PIPELINE 3D-POSITIONING AT RIVER CROSSING: LONG-RANGE MAGNETIC MAPPING VIA UNMANNED AERIAL SYSTEM (UAS)

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ABSTRACT

Pipeline networks traverse modern societies' national territories and can be located in areas difficult to access, making maintenance logistically challenging and potentially dangerous for field personnel. River crossings, where pipelines are buried under the bed of a water stream, fall under such a definition. Recurrent safety monitoring operations entail the deployment of divers with accompanying operational risks and constraints. In addition, most of the tools available are inefficient due to the presence of water. In particular, traditional Ground Penetrating Radars (GPR) are not applicable. Other radio-frequency equipment will provide low-density datasets which rely significantly on human interpretation, introducing measurement biases impacting accuracy and reliability.

Skipper NDT has enhanced its proprietary autonomous technology to serve clients looking to position and secure their pipeline networks under river crossings. Magnetic mapping using a UAS vector allows, firstly, quick data acquisition with less than 30 minutes of flight time per 100-m of river inspection, and, secondly, an automated survey without putting field personnel at a safety risk. Datasets that are developed using such a system present a high spatial density, up to 20 points per meter (6 points per foot), which enables the creation of high-precision digital twins of the buried structure. Data processing is also automated through proprietary and patented algorithms.

In addition, Skipper NDT deliverables are ESRI® compatible and can integrate third-party GIS datasets, such as bathymetric or photogrammetric measurements. Thus, a 3D model of the river crossing features using QGIS software was made possible, to further enhance decision-making capabilities of pipeline integrity departments. The performance of the Skipper NDT technology was tested under real field conditions with the collaboration of the incumbent French Gas operator GRTgaz managing over 32’500 km of pipeline network. This paper is based on 3 case studies from 160 to 220 m (522 to 722 ft) river crossings with a maximum depth of 12 m (39 ft). The data show a strong correlation with existing information while enhancing data quality and reliability.

I. INTRODUCTION

Locations where pipelines cross rivers require special attention to ensure continued safe operation without leakage that can pollute water supplies on which local communities, livestock, and wildlife depend.

There are generally two different designs for a pipeline to cross a waterbody. The open-cut crossing method involves excavating a trench across the bottom of the river or. Depending on the depth of the water, the construction equipment may have to be placed on floating platforms to complete the excavation of the pipe trench. The Horizontal Directional Drilling (HDD) method involves drilling a hole under the waterbody and installing a prefabricated segment of pipe through the hole.

Once installed these pipelines must be inspected and monitored. Many operators are implementing programs to survey their water crossings every 5 to 10 years to determine the depth of cover, to identify water crossings prone to erosion and geometry changes, to detect pipeline leaks, and to assess bending strain using in-line inspection tools [1].

In more extreme circumstances, flooding can wash away a portion of a riverbed leaving a pipeline exposed and susceptible to damage, sometimes called scouring. In the US for example, regulators require pipeline operators to address any conditions, including flooding and a lack of depth of cover, that may adversely impact the safe operation of the pipeline according to the Code of Federal Regulations Title 49 part 195.401(b), 195.452, and 195.412(b), which require operators to inspect pipeline facilities within 72 hours of an extreme weather event such as flooding [2].

Sometimes buried under sediment layers and several feet of water column, these structures may be challenging to survey. Skipper NDT has developed a method for accurately mapping pipelines remotely using UAS – without being in contact with the pipeline or interfering with the flow rate. The method relies on the measurement of the total magnetic intensity above the pipeline right-of-way to encompass its magnetic signature [3]. This procedure turns out to be particularly useful at river crossings to reduce operational risks and help to ensure pipeline reliability, energy deliverability, public safety, and environmental protection.

II. MATERIAL, PROTOCOL, AND MISSION

The hardware developed by the Skipper NDT team consists of a payload weighting between 4.2 and 2.2 kg (9.2 and 4.85 lbs) depending on the drone vector capacity. In terms of width, the payload is between 90, and 160 cm (35,4” and 63”) which can be mounted under various types of UAS (Figure 1). The main components are the same and comprise: 1) three to four three-component 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 for 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. On the left, the 4.2kg and 90cm payload. On the right, 2.2 kg and 160cm payload.

The main sensors in this system are the magnetometers and the GNSS, upon which the acquisition of the magnetic map depends. The fluxgate magnetometers are light, 112 g (4 onces) per unit, and robust sensors that measure the three components of the magnetic field at a 2000 Hz sample frequency. Even if they are considered lower resolution/precision than other magnetometry technologies, they can be calibrated easily before each acquisition, and they are adaptable to neighboring equipment through a compensation process [4].

Light payload UAS imposes stringent constraints on GNSS hardware in terms of weight, precision, and logistics. Real-Time Kinematic (RTK) protocol with a base and a lightweight rover would have been the natural solution but the use of a base complicates the logistics considering theft risks. A 606-g multi-frequency and multi-GNSS receiver was chosen for real-time precise point positioning (PPP) correction services. Corrections ensure positioning accuracies down to ± 4 cm (1.5”) at 95% root-mean-square worldwide (between –75° and + 75° latitude) without operational difficulties. This real-time PPP is supported by a post-processed kinematic (PPK) differential correction (by recovering the satellite's ephemeris at day+1) using a permanent base to enhance positioning when signal reception is challenged, for example, near trees or other masks [5].

Other components of the Skipper NDT system serve mainly a corrective purpose. Indeed, flying equipment requires supplementary corrections such as level control [x] and telemetric measurements. A combination of ultrasonic and Lidar measurements is used to evaluate the distance between the magnetometers and the ground or canopy and then infer the depth of cover (depth of the pipeline below ground surface). In this case, the ground corresponds to the surface of the water which makes a distinct water/air interface for the sensors. Thus, we have access only to the depth below the water surface, and a bathymetric survey is necessary to complement the results.

A bathymetric survey is a type of hydrographic survey that maps the details of underwater terrain, illustrating the depth of water and mapping the land that lies beneath the water. Traditionally, bathymetric surveys are conducted using an echo sounder attached to a survey boat or uncrewed vessel, remotely controlled or autonomous – preferably used in surveys of inland waters (rivers, reservoirs, etc.), as in the three case studies discussed in this paper. As the boat moves across the water, the echo sounder generates electrical signals, which are converted into sound waves by an underwater transducer. Soundwaves will bounce off features under the water and this echo is then identified by the echo sounder and the distance to the identified feature is calculated. Bathymetric survey systems rely on highly accurate GNSS systems to link each measured distance to a particular depth on the surveying map. The next stage in a bathymetric survey consists of transforming the data captured from the boat into an elevation model [6].

As part of the “Multi-fluide” decree, GRTgaz is required by the DREAL (the Regional Directorate for Environment, Development and Housing) to inspect its network at waterbody crossings at least every 10 years. The purpose of this study is therefore to identify the areas sensitive to river events that may represent a danger for the gas pipeline in an area of 100 m on either side of the crossing. To this end, detection and a detailed topographic survey are carried out in order to assess:

- The existence or absence of an anomaly (low sediment load).
- The evolution of the sediment load on the pipeline.

A complete inventory of the crossing and its environment is carried out in order to predetermine the geomorphological evolutions of the study area. In accordance with Health, Safety, and Environment requirements, a preliminary visit and a hydrological visit were carried out under *La Seine* and *La Loire* rivers with three case studies from 160 to 220 m (525 to 722 ft) river crossings with a maximum of 12 m (39 ft) depth below water surface.

III. CASE STUDY DN900 AND QUANTITATIVE COMPARISON

Two river crossings were done on *La Loire* river with a 200 m and 220 m (656 to 722 ft) long inspection with a maximum of 3 m and 5 m (10 and 16 ft) water depth, respectively. The river crossing considered for this case study is the deepest one, performed on *La Seine* river with a total distance of 160 m (525 ft) from shore to shore with an average 9 m (29 ft) water column. The corresponding pipeline is an X42 grade steel, 900 mm (35”) nominal diameter pipeline, installed in 2000 with a double polyethylene coating.

A current injection was necessary with the characteristics described in Table.1. The electrical connection was done 600 m (0.3 miles) away from the inspection area at a test point.

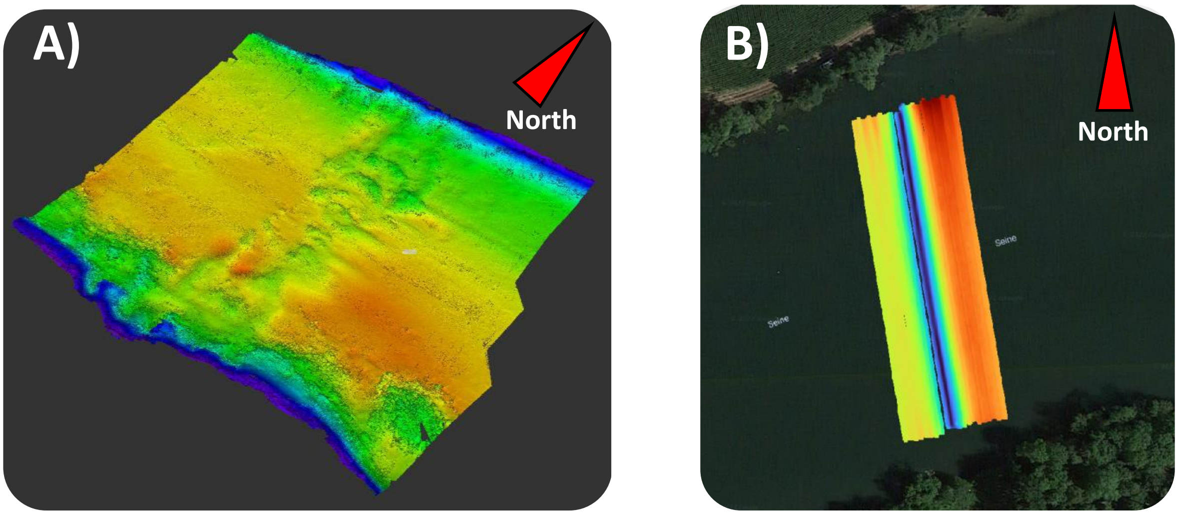
Table.1: Automatic UAS Inspection parameters on the 900-mm (35”) diameter pipeline.

Inspection parameters

Pipeline’s Nominal diameter (mm/inch)	900 / 35
UAS used	DJI M600 Pro
Acquisition frequency (Hz)	2000
Inspected distance (m / feet)	110 / 361
Average velocity (km/h and mph)	7.2 / 4.5
Flight time (minutes)	37
Flight height (m / feet)	1 / 3.3
Current injection characteristics (A) / (V)	0.87 / 49

The multibeam bathymetry analysis of the riverbed (Figure 2A) shows topographical irregularities above the pipeline trajectory that are most certainly due to the embankment after the pipe-laying. The main composition of the riverbed is alluvium of clay and sand. The total magnetic intensity map in Figure 2B focuses on the injected current in the pipeline. The maximum field value recorded does not exceed 22 nanoTesla. It can be explained by the distance from the source (13 m / 42 ft) and the potentially higher dispersion of current to the ground considering the high conductivity of the neighboring humid soil.

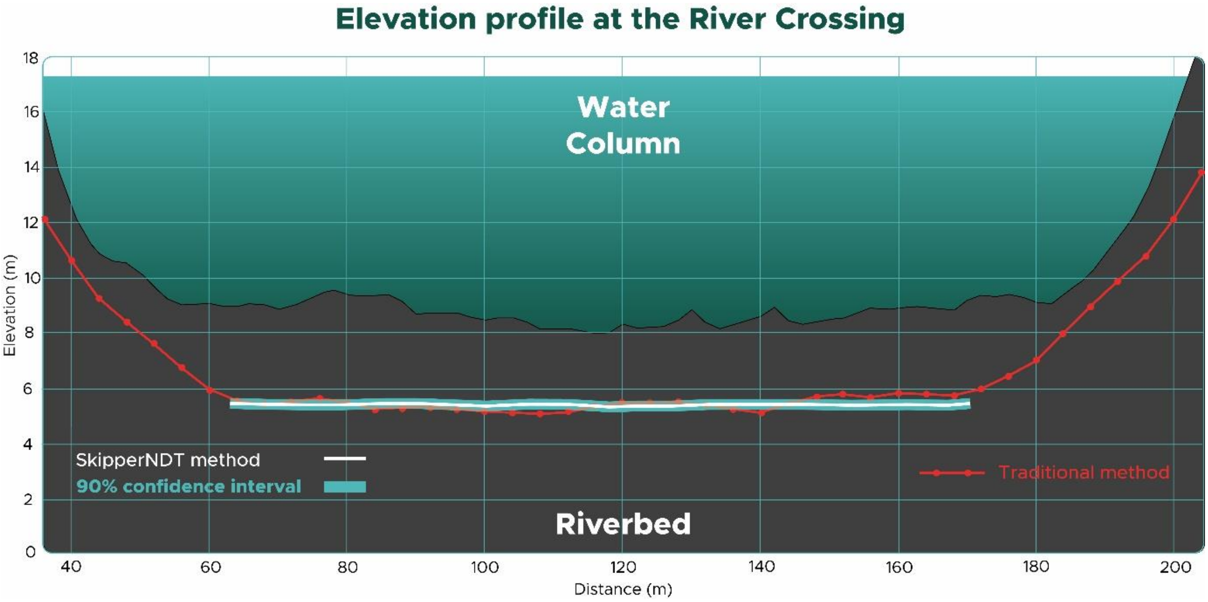
Figure 2: A) Digital Terrain Model based on multibeam bathymetry survey; color scale goes from 7.1 m / 23 ft (blue) to 16.7 m / 52.4 ft (red) above mean sea level. B) Total magnetic intensity of the injected current of the pipeline right-of-way; color scale goes from 0 nT (blue) to 21.8 (red) nT.



The total magnetic intensity, resulting from the current injection in the pipeline, allows to clearly distinguish the associated magnetic anomaly described by Biot-Savart law [7]. A 2D-inversion of the magnetic map along the pipeline with a spacing of 50 cm (19.6”) leads to a 3D positioning of the source and allows an elevation profile to be established in Figure 3.

The so-called traditional method used here requires the intervention of a diver and a team of 3 to 4 people to assess the depth of cover. Using a submersible double depth antenna [8] that communicates the depth results to a ground base team on the river bank, the diver moves at the bottom of the water body detecting the buried line and measuring its depth at a spatial frequency of 2 to 4 m (6.5 to 13.1 ft). Since no positioning system records the trajectory of the equipment during the acquisition, the pipeline is assumed to be straight from one side to the other.

Figure 3: Elevation profile of the 900-mm (35”) diameter pipeline at the river crossing, comparing results from the traditional method and from Skipper NDT magnetic mapping.



The origin of the x-axis corresponds to a pipeline marker on the west bank. At 110 m (361 ft) away from the origin we can evaluate a 9 m (29.5 ft) water column and a 2.9 m (6.5 ft) depth below the riverbed. The total range from the UAS to the centerline of the pipe is 13.4 m (42.6 ft).

The magnetic mapping accuracy and precision were established in our previous papers [9]. An average accuracy of 15 cm and 27 cm for the 90% (5.9” and 10.6”) confidence interval, represented by white and light blue lines in Figure 3. According to the specifications, the accuracy of the submersible double depth antenna, used for the traditional method, depends on the depth and corresponds to 15 cm (5.9”) on average in this case. Since acquisitions are done by hand by divers on the riverbed, the measurement chain must include an important part of measurement biases that will impact the final accuracy contrary to the automatic UAS acquisition.

Indeed, results of both types of measurement converge around the same average pipe elevation, 5.40 m (17.71 ft) for the traditional method and 5.39 m (17.68 ft) for the magnetic mapping. However, the precision of the results is significantly higher for the Skipper NDT method, with a 3 cm (1.2”) standard deviation compared to the 22 cm (8.7”) standard deviation for the traditional method. The use of an automated and repeatable method had a significant impact on the precision, being seven times more precise, without depreciating the accuracy levels.

An actual 3D-geolocalization of the pipeline, rather than a depth of cover assessment, adds valuable information about planimetric variations. The assumption of a straight pipeline between a riverbank to another is no longer relevant considering the Out-Of-Straightness assessment (OOS). OOS assessment characterizes the linear variation of the pipeline with respect to a theoretical straight line connecting the two ends of the section considered.

Figure 4: A) Planimetric view of the trajectory of the 900-mm diameter pipeline at the river crossing compared to a straight line. B) Horizontal Out of Straightness.

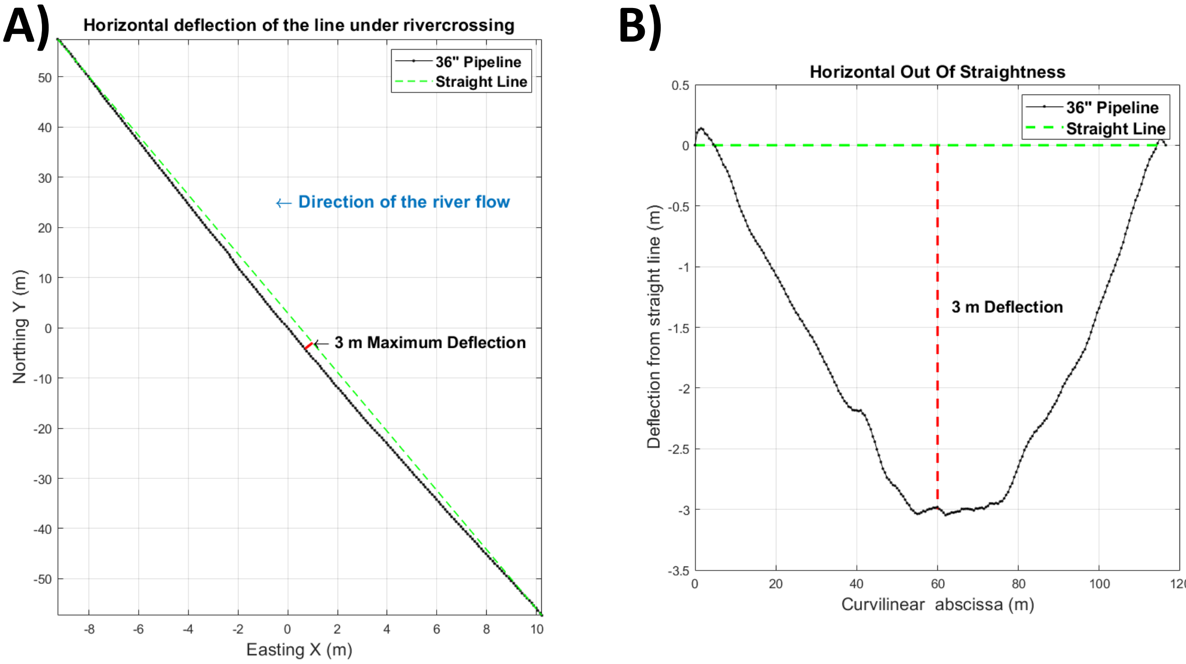
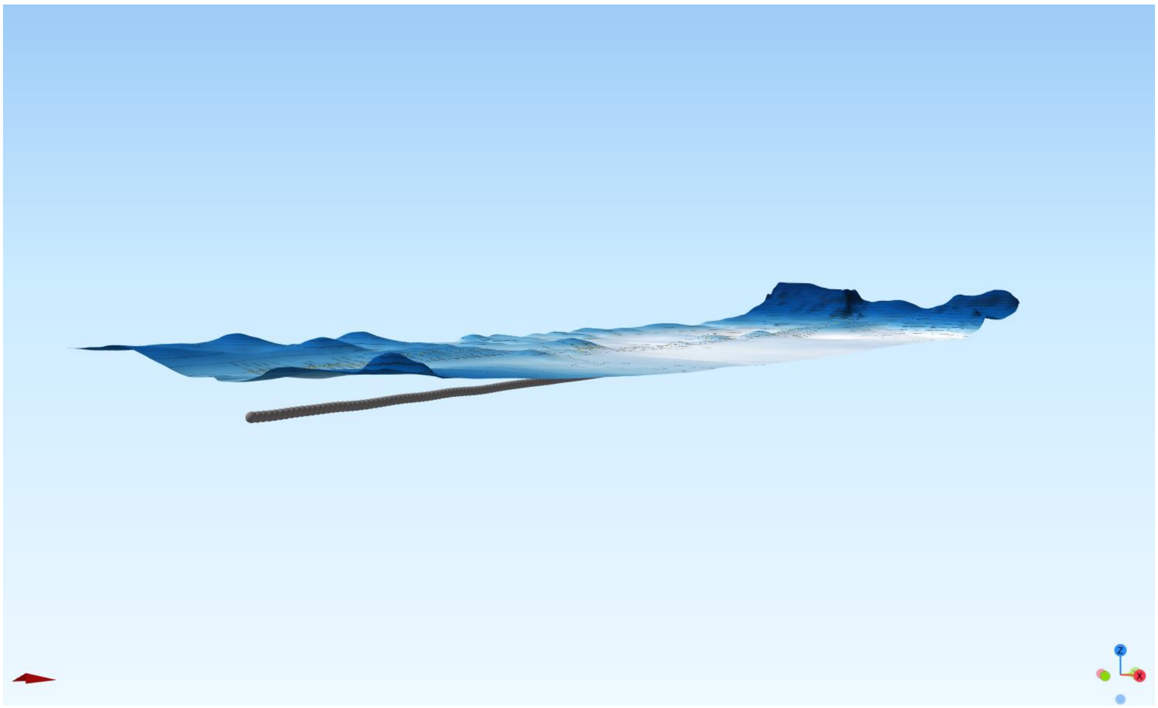


Figure 4 shows a deflection of the pipeline that invalidates the straight-line assumption made for traditional methods. At maximum, around 60 m (196 ft) along the curvilinear abscissa, the pipeline trajectory is offset by 3 m (9.8 ft) over the 116-m (380.5 ft) length of the inspection. This curvature seems colinear to the river flow and in the same direction. However, no conclusions can be made regarding the cause of this geometry since the pipeline could have been installed with this OOS. A comparison with the as-built drawing is necessary to establish whether the OOS existed at the time of installation.

IV. 3D MODEL USING QGIS2THREEJS PLUGIN

The 3D geolocation generated by Skipper NDT coupled with the bathymetry survey are the basis of an accurate and to-scale 3D representation of the pipeline river crossing. The 3D representation makes it possible to obtain a more intuitive visualization of the data for the operator in order to understand better the characteristics of interest in the structure. In order to facilitate its visualization, the interactive 3D model can be displayed on a web browser with an HTML file. It can also be managed, in a more complete way, on dedicated GIS software (QGIS, ArcGIS, etc.) equipped with the qgis2threejs extension [10].

Figure 5: Three-dimensional model showing the pipeline and riverbed using Qgis2threejs plugin.



V. DISCUSSION

Results obtained on the 900mm diameter pipeline are representative of the other two inspections on *La Loire* river which have a lower depth below the water surface, between 3 and 5 m (9.8 and 16.4 ft). The case study inspection illustrates the longest range the Skipper NDT technology has encountered to date, with a total distance of 13.4 m (42.6 ft) from the sensors to the pipe's centerline. However, it does not represent a maximum range for the technology. In the appropriate conditions, a measured magnetic signal greater than 15 nT, and enough width on the right-of-way, 2.2 times the average pipe to sensors distance, the technology has an unlimited range.

The tendency for inspected pipelines to present a bow, from 50 cm (19.6") over 200 m (656 ft) up to 3 m (9.8 ft) over 110 m (361 ft) in the case study, in the same direction as the river flow is a phenomenon that needs to be investigated. There are mainly two possible answers to explain this geometry. Either it is a progressive change of geometry due to the river flow, which could require a bending strain assessment and a potential stress relief if above a certain threshold, or a misalignment during the installation of the pipeline.

In both cases, the utility of monitoring precisely the orientation changes in planimetry at the river crossings seems fundamental in this changing environment, since it does not imply any operational complications.

VI. CONCLUSION

In summary, magnetic mapping technologies carried out by UAS add significant value to pipeline surveys and monitoring, especially in the case of river crossings. Indeed, this type of inspection entail significant logistical constraints and carry potential physical risks for field operators. In terms material functioning, Skipper NDT can accommodate harsher operational conditions in terms of GPS coverage and magnetic environment, correction systems have been implemented to overcome GNSS coverage, with PPK solutions, or interference problems with advanced filtering for example.

Compared to the traditional methods considered here, this innovative method seems more efficient and reliable during the acquisition process. Large areas can be mapped rapidly, less than 30 minutes per 100 m (328 ft) of water crossing, with a highly repeatable and reproducible process allowing reliable monitoring of the line over time. Most importantly, this fully automated method enhances the operator’s safety, since it can be carried out by one person operating the UAS from the river bank, without the involvement of divers. The inspection is carried out remotely without contacting the pipeline or interfering with the flow inside the pipeline. It can also be deployed rapidly to respond to potential integrity threats on the structure resulting from extreme weather conditions or external factors.

The precision and high density of the output positioning already showed interesting results in terms of OOS. The natural next step would be to evaluate the capabilities of this technology for bending strain assessments in landslide conditions and profit from the advantage that a remote survey can provide.

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