IMPROVING SUBSURFACE NON-METALLIC UTILITY LOCATING USING SELF-ALIGNING ROBOTIC GROUND PENETRATING RADAR

PROJECT DEBRIEF

CONTRACT # 693JK31910017POTA

APRIL 7, 2022

ULC TECHNOLOGIES

PRESENTERS

SPONSOR: Pipeline and Hazardous Materials Safety Administration

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AGENDA

- PROJECT BACKGROUND
- TASKS PERFORMED
- PROJECT RESULTS AND CONCLUSIONS
- FINDINGS AND FUTURE WORK

BACKGROUND

- Improve locating and mapping of buried plastic pipe
- Project Completion Date: Dec 31, 2021

Challenge: Detecting underground non-metallic pipe from above-ground is challenging. Soil type, depth of burial, pipe diameter, and pipe layout can affect the detection performance. Operator training needs can compound the difficulty of deploying technologies and can increase detection costs.

Project Goals: A semi-autonomous, prototype robot with enhanced detection capabilities and improved locating abilities :

- Use commercially available GPR
- Improve detection using a dual antenna system
- Employ precise motors, encoders for antenna movement
- Develop algorithms to reduce uncertainty in identifying assets

Objective: Develop Semi-Automated Robotic System for Improved Detection and Locating Accuracy

PROPOSED APPROACH: CONVENTIONAL VS. ROBOT

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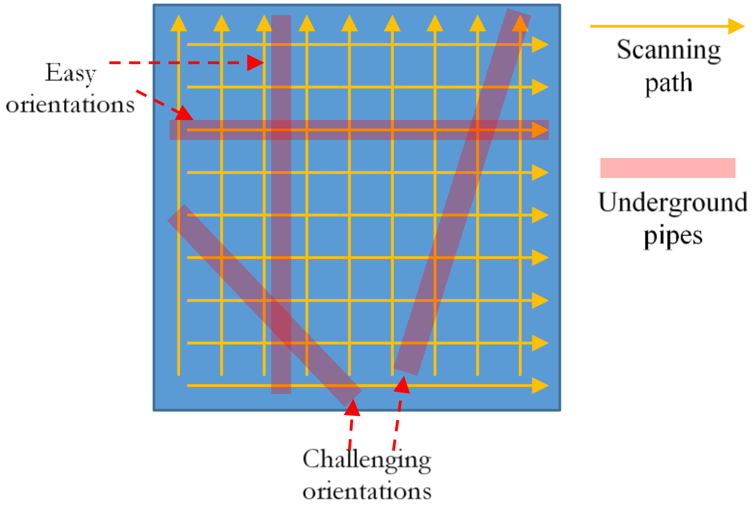
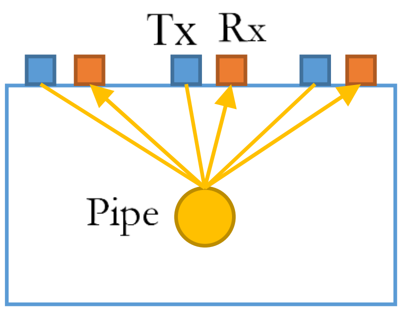
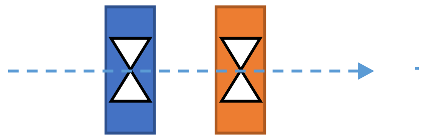
Conventional Scanning Mode and Scan Path





Common offset



Co-polarized, perpendicular to scanning path

Challenges

- Challenging pipe orientations could result in missed detections
- Low-resolution scans
  - Grid lines with 2 directions, the spacing is usually at least 0.15m (or 6in).
- Limited data collection due to fixed antenna arrangement

Opportunity

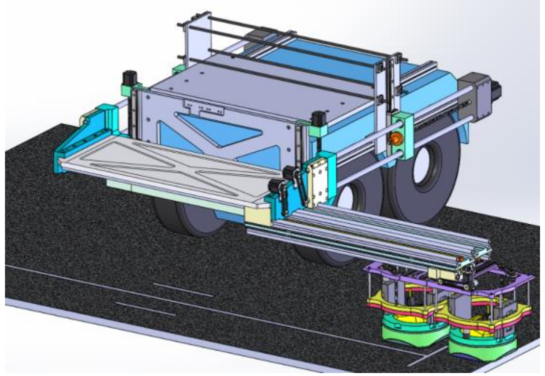
- Grid lines with a smaller spacing would enable the use of advanced signal processing methods that are independent of pipe orientation.
- Multi-static data acquisition could further improve the performance in a complicated underground environment.

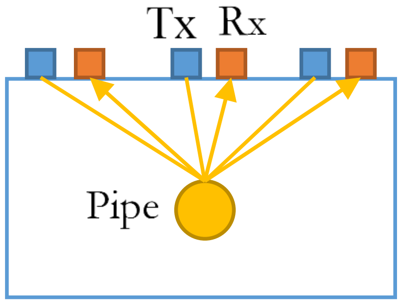
PROPOSED APPROACH: CONVENTIONAL VS. ROBOT

Possibilities for Enhanced Scanning Modes Using a Robot

Common Offset Mode

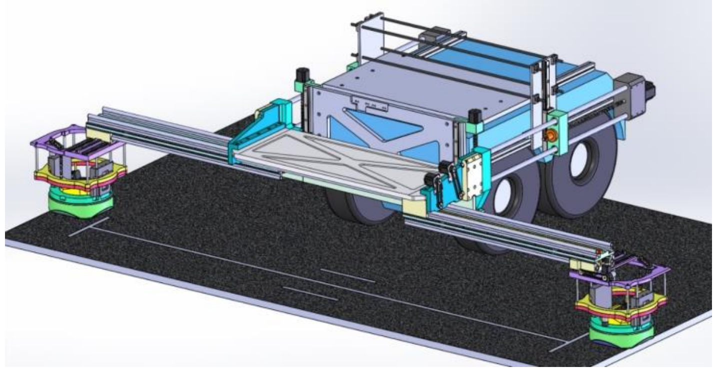
- Dense grid scan
- Multi-polarization

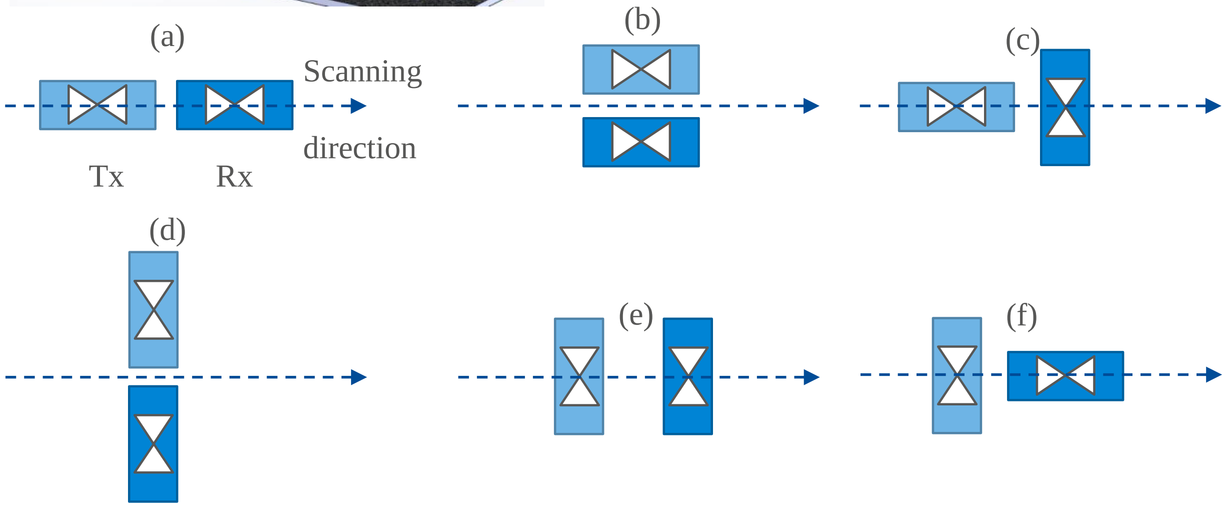


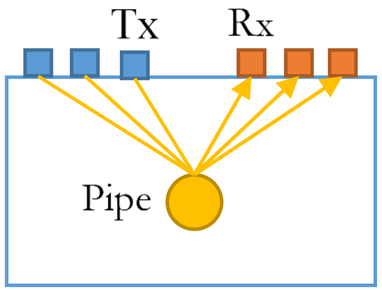


Common offset

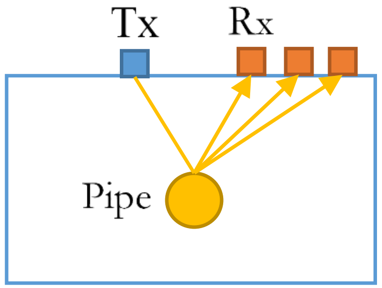
Common Midpoint and Common Tx Mode







Common mid-point



Common transmitter

HIGH LEVEL TASKS AND FUNDING

ULC TECHNOLOGIES

Task 1: Study Sensor and Pipe Configurations and Develop Algorithms

Task 2: Design for Platform Sensors and Support

Task 3: Robot Detailed Design

Task 4: Fabrication, Integration, and Testing of Robotic System

Task 5: Outdoor Validation Testing and Industry Demonstration

PHMSA Funding	$393,690
ULC Cost Share	$393,690
Total Project Cost	$787,380

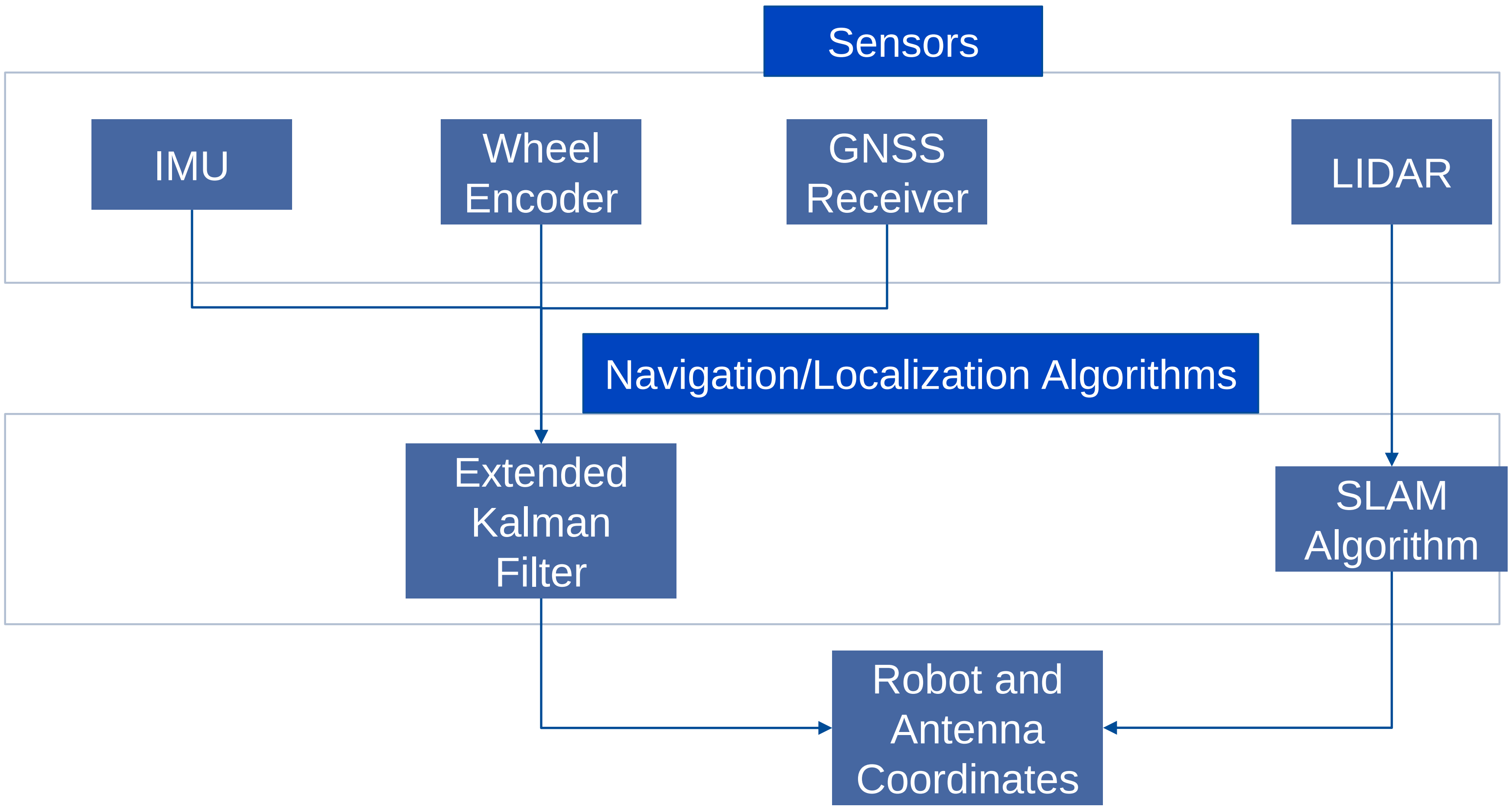
Task 1: Study Sensor and Pipe Configurations and Develop Algorithms

- Conducted numerical simulation using both frequency and time domain models to study
  - Difference, amplitude and phase, in reflections from metallic and plastic pipes.
  - Influence of pipe orientation on GPR signal characteristics.
  - The advantages of data collection at finer 2D grid vs. conventional line scanning
  - The value of conducting Full Matrix Capture (FMC) to improve the imaging quality
- Developed 3D Synthetic Aperture Focusing Technique (SAFT)
- Developed the imaging algorithm using FMC data
- (The results of the numerical simulation will be shown in the Project Results and Conclusions section)

Task 2: Design for Platform Sensors and Support

- A bistatic GPR configuration is selected because of its excellent flexibility.
  - Sensors & Software pulseEKKO 500 GPR with NIC system
- Two scanning modes are designed
  - Common-offset: the relative position between transmitter (Tx) and receiver (Rx) antennas are kept constant. Tx and Rx move together. Finer grid lines.
    - Add-on: the polarizations of Tx and Rx can be changed independently to compose 4 combinations: X-X, X-Y, Y-X, and Y-Y.
  - Multi-static: the distance between Tx and Rx changes. Data is collected with different Tx-Rx position combinations.
  - Localization and navigation sensors were selected, and performance was characterized

ACCURATE LOCALIZATION

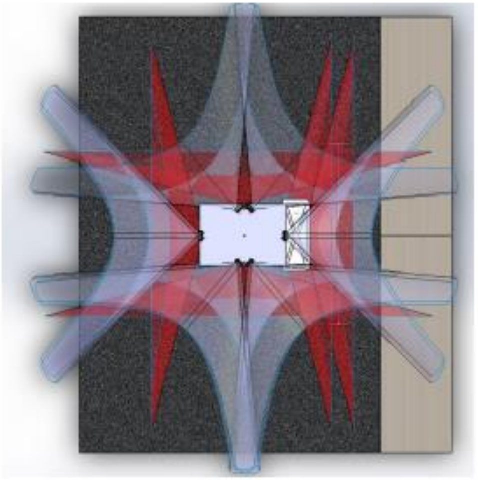


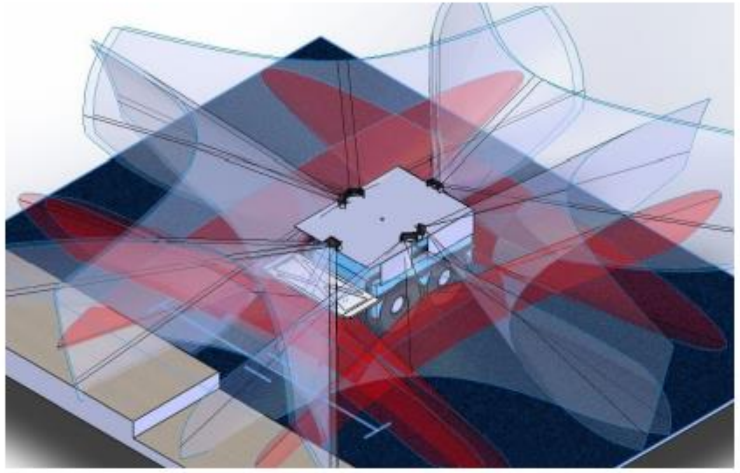
Initial measurements show worst-case accuracy of the robot position estimate is within 16 inches. This can be further improved through tuning the algorithm.

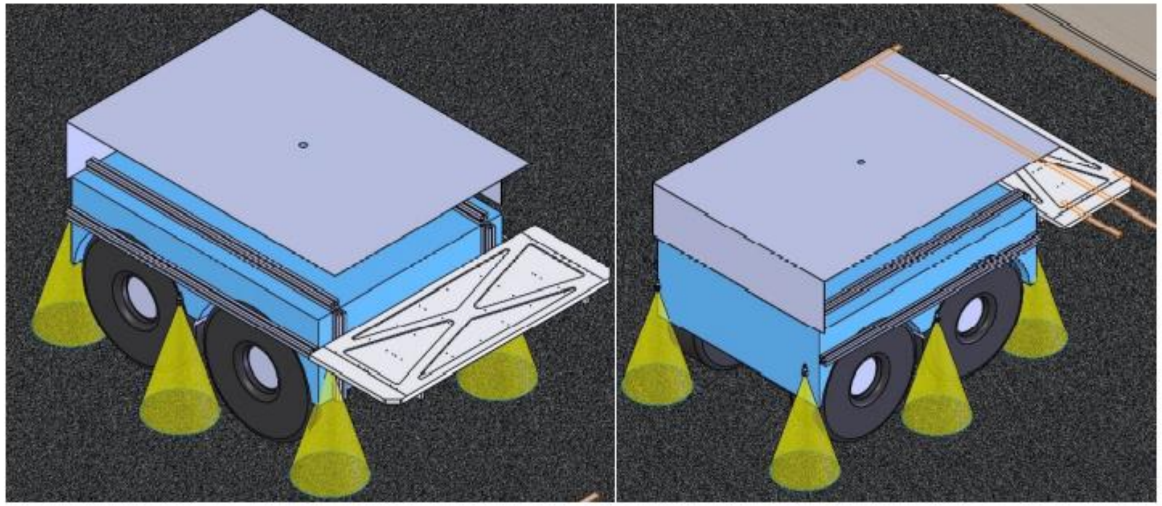
COLLISION AVOIDANCE AND CURB DETECTION

- Sensors selected for obstacle avoidance and curb detection
- Sensors were tested and the coverage and detection ranges were established
- Sensor coverage maps were developed
- Robotic platform design was performed to integrate these sensors

Note: Fabricated robot platform does not incorporate all sensors. Some of the integration work will be performed in the future.



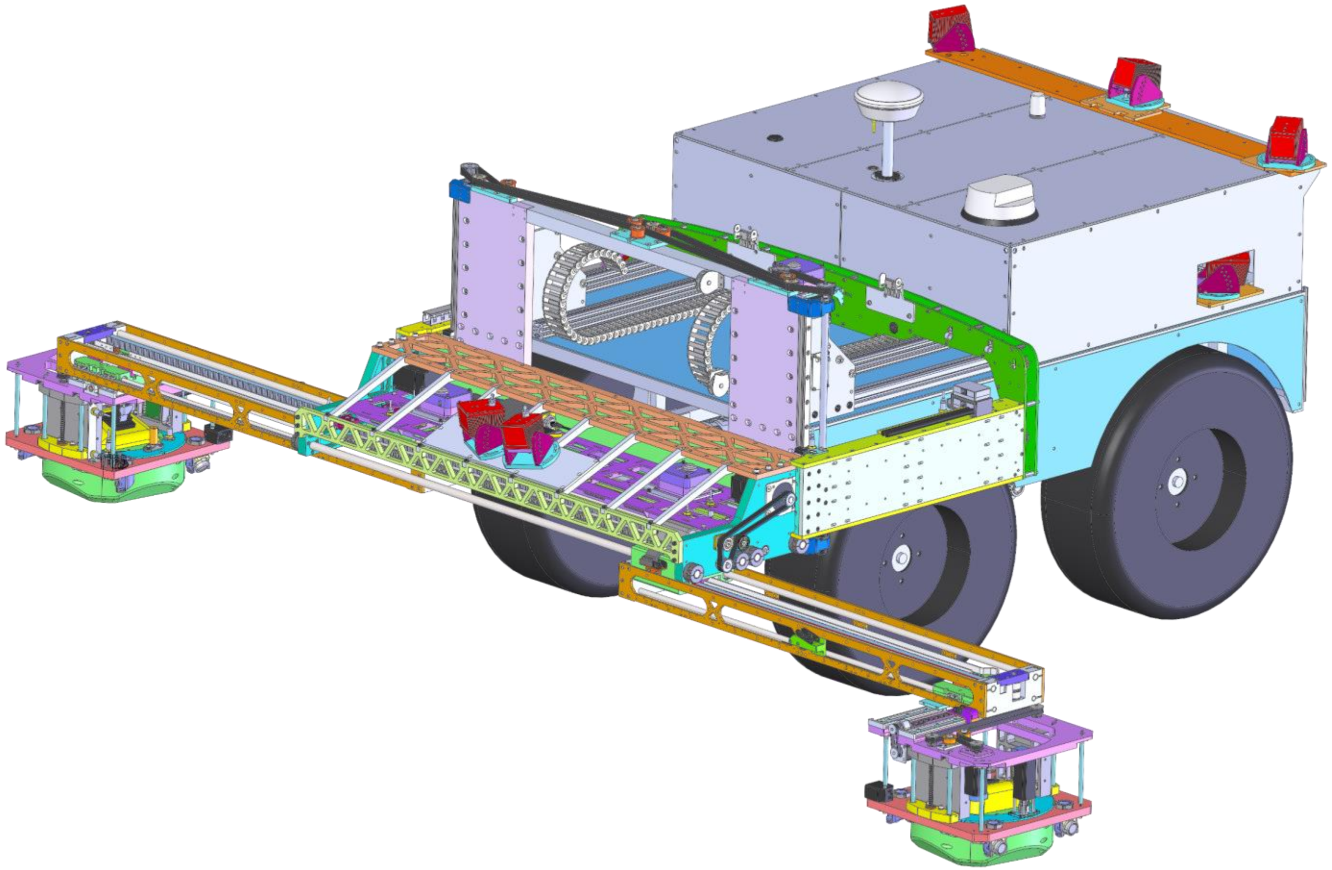




Task 3: Robot Detailed Design

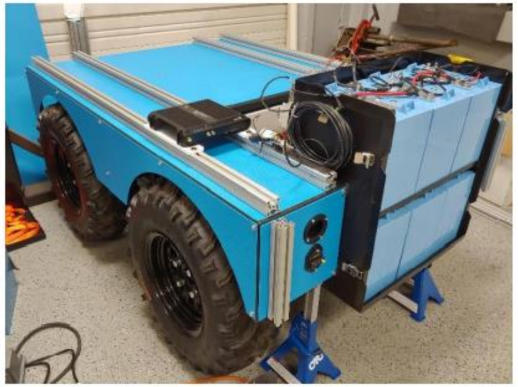
PROTOTYPE ROBOT FOR LOCATING AND SURVEYING

- Battery Powered
- Curb Climbing with 24” Tires
- Operated by Handheld Wireless Controls
- Motorized Antenna System for Precise Positioning and Locating
    - Uses Encoder Feedback
    - Antenna Rotation for Changing Polarization Angle
- Accurate Localization Also Provided By
    - GNSS
    - Wheel odometry
    - Inertial Measurement Unit
    - LIDARs
- Collision Avoidance Can Be Integrated for Autonomous Operation

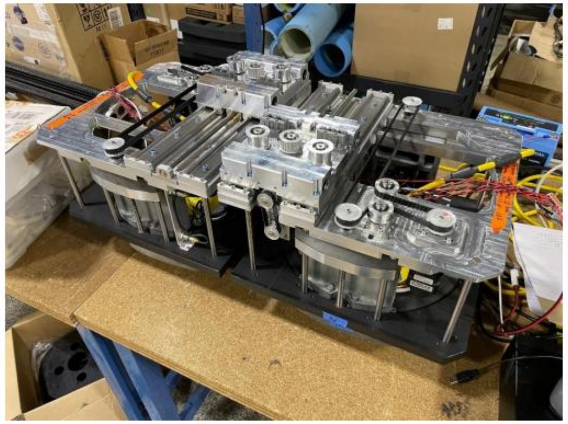


Task 4: Fabrication, Integration, and Testing of Robotic System

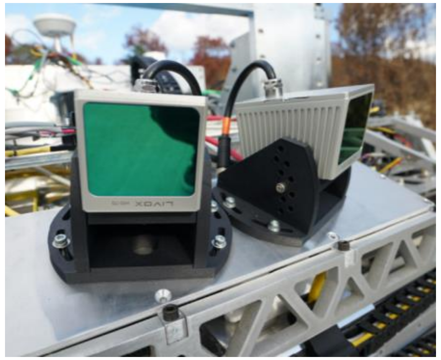
- Fabrication of drive platform and antenna assembly was independently completed
- Antenna assembly was integrated with the drive platform along with sensors and control hardware
- Testing and modifications were completed to ensure that the antenna assembly could travel its full extent
    - No collisions of receiver and transmit antenna
    - Ability to perform different scanning modes



- Primary focus on testing was to perform antenna scanning modes.
- Limited testing was performed for autonomous scanning using navigation and collision avoidance algorithms.



Fabrication, Integration, and Testing of Robotic System



Task 5: Outdoor Validation Testing and Industry Demonstration

Robot Operation

Robot can be driven on rough and smooth terrain

- Antennas remain stowed at an elevated position to prevent damage
- Operator drives the robot to the starting point to begin the survey or locate

Testing was performed using antennas on mock roadway

Industry demo was conducted

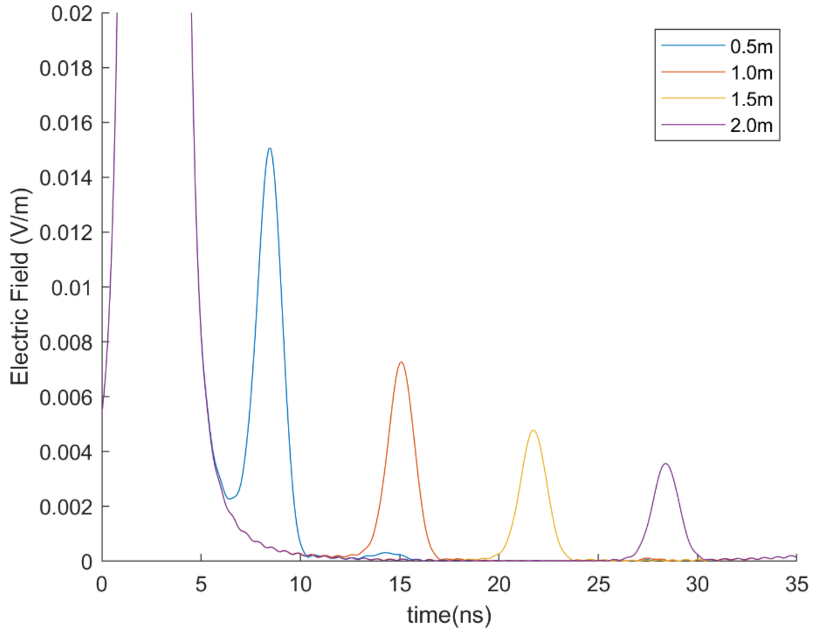
Video

Project Results and Conclusions

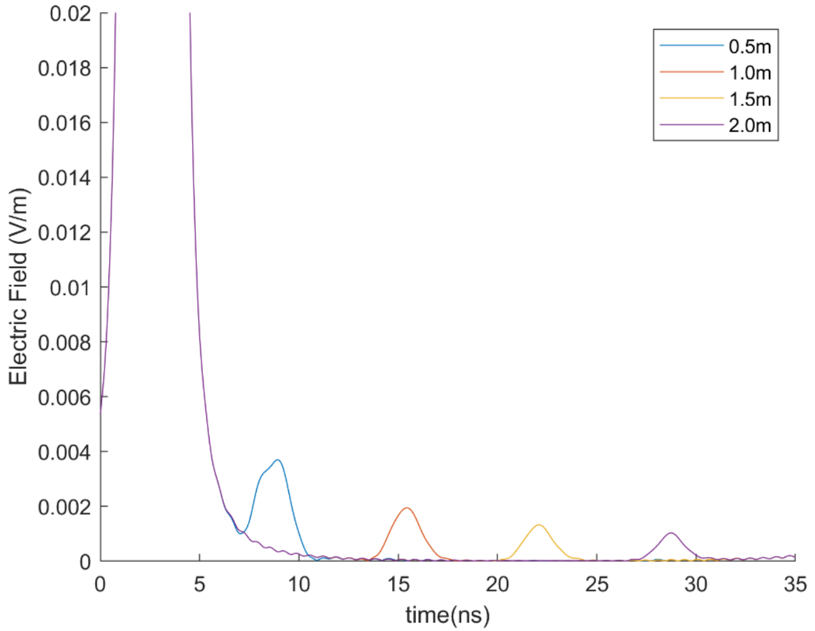
SIMULATION

Metallic vs. Non-metallic

Steel Pipe (4in)



HDPE (4in)



Properties affecting GPR signal:

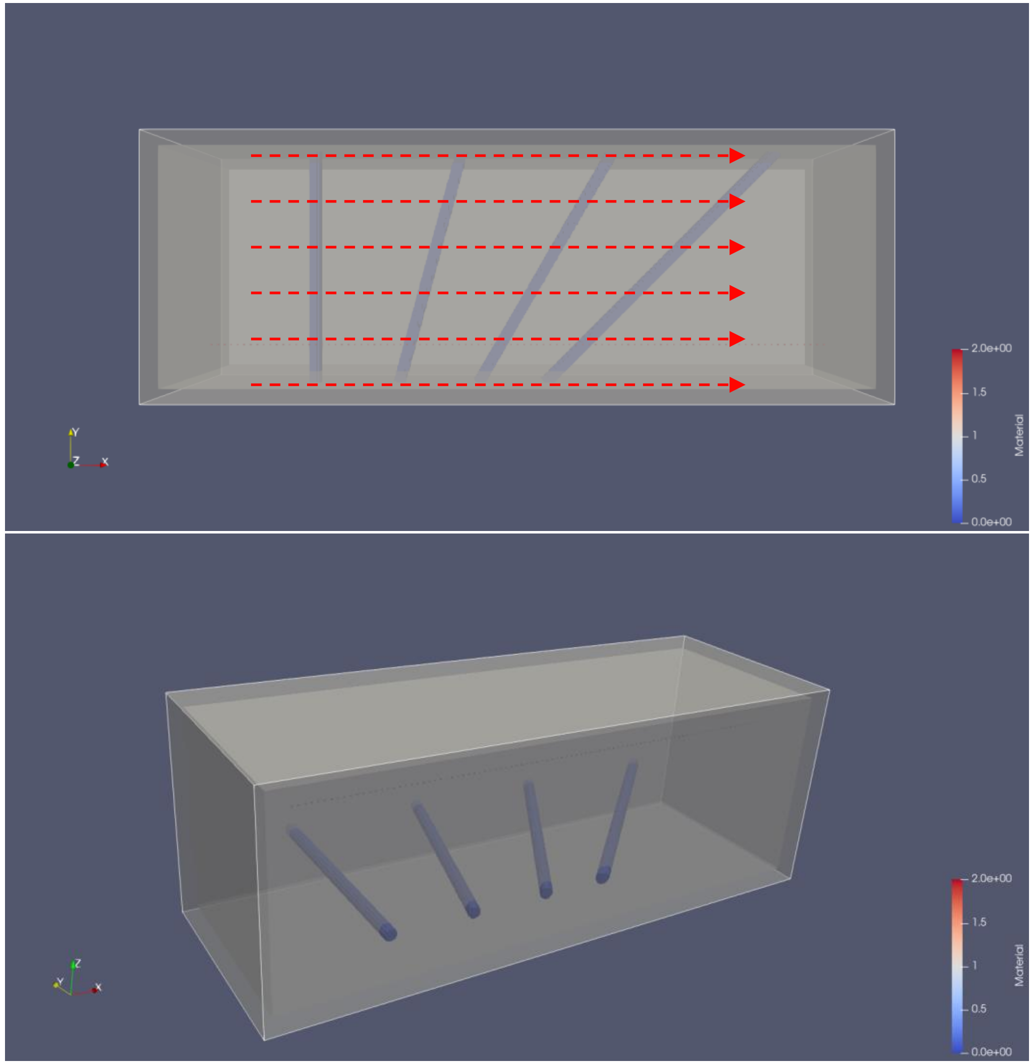
- Pipe material
- Carrying media: gas vs water (only matters for non-metallic pipe)
- Pipe size
- Pipe diameter

- The physical properties dictate the reflection coefficient.
- It is impossible to ONLY improve the sensitivity to plastic object.
- The goal is to improve the overall GPR performance to bring the visibility of plastic objects to a higher level.

SIMULATION

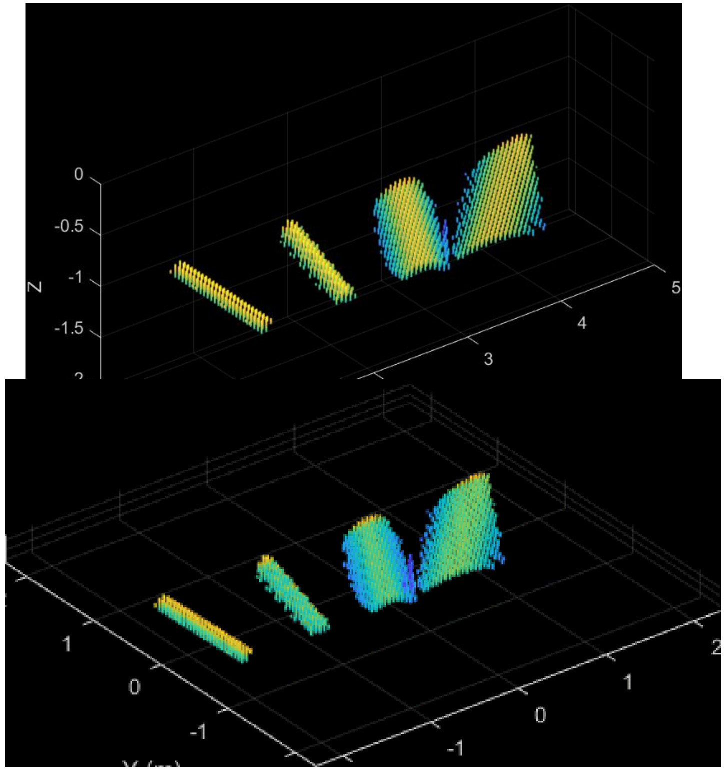
Fine Grid Scanning with Common Offset Mode

Model Description
- 4 steel pipe, D=100mm
- Angle relative to the ideal orientation: 0, 15, 30 and 45 degs
- Point-source transmitter and receiver
- 500 MHz center frequency



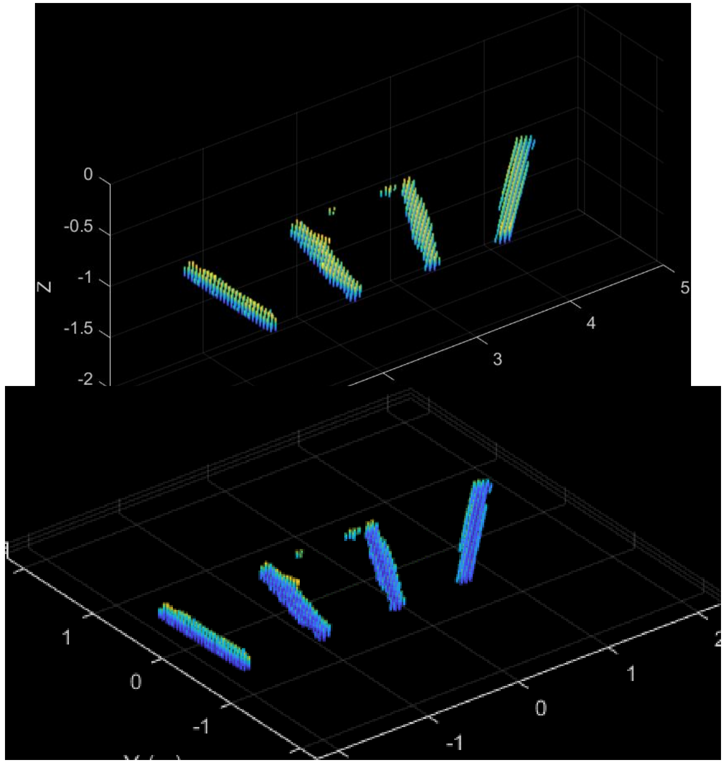
SIMULATION

Traditional signal processing
- Stacked 2D migration



Animation

Advanced signal processing
- 3D Migration



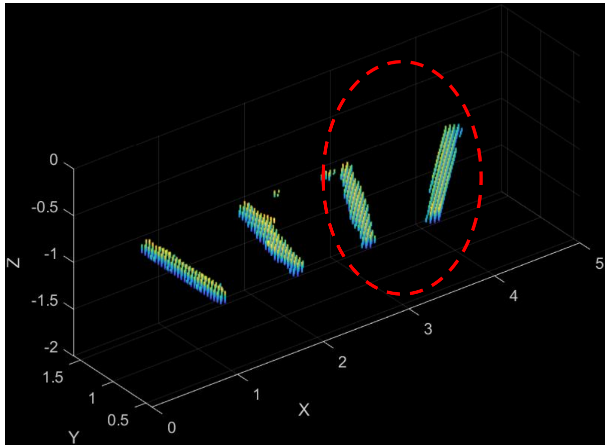
Animation

The 3D migration is insensitive to pipe orientation and has better focusing than stacked 2D migration.

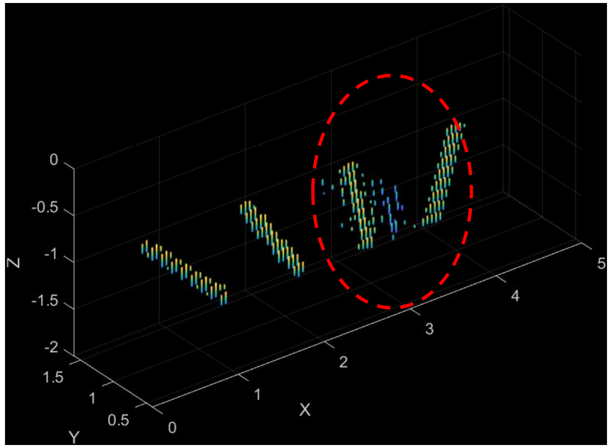
SIMULATION

3D migration requires high-resolution scan.

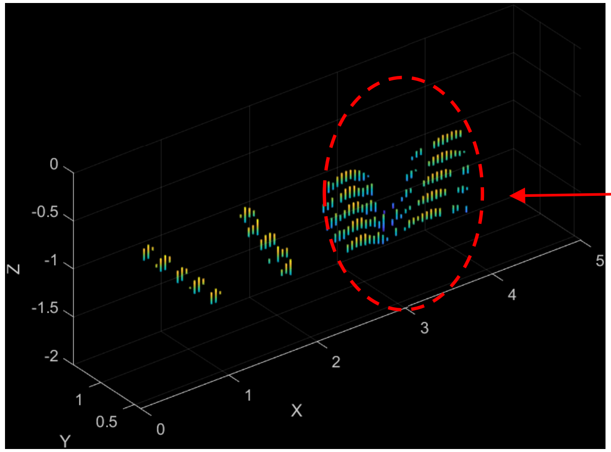
dx=0.05m, dy=0.05m



dx=0.05m, dy=0.15m



dx=0.05m, dy=0.25m



Aliasing

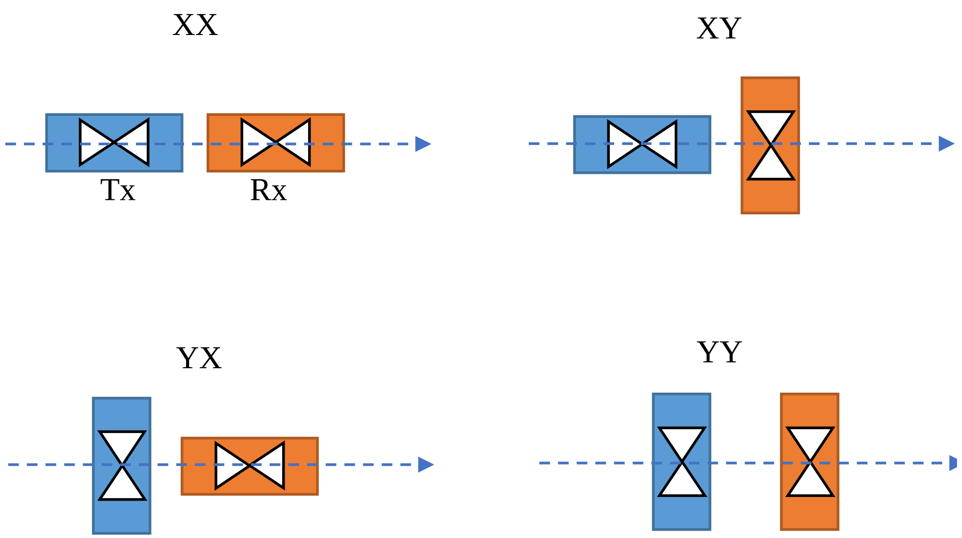
- Sampling rule: $spacing \leq \lambda/2$
  - Sandy, $\varepsilon_r = 4, \frac{\lambda}{2} = 0.15m$@500MHz
  - Clayey, $\varepsilon_r = 9, \frac{\lambda}{2} = 0.1m$@500MHz
  - Clayey (wet), $\varepsilon_r = 16, \frac{\lambda}{2} = 0.075m$@500MHz

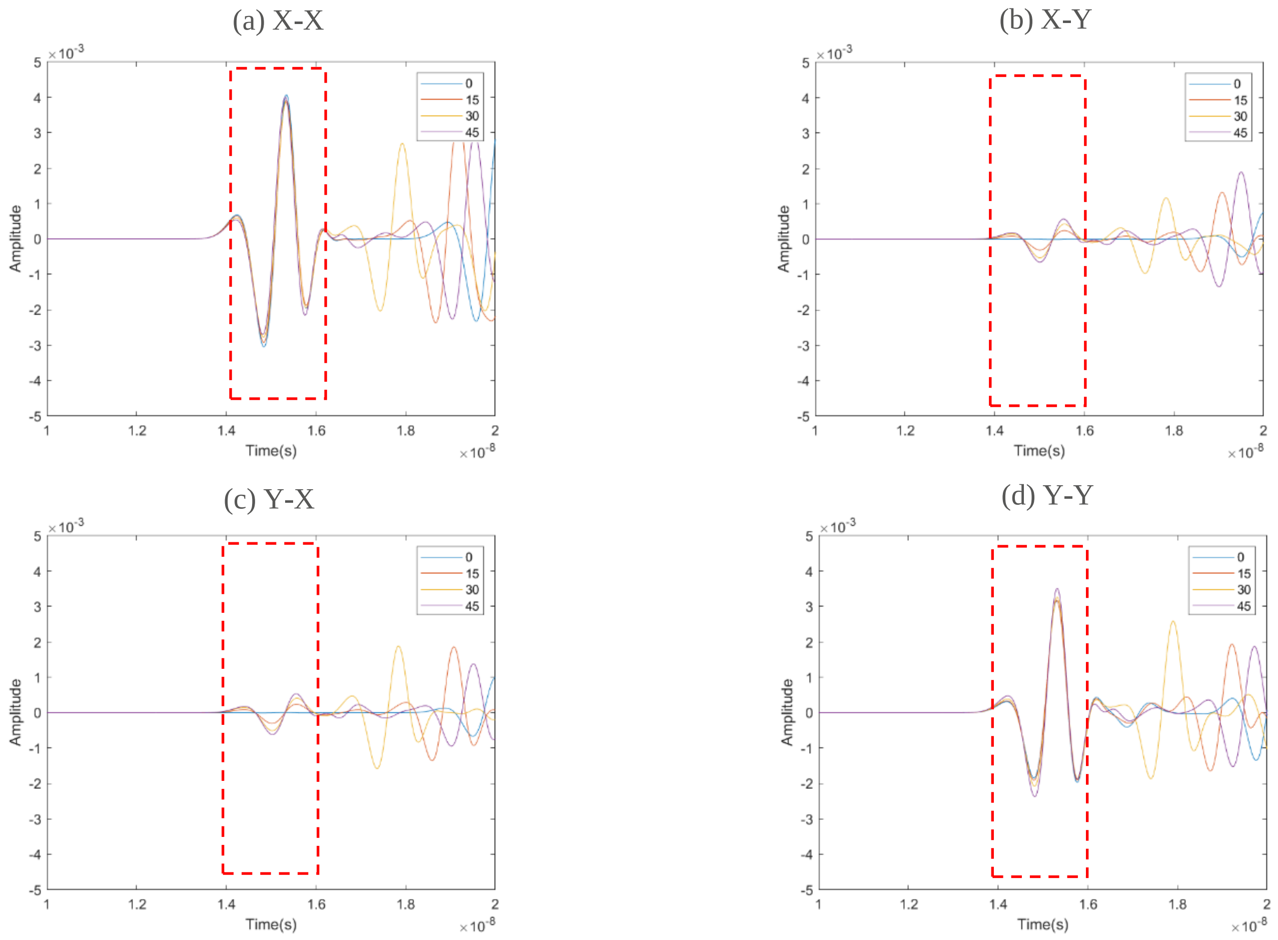
By using pushing cart, it could be challenging to maintain straight lines and small spacing between lines.

A robotic system can provide the accuracy and resolution needed.

SIMULATION

Multi-Polarization Data Collection

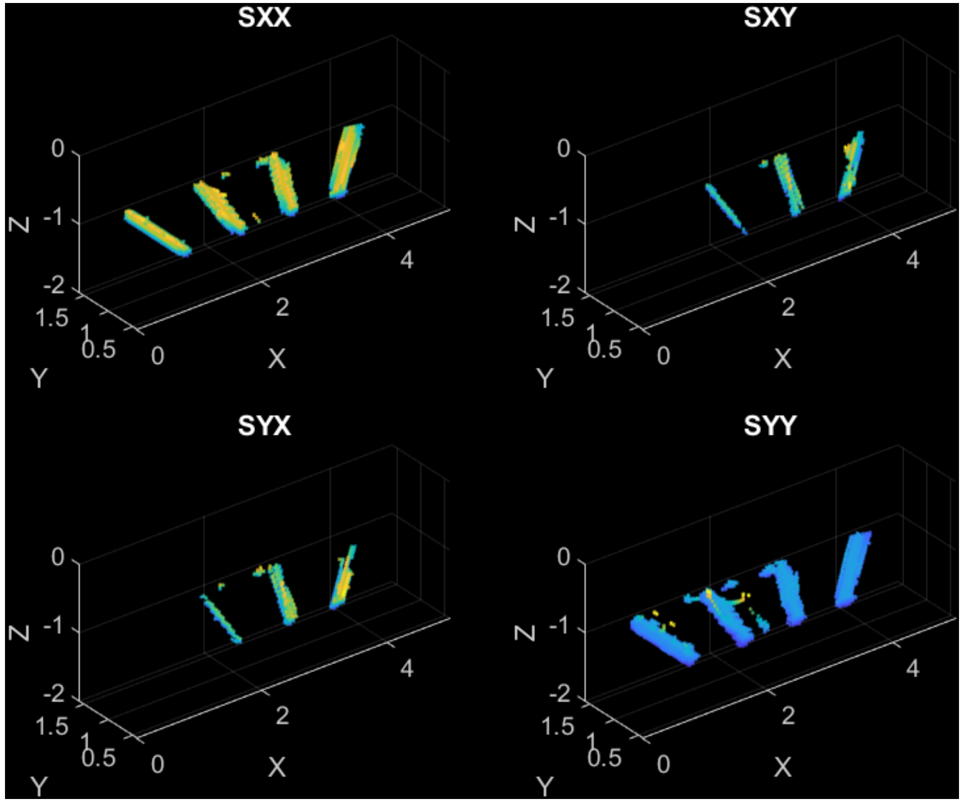




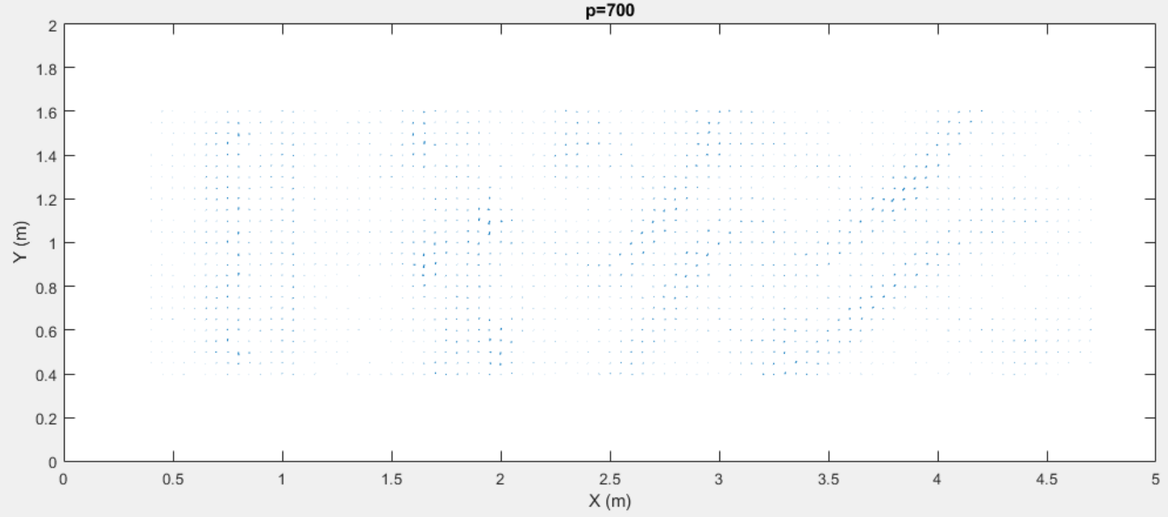
- 0-deg pipe produces zero amplitude in X-Y and Y-X configuration.
- By comparing the 4 polarizations, it is possible to differentiate the object orientations.

SIMULATION

Multi-Polarization Data Collection



Animation



- The C-scan (top-view) in vector field format shows orientation of slender object.
- A highly polarized object is more likely to be a utility line.

SIMULATION

Multi-Static Data Collection

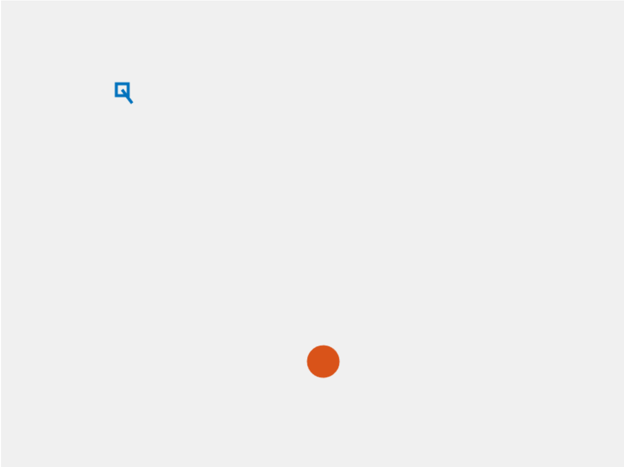
Full Matrix Capture (FMC)

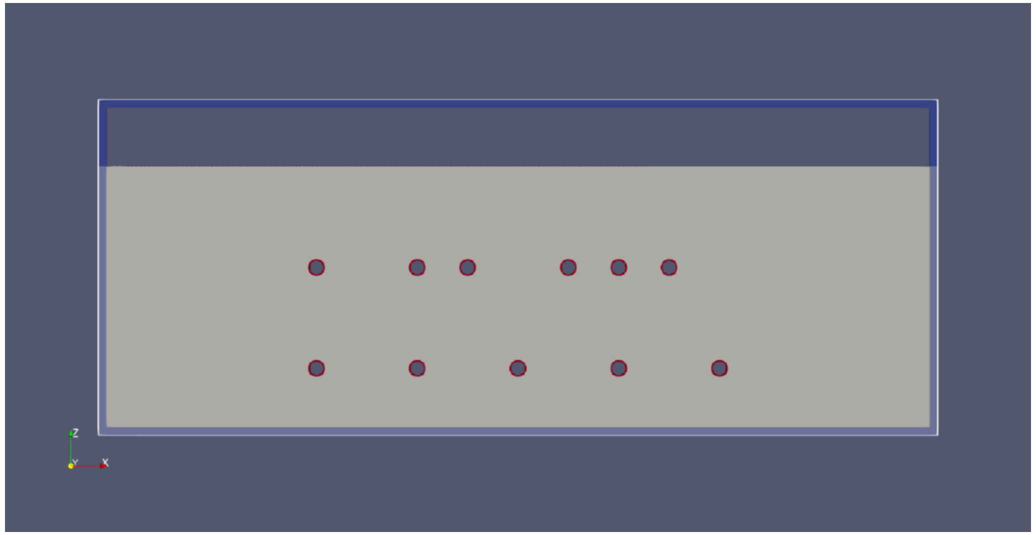
- Assuming N positions in a line, Tx fires in turns at every position and at each firing, Rx receives at all N positions. In total, there are N x N = N^2 Tx-Rx combinations.
- Common mid-point, common transmitter and common receiver modes are all subsets of FMC.

Model Description

- 11 hollow HDPE pipe, D=100mm
- 2 Layer. “Block Sight” condition
- Point-source transmitter and receiver
- 500 MHz center frequency

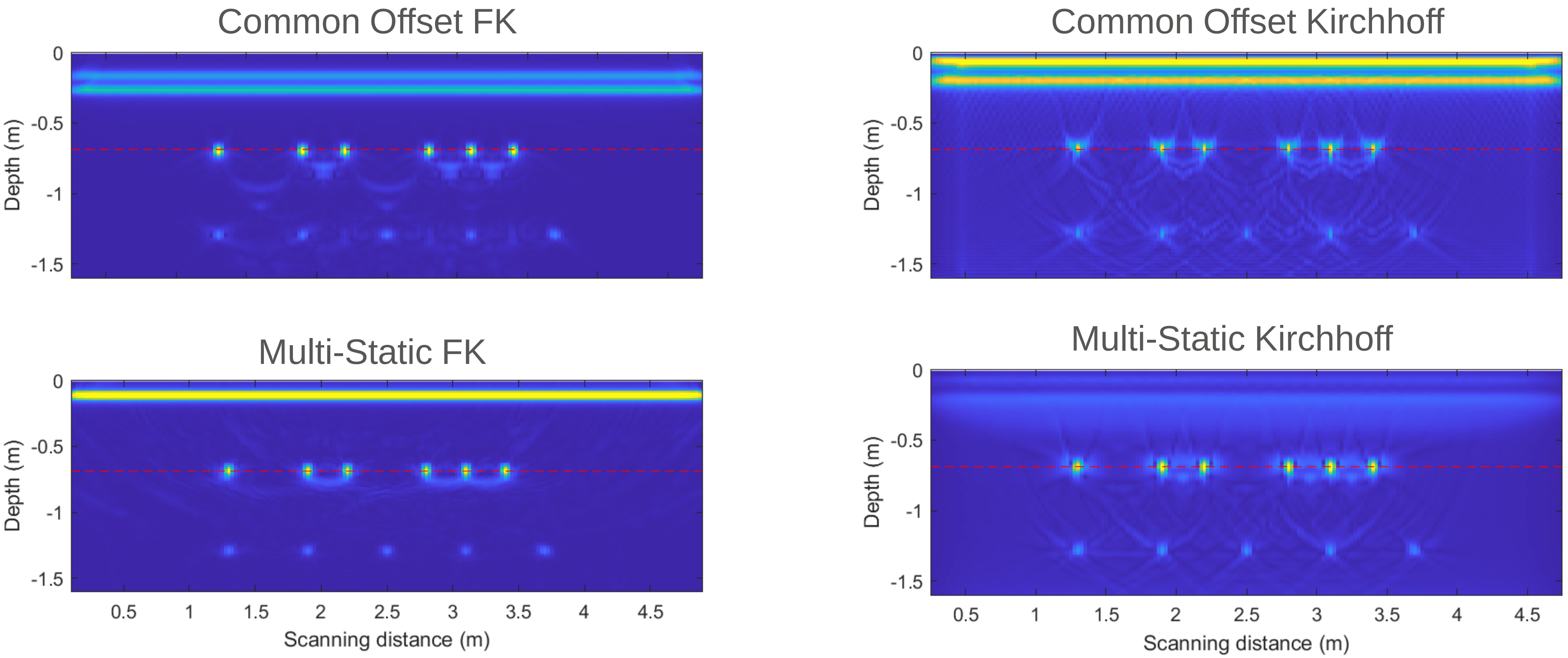
Animation





SIMULATION

FK: frequency-wavenumber domain method



Multi-static data has less artifacts than common offset data.

DEMONSTRATION – COMMON OFFSET SCANNING MODE

Common Offset Scanning

The operator commands the robot to perform an autonomous scan

- Robot Antennas are first lowered to the ground
- Antennas are moved together to complete a line scan
- After each line scan, precise motor control indexes the antennas a small distance forward for the next line scan

Video

DEMONSTRATION – MULTI-STATIC MODE

Multi-Static Scanning

Operator initiates an automated scan

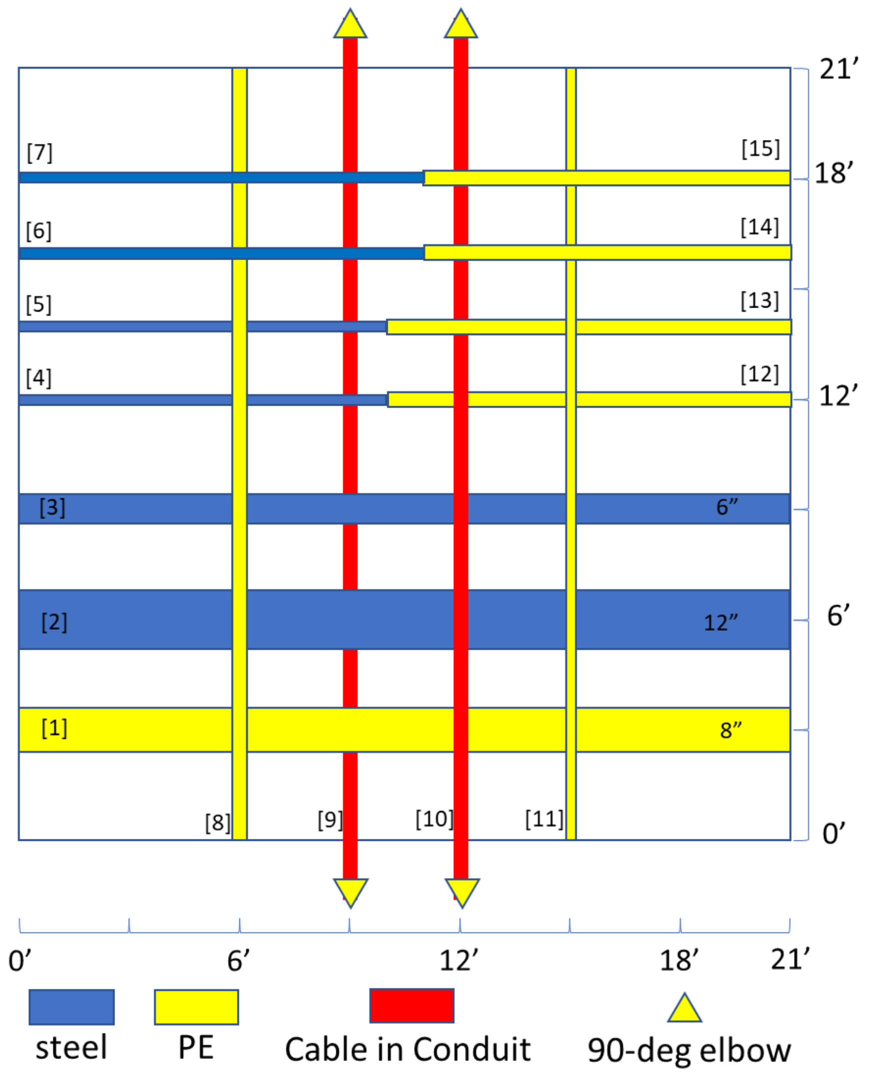
- The antennas are moved forward for clearance on the robot side
- Antennas are then separated from each other and positioned so that they don't collide when crossing over
- The multi-static scan is performed

Video

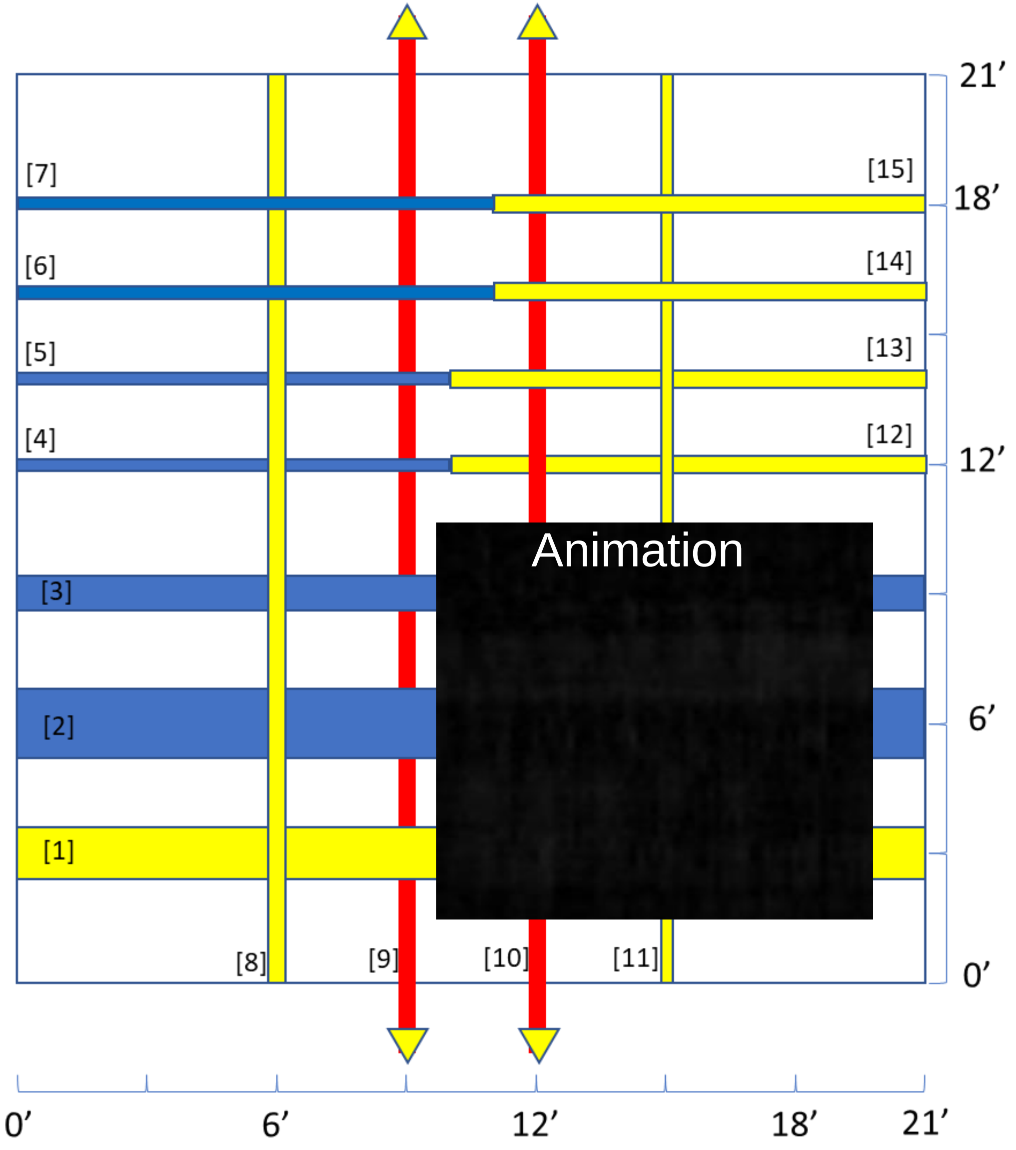
RESULTS OF TESTING

No.	Size (in)	Depth (ft)	Matl.
1	8	3	HDPE
2	12	3	Steel
3	6	3	Steel
4	2	3	Steel
5	2	2	Steel
6	2	1	Steel
7	2	1	Steel
8	3	1.5	HDPE
9	2	4	Cable in HDPE
10	3	2.5	Cable in HDPE
11	2	1.5	HDPE
12	3	3	HDPE
13	3	2	HDPE
14	3	1	HDPE
15	3	1	HDPE

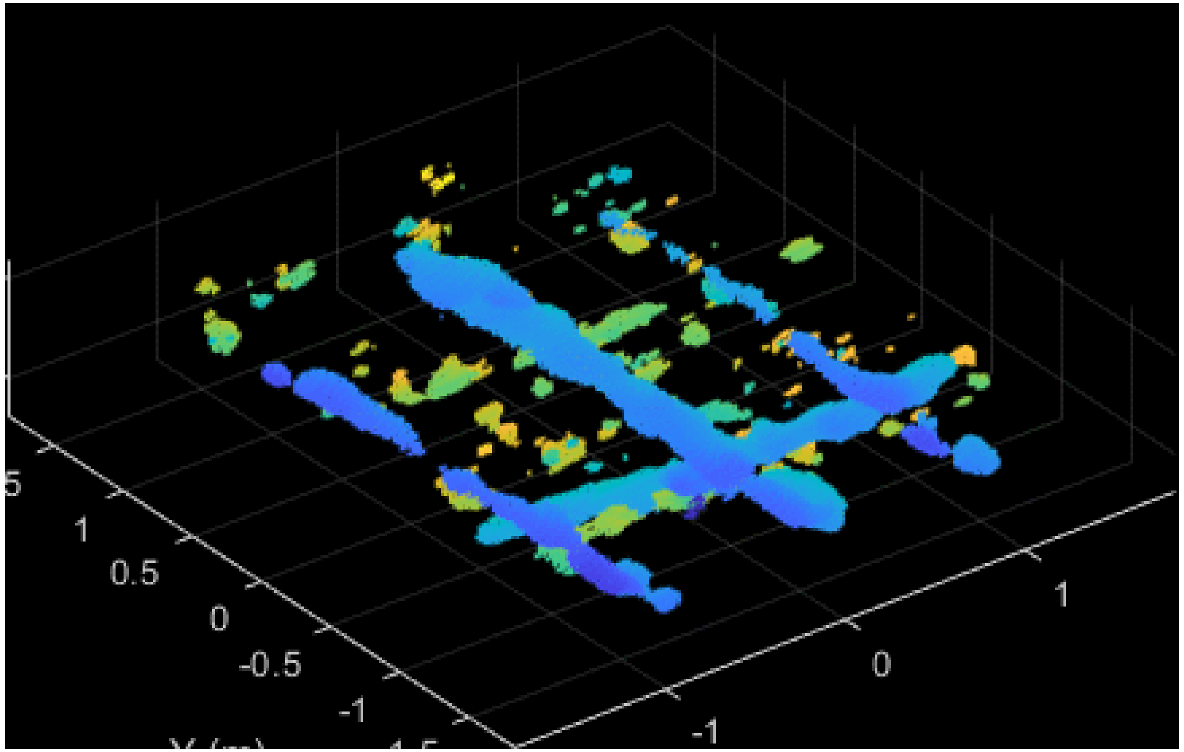
Clay soil with 9in concrete surface



RESULTS OF TESTING



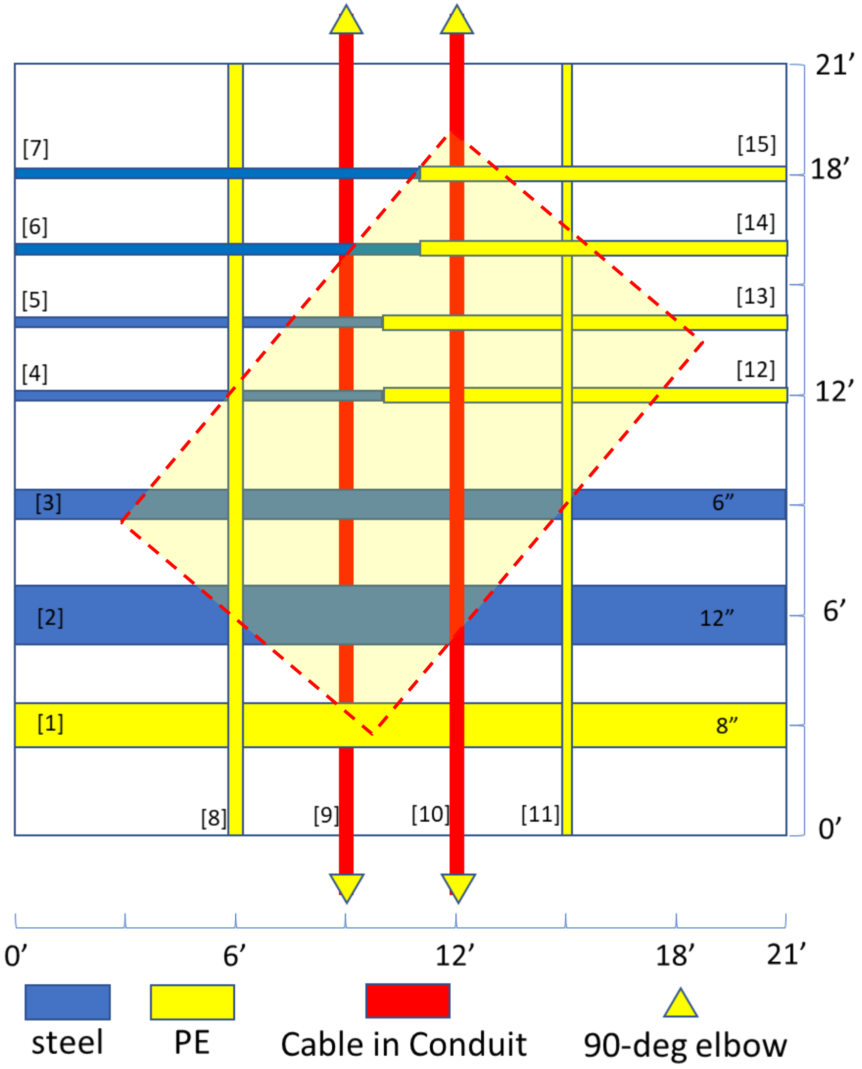
Animation

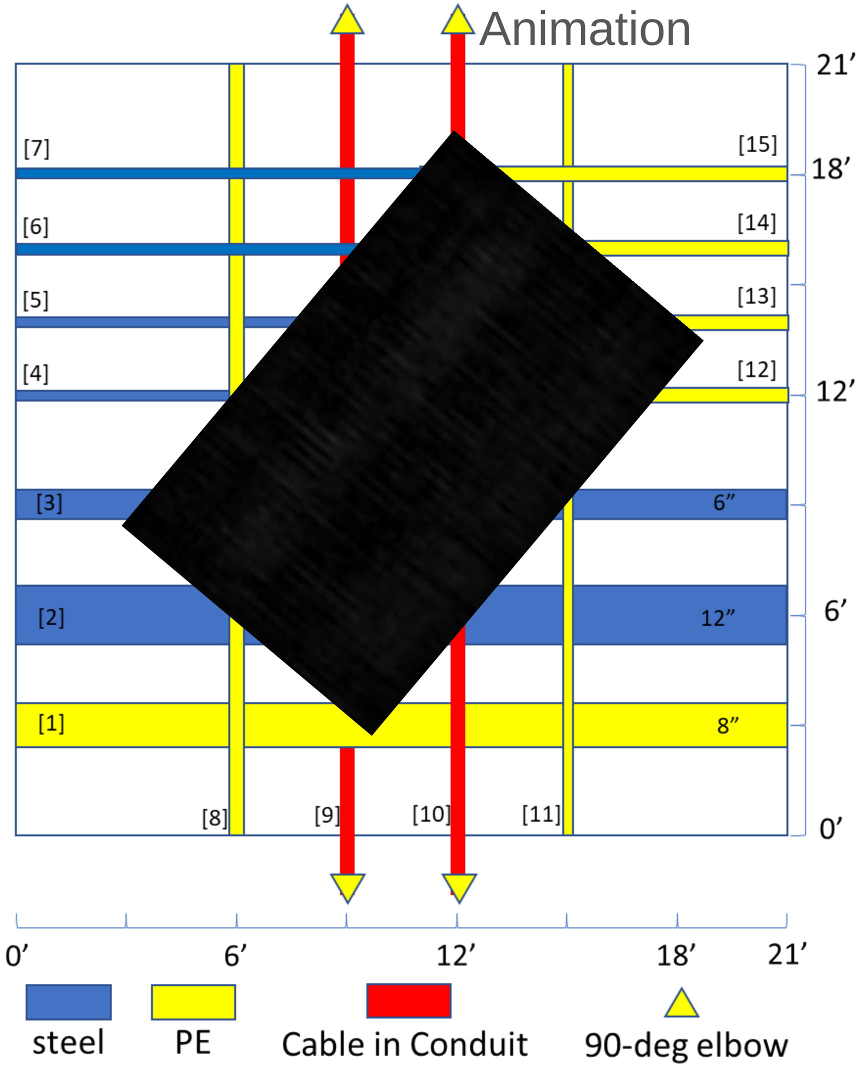


Detected non-metallic pipe:

- 8in HDPE @ 3ft
- 2in HDPE @ 1.5ft
- *3in HDPE conduit with copper wire @ 2.5ft

RESULTS OF TESTING





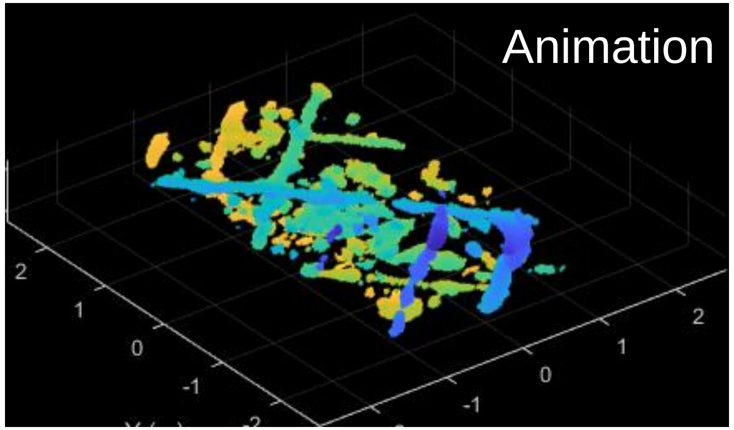
The scanning direction is 45deg respective to all the pipes.

Detected Non-metallic pipe:

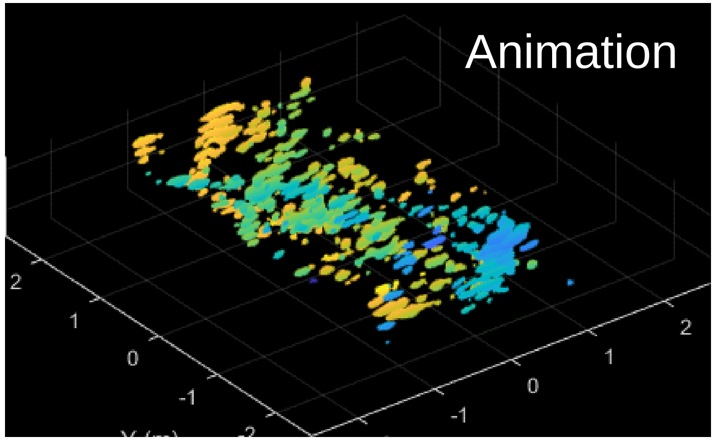
- 2in @ 1.5ft
- 3in @ 1ft, 1.5ft, 2ft & 3ft

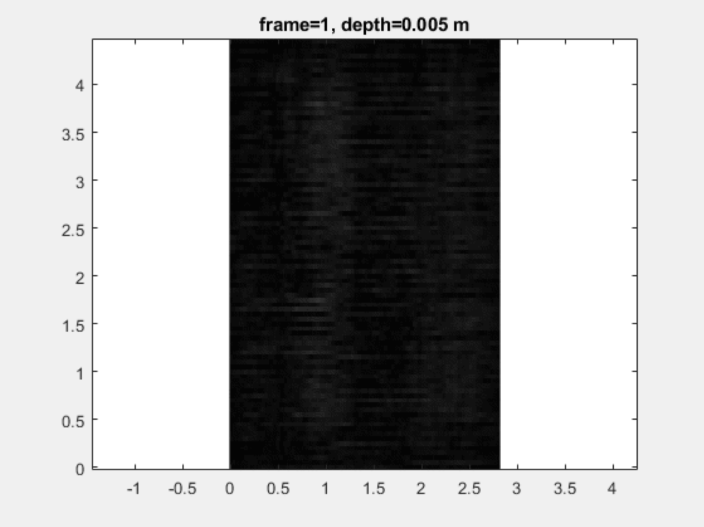
RESULTS OF TESTING

3D migration, dy=0.05m

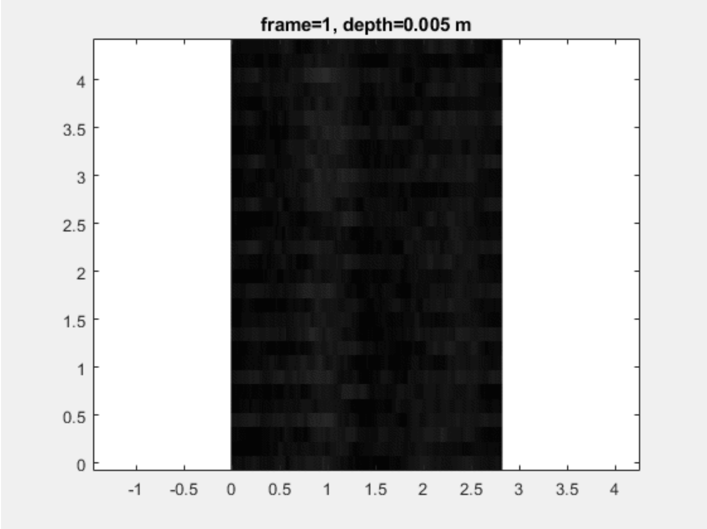


2D migration, dy=0.15m





Animation



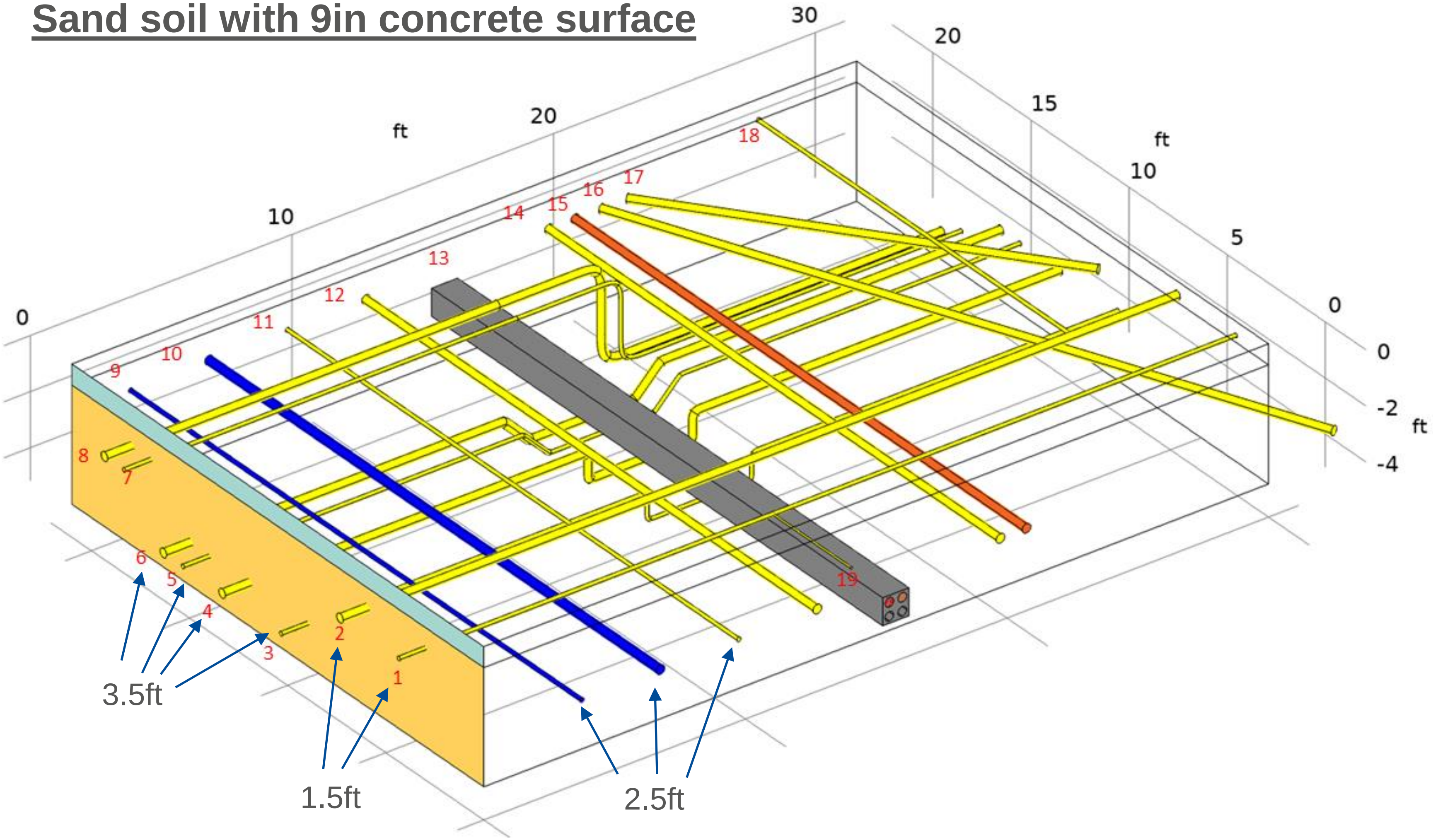
Animation

- Both non-metallic and metallic pipes are easier to identify from 3D-migration results.
- Fine grid size increases the chance of success in unknown environment.

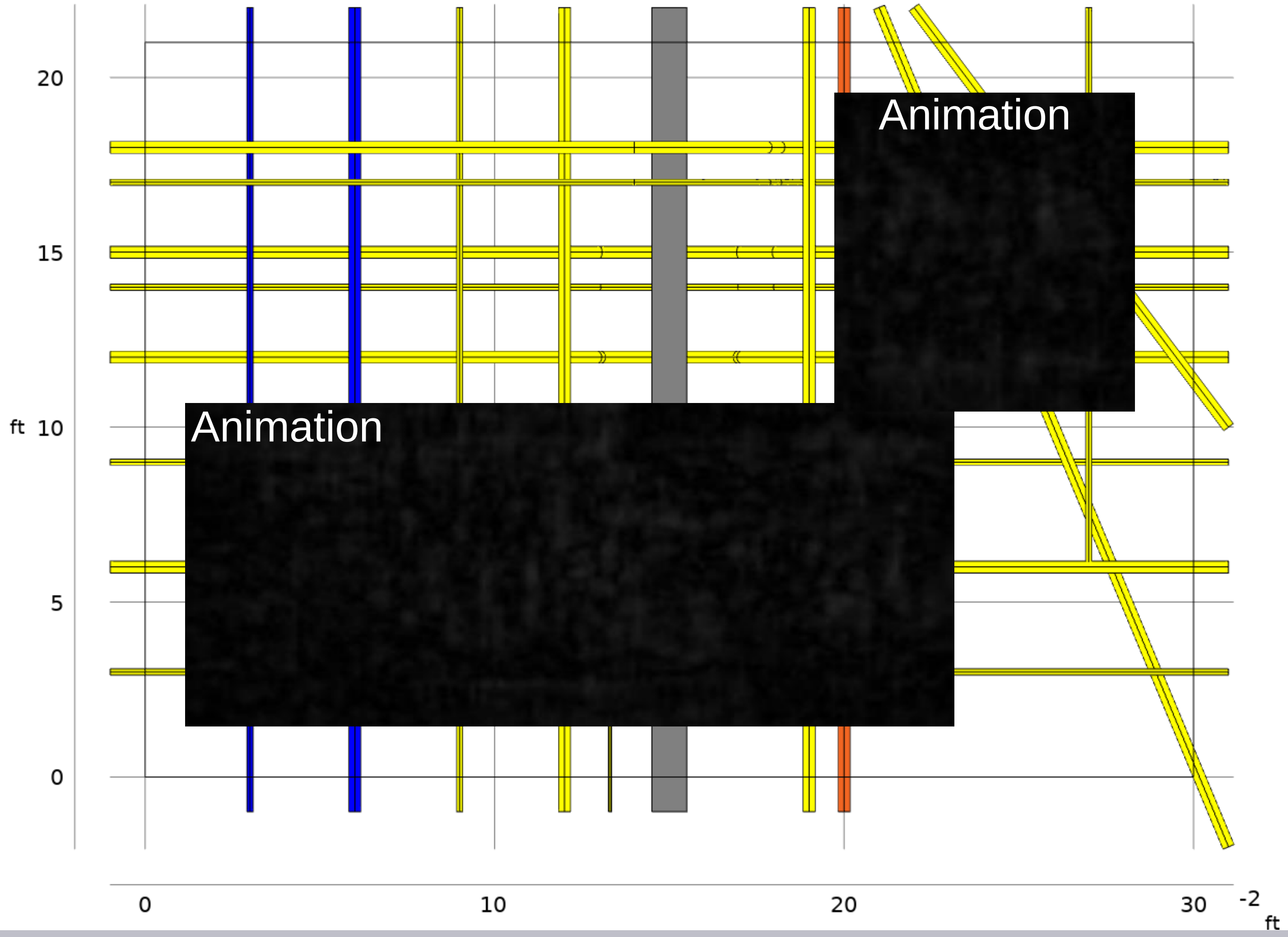
RESULTS OF TESTING

Pipe number	Pipe material	Pipe diameter
1	PE	2"
2	PE	4"
3	PE	2"
4	PE	4"
5	PE	2"
6	PE	4"
7	PE	2"
8	PE	4"
9	Steel	2"
10	Steel	4"
11	PE	2"
12	PE	4"
13	Concrete Duct bank	4"
14	PE	4"
15	PE	4"
16	PE	4"
17	PE	4"
18	PE	2"
19	PE	1"

Sand soil with 9in concrete surface



RESULTS OF TESTING



Detected Non-metallic pipe:
- 2in @ 2.5ft
- 4in @ 1.5ft, 2.5ft
- *Concrete conduit @ 3.5ft

FINDINGS AND FUTURE WORK

Highlight

- The robotic system offers high scanning resolution and accuracy to enable the use of advanced imaging & focusing algorithms. The pipes are more distinguishable and the C-scan + 3D model is easier to understand.
- Plastic pipes were successfully detected in both clay and sand soil.
- Pipe detection is independent of the antenna scanning direction.

Future work

- Lower frequency antenna for higher penetration depth and less clutter
- Test multi-static data collection at a real-world site
- Improve ground coupling of the antenna

Advantages of a robotic system over the traditional method are clearly demonstrated

KNOWLEDGE TRANSFER AND FINAL REPORT

- Industry demo was delivered in December 2022
- Case Study was developed for the Common Ground Alliance
  - Under review by the CGA Technology Committee and to be published in the Annual Technology Report for 2023

- Project Final and this presentation is available here: https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=861

QUESTIONS AND CONTACT INFO

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