3D-LOCALISATION AND MAGNETIC MAPPING OF BURIED PIPELINES USING UNMANNED AERIAL SYSTEM (UAS)

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ABSTRACT

Pipeline incidents related to third-party work around the world reached a peak last year. About 30% of reported incidents were due to poor pipeline geolocalisation (DIRT Report 2019). The integrity of pipeline networks is also at risk due to increased encroachment because of urbanization. As a result, some governments enforce stringent rules on pipeline operators concerning their network georeferencing. The currently available tools, which use electromagnetic or ground-penetrating radar technologies, are handheld and particularly challenged in remote rural locations, where constraints are related to the safety of field operators, specific soil and culture conditions, potential human errors in data interpretation, and time consumption (authorization, accessibility).

UAS are often deployed in difficult-to-access locations as they present significant operational advantages in terms of operators' safety, speed of execution, cost-efficiency, and access to impracticable terrains. Currently available technologies focus on above-ground measurements through various methods, such as thermal and hyperspectral imaging or Lidar. Skipper NDT has developed a proprietary embedded system and acquisition protocol that combines the advantages of a drone vector and high precision magnetometry. The technology allows Skipper NDT to provide information about the magnetic underground environment of the pipeline as well as an accurate and continuous 3D-localisation (longitude, latitude, and depth of cover).

An extensive series of field trials were conducted in France. Europe's leading gas pipeline operator, GRTgaz, qualified the georeferencing performances of the technology in the highest precision category (Class A, according to the French regulation), under various operational conditions.

I. INTRODUCTION

Buried pipelines have been used for many years and will continue to be used for many years to transport oil, gas, and water. Addressing the challenge of third-party damage to this critical infrastructure is a pressing issue for operators and regulators. Some countries have started to enforce stringent legal requirements. In France, a government decree mandates operators to map critical pipelines, at least at 40 cm precision, both in planimetry (X, Y) and in altimetry (Z) for 90% of the measured points. It corresponds to the class A precision detailed in the *NF S70-003* AFNOR standard.

Geolocalisation of pipelines can be achieved using different technologies on an open or closed ditch. The focus here is on geolocalisation of pipelines on closed ditch which is traditionally and mainly done using electromagnetic field (EMF) with handheld receivers (1–4) and ground-penetrating radar (GPR) techniques. Operationally, these measurements require an operator carrying or pushing the measuring device along the right-of-way (ROW).

Based on the previous research of Laichoubi et al. (5) involving acquisition and processing of magnetic maps as a method for pipeline 3D-geolocalisation, it has been proposed that recording the magnetic field components along with geopositioning data on a pipeline ROW allows determining its horizontal location and the depth below ground with a precision level corresponding to the class A requirements. In recent years, technological advances have been made in the integration of remote sensing and magnetic measurement systems for unmanned aerial systems (UAS), which makes it possible to perform a survey without involving operators on the ROW.

In this paper, we illustrate several trials conducted jointly with GRTgaz (France) in 2021. In order to demonstrate this proof of concept study, 8 pipeline locations with different diameters ranging from 3 to 48 inches (80 to 1200 mm) were selected by GRTgaz. It took 5 hours of cumulative flight time for a 2.7 km inspected distance. Table 1 illustrates the performance of this innovation and the accuracy of georeferencing in class A.

Our analysis and methodology are illustrated on an 8-inch (200 mm) diameter pipeline with: i-total magnetic intensity maps, ii- comparison between this detection versus a land surveyor reference, as well as iii- the error histograms in planimetry and depth.

II. MATERIALS AND METHODS

The hardware developed by the Skipper NDT team consists of a 4.2 Kg and a 90 cm wide embedded system that can be mounted under a UAS (Figure 1). The main components of the device are: 1) 5 three-components fluxgate magnetometers; 2) a real-time global navigation satellite system GNSS receiver with a centimetric-level precision; 3) a Tactical grade Inertial Measurement Unit (IMU); 4) a remote sensor measuring the distance between the magnetometers and the ground (or canopy) and 5) a proprietary electronic card for data acquisition, digitalization, and synchronization.

Figure 1. Skipper NDT's embedded system mounted under an off-the-shelf UAS.

The main sensors in this system are the magnetometers and the GNSS, upon which the acquisition of the magnetic map depends. The fluxgate magnetometers measure the three components of the magnetic field at a 1000 Hz sample frequency for 112 g mass per unit. Compared to scalar magnetometers, fluxgate magnetometers are more suited to UAS constraints with overall lighter, more robust sensors with a ten to hundred times higher sampling frequency. Even if the fluxgate magnetometer suffers a lower resolution/ precision, it is sufficient for the nanoTesla to microTesla range of magnitude that is required. The other point to be considered is that, compared to scalar magnetometers, fluxgate magnetometers are used to measure the components of the magnetic field, allowing compensation of the magnetic effect of the embedded equipment and UAS. Thus, the system can be adapted to different vectors without any custom characterization. This subject is not new and was developed in the 1970s for magnetic compensation of airplanes in airborne geophysics (6,7). On the other hand, because fluxgate magnetometers are not absolute instruments with inherent errors of offset, sensitivity, and angle (non-orthogonality), they must be calibrated.

In our context, GNSS hardware needs to face stringent precision and weight constraints. Whereas lightweight GNSS hardware is commonly used for UAS applications, we chose a 606g receiver and antenna system offering more technical capabilities. Multi-frequency and multi-GNSS hardware is used for real-time precise point positioning (PPP) correction services. The corrections ensure positioning accuracies down to ± 4 cm at 95% root-mean-square worldwide (between –75° and + 75° latitude). This precision can be reached without deploying a base station on the field and without the need for an internet connection, facilitating operations and logistics.

Other components of the Skipper NDT system serve mainly a corrective purpose. Indeed, contrary to ground-based systems, flying equipment requires supplementary corrections. The IMU is used to perform level control to correct the navigation in case of heading misalignment with the route. The level control can also be used for the change of reference frame for the measured magnetic components (8). The remote sensor combines measurements from ultrasonic and Lidar to evaluate the distance from the magnetometers and the ground or canopy and then infer the depth of the pipeline below ground.

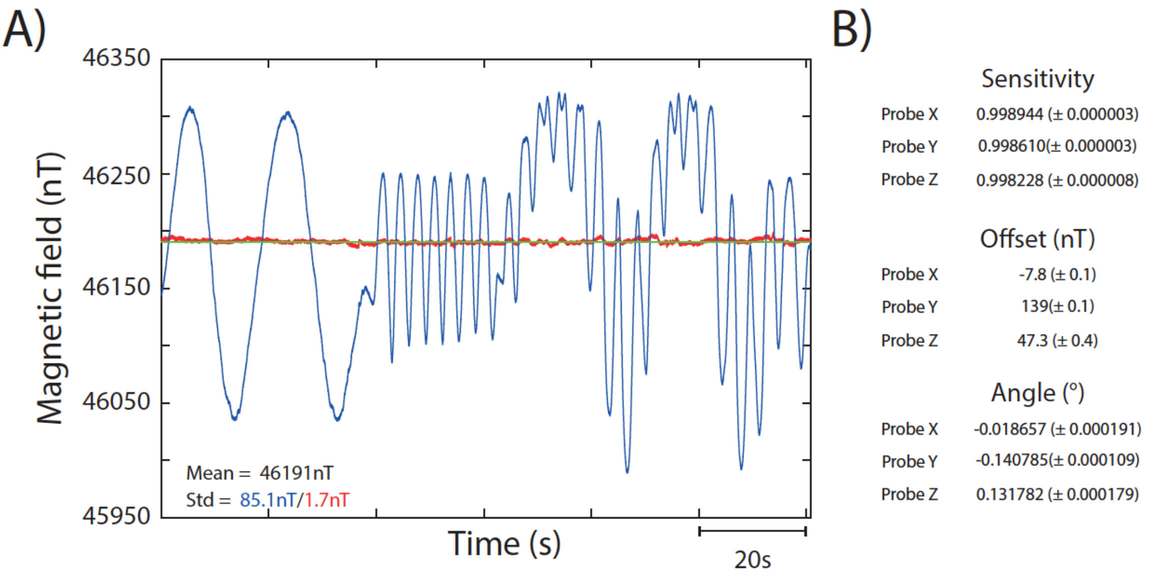
III. CASE STUDY AND OPERATING PROCEDURE

Obtaining the total magnetic intensity map follows a 4-step protocol, described in the following paragraphs, on a real case study on the ROW of a GRTgaz buried pipeline. Parallel magnetic profiles are acquired on an 8-inch diameter gas pipeline over 400 m. The data are processed as follows to obtain the total magnetic intensity map: 1) calibration parameters are used to calibrate the data, as shown by Munschy et al. (9), where both calibration and compensation are applied using the same kind of function (Figure 2); 2) the start and end of each profile is identified; 3) the data are edited to check for spikes; 4) the total magnetic intensity map is computed by interpolation of data profiles. More often the node spacing of the magnetic map is 0.2 m. The total magnetic intensity map and related analytic signal are then used to locate the pipeline by computing its horizontal location and depth below the ground.

The magnetic map shown in Figure 3A was obtained using the UAS-embedded magnetic device described above. This map results from the acquisition of 7 to 10 profiles per flight, spaced by 1.5 m, over 3 flights, with the five sensors 2 m above ground level for each flight. The map mainly shows the alignment of magnetic anomalies due to the pipe sections with an amplitude of about 3000 nT. The spatial derivatives of the magnetic map are computed and used to determine the analytic signal in Figure 3B.

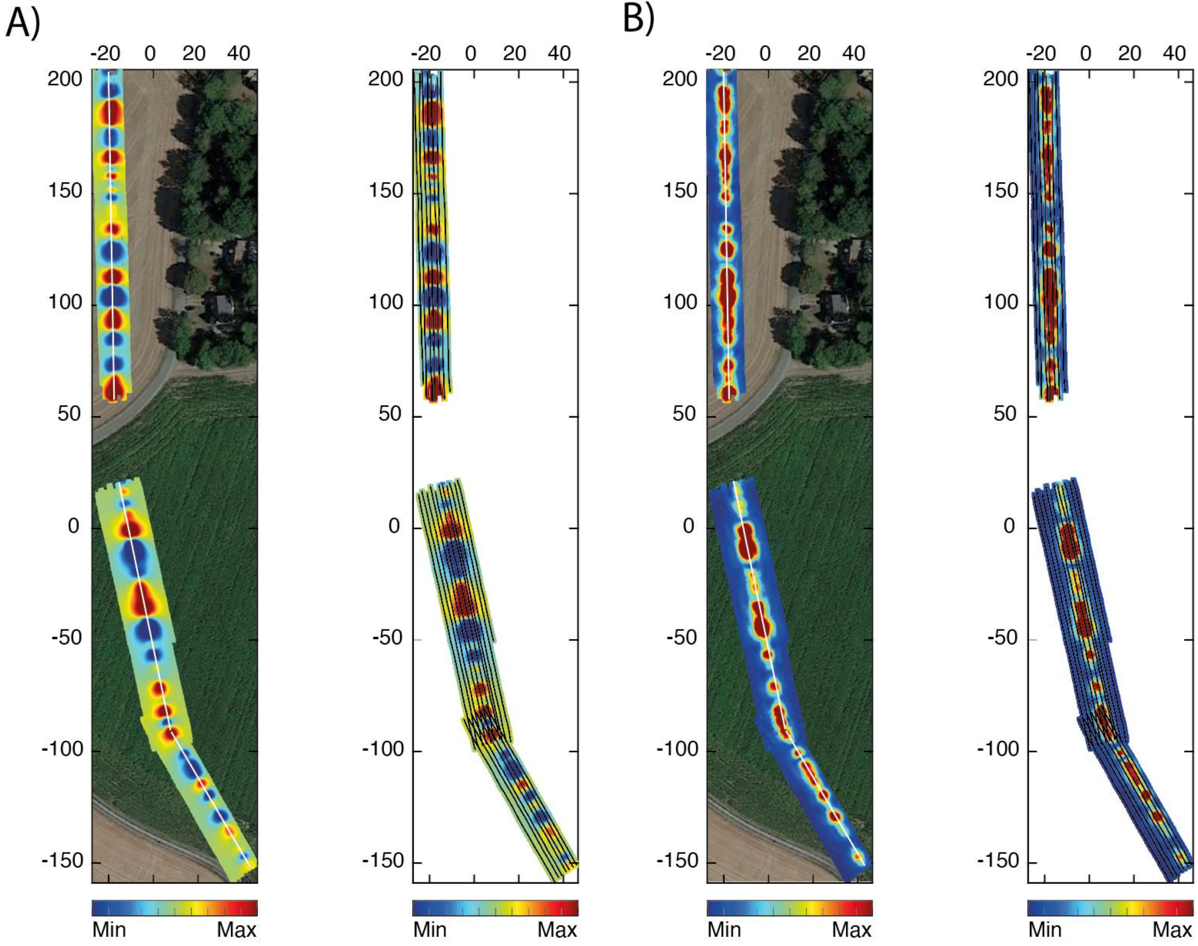
Profiles orthogonal to the pipeline direction are extracted from the magnetic maps using the full 500Hz exploitable magnetic spectrum to determine the horizontal position and depth under the ground of the considered line (5).

Figure 2. Example of calibration results for one of the five magnetic sensors. A) the two curves correspond to the noncalibrated (blue line, standard deviation 85.1 nT) and calibrated (red line, standard deviation 1.7 nT) intensities of the magnetic field measured by the fluxgate sensor. The green curve is the intensity of the Earth’s magnetic field at the location of the calibration. B) the nine estimated calibration parameters and their standard deviations.



	Sensitivity
Probe X	0.998944 (± 0.000003)
Probe Y	0.998610(± 0.000003)
Probe Z	0.998228 (± 0.000008)
	Offset (nT)
Probe X	-7.8 (± 0.1)
Probe Y	139(± 0.1)
Probe Z	47.3 (± 0.4)
	Angle (°)
Probe X	-0.018657 (± 0.000191)
Probe Y	-0.140785(± 0.000109)
Probe Z	0.131782 (± 0.000179)

Figure 1. A) Total magnetic intensity map with estimated positioning (x,y) of the buried pipeline (white line, left panel). The UAS trajectory that generated this map is indicated by black lines. B) Analytical signal map with estimated positioning (x,y) of the buried pipeline (white line, left panel). The trajectory of the UAS that generated this map is indicated by black lines. All maps are displayed considering the x-axis as distance east and the y-axis as distance north.

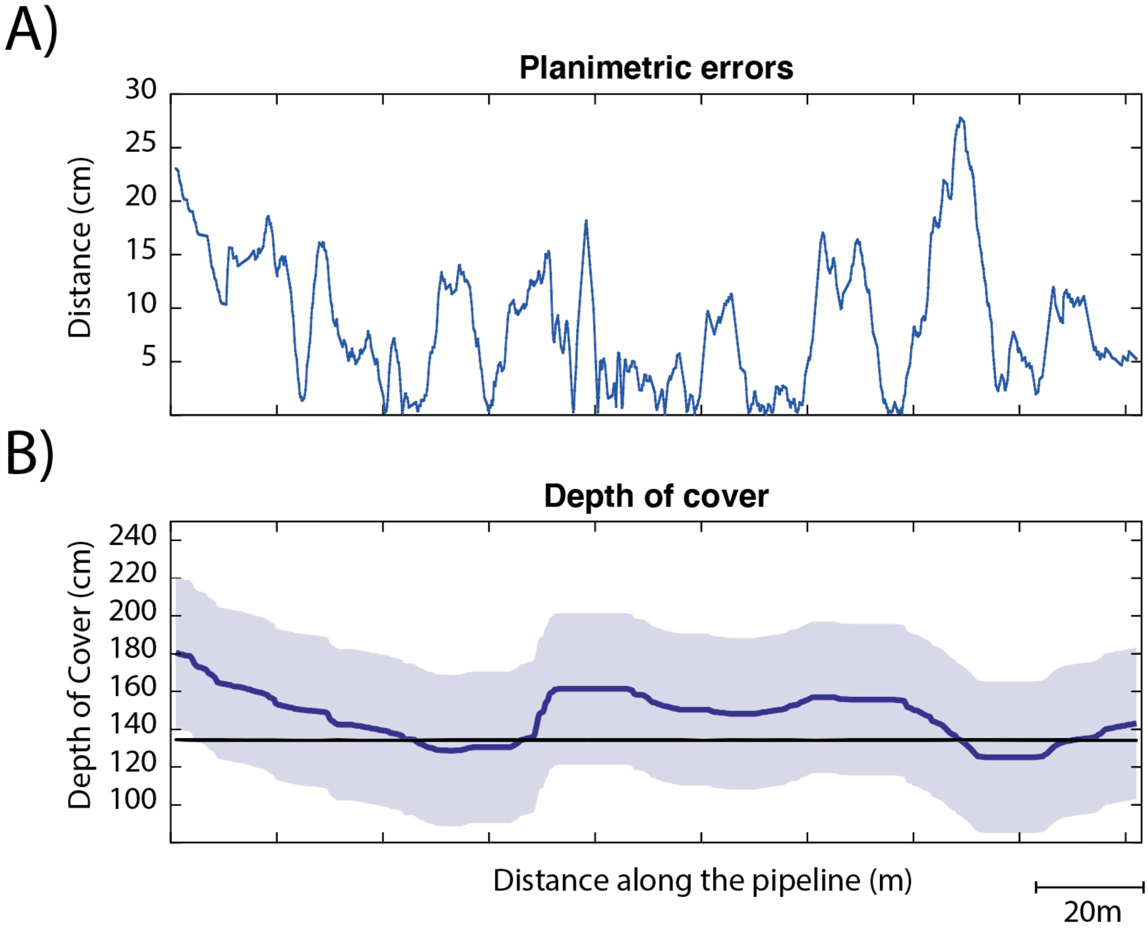


IV. PERFORMANCES OF THE 3D-LOCALISATION

The objective of this study was to evaluate the capabilities of the UAS magnetic mapping method to localize a pipeline within the highest positioning thresholds defined by the French regulation for rigid buried facilities: class A. This benchmark is detailed in the standard *NF S70-003-3* with three planimetric error thresholds and 2 altimetric/depth error thresholds. It can be summarized by one threshold for both planimetric positioning and depth positioning error of 40 cm for 90% of the measured points on a line.

To establish the error histograms on our 8-inch pipeline case study we compared our 3D-localisation using UAS magnetic mapping to a reference line measured by a land surveyor using traditional methods. We will focus on the 183-meter south section of the line including a bend to estimate the relative errors (i.e., differences between locations identified using UAS magnetic mapping and the locations measured by a land surveyor), as illustrated in Figure 4.

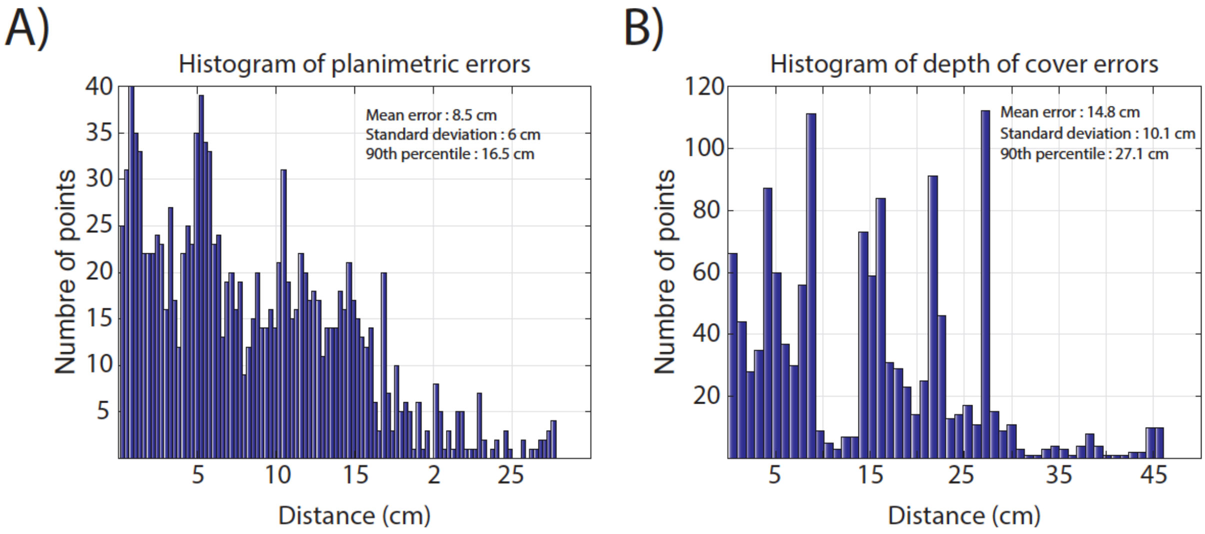
Figure 2. Estimation of error relative to the reference line. A) Planimetric errors relative to the reference line. B) Depth of cover relative to the reference line.



The planimetric error shown in Figure 4A is mainly under the 20 cm line with a maximum of 28 cm. The error histogram in Figure 5A is compliant with class A requirements in terms of planimetry. The variations around the reference line may be explained by the cumulative errors of each system but we neighbor the measurements uncertainties of the reference line positioning.

The depth error is presented with a ±20 cm error halo that encompasses the black reference line everywhere but in the first few meters. The error histogram in Figure 5B is also compliant with class A requirements in terms of depth below ground with a maximum error of 47 cm in the first meter of inspection. The change of topography during the 11 months between the time that the magnetic map was acquired and the time that the reference line was established may explain the fact that the histogram of depth errors does not follow a folded normal distribution. Ultimately, the pipeline was successfully positioned within the requirements of class A by the system in 36 minutes of cumulative total flight time.

Figure 3. Histograms of distance error in geolocalisation by SKIPPER NDT to the reference line. A) Histogram of the planimetric error to reference line and its mean, standard deviation, and 90th percentile. B) Histogram of the depth of cover error to the reference line and its mean, standard deviation, and 90th percentile.



V. GENERALIZED STUDY ON EIGHT GRTGAZ PIPELINE SPOTS

The same protocol was repeated on an extensive set of 8 pipelines with different diameters and ROW conditions for a total distance of 2.7 km. The test sessions included inspection near railways, under high-voltage lines, with the presence of concrete protections, and on steep terrains and wheat fields.

In Table 1, the valid inspected distance represents the inspected areas compliant with the requirements of our technology, which excludes areas where the ROW is too narrow to get the full magnetic anomaly, areas of poor GNSS coverage, or simply areas where the flights were prohibited, such as construction sites, roads, etc. The percentage of class A corresponds to the ratio between the distance successfully geolocalised within A class planimetric requirements and the valid inspected distance.

Table1: Summary of eight GRTgaz pipeline spot inspections under various operational configurations.

Nominal Pipe Size (inch/mm)	Valid inspected distance (m)	Percentage of class A	Cumulative flight times (minutes)
3 / 80	119	100 %	20
4 / 100	335	100 %	37
6 / 150	280	100 %	18
20 / 500	263	56 %	39
24 / 600	387	100 %	51
24 / 600	63	100 %	17
36 / 900	861	89 %	80
48 / 1200	404	64 %	37

VI. CONCLUSION AND DISCUSSION

This study demonstrates successful trials conducted with Skipper NDT and GRTgaz. 89% of the valid inspected distance was georeferenced in class A on a variety of pipeline configurations, ROW, and diameters. Skipper NDT technology and results were validated by GRTgaz which makes the system approved for use by landsurveyors for the rural geolocalisation campaign AcaPulCO 2.

The UAS embedded system for magnetic mapping proved that it was affected by neither high voltage lines and railways interferences nor crops and soil conditions on the ROW. GNSS convergence time and PPP capabilities were challenged in several locations which make near forest areas difficult to inspect. This issue is now solved by post-processed kinematic (PPK) differential correction (by recovering the satellite's ephemeris at day+1) using base stations (public or private) on georeferenced points.

Some limitations remain such as flight authorizations and obstructed ROW. Indeed, the ROW needs to be free from 2m or higher obstacles, for a 10m width and also present a uniform elevation in the line’s perpendicular direction. The geolocalisation on 90°-bends for large pipelines (30-inch and higher) tends to follow the exterior of the elbow causing a mispositioning which explains the results for the 36-inch and 48-inch diameter pipelines in Table1. Ultimately, we observe that ferromagnetic parallel lines under 5 m distance have an impact on the positioning performance especially if they are electrically connected. All these aspects are considered for an ongoing R&D program.

The Skipper NDT technology is currently available for geolocalisation applications as a tool for difficult-to-access and complex locations. Moreover, the technology may also be compatible with river crossings and Out-Of-Straightness assessments.

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