Monitoring Pipeline Movement Using Magnetic-Based Technology: A Comparative Study

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Abstract

There are several threats to the integrity of buried pipelines, including geohazard events such as landslides, earthquakes and other types of ground movements. These events may cause axial and/or lateral deformations that induce bending strains in these structures, leading to catastrophic consequences. It is estimated that 16% of pipeline failures over the last 10 years have resulted from geohazard events.

To address this issue, Skipper NDT has developed a proprietary system which can be mounted on a drone or ground-based cart, capable of generating a high-precision digital twin of buried pipelines. This technology enables the acquisition of position data with high data density, which can be utilized to assess bending strain.

A three-step validation process was undertaken to validate the drone-based positional data. Step one involved controlled validation of the XYZ data for precision and accuracy. The second step, previously completed and reported during PPIM 2024, involved limited testing and validation to a segment of pipe with cold bends. This verified the ability of the technology to identify small changes (2.5°) in pipeline geometry as a proxy for ground movement.

This paper will focus on the third and final step used to validate this technology's effectiveness by way of a case study completed with a leading pipeline operator. For this study, Enbridge Gas Transmission and Midstream selected candidate pipelines in active, high-risk geohazard locations. Data from this study were compared against bending strain data acquired from ILI tools in 2022 and 2023. The results confirmed that the drone-based acquisition produced reliable and repeatable data within 0.02% agreement with the baseline ILI IMU and bending strain data. The details of this study and its results are presented in this paper.

Introduction

The effective management of geohazard threats to buried pipelines is an essential component of pipeline integrity management initiatives. Given the potential for geohazards to trigger catastrophic failures in underground pipelines, timely identification, assessment, monitoring, and mitigation of such risks is paramount. Moreover, the location of geohazard-prone areas in remote and rugged terrain exacerbates the complexities surrounding assessment, monitoring, and mitigation efforts.

Considering these challenges, there is a pressing need for methodologies to monitor and quantify changes in curvature of pipelines where geohazards pose a risk. Such advancements are imperative to bolster the capabilities of pipeline operators in safely and reliably managing this pervasive threat.

Challenges and Advanced Monitoring Techniques

Managing pipelines in areas susceptible to geohazard threats is a difficult task compounded by several factors:

- These locations are often coincidental with sensitive environmental and societal factors which increase the potential for severe consequences.
  An increase in the frequency and intensity of significant weather events are affecting pipeline integrity and the need for rapid assessment.

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- There are limited options to pipeline operators for direct measurement of buried pipeline locations. Currently only an In-Line Inspection (ILI) based Internal Mapping Unit (IMU) or Strain Gauges can provide this information accurately.

Traditional methods for assessing and monitoring pipelines susceptible to geohazards can be divided in 2 major categories:

Indirect Measurements:

- Survey Pins
- Slope Inclinometers
- Aerial Patrol (imagery/LiDAR)
- ROW Patrol (ground patrol, photos, etc.)

These methods can be very effective in providing data for monitoring geohazard locations; however, they all require integrity engineering teams to extrapolate surface observations and data to correlate them with movements of the underground pipeline. In many cases, it is preferable to have both indirect and direct data for accurate and timely decision-making.

Direct Measurements:

- ILI based IMU is the technology of reference for collecting accurate and complete data to support bending strain analysis within geohazard locations. ILI can be costly and disruptive to operations and in some cases is not applicable due to the configuration of the pipeline. ILI is also often difficult to schedule on short notice, and reporting periods can be prolonged.
- Strain Gauges provide a direct measurement of any changes in strain on the pipeline; however, they are discrete in coverage, require construction for installation and regular maintenance, and management to ensure they are correctly recording and transmitting data.
- Aerial-based magnetometry, such as that discussed in this paper, provides a non-intrusive option to collect data like ILI-based IMU without disrupting operations. This is an effective method to monitor locations of concern between ILI inspection cycles where instrumentation has not been installed. This technology also allows pipelines that are “unpiggable” due to geometry constraints to be monitored.

Testing: Drone-Based Magnetometry

Skipper NDT’s ARGOS is a multi-sensor payload comprising of the following components:

- Four fluxgate-type triaxial magnetometers for recording magnetic data in three spatial directions.
- Centimeter-precision GNSS.
- An IMU (accelerometer and gyroscope).
- A radar-based altimeter.
- A proprietary data logger to interpolate the various information recorded.

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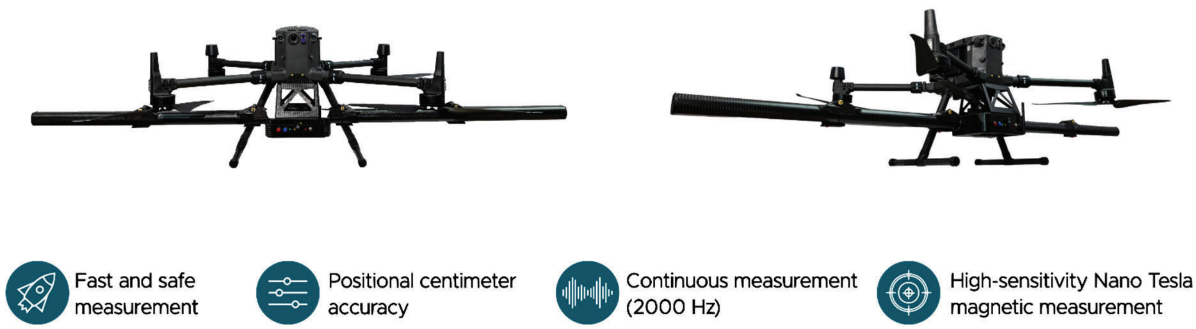

Figure 1: Drone-based technology mounted with the payload.

The system relies on two primary sensors: magnetometers and GNSS for the acquisition of magnetic data. Of these, the fluxgate magnetometers are particularly crucial, as they can measure the three components of the magnetic field at a sample frequency of 2000 Hz with a mass of 112 g/3.9 oz per sensor.

Skipper NDT utilizes a systematic multi-step process that has been designed to determine the 3D positioning of buried pipelines using magnetic-based data (**Error! Reference source not found.**).

The ARGOS payload is integrated into a commercially available Unmanned Autonomous Vehicle (UAV), also know as a drone. The drone flies a pre-programmed and automated flight path taking multiple passes over the pipeline to fully record the magnetic signal.

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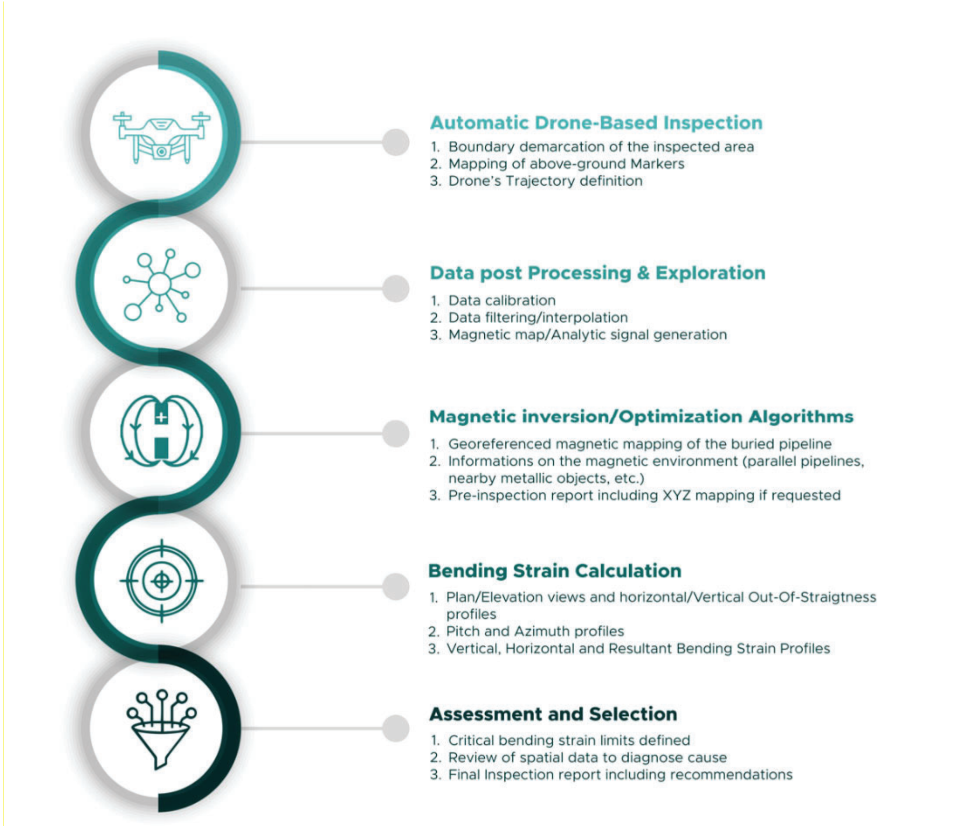

Figure 2: Multi-step procedure from magnetic data collection to assessment and selection.

After data is acquired, Skipper NDT utilizes a proprietary software to process the raw data and confirm its integrity. Skipper NDT patented algorithms will then perform a series of operations [1] to clean the data and perform the magnetic inversion allowing to retrieve a precise geospatial positioning of the asset. This data will then be utilized to perform out of straightness calculations, pitch and azimuth profiles, and to calculate bending strain in both the vertical and horizontal directions [2], as well as total resultant bending strain. More details of the inspection and data processing process can be found in a paper published at PPIM 2024, [3].

Historical field validation data

Skipper NDT's magnetometry-based technology and process has been validated through various programs in collaboration with major operators in Europe and North America. In France, GRTGaz has validated this technology through a series of tests across its pipeline network. The geospatial positioning performance of the technology has been tested for different use cases, including varying depths of cover, parallel pipelines, curved pipeline sections, and river crossings [4].

To further validate the data in reference to geohazard monitoring and strain calculation in the US, additional validations were undertaken. These additional efforts can be broken down into three phases:

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Phase One involved a controlled validation of the XYZ data for precision and accuracy. This test was undertaken by the Pipeline Research Council International, project PR-105-18391-R01, and took place at a Southwest Research Institute facility. This was performed on a 1600-foot section of 24" diameter pipeline. The test pipeline was inspected then surveyed at regular intervals using pot-hole excavations for validation of the inspection results. This step was independently verified for both inspection vectors, drone and cart. The conclusion of the study was as follows:

- Depth of Cover (Z) average accuracy: 3.4"
- Horizontal (XY) average accuracy: 5.5"
- Repeatability (precision): 3.3" STD
- Reproducibility: 1.7" STD

Results of this study can be found in [5] and [6].

Phase two involved testing and validation of a segment of pipe with cold bends. This verified the ability of the sensor to identify small changes in pipeline geometry as a proxy for ground movement. Two criteria were used to select the site for the trial:

- The presence of small cold bends, to simulate curvature changes resulting from permanent ground displacement and to test the lower detection limit of the Skipper NDT technology.
- Comparison data. The selected site had recent ILI-based IMU survey data so that the results of the two different technologies could be compared.

In collaboration with Enbridge, a 500-meter/1,640 foot-length, 24-inch diameter pipeline was selected that had a 2.5° horizontal cold bend.

The comparison revealed agreement within 0.05% between the two data sets, thereby instilling confidence in the accuracy and relevance of the Skipper NDT technology when identifying and quantifying geohazard threats on pipelines.

Details of this study were presented by Skipper NDT and Enbridge at the 2024 Pipeline Process Integrity Management conference [3]. The results indicated that Skipper NDT's Argos system, enables a curvature-based analysis to identify potential areas of concern in geohazard areas.

Phase Three is the focus of this paper. The intent of this activity was to evaluate the performance of magnetometry-based technology for monitoring pipeline integrity in the event of geohazard occurrences. The primary focus was on the accuracy of pipeline geospatial positioning for identifying and analyzing potential mechanical deformations and assessing the capability of the technology to detect areas impacted by geohazards.

To achieve this, Enbridge once again partnered with Skipper NDT to perform a real-world inspection of operational pipelines. Two sites were selected to encompass 2 different active geohazard locations. The aerial magnetometry-based technology was to collect the geospatial data and perform bending strain calculations. Those results were then to be compared to two previous data sets (from 2022 and 2023) that were acquired using ILI-based IMU tools for accuracy and precision. This activity is described in the following sections.

Comparative Assessment of Case Studies

In North America, where numerous sites are stuck by geohazards events impacting many pipeline sections, arial-based magnetometry technology is an effective and efficient mean to assess and monitor areas of concern. It can be deployed at discrete geohazard-susceptible locations, enhancing safety for

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both people and infrastructure with minimal operational disruption. The technology allows for quick mobilization and provides full coverage of the network, including" unpiggable" pipelines.

In additional to the logistical and operational efficiencies, the technology also creates direct financial benefits. Operators are finding that, for pipeline segments with limited geohazard sites to monitor (five or less), this technology is a more cost-effective solution than running additional ILI-based IMU tools between regulatory required inspections. Additionally, the speed of deployment makes this technology critical after weather events such as hurricanes, heavy rainfalls, land slides, earthquakes and floods.

To demonstrate that this technology can stand-in for ILI-based IMU data to determine movement and bending strain, two sites with active ground movements on Enbridge's network in East-Central Ohio were chosen for a pilot study. The sites have been selected based on the following criteria:

- Relatively free from overhead obstructions.
- Active geohazard sites with a potential pipeline impact.
- Available recent ILI-based IMU data to be used as a baseline.
- One site should include at least two pipelines on its ROW.

Figure 3: Inspected pipeline section at two sites and pictures of the Right-Of-Way (ROW)

The magnetic data collection took one day per site utilizing the ARGOS payload on two different vectors: an aerial drone and a ground-based cart. The ground-based cart was utilized in this pilot to demonstrate the capability of this deployment vector when there is not adequate space to fly the drone. The data collection utilizing the different vectors was done in parallel. A comparison between the data sets collected by the two vectors was conducted, yielding an average accuracy within 2.5 centimeters / 1.5 inches. To streamline the figures and enhance readability, only the arial-based dataset is presented in this paper.

The general results of the analysis are presented in the next section. Six-panel plots are highlighted for assessing the evaluation metrics defined as follows:

- Out-of-straightness: The deflection of the actual configuration of the pipeline compared to a fictive line that connects the start and end of the pipeline section. This metric allows the general trend of the shape of the pipeline to be evaluated.
- Pitch and azimuth: Captures the directional trend of the pipeline.
- Bending strain: Deformation values along the pipeline, resulting from curvature changes/ground displacement.

Site 1

At this site, the geolocation between the three datasets remains consistent. Regarding out-of-straightness, a deflection of approximately $1.3\,m/3\,feet$ over a $40\,m/131\,feet$ span at the beginning of the pipeline section was observed. Vertically, the pipeline appears intact, with no significant curvature changes resulting from ground movement. The curvature alterations are attributed to the presence of cold bends. A total of $220\,meters/721\,feet$ was inspected.

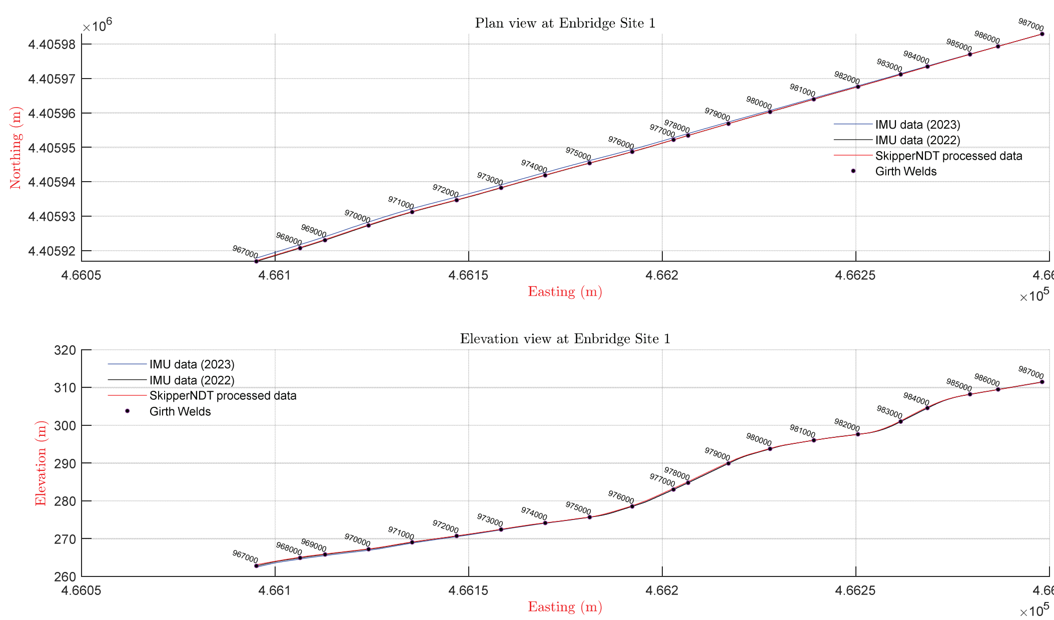

Figure 4: Plan and elevation views at Site 1.

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At this site, the azimuth profile revealed a $5°$ change in the pipeline orientation at the area impacted by ground movement.

The horizontal bending strain profile illustrates a strain change due to ground movement. This characteristic signature deformation is defined by low intensity 0.15% (compared to initial state) and occurs gradually over $50m/164\ feet$, corresponding to ground displacement signatures.

In the ILI-based IMU data, the pipeline remained stationary between 2022 and 2023, with all three datasets showing consistent strain levels in this area.

Regarding the vertical direction, despite magnetic-based technology not being designed to capture cold bends, we successfully detected 80% of those present on the line (8 out of 10). However, cold bend detection is outside the scope of this study.

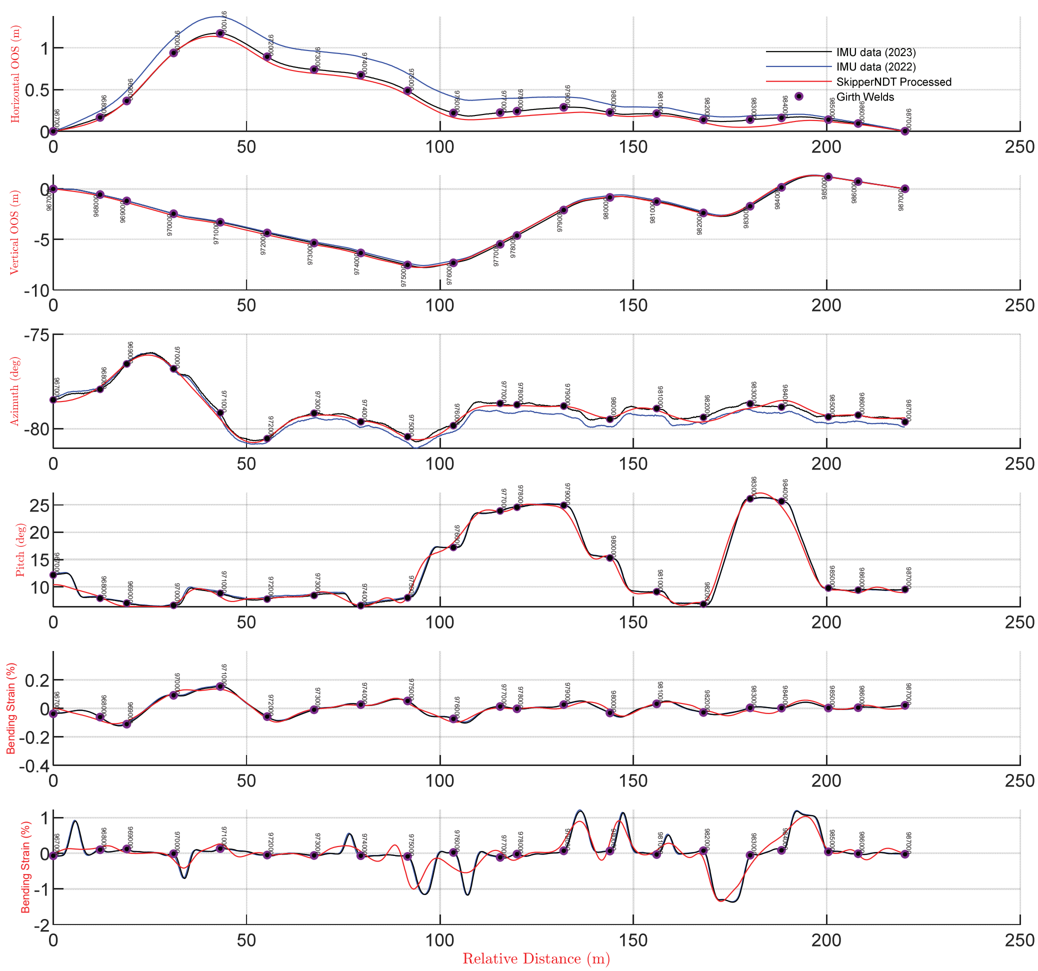

Figure 5: Top to bottom: a) Horizontal out-of-straightness profile, b) Vertical out-of-straightness profile, c) Azimuth profile, d) Pitch profile, e) Horizontal bending strain profile and f) Vertical bending strain profile at Site 1.

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Site 2

At this site, the overall trend of the pipeline is accurately represented using magnetic-based technology. In terms of out-of-straightness, the horizontal curve reveals two areas $(50 - 100m/164 - 328\ feet,\ 200 - 250m/656 - 820\ feet)$ potentially affected by ground displacement of respectively, $0.6m/1.9\ feet$, $0.9m/2.8\ feet$. This observation aligns with field observations and information provided by Enbridge. Vertically, aside from changes corresponding to cold bends, no curvature changes that could indicate ground displacement are observed. A total of $300m/984\ feet$ have been inspected.

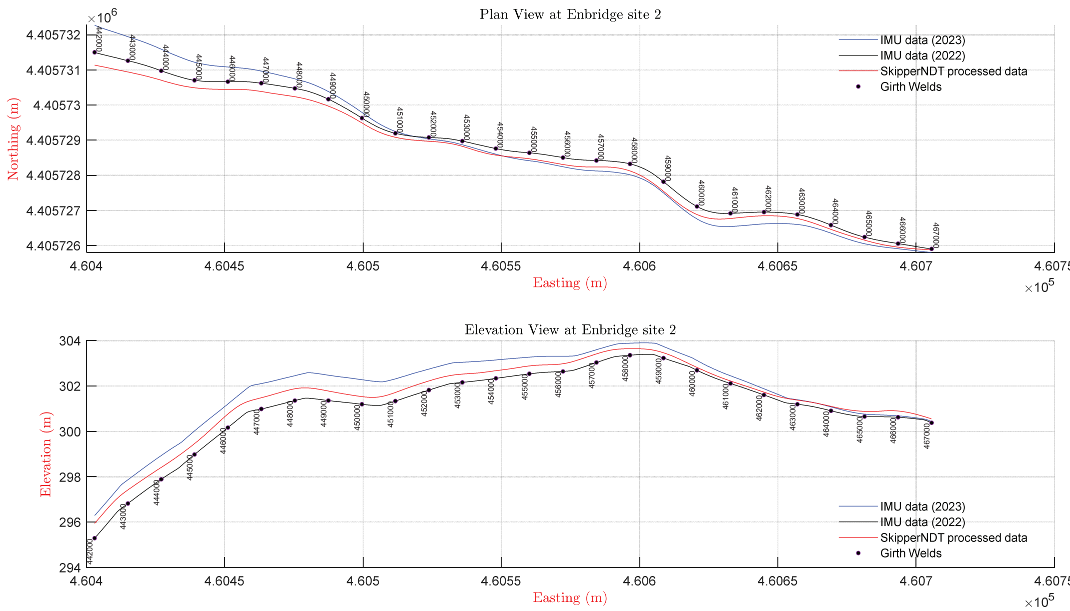

Figure 6: Plan and elevation views at Site 2.

At this site, the azimuth profile revealed $3°$ and $4°$ changes in the pipeline orientation at areas potentially impacted by ground movement.

For the strain profiles, the horizontal deformation reveals low-frequency signatures corresponding to pipeline movement at $130\ m/426\ feet$ and $200\ m/656\ feet$. Based on strain plots obtained with ILI-based IMU captured in 2023 and 2022, the pipeline did not move between the two passes. The magnetic-based technology found the same trends in its plots.

Regarding the vertical direction, despite magnetic-based technology not being designed to capture cold bends, we successfully detected 81% of those present on the line (9 out of 11). However, cold bend detection is outside the scope of this study.

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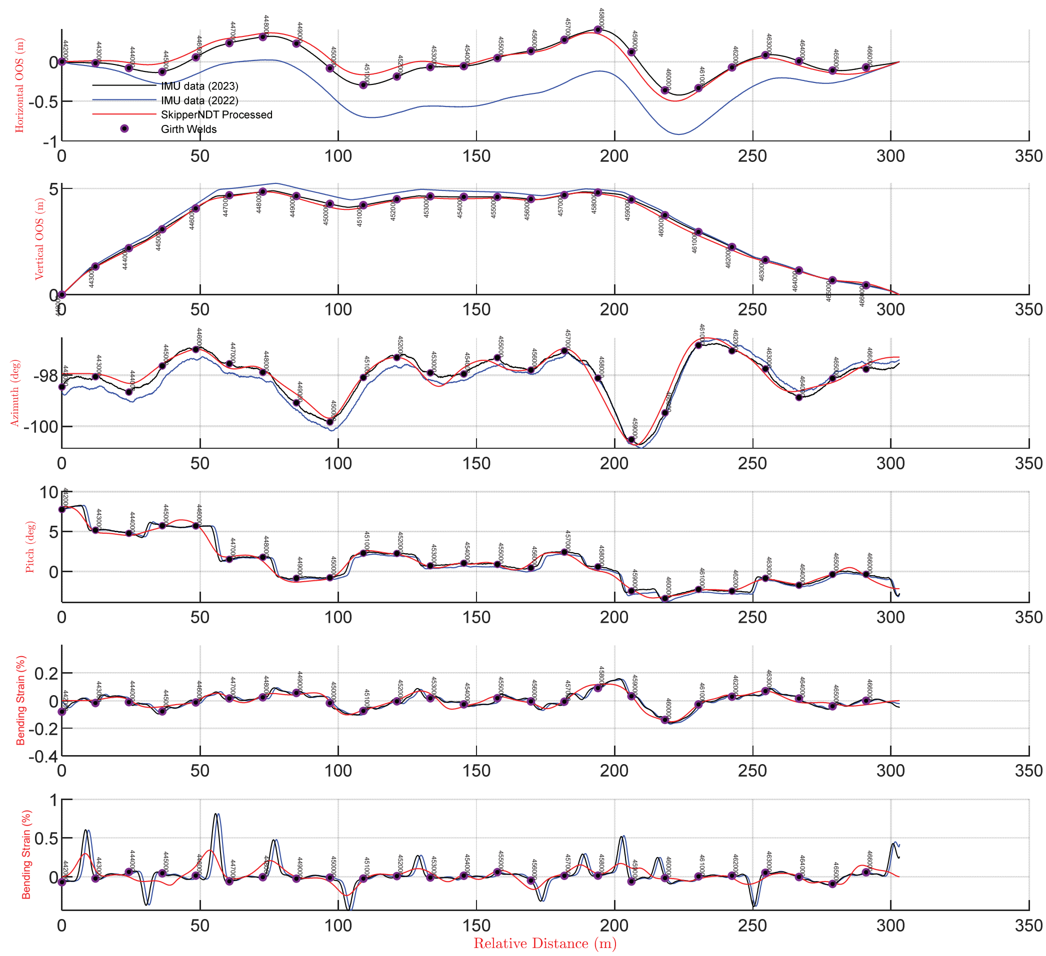

Figure 7: Top to bottom : a) Horizontal out-of-straightness profile, b) Vertical out-of-straightness profile, c) Azimuth profile, d) Pitch profile, e) Horizontal bending strain profile and f) Vertical bending strain profile at Site 2

Statistical Analysis on Horizontal Strain Profiles

A statistical analysis of the comparison between the strain profiles of the magnetic-based results and the 2023 ILI-based IMU data is presented in this section. To conduct this comparison properly, cold bend signatures need to be removed from the dataset since they do result from ground displacements. However, since horizontal strain profiles do not present cold bends, the analysis can be made. The median difference between the Skipper NDT data and the ILI-based IMU data is less than 0.02% with a standard deviation of only 0.019% for both sites. The linear regression reveals a highly correlated relationship between the two datasets, respectively a = 0.96 and 0.87 at Sites 1 and 2. This shows a strong correlation between the strain data calculated using a magnetic-based technology powered by Skipper NDT proprietary algorithms and the data calculated using an ILI- based IMU tool.

Site 1

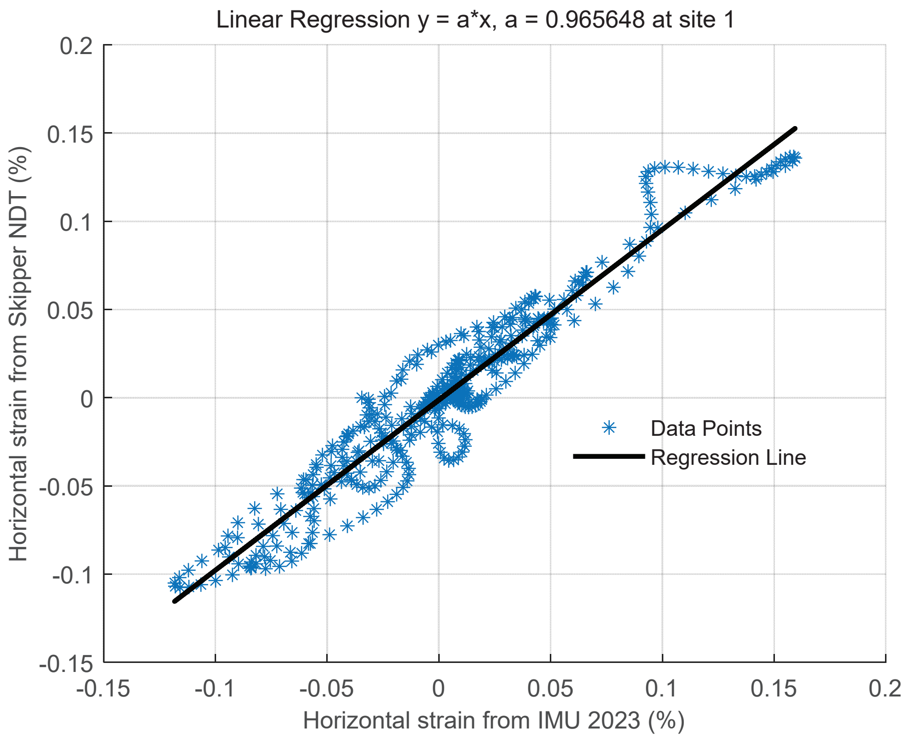

Figure 8: Linear regression between magnetic-based horizontal strain and IMU horizontal strain at Site 1.

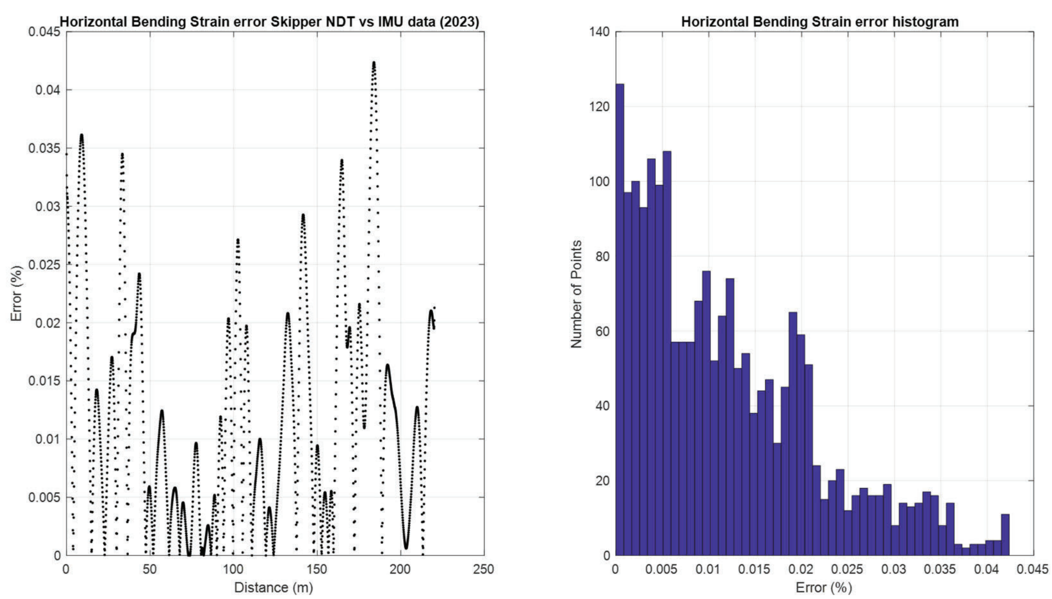

Figure 9: Horizontal bending strain error between magnetic-based and IMU 2023 at Site 1. Median = 0.00979%, STD =0.00958%

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Site 2

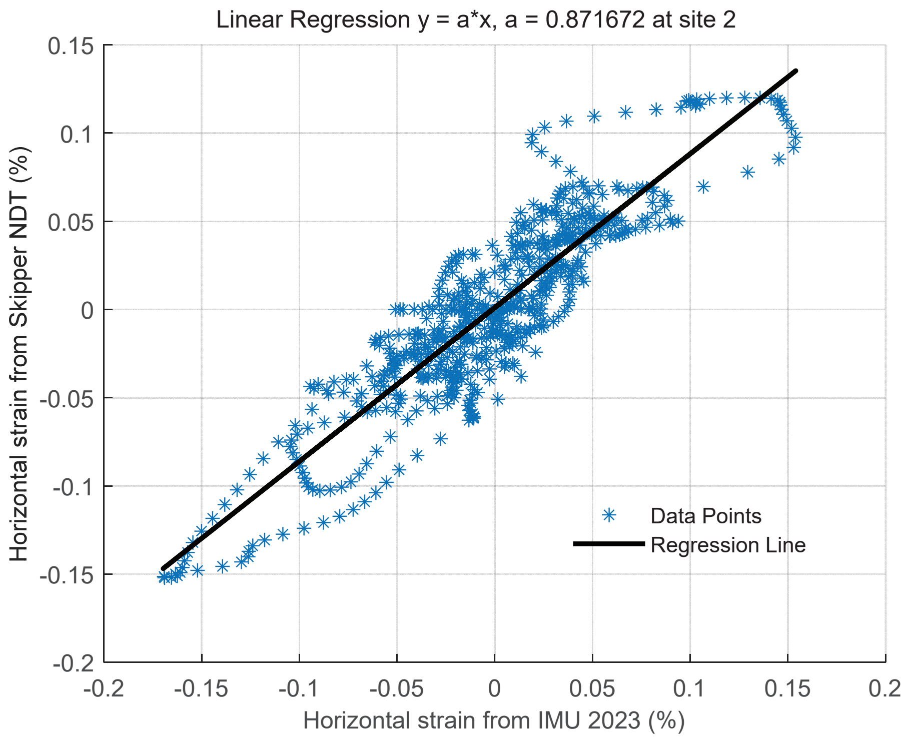

Figure 10: Linear regression between magnetic-based horizontal strain and IMU horizontal strain at Site 2.

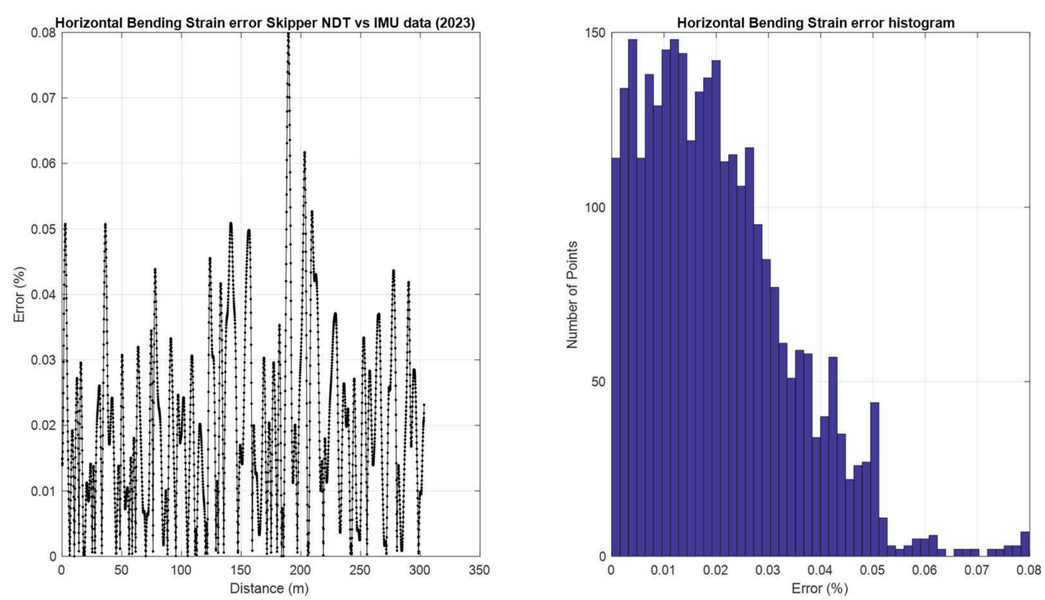

Figure 11: Horizontal bending strain error between magnetic-based and IMU 2023 at Site 2. Median = 0.0171%, STD = 0.0131%.

Conclusion

In collaboration with Enbridge, field trials were conducted to quantify the performance of magnetic-based technology for assessing pipeline movement in areas with active geohazard threats. The evaluation compared data from ILI-based IMU runs in 2023 and 2022 using three metrics:

1. Out-of-straightness
2. Pitch/azimuth
3. Bending strain profiles

Magnetic-based technology was used to assess pipeline movement in areas impacted by geohazards with a high degree of confidence.

The data obtained using magnetic-based technology was consistent with that obtained using ILI-based IMU. Statistical analysis of the differences between ILI-based IMU and magnetic-based technology showed less than 0.02% error in horizontal profiles. This confirms the reliability of the magnetic-based technology in supporting pipeline integrity programs and monitoring geohazard locations.

The magnetic-based technology offers safe, logistically simple deployment. The technology can be rapidly deployed after weather events (such as hurricanes, landslides, earthquakes, floods etc). It can be utilized on "unpiggable" pipelines, and targets only the areas of interest/ concern. For pipeline segments that have finite areas of interest (up to approximately five locations identified), it can be a more cost-effective solution compared to running additional ILI-based IMU tools.

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