Modernizing Aerial Patrol – Real Life Remote Sensing for Liquid Leak and Threat Detection Along the Right of Way

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Abstract

Since the end of 2022, Marathon Pipe Line LLC (MPL) has been using and testing Flyscan Systems' (Flyscan) remote sensing technology over their liquid pipeline right of way (ROW) to benchmark and validate the use of machine learning (ML) algorithms, photogrammetry, and hyperspectral imaging to perform real-time threat detection, liquid leak detection of crude oil and refined products, as well as other advanced imaging features related to geo-hazards.

This paper will present scientific approaches and real-life results from over 200 aerial patrols between November 2022 and December 2023, covering over 50,000 miles and identifying more than 3,000 potential threats over ROWs from Alaska to Texas, including the Rockies and the Midwest.

To the best of our knowledge, for the first time in the industry a hyperspectral system was used to detect a real underground seeper diesel leak during a ROW aerial patrol flight. Other examples noted in the paper will include the detection of contaminated soils from third-party activity, the detection of real encroachment, and massive documentation of various types of objects in the ROW. Finally, examples of new imaging capabilities will be presented, including detection of exposed pipes after serious weather events, vegetation analysis, and erosion monitoring for Depth of Cover (DOC).

Automating pipeline patrol to increase effectiveness and improve pipeline safety

US Federal regulations require that pipeline operators conduct routine inspections of their ROWs to identify potential threats to the safe operations of the pipeline. For liquid pipelines, these inspections are required at intervals not exceeding three weeks and at least 26 times per calendar year. MPL operates more than 10,000 miles of pipe across 26 states in a variety of unique terrains and topographies. MPL, along with other pipeline operators, primarily utilizes fixed-wing aircraft piloted by trained and certified crew to conduct these visual inspections.

Identifying threats is a largely manual task, relying on pipeline patrollers to maintain focus on the ROW and identify notable observations such as construction activity, new encroachments, sheen on waterway surfaces, or evidence of dead vegetation. The inherent challenge of detecting potential threats remains due to a variety of factors, such as the complexity of the terrain, lack of surface visibility due to vegetation, activity occurring between patrols, human error, fatigue, etc.

MPL's mission is to safely and reliably operate pipelines and grow its business. In an effort to achieve this mission, MPL is pursuing ways to advance and develop new technologies to mitigate risk and enhance efficiencies. Automating pipeline patrol through the use of artificial intelligence and advanced imaging is one way routine ROW inspection can become more effective, increasing overall pipeline safety. MPL partnered with Flyscan Systems Inc. to evaluate the use of their remote sensing technology as a viable replacement for traditional aerial patrol. Over the course of 2023, MPL

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conducted a pilot of the technology, deploying one plane with an attached instrumentation pod to inspect assets across the United States. This paper provides a detailed background on the technology as well as sharing some of the findings from over the course of the pilot.

What is Flyscan and its technology?

Flyscan Systems Inc. is a cleantech software technology company active in remote sensing and machine learning systems. The company is focused on enhancing the detection of threats to the environment, the public, and the assets of its customers in energy markets and linear infrastructure. Flyscan is developing an integrated package based on:

- Gasoline, diesel, and crude oil leak detection
- Theat detection like unauthorized third-party machinery
- Detection of exposed pipes and tile drainage coils
- High-resolution orthomosaics, 3D point clouds, and Digital Surface Models (DSMs)
- Change detection, depth of cover analysis, and geohazard assessment
- Vegetation management (encroachment and volumetric measurement)

The principle of operation is to enhance an existing process mandated by regulation: the biweekly visual inspection of pipeline ROWs. There are already regular aircraft surveys of these assets mandated by regulation and Flyscan offers a remote sensing package (called the "pod") to be bolted onto regular patrol planes, drastically increasing survey quality with minimal change to operational procedures and flying costs. The pod rides along and provides these outputs. It is fully certified for airworthiness and is compatible with Cessna C172K to C172P, Robinson helicopters, Cessna 182, 206, and 208. The pod is small, simple to install, auto-calibrating, and designed to be used by a single pilot-operator. It is equipped with a variety of technologies:

- Three high-resolution, high frame rate Red Blue Green (RGB) imagers (center, left, and right) providing about 440m/1500ft wide imaging
- One short wave infra-red (SWIR) hyperspectral push broom camera
- One high-precision inertial and GPS platform
- One laser range finder
- One real-time processing computer
- Real-time communication equipment to send geo-referenced alerts

Below is shown the pod mounted onto a C-172 aircraft with both the first generation model and the new Meeker mount generation. The results presented in this paper were acquired from this first generation system:

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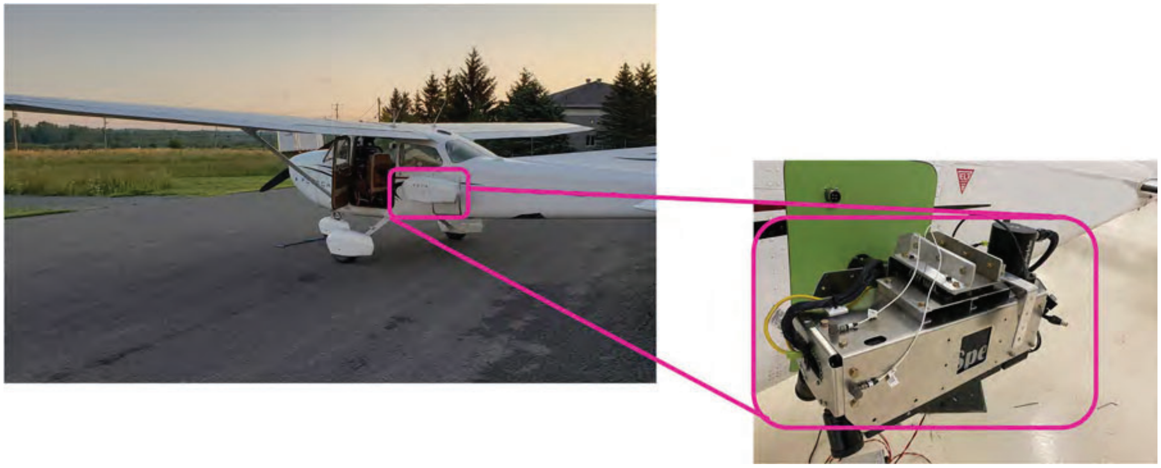

Figure 1. Generation 1 pod

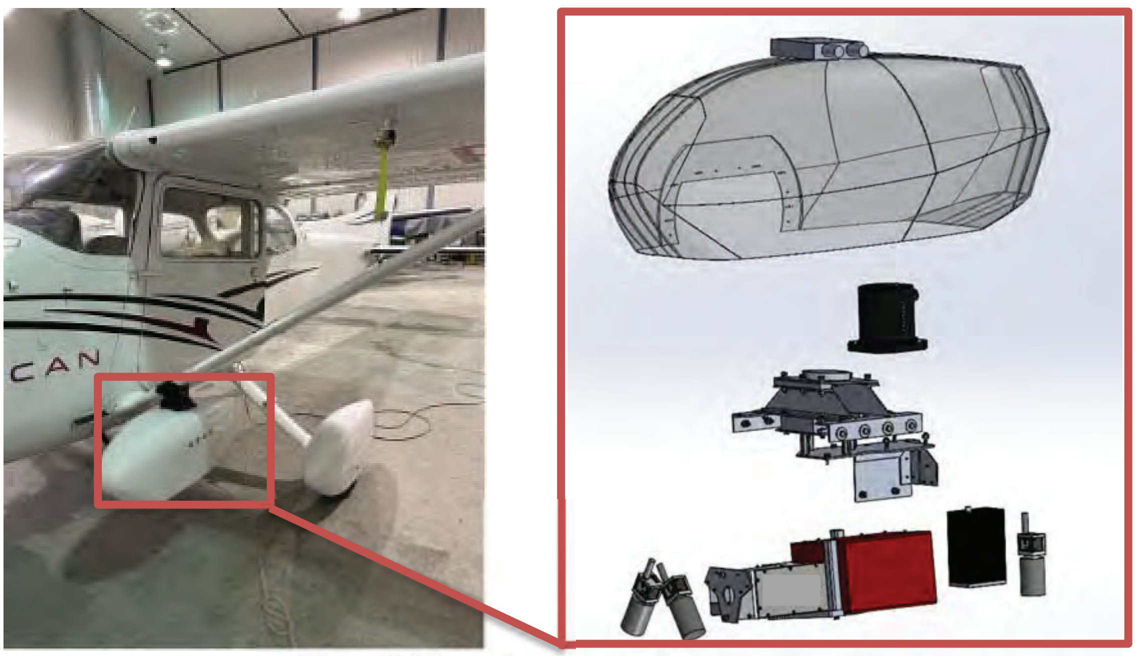

Figure 2. Generation 2 pod with Meeker Mount

Hyperspectral liquid leak detection solution

One important component of the pod is the hyperspectral imagers enabling liquid hydrocarbon leak detection and more upcoming capabilities.

Principle

The source of energy for the measurements is the sunlight. The sun sends its light to the surface, and as it interacts with the atmosphere, each gas present in the atmosphere imprints its absorption features in it. The light bounces on the ground which will reflect its colors and absorption features to be precisely measured by the camera. The camera is a push broom hyperspectral system creating

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images one line at a time. It measures the intensity of the light in over 288 bands (or colors). The figure below is a visualization of the light path and the Short Wave Infrared (SWIR) spectral range.

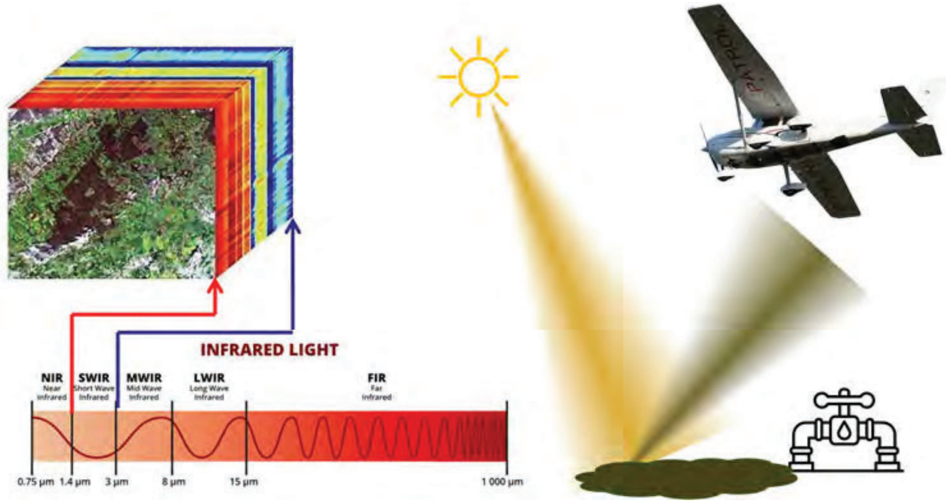

Figure 3. SWIR remote sensing of oil

Algorithms

Using internally developed algorithms, the atmospheric and solar effects (colors) are compensated and removed, leaving only the ground reflectance. Specific spectral signatures are then identified to detect targets of interest. An example of this is liquid hydrocarbons (LH) using various spectral techniques. Spectral classifiers, un-mixing methods, band ratios, normalized differences, machine learning, and other algorithms are chained in a workflow to create a detection score between 0-100. The closer to 100 the score is, the more confidence the algorithm has to have detected liquid hydrocarbons. Lastly, machine vision and image processing techniques are applied to filter out potential false alarms. All the workflow is programmed to be computationally very efficient able to provide results within 24 hours of data reception. The figure below is a visualization of the workflow.

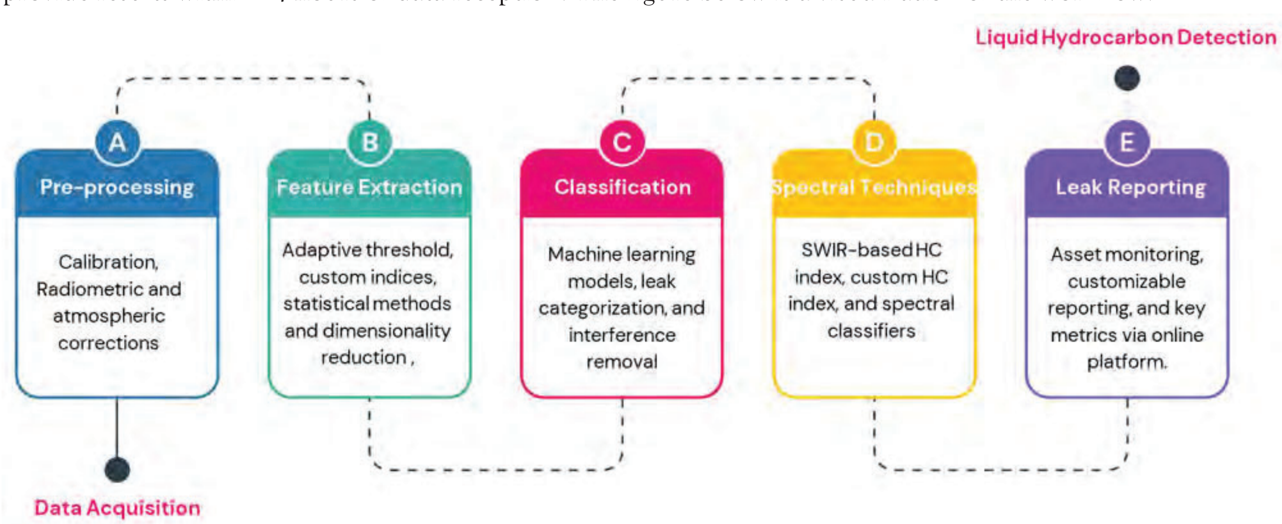

Figure 4. Liquid hydrocarbon detection algorithm workflow

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Dimensionality reduction

One very important part of the algorithm that enables detection even in very high data volume is the dimensionality reduction techniques, as part of Step B. Hyperspectral data acquisition creates large datasets with highly correlated data points, which is problematic in the calculation of spectral indices such as the adaptive cosine estimator. Principal component analysis is performed to reduce the dimensionality of the data, i.e., express the variability of the data through a subset of hyperspectral vectors or "components." Such components correspond to directions of high variance in the n-dimensional space containing all possible hyperspectral vectors. Components are identified by singular value decomposition (SVD) of the data matrix X, which is equivalent to solving the eigenvalue problem for the covariance matrix XTX:

X=UΣW^T

Where X is the matrix containing the measured spectra, Σ is a diagonal matrix containing the singular values of X, and U and W contain the left and right singular vectors, respectively. The singular values correspond to the variance of the dataset X in the direction given by the associated singular vector. The hyperspectral vector base is truncated at the m^{th} singular value, expressing the data in an m-dimensional vector space. This technique is a critical part of accelerating processing to report environmental threats faster and more reliably.

Characteristics of the technology in operation

The leak detection technology has the following characteristics:

- Sensitive down to $1m^2$ of contaminated terrain
- Sensitive from fully saturated to partially saturated ground
- Gasoline, diesel, jet fuel, diluent, light and heavy crude oil detection
- 42m swath at 550ft altitude (the current flight altitude)
- Down to 24-hour alert generation time for leaks from data reception
- Event context categorization (from recommended immediate intervention to ignore)
  - Important: Recommend immediate intervention, high confidence.
  - Investigate: Signs of important contamination
  - Other events: Clear signs of contamination, but an explainable cause like a pool of gasoline in a car scrap yard is normal and not of concern.
- Event tracking over time
- Comprehensive patrol reports
- Very-low amount of false positive

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Current limitations and challenges

The SWIR spectrum is very useful to detect multiple targets of interest, but unfortunately does not travel well in thick clouds or in raining conditions. Visible light on the other end does. This is why when fully overcast we can see, drive our cars, and live life normally. While in the SWIR spectrum, the signal remains very minimal, especially in the regions of interest for hydrocarbons. For this reason, the technology will not work in fully overcast conditions or when it rains, limiting its scope of operation. To work around this limitation, it is best to plan flights and adapt to weather whenever possible and rely on a combined automated and manual visual inspection for routine patrols. New algorithms are in development to enhance performance in low sun conditions (e.g. in Northern latitudes like Alaska) and overcast weather.

Threat detection

Principle

Today, the current method for patrolling pipeline ROWs is not standardized in the sense that it is prone to human error. Implementing object detection models for real-time threat detection on pipeline ROWs offers several advantages over traditional survey methods. The utilization of advanced computer vision algorithms enables the swift and automated identification of potential threats, such as unauthorized intrusions like excavation equipment or environmental hazards such as erosion. Unlike traditional survey methods that often rely on manual inspection and periodic surveys, object detection models provide consistent results regardless of the operator, enhancing the overall security and safety of pipeline infrastructure. The real-time nature of these models allows for immediate response to emerging threats, minimizing the risk of incidents, and reducing downtime. Additionally, the automation of ROW visual inspection through object detection models contributes to increased efficiency and cost-effectiveness.

Algorithms

The YOLO (You Only Look Once) brand of object detection models, known for their efficiency and speed, offers a versatile framework that can be tailored for specific tasks such as aerial threat detection. YOLO models excel in real-time image processing, making them well-suited for applications where timely threat detection is crucial. One of the significant advantages is their ability to process entire images in less time than the trigger interval for the subsequent image, enabling the ability for real time detection. When utilized for aerial threat detection, YOLO models can efficiently identify potential hazards, such as unauthorized access or anomalies, and when deployed with the associated navigation and reporting system give actionable information to the pilot to assess the risk and take action. However, there are trade-offs to consider. The real-time processing capability demands substantial computational resources, which can be a challenge for deployment on resource-constrained platforms. Even with advancements in inferencing hardware there are still limitations that need to be considered when this technology will be deployed on older model aircraft, some of which can exceed 50 years old. Additionally, the detection accuracy may vary based on the complexity

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and diversity of the dataset used for training. Fine-tuning YOLO models on specific datasets is essential for optimal performance in tasks like aerial threat detection. Flyscan now has a library of over 13 million images consisting of a wide geographical spread across the continental US as well in a variety of common weather conditions that are used for model development. Despite the computational demands and the need for careful dataset curation, the speed and efficiency of YOLO models make them a compelling choice for real-time threat detection applications with aerial imagery.

Characteristics of the technology in operation

Threat detection currently deployed in operations today consists of the following categories:

1. Regular passenger vehicles
2. Oversized passenger vehicles
3. Commercial trucks
4. Mechanical equipment
5. Movables (trailers, containers)
6. Structures
7. Personal property (e.g. swimming pools)
8. Customer-specific vehicle recognition with operator logo present
9. Recreational off-road vehicles

All object categories are detected live in flight with the ability to send real-time notifications of threats via SMS and email. All detections and flight stats are published on a web portal post-flight in the form of a post-flight report.

Additional categories that are soon to be offered include:

1. Drainage tile indicators
2. Exposed pipe detection
3. Erosion indicators

Adding these additional categories allows for further automation of the routine visual survey.

Geohazards and geospatial analysis

Principle

Flyscan's system is a direct georeferencing system. The principle of utilizing direct georeferencing in remote sensing represents a pivotal advancement in geospatial data acquisition, providing a foundation for deriving accurate and detailed geospatial products through photogrammetry software. Direct georeferencing involves integrating Global Navigation Satellite System (GNSS) and Inertial Measurement Unit (IMU) data directly into the image acquisition process, obviating the need for ground control points. This methodology offers the advantage of increased efficiency, as it allows for rapid and large-scale data collection, minimizing fieldwork requirements. In the context of generating geospatial products, such as ortho mosaics, Digital Surface Models (DSM), Digital Terrain Models (DTM), and point clouds, direct georeferencing facilitates the creation of high-precision, spatially accurate datasets. These products of the photogrammetry process can then be used to add additional analytical tools, such as the ability to do spatially accurate vegetation analysis as a desktop exercise

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rather than a field-based survey or calculating on a network scale the depth of cover (DOC) over a pipeline to a certain degree of accuracy. However, challenges exist, particularly regarding the potential for positional errors and accuracy degradation in areas with limited GNSS visibility. The reliance on IMU data also introduces the possibility of drift over time. Careful consideration and calibration are essential to mitigate these drawbacks and ensure the reliability of derived geospatial products. Despite these challenges, the integration of direct georeferencing as part of an automated survey system significantly enhances the efficiency and accuracy of geospatial data, offering a valuable tool for various applications, including environmental monitoring as it relates to pipeline integrity.

Algorithms

Geohazards – There are many types of geohazard that exist on pipeline ROWs. There are also many techniques for detecting these and subsequently monitoring them. Flyscan is using a change detection methodology from point cloud to point cloud to determine the difference from one data set to another, this method can be applied to both detection of new geohazards as well as monitoring ongoing hazards. This technique is designed to detect slow moving geohazards that cannot confidently be detected as part of a standard visual inspection. Other methodologies that will be applied include additional object detection categories within live threat detection for exposed pipe and obvious sign of erosion. All these techniques are extremely useful for pipeline operators to perform inspections after serious weather events in a way that is reliable, visually easy to interpret and document/report/audit.

DOC – Utilizing a photogrammetry derived DTM along with existing pipeline elevation the depth of cover over a pipe can be determined.

Vegetation management – This software utilizes photogrammetry products and derives the height of vegetation as well as the extent of vegetation encroachment within the pipeline ROW. Additional software features have been added to create sites, which can then be used to record additional information relevant to vegetation management activities.

Results from regular patrols using the technology

Hyperspectral diesel, gasoline, and crude oil detections:

Since the beginning of 2023, the passive leak detection technology has been tested in real life to reliably identify multiple areas of contamination, including the potential first-ever seeper diesel leak from an underground pipeline. Four use-cases are presented alongside the results obtained for each. The hyperspectral detection score is shown using the rainbow color map from blue to green to yellow and red. Blue is 0 and red is 100.

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1 – Seeper leak and diesel spill

During the pilot phase of the technology implementation, a mission was requested to be analyzed, and results provided to the customer. The algorithm was run, and multiple findings were reported. The histogram presented below shows the rank of each potentially contaminated zone based on the Flyscan liquid hydrocarbon score. The top events did contain false positives. After a combination of humans in the loop and automated inspection of filter false positives, most of them were filtered out, but a few were of significant interest and were reported to the customer in a Leak Detection Patrol report. The score of 3 events is shown: diesel spill, diesel leak, and strong false positive example. Their score is respectively: 93.25, 91.1, and 97.5.

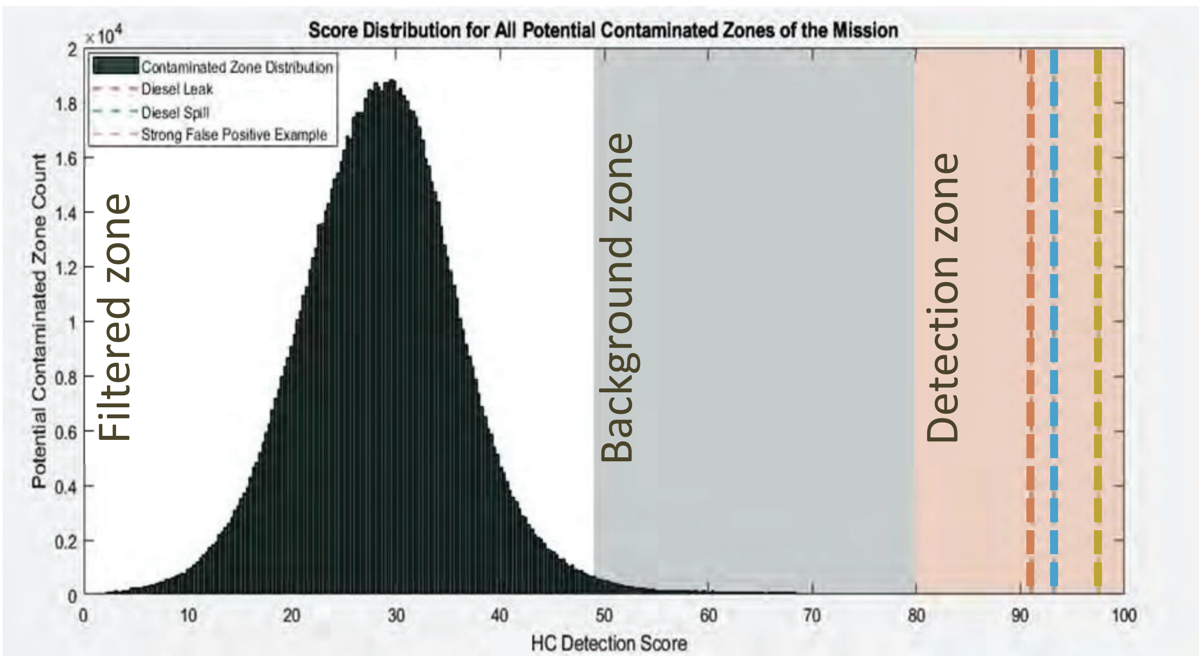

Figure 5. Liquid hydrocarbons detection algorithm distribution

The below figure shows the black and white hyperspectral broadband image on the left, the view from the plane on the right, and the detection score overlayed on the left image. Looking at the RGB image, it is impossible to tell if there is something. This mission was 300 miles long. Upon investigation, it was confirmed to be a diesel spill from a previously parked agricultural machinery. This kind of event is important because a leak can look exactly like this. The signal is strong in the center of the zone and fades out in the outer edge, possibly indicating a concentration gradient.

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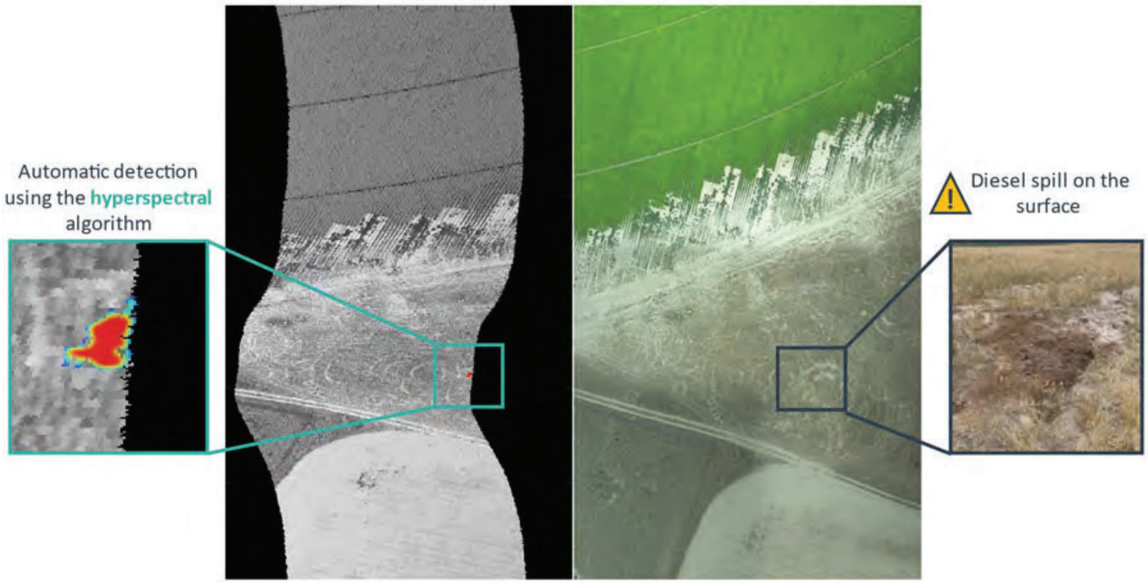

Figure 6. Diesel spill

Later in the analysis, another detection came through. We can observe the profile and high score of the patch of contaminated soil in the hyperspectral product image. The right of way is visible beside all-terrain vehicule tracks, under which the pipeline is buried. On the scene, MPL's local operations team found a brown patch of ground with clear indications of diesel. After an integrity dig, a pinhole leak caused by external corrosion was revealed, which caused a small seeper leak. The release was estimated to be in the order of 50 barrels, which is well below the limit of detection of existing Computed Pipeline Monintorig (CPM) systems. This demonstrates the ability of the technology to detect a needle in a haystack, i.e., liquid hydrocarbon-contaminated areas with the potential to be coming from the nearby pipeline. This ability fills a gap in leak detection that has been present for years.

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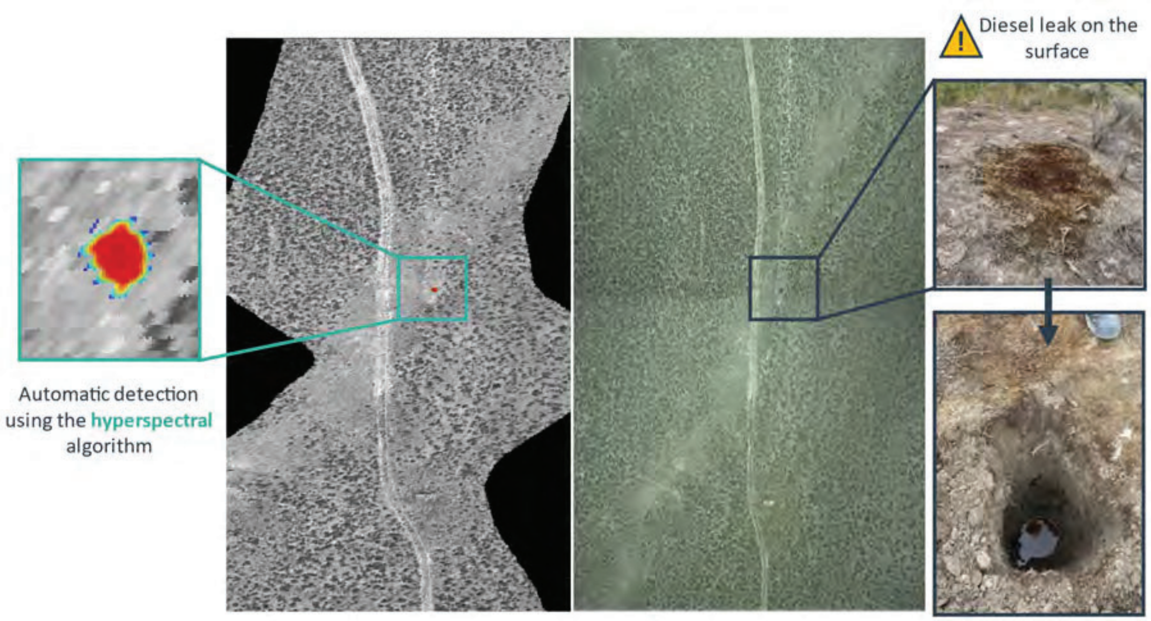

Figure 7. Seeper diesel leak – Bottom right pictures shows foot of employee for scale

A mission was flown after this event, and we can see the pipeline being repaired and the area cleaned up with no sign of liquid hydrocarbon contamination. This was helpful to the customer for keeping high-quality records of their intervention on the ROW. Data was used for documenting the event before and after detection. It is clear in the following images that no signs of contamination are present, showcasing the usefulness of the technology even after an incident. The seeper leak event survey showed no signs of contamination. The pipeline has been repaired, and the work are being cleaned up on the picture.

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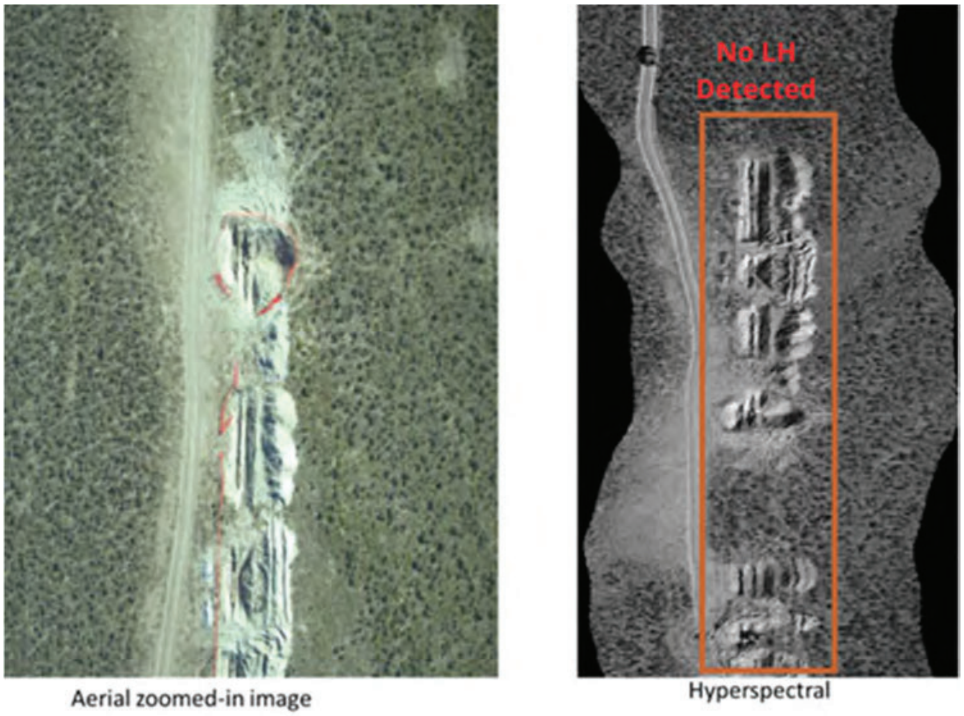

Figure 9. Pipeline repair image

The agricultural machinery spill was cleaned up, and nothing is visible in the hyperspectral product in the area.

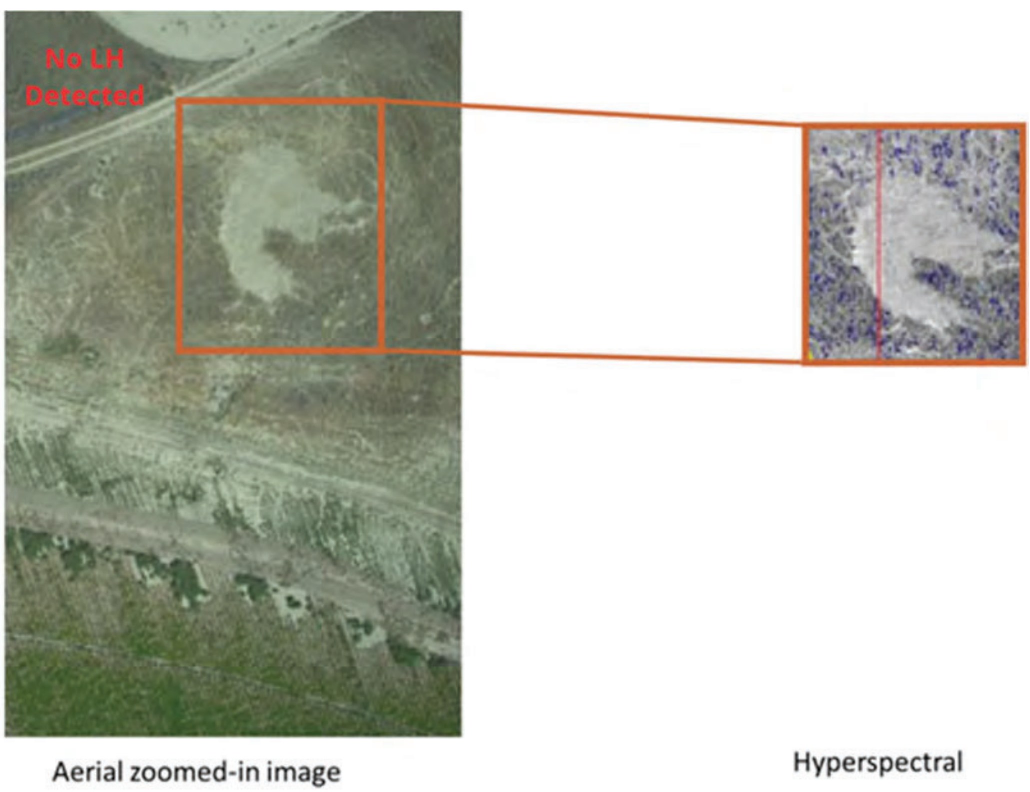

Figure 10. Cleaned up diesel spill

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2- Examples of ground-validated detection during commercial operations on the ROW and within facilities

This section presents various examples of liquid hydrocarbon detection along the ROW and within facilities. These detections were reported, investigated, and ground-validated by MPL to be contaminated with liquid hydrocarbons. An aerial view from the plane is always presented alongside the hyperspectral product detection score, and a ground picture during investigation so the context can be understood by someone who was not on site.

Event 1: An aerial view of the ground shows a dark spot on the grass. The detection score is very high and near the pipeline therefore reported as Investigate. Upon investigation, it was indeed a pool of crude oil on the ground probably from an old extraction site. The contamination was reported and the site cleaned up.

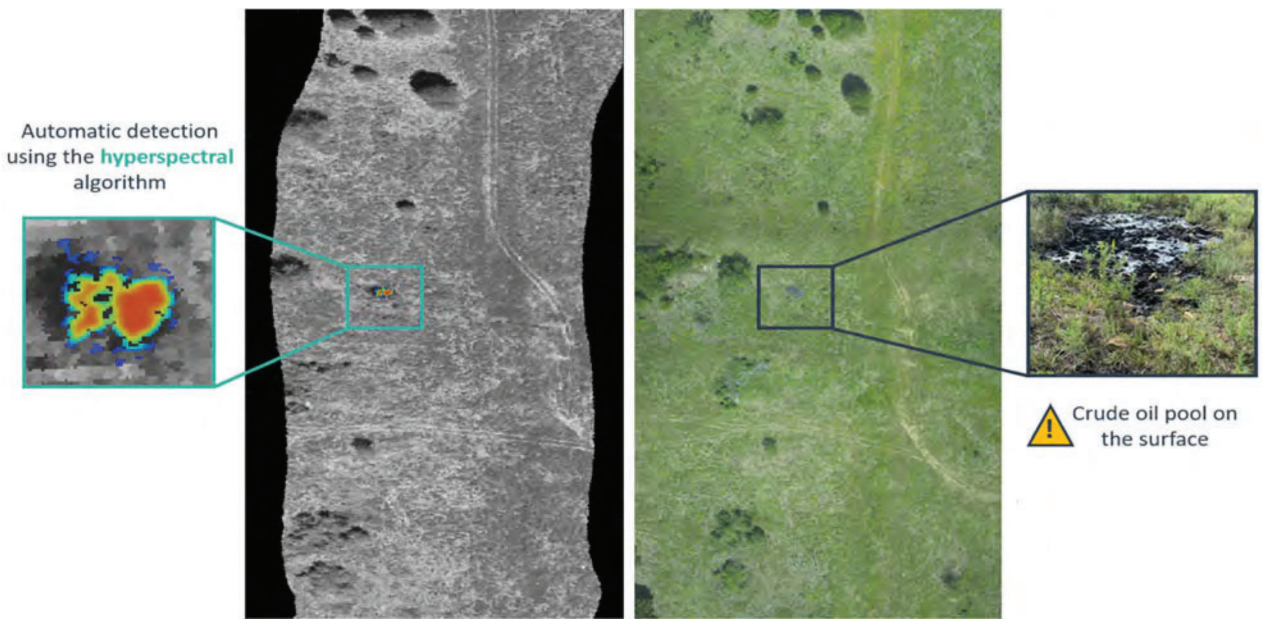

Figure 11. Crude oil pool contamination detected from regular patrol

Event 2: An aerial view of a facility shows a brown soil area beside the tank. The detection score of the area is very high, indicating high confidence of liquid hydrocarbon. It was confirmed to be diesel contamination in the area.

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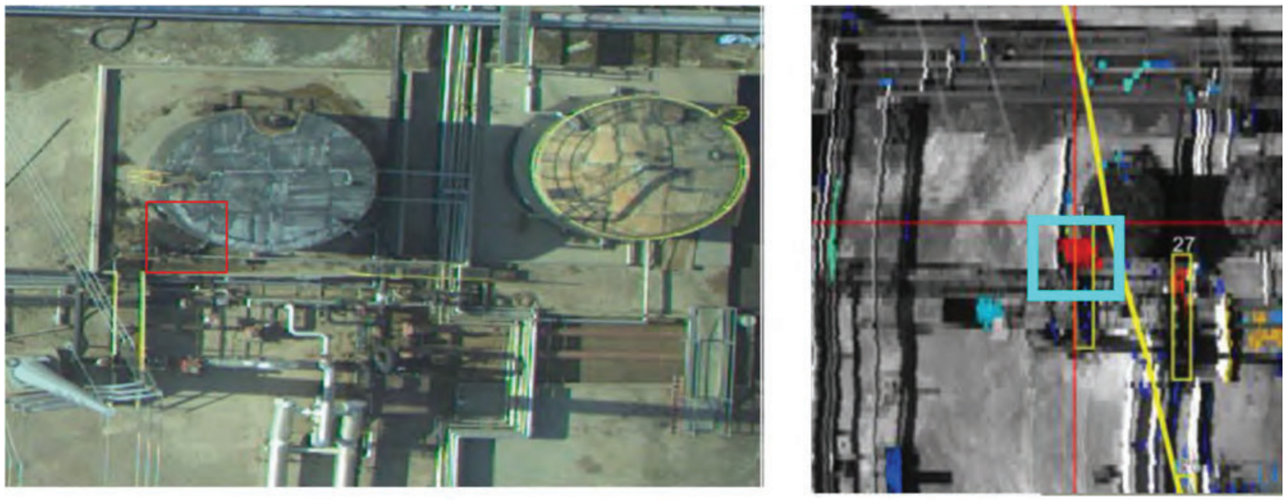

Figure 12. Contamination detected within a facility

Event 3: An aerial view of the agricultural field shows nothing of interest. The hyperspectral detection signal is very strong on a very small patch of grassy vegetation. Due to its proximity to the pipeline and high score, it was reported and investigated. No active leak was found, but it was confirmed to be a diesel-contaminated patch of grass likely from machinery.

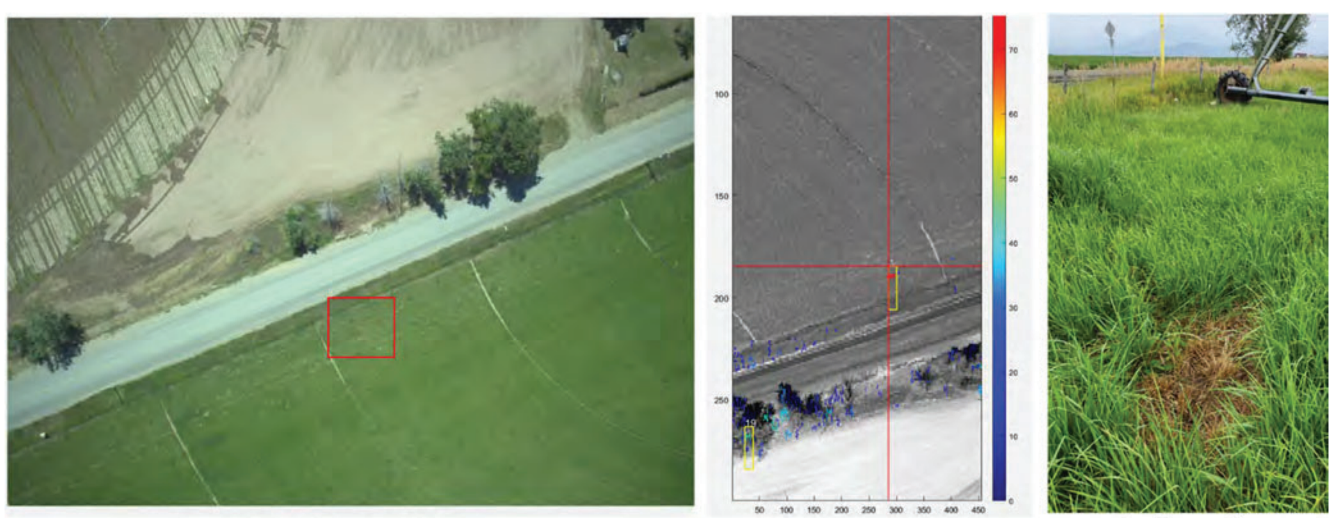

Figure 13. Diesel contaminated grass detected

Event 4: This event is the perfect example of a non-important real detection. The system picked up a strong signal on known parking area with heavy gasoline contamination. The pipeline does go under the parking lot, but it has a very likely non-pipeline cause. The area is being monitored, but the detection was noncritical. These events are important because the instrument does not differentiate between contaminated ground in a parking lot or in the middle of a field. They are always reported for the customer to judge and plan the best intervention based on context.

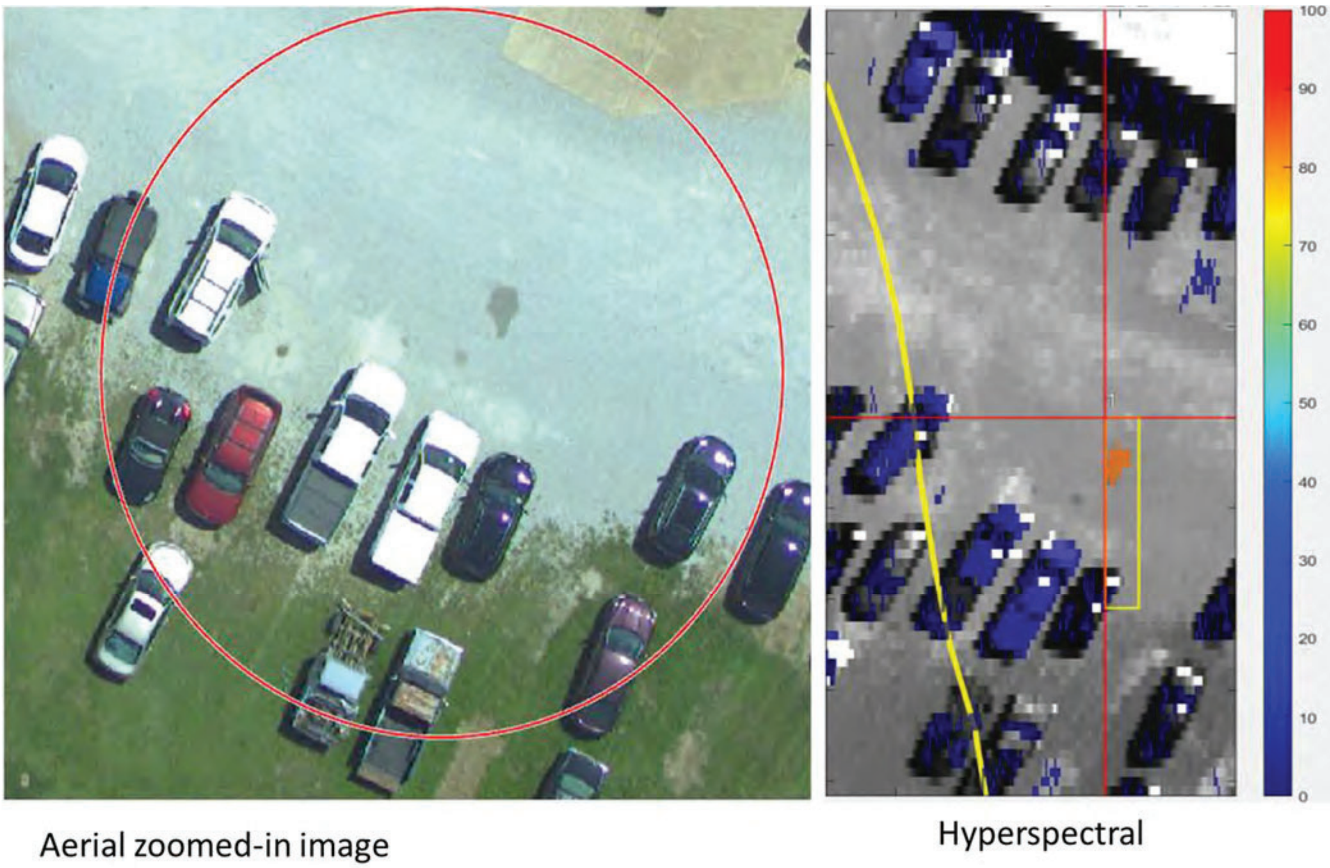

Figure 14. Diesel spill detected in a parking lot

Threat detection, exposed pipe, and depth of cover

The following are three examples of critical events identified by the threat detection product and one example of depth of cover analysis, illustrating their effectiveness in pipeline monitoring.

Exposed pipeline detection

The threat detection technology successfully identified 2 exposed pipeline segments, revealing areas where erosion had left the pipeline uncovered and at increased risk of damage. These cases demonstrate the system's effectiveness in detecting such vulnerabilities, crucial for pipeline integrity and safety. The score ranges from 0 to 1, with 1 being a certain match.

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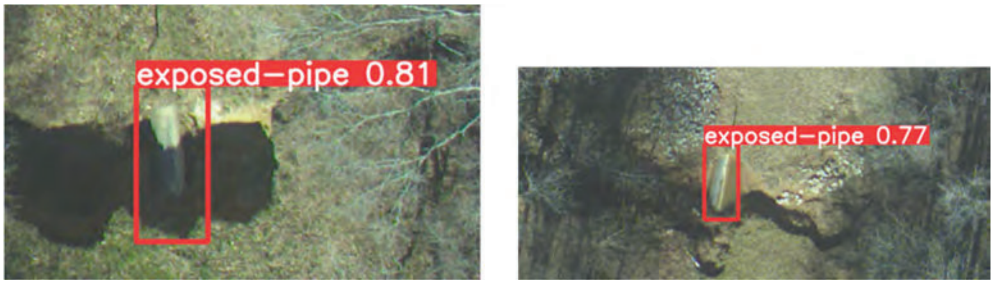

Figure 15. Two exposed pipeline detection examples

Real threat identification

Another success of the threat detection technology was the identification of unexpected mechanical equipment near the pipeline, showcasing its crucial role in recognizing unforeseen hazards. In the example below, this was the first real active threat Flyscan detected over a MPL ROW. A real time alert was sent to operations to investigate the activity of that unknown third party.

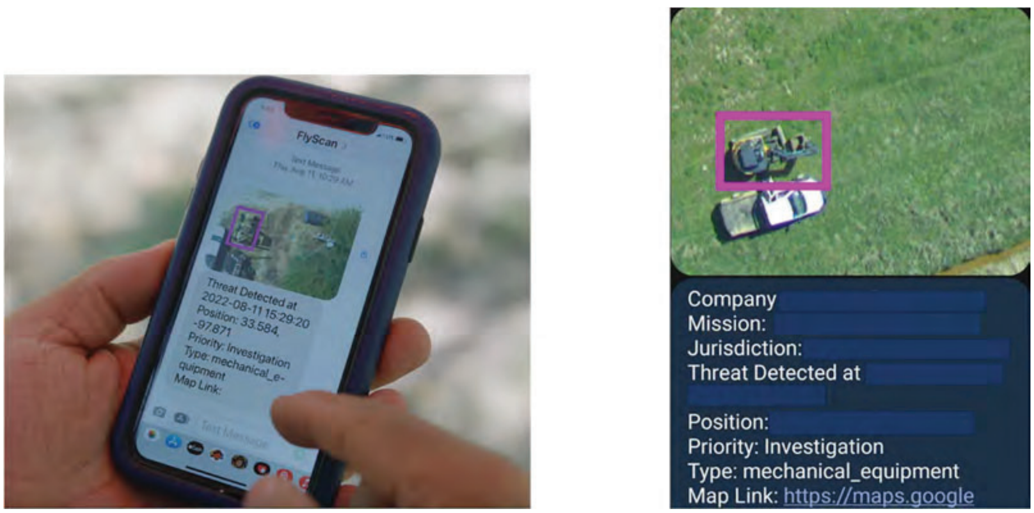

Figure 16. Threat alert interface example on the left and real un-staged important detection of an unknown 3rd party in the ROW on the right.

Depth of Cover (DOC) analysis

Under development, this DOC Analysis tool is designed to precisely measure the distance between pipelines and the surrounding ground. It presents these measurements visually, as shown in the example image, where different colors indicate varying depths of cover. This method simplifies the understanding of pipeline depth profiles for enhanced safety monitoring.

Figure 17. Example of a DOC analysis output

Flyscan Systems solution road map

Flyscan is currently developing additional capabilities that will be active in 2024 to enable comprehensive ROW monitoring. These capabilities include:

- Liquid leak detection for gathering lines, including produced water
- Shared ROW multi-operator inspection
- Methane (Ch4) leak detection on gathering and transmission lines
- Geo-hazards alerts (land slippage, erosion)
- Vegetation management reports

Conclusion

In summary, Flyscan delivered to Marathon important alerts about their ROW management for leak detection and threat detection that were used to perform interventions on their assets.

Flyscan also demonstrated potentially the first-ever detection of an onshore seeper diesel leak well below the limit of detection of Computed Pipeline Monitoring systems, using hyperspectral remote sensing and many other ground-validated contamination detections, proving the technology's performance and usefulness.

Results from the patrols highlight the viability of using artificial intelligence and remote sensing technology to automate regulatory pipeline patrols and visual inspection. During the pilot, MPL experienced no misses of staged or known ROW activity. The detection of soil contamination described above highlight the potential to catch and address even subtle operational issues quickly. Given these results, MPL will continue to expand the usage of this technology in 2024, integrating it into its ROW inspection program to further the mission of safely and reliably operating its pipelines.

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