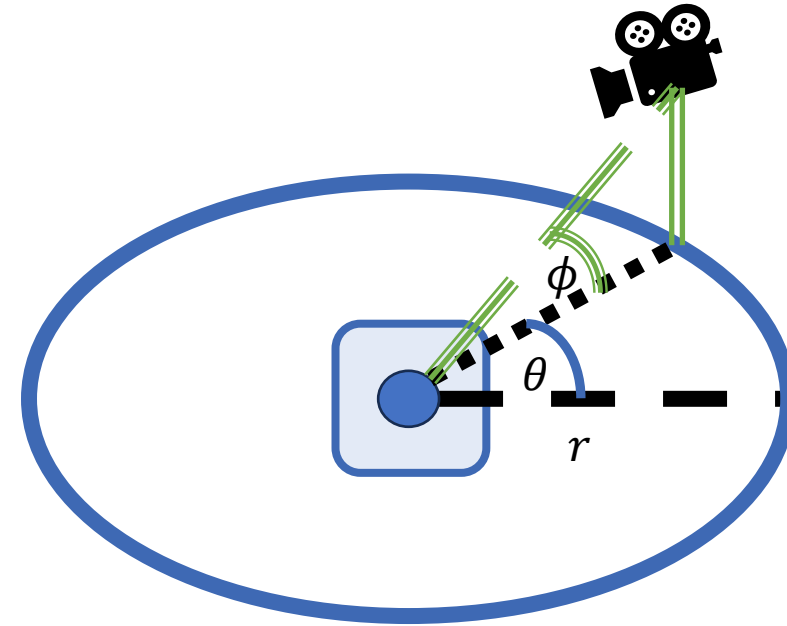
➤ Object Qualifications from 3D

With the image mask, the scan can be translated back into 3D. The labelled points and pixels can then be separated by Euclidean segmentation to determine the objects position, dimensions, and orientation.

- Segmentation requires 2D image including object of interest
- **Autonomously generate multiple perspectives of the object to determine Next Best View (NBV)**
- Track each perspective utilizing 3D depth-map indexing

$$\mathbf{p}_{\text{cam}} = \mathbf{p}_{\text{target}} + r \begin{bmatrix} \cos \theta \cos \phi \\ \sin \theta \cos \phi \\ \sin \phi \end{bmatrix}$$

- A number of random camera poses are generated around the target point utilizing the azimuth and elevation angles
- A target box is created around the target point

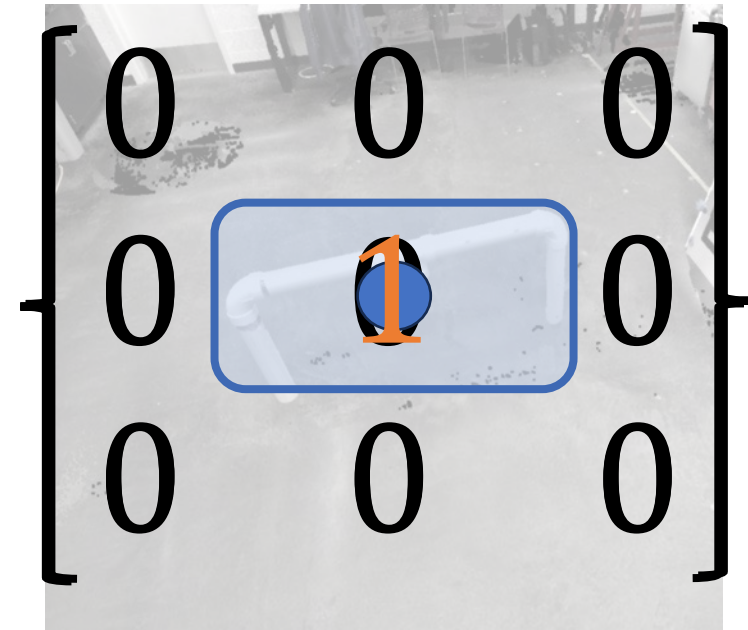


Camera Position Generation and Variables



Example of Pose Generation

- Best poses are determined using a cost function
- Utilizing depth mapping, we can determine the best camera positions given occlusion and perspective variables
- Vector rays are cast from the camera pose to the target, finding the number of rays that connect, finding a calculated occlusion value
- The perspective is considered, steeper angles or distortions incur higher cost
- With a **weighted cost function**, the results of the occlusion and perspective parameters are processed to rank the best perspectives



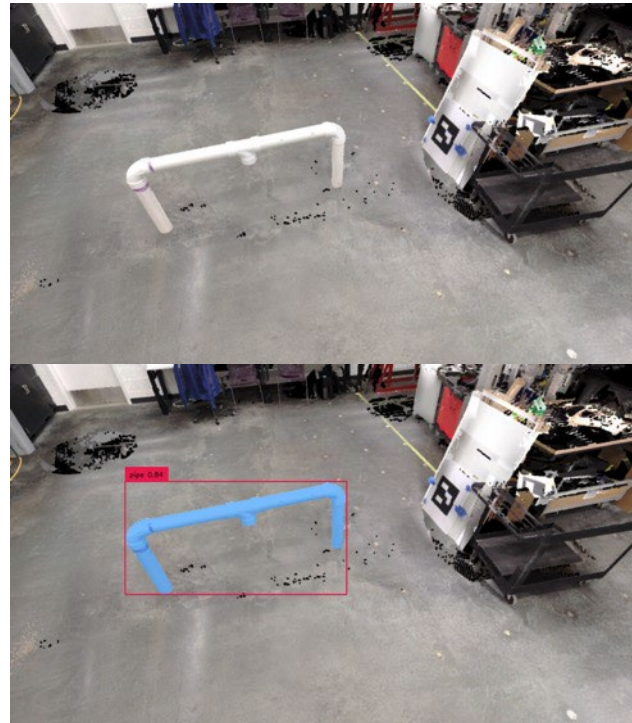
Vector Ray Generation from Camera Pose to Determine N

$$J_{occ} = \left(1 - \frac{N_{target}}{N_{total}}\right) + \frac{N_{non-target}}{N_{total}}$$

$$J_{persp} = \frac{\sigma_z}{\mu_z + \epsilon} + |A_t - 0.5|$$

$$J_{total} = w_1 J_{occ} + w_2 J_{persp}$$

- The current pipeline takes a **3D cloudpoint**, and computes camera poses to generate NBV
- Segmentation identifies objects of interest with the **classification mask**
- Data is translated back into **3D to output characteristics** such as location, radius and orientation with Euclidean segmentation
- Object mask, depth map, and characteristics are output
- Current implementation allows for comparison of object spatial comparisons to determine movement between scans



Object Segmentation from Best Camera Pose



Pipe Measurements	
Center	: [5.7459 5.7658 0.5298]
Orientation	: [-0.9999 0.0129 0.0115]
Radius	: 4.86 cm
Diameter	: 9.72 cm
Inliers	: 190 / 455 (41.8%)
Fit time	: 0.09s
Total elapsed: 6.50s	

Object Characteristics from Identification and Processing with Random Sample Consensus (RANSAC)

- To assess feasibility of **autonomous monitoring solutions** and applications, benchmarking problems are developed by constructing a methodology combining **computer vision** and **robotic navigation**
- Utilize pinhole camera projection and virtual camera poses to create depth-mapped 2D images of 3D cloudpoints, converting the segmented image back into 3D
- Apply additional segmentation protocols for object characteristics such as dimension, position, and damage
- Compare to historical scan data and inspection procedures to evaluate safety and risk
 - Identify **damage due to ground motion**
- Compile procedures and parameters to develop guidelines based on modern benchmarks



Maintenance Facility Registered Cloudpoint

Thank you!

Questions?

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