Novel Non-Contact, Drone-Based technology for Pipeline Movement Assessment

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1 ABSTRACT

Buried pipelines are critical for infrastructure transporting large amounts of oil and gas products across long distance. Several integrity threats need to be monitored to avoid incidents amongst which geohazard events responsible for at least 16% of failures over the last 10 years*. Geohazards result in permanent ground displacements, which may cause axial and/or lateral deformations that induce bending strains in these structures, leading to catastrophic consequences. To address this issue, Skipper NDT has developed a proprietary embedded system mounted on a drone, with the aim 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. To validate the effectiveness of the technology, a series of tests were conducted in coordination with a North American pipeline operator. The results of the drone-based technology runs were compared against those obtained with an Inline Inspection tool. The comparison showed good agreement in the trends detected in terms of bending strain profiles.

2 INTRODUCTION

Based on its R&D experience, Skipper NDT decided in 2019 to address pipeline geolocation and strain assessment using UAS. This effort has provided a 2.2-kg and a 160-cm/5,2 feet wide embedded system that can be easily mounted on any UAS (**Figure 1**: The embedded system, mounted on an off-the-shelf UAS (DJI M300).). The main components of the system are:

- Four three-components fluxgate magnetometers
- Real-time Global Navigation Satellite System GNSS receiver with a centimetric-level accuracy
- Tactical grade inertial measurement unit (IMU)
- Telemetric sensors measuring the distance between the magnetometers and the ground (or canopy)
- Proprietary electronic card for data acquisition, digitalization, and synchronization

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 1000 Hz with a mass of 112 g per sensor.

In comparison to scalar magnetometers, fluxgate magnetometers possess sensors that are overall lighter and more resilient, with a sampling frequency that is ten to a hundred times higher, making them more suited to the constraints of UAS.

One notable advantage of fluxgate sensors is that they can capture the 3-D components of the magnetic field, making it possible to compensate for the magnetic effect of the embedded equipment and UAS. As a result, the system can be adapted to different vectors without the need for custom characterization.

However, it is important to note that these fluxgate magnetometers are not absolute instruments and may contain errors related to offsets, sensitivity, and angle (non-orthogonality), which is compensated for through a proprietary calibration protocol.

Figure 1: The embedded system, mounted on an off-the-shelf UAS (DJI M300).

Within the scope of our work, it is essential for GNSS hardware to satisfy stringent requirements with respect to both accuracy and weight. Although lightweight GNSS hardware is commonplace in UAS applications, we opted to use a 606-g receiver and antenna system that offers greater technical capabilities.

Moreover, the system is composed of various components that primarily serve a corrective function. Due to the unique demands imposed by airborne systems as compared to ground-based systems, these corrections are essential. To mitigate any heading misalignments with the route, IMU is utilized to perform level control, which corrects the navigation system.

The remote sensors, which incorporate both ultrasonic and Lidar measurements, are used to calculate the distance from the magnetometers to the ground or canopy, enabling the system to precisely infer the depth of the pipeline below the ground surface.

3 3D-Localization

Skipper NDT has developed an automatic multi-step procedure to derive position profiles of buried pipelines. The first step involves an automatic drone-based inspection that includes boundary demarcation of the inspected area and definition of the drone’s trajectory (Figure 2).

This step enables the collection of data from hard-to-reach or hazardous areas and ensures that the inspection is carried out efficiently and safely. The second step involves data post-processing and exploration, which includes data calibration to reduce noise, and terminates with magnetic map generation (Figure 2).

This step ensures that the collected data is accurate and reliable, and the magnetic map provides a comprehensive overview of the pipeline's environment. The third point involves magnetic inversion to derive the XYZ position and depth of cover of the pipeline.

The typical data spacing is 0.5m/1,6 feet since it is not necessary for most operators to have a higher definition of their pipeline trajectory for positioning purposes. This data spacing can be reduced to 0.05 m/0,2 in without interpolation. This provides clients with the precise location of the pipeline. For the case study presented in the present article, the data spacing is equal to 0.06 m/0,23 in to match IMU data spacing.

The pre-inspection report is made available on an online platform, allowing for easy and secure access to the pipeline's position profiles. Figure 2 illustrates a simple localization exercise carried out in coordination with GRTGaz (French incumbent gas operator) on a buried pipeline.

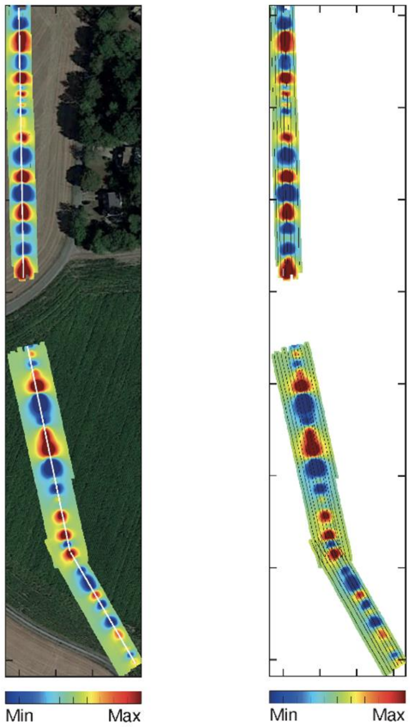

Figure 2: An inspected area and the drone's trajectory definition (left), corresponding analytic signal (right).

The data goes through several processing steps: First, the magnetic map is determined. An optimization problem is then solved to find XYZ values. Once XYZ values are obtained, the Ramer-Douglas-Peucker algorithm is applied to separate the result to a set of polylines. Then a linear regression filter is applied to a typical window length along each section of polylines. Further details regarding the inversion algorithms and validation studies can be found in the references provided [2] and [3].

This article specifically focuses on using the pipeline location data to calculate bending strain profiles and investigate pipeline movements. The following section will outline the general steps followed to develop the horizontal and vertical bending strain profiles using XYZ position profiles, prior to presenting the case study and validation test.

4 BENDING STRAIN CALCULATION

Typically, when the pipe material is within its elastic deformation range, the bending strain corresponds to the curvature of the pipeline in a proportional manner. Consequently, by using the position information of the centerline, the curvature of the pipeline can be accurately determined, allowing for the calculation of the pipeline bending strain. The following expression can be used to describe the pipeline bending strain:

$$\varepsilon = \frac{\kappa D}{2} \tag{1}$$

Where ε is the pipeline bending strain, κ is the curvature, and D is the pipeline diameter. The total curvature of the pipe centerline path is described at each point along the pipeline by the curvature vector κ.

To calculate the pipeline curvature, the centerline profile of a pipeline (data obtained with magnetic inversion) is considered as a 3D parametric curve described in a Cartesian system by a vector $\Gamma(s)$, which is a function of a curvilinear coordinate s along the pipeline.

$$\Gamma(s) = [X(s), Y(s), Z(s)] \tag{2}$$

Assuming the vector t is a tangent vector to a point M of the trajectory, we can conclude that the tangent vector t and the curvature vector at point M are:

$$\begin{cases} \boldsymbol{t}(M) = \left.\dfrac{d\boldsymbol{\Gamma}}{ds}\right|_M \\ \boldsymbol{\kappa}(M) = \left.\dfrac{d\boldsymbol{t}}{ds}\right|_M \end{cases} \tag{3}$$

As detailed in Reference [4], the vertical and horizontal curvatures can be described as follows:

$$\kappa_v = -\frac{1}{\sqrt{1 - \left({dZ}/{ds}\right)^2}} \left({d^2Z}/{ds^2}\right) \tag{5}$$

$$\kappa_h = -\frac{1}{\sqrt{1 - \left({dZ}/{ds}\right)^2}} \left\{\left({dY}/{ds}\right)\left({d^2X}/{ds^2}\right) - \left({dX}/{ds}\right)\left({d^2Y}/{ds^2}\right)\right\} \tag{6}$$

Once curvatures are derived, bending strains can be calculated as

$$\varepsilon_v = \kappa_v \frac{D}{2} \times 100\% \tag{7}$$

$$\varepsilon_h = \kappa_h \frac{D}{2} \times 100\% \tag{8}$$

Where, ε_v is vertical bending strain, ε_h is horizontal bending strain, and D the pipe outer-diameter.

From the above equations, it can be seen that the pipeline bending strain is calculated using the trajectory of centerline path, which can be obtained from the drone-based tool.

As a preliminary test of our ability to detect bends due to permanent ground movements, we collaborated with Enbridge and selected a site that contained a small cold bend, which could approximately simulate certain aspects of the behavior of a pipeline subject to permanent ground displacement.

The following section presents a case study and a comparison of the results obtained using our drone-based tool against those obtained with an IMU survey tool.

5 CASE STUDY

Our technology has a primary application of detecting pipeline bending signatures caused by landslides before they pose a significant threat to pipeline integrity.

To achieve this, site selection was conducted in collaboration with a North American pipeline operator, using two primary criteria. The first criterion was that the site should contain a small cold bend that can simulate aspects of the curvature changes resulting from permanent ground displacement.

The second criterion focused on selecting sites for which IMU survey data was available for comparison. Ultimately, a 500-meter / 1’640 feet length, 24-inch pipeline (Figure 3) was selected that had a 2.5° horizontal cold bend. describes the inspected area where, red polygon corresponds to limits of the inspection area. White lines correspond to the trajectory followed by the drone during this mission.

Figure 3 : The inspection area.

In this inspection, the drone-based technology was used to collect data on the pipeline’s magnetic map. The average magnetic map dimension was 590-by-5 meters / 1’935-by-16 feet by 7 profiles.

The drone flew at an average height of 2 meters / 6.5 feet, with an average flying speed of 6,5-km/4 miles per hour. The acquisition time for the inspection was 45 minutes.

Once the field data acquisition was completed, the collected magnetic signals were calibrated and filtered to remove any noise or interference. Then, the data need to be interpolated to fill in any gaps or missing data points. Finally, the processed data can be used to create magnetic maps to be inverted (Figure 4) for low- and high-frequency. Based on the magnetic map (low frequency) illustrated in Figure 4, two conclusions can be drawn: First, there is a noticeable intensification of the magnetic spots in the area corresponding to a cold bends in the pipeline.

These bends generally cause the magnetic field in the area to be amplified, leading to a more pronounced magnetic signature on the map. Secondly, an unusual magnetic spot is localized near the end of the surveyed section of the pipeline, which corresponds to a sudden change in curvature. This location corresponds to an intentional cold overbend-sagbend sequence.

Figure 4: Total magnetic field overlay image of the inspected area: low frequency map (left) high frequency map (right).

To visualize subtle changes in the centerline of the pipeline, we utilize out-of-straightness (OOS) profiles, which are defined as the horizontal and vertical deviation from a straight line connecting the start and end points. This metric is particularly useful in analyzing small pipeline deflections and can be a reliable indicator of potential ground movement signatures.

To provide a comparative analysis of the OOS profiles generated by our drone-based tool, we have also included IMU data provided by the operator and obtained through a previous in-line inspection.

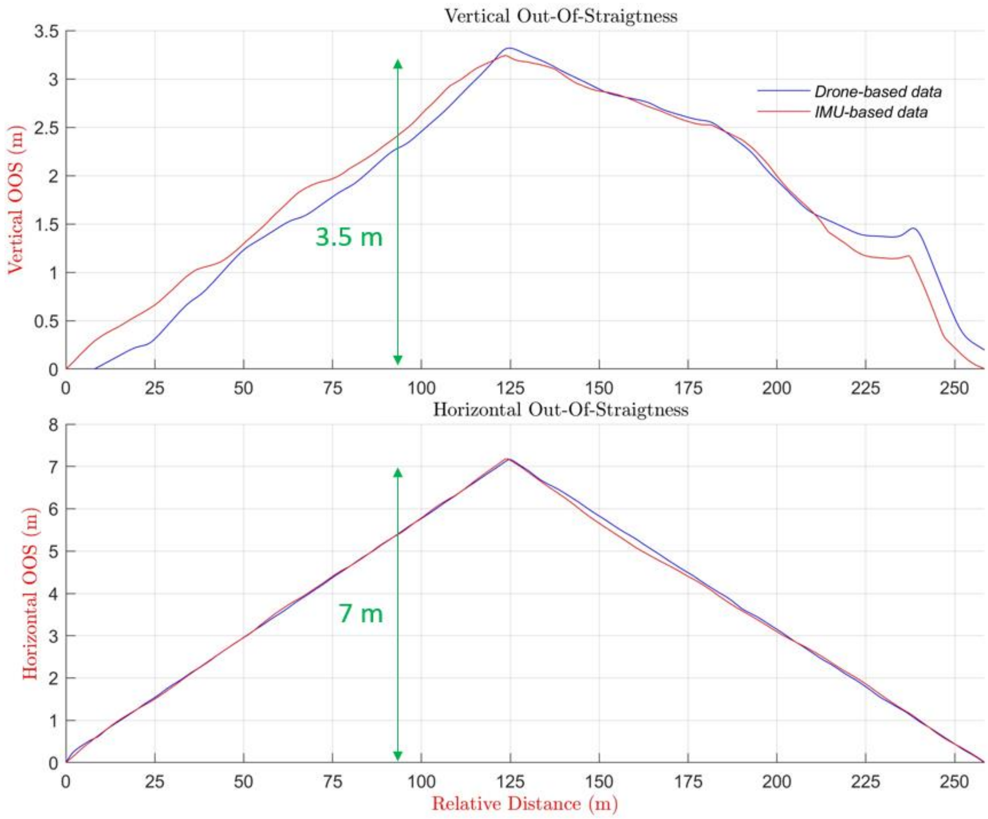

Figure 5: Comparison of OOS profiles from drone/IMU-based tools.

Before developing bending strain profiles, it is necessary to evaluate the orientation profile deviation along the pipeline. One way to do this is by analyzing the azimuth/pitch orientation profiles. The azimuth/pitch profiles capture the directional trend of the pipeline, which can be readily compared to those provided by IMU survey data.

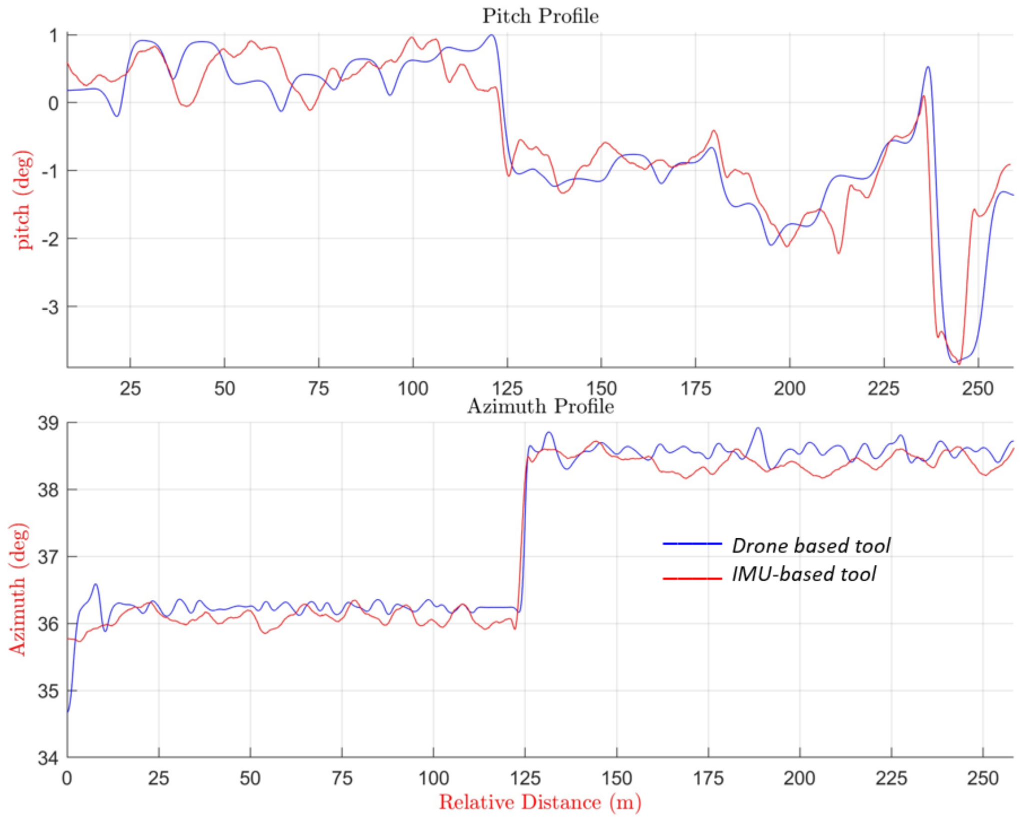

Figure 6: Comparison of pitch and azimuth profiles from drone/imu based tools.

There is a reasonably good agreement between the two datasets (Figure 6), indicating that our drone-based technology was able to accurately capture the orientation change trends. Furthermore, the comparison revealed a 2.5° change in the pipeline orientation, which was well-captured by our technology.

Once the location data is at hand, we develop the vertical/horizontal out-of-straightness using procedures developed [6].

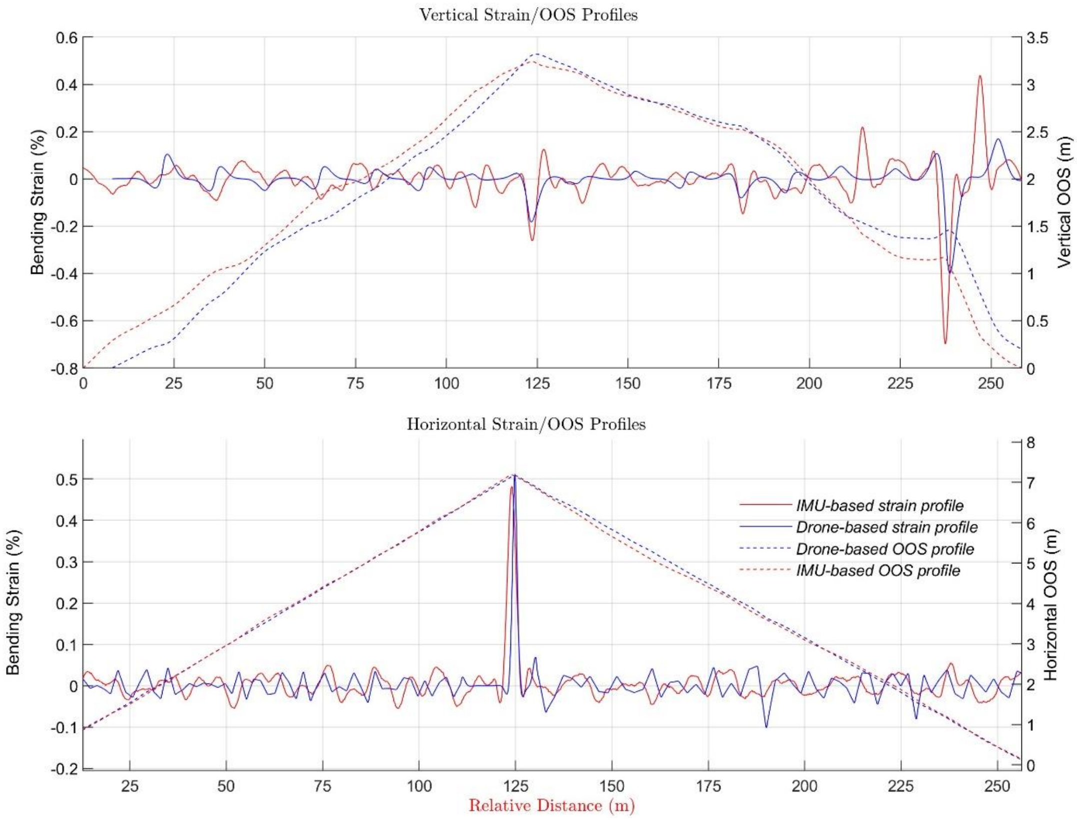

Figure 7: Comparison of bending strain and OOS profiles from drone/imu based tools showing cold bend locations.

In

Figure 7, the blue curve obtained from the drone-based approach was compared with the results (red curve) of an inline inspection to evaluate the changes in orientation and bending strain.

With respect to the horizontal view (bottom), the cold bend located at 125 m/410 feet is distinctly identified and captured. Elsewhere, in the straight parts, the noise has been minimized using a modified linear regression filter. Concerning the vertical out-of-straightness (top), there is a sudden curvature change near the end of the surveyed section of the pipeline which corresponds to a strain peak that is well-identified using both technologies. It is worth noting that we have missed/underestimated some peaks at both 210 m/689 feet and 235 m/771 feet.

The primary reason for this inaccuracy is the less precise GNSS positioning in the Z (vertical) axis, which could be improved on our part through the implementation of Post Processed Kinematic (PPK) corrections using a permanent base to enhance positioning [7]. Finally, the comparison revealed a reasonably satisfactory level of agreement between the two sets of data, thereby instilling confidence in the accuracy of our approach.

The preliminary test, conducted in coordination with Enbridge, demonstrated the efficiency of our technology in performing bending strain analysis, especially in the horizontal direction. This result is a promising indication of the potential of our technology in the pipeline industry. However, it is important to note that this is a single instance and, therefore, further data and testing are necessary to provide a more comprehensive assessment of our technology's capabilities for bending strain evaluation.

Rigorous testing and evaluation will enable us to quantify our performance metrics and validate the reliability of our approach. However, we must continue to refine and improve our approach through additional testing and evaluation to ensure the accuracy and reliability of our methodology.

6 BENDING STRAIN ASSESSMENT

The results presented above indicate that the contactless drone-based magnetic technology enables a preliminary curvature-based analysis to identify potential zones of distress/failure. This can be highly advantageous for operators in several ways:

- Firstly, the use of this technology is rapid, meaning that the process of identifying potential failure zones can be completed quickly. This is especially useful when time is of the essence, and immediate action needs to be taken. This will enable operators to take necessary remedial actions to ensure the safety of pipeline operations and comply with regulatory requirements.
- Secondly, the technology can be deployed in difficult-to-reach areas, which may not be easily accessible by conventional inspection methods.
- Finally, one of the major advantages of using a drone-based tool is that it can be designed to operate without the need for human intervention. Reducing the risk of human error and improving personnel safety.

Hence, the multi-step procedure described in Section 2.1 can be complemented with two additional steps (Figure 8) to assess pipeline movements and bending strain profiles for geohazard management purposes.

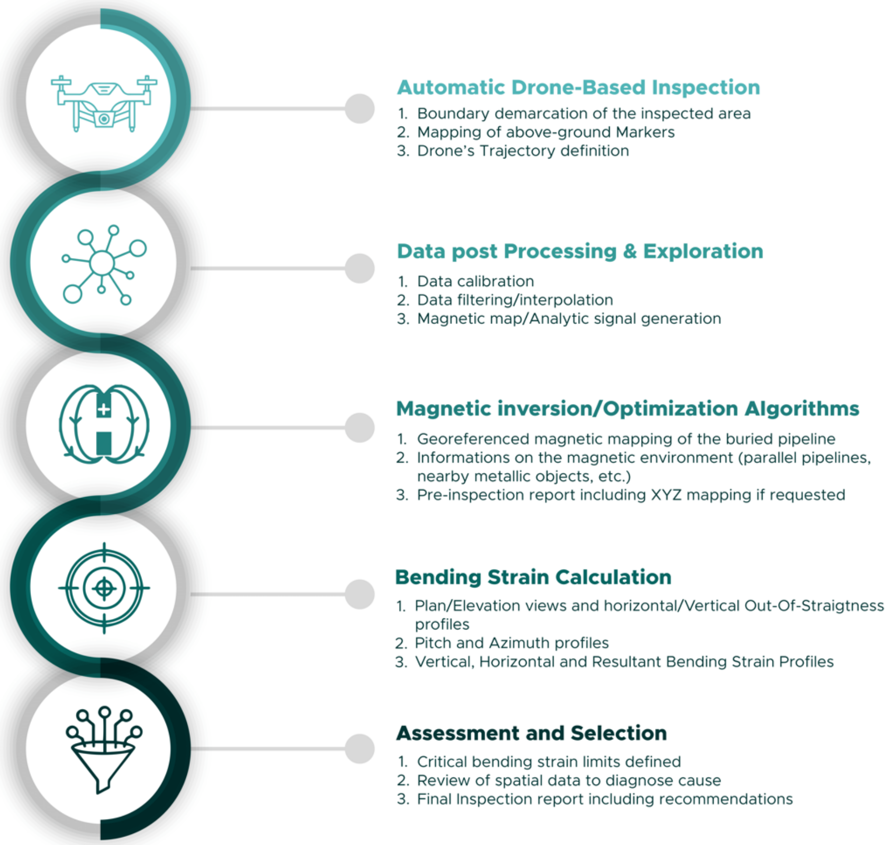

Figure 8: multi-step procedure for pipeline integrity management.

These last two steps consist of developing vertical and horizontal pipe curvature/bending strain profiles. This provides a more detailed analysis of the pipeline's condition and helps identify areas of concern.

The assessment and selection step focuses on the assessment and prioritization of the zones where strain limits are exceeded. This ensures that the client has a comprehensive understanding of the pipeline's integrity, and any potential issues are identified and addressed promptly.

This five-step process can be declined in various ways to address a broad range of remote services listed (Figure 9). These services can help ensure the safety of buried pipelines, reduce downtime and maintenance costs.

Figure 9: Remote services proposals.

7 PERSPECTIVES

The method presented in this study demonstrates promising results in terms of positioning and out-of-straightness assessment when compared to the "gold standard" (IMU). After applying an adapted filter to the signal, the strain profiles for both horizontal and vertical strains on the Enbridge use case reasonably match the IMU based curves.

This technology is designed to be a screening tool that provides a rapid response in landslide or other geohazard situations. The signature geometry of real-life landslides is less abrupt in XY and Z than the sharp cold bends considered in this use case [8].

Consequently, the drone-based magnetic inspection results will likely be much better for the end use application. Ideally drone surveys can distinguish between ground movement signatures and intentional bend (cold bends, induction bends, elbows) signatures [9].

In addition to serving as a validation tool, the technology can also be used in between two ILI runs. When IMU deployment is time consuming and logistically challenging the Skipper NDT technology can help fill the gap by providing clients with quick and reliable data on the condition of their pipelines with direct overlay comparisons with the most recent previous IMU survey. This enables them to stay up to date with the status of their pipelines, even when a full IMU inspection is not possible.

Finally, to enhance the competitiveness of the Skipper NDT technology in the market, it is imperative that we address several key factors in a coordinated effort, ideally in collaboration with a prominent industry leader. Among the measures that ought to be implemented to capitalize on the favorable outcomes achieved:

Confirm the solid results obtained by comparing our bending strain results at known geohazard sites against recent IMU data. This will enable us to establish the relative accuracy of the strain estimation. Ideally this would be done with 5 to 10 locations in varying conditions to understand how certain variables can affect our accuracy of strain estimation.
Refine the filtering to find the best parameters if a unique set exists. If not, find a method to adapt the filtering to each case.

Enhance the vertical strain estimation by improving the vertical positioning. This issue is most certainly due to GNSS capabilities that are typically better in XY positioning and it can be addressed by using GNSS corrections like PPK.

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