Position Estimation of Inline Inspection Tools Without Odometers or Above Ground Markers

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1 ABSTRACT

Accurate position estimation of inline inspection (ILI) tools is critical if repairs are to be made to a pipeline based on survey results. Traditional ILI tools solve this problem by using odometer wheels in combination with above ground markers to provide estimates of inline distance and speed. For unconventional free-floating ILI tools, position estimation can be done without these. To accomplish this, correlations between onboard sensor data and known information about a pipeline and its environment are utilized. These correlations and how to apply them to constrain the tool position and speed towards the true values is discussed. A real-world example of this methodology demonstrating a verified location accuracy of within just a few meters is discussed.

2 INTRODUCTION

Neutrally buoyant, or free-floating, inline inspection (ILI) tools have emerged as an effective alternative to conventional ILI tools (i.e. smart pigs) for several inspection needs. Their chief advantages include the reduced cost of inspection, no requirement on pipeline cleanliness, and operational simplicity during deployment. All ILI tools must provide an accurate estimate of the location of each reported feature to enable operators to act on inspection results. Because GPS signals cannot reach the inside of a pipeline, conventional ILI tools rely on odometer wheels and above ground markers (AGMs) to provide continuous estimates of the inline position and geospatial coordinates of the tool. By design, free-floating tools do not use odometer wheels and AGMs require manual placement of markers along the pipeline path before deployment. This can be a time-consuming or simply impossible exercise and undermines the cost effectiveness of free-floating ILI tools.

This paper explains how position accuracies comparable to conventional ILI tools are achieved for free-floating tools. In short, known information about the pipeline is correlated with onboard sensor data. These correlations derive from relationships between the measured physical variables, like pressure, and provided or inferred data on the pipeline and deployment conditions, like an elevation profile. These relationships are demonstrated with both real-world examples and a case study to illustrate how they can be combined to constrain the tool's position towards true values with a maximum error in the range of a few meters.

3 INSPECTION TOOL

A free-floating inline inspection tool is an untethered inspection device that is weighted to be neutrally buoyant in the pipeline fluid under operational conditions so that it travels with the flow. This puts design constraints on the tool size and mass, limiting power supply and sensor options. The tools explored in this paper are called Pipers®. They are a spherical multi-sensor unit with diameters of 1.5, 2.2 and 2.8 inches. The unit size does not impact the methods described here and so is not distinguished case to case. These devices employ passive sensors including an inertial measurement unit capturing three-dimensional (3D) acceleration and rotation rate, a 3D magnetometer, a pressure gauge and thermometer measuring the external fluid conditions, and a microphone.

Pipers® do not magnetize the pipe wall; instead, they measure the remnant magnetic flux density in the pipeline rather than measuring magnetic flux leakage. Pipelines built out of ferromagnetic materials will generate a remnant magnetic field. The flux density of this field is affected by the pipeline material properties, quantity, loading history and heating history; the current stress/strain on the pipe; additional material or hardware fixed to the pipeline or placed nearby; and Earth's ambient magnetic field. This allows Pipers® to identify when they pass different features, such as additional hardware or the heat affected zone of a weld.

Operators generally run deployments at near constant flow rates, however this isn't always possible. To tell measurements due to pipeline characteristics (e.g. a change in pressure when the pipeline elevation changes) apart from those due to operational changes (e.g. variable flow rate due to a reciprocating pump), multiple Pipers® are deployed with a short time delay between them. This serves the secondary purpose of confirming data repeatability for each deployment.

4 PHYSICAL RELATIONS

The position and speed of the free-floating tool is identified at discrete locations by leveraging simple physical relations to correlate the onboard sensor measurements at a given time to known features of the pipeline at a given position. At times between these correlations, the tool is assumed to be moving at a constant speed.

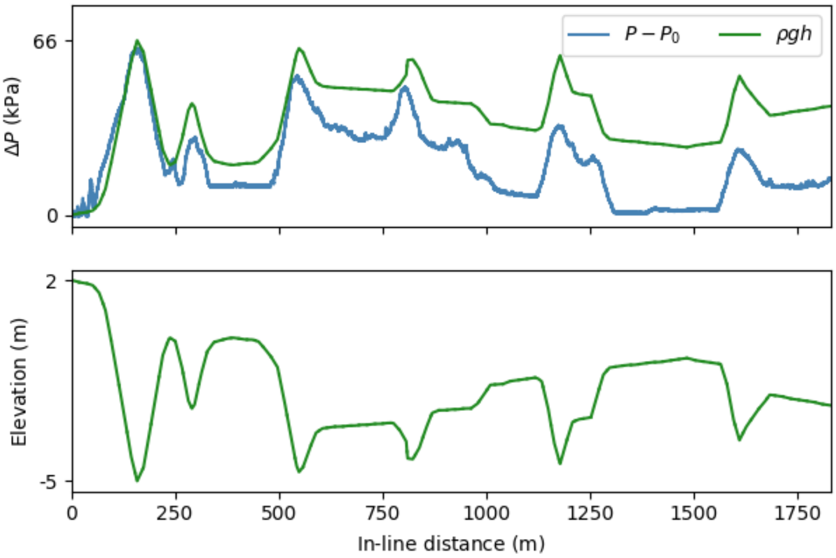
4.1 CHANGES IN PIPELINE ELEVATION

By measuring local pressure as the inspection tool travels through the pipeline, changes in pipeline elevation can be detected. The change in pressure between two points, ΔP, in steady, incompressible pipe flow is often modeled by the modified Bernoulli equation,

$$\Delta P = \rho g h + \frac{\rho}{2}(v_2^2 - v_1^2) + H_L\,,$$

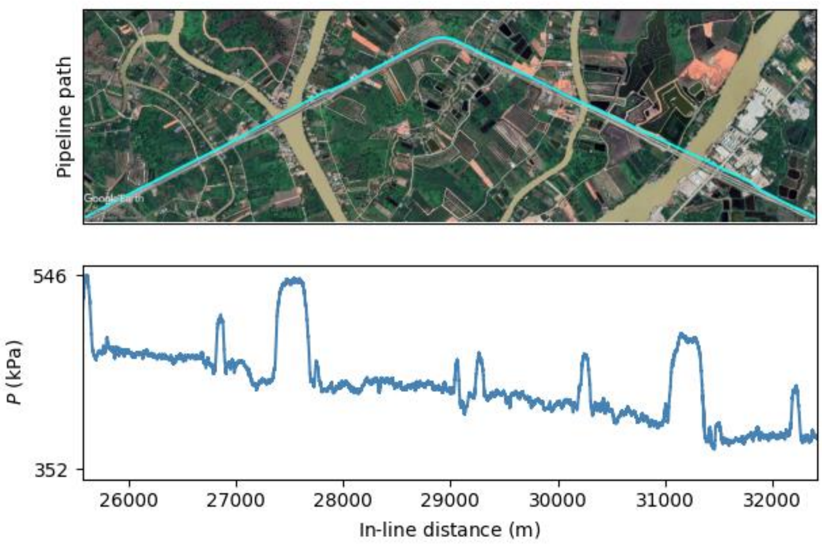
where ρ is the fluid density, g acceleration due to gravity, h the change in elevation, v_1 and v_2 the fluid velocity, and H_L the head loss due to friction. Under typical inspection conditions the change in pressure due to the weight of the fluid, $\rho g h$, far exceeds that due to changes in flow speed or losses due to friction. For example, Figure 1 compares the measured pressure delta relative to the launcher pressure to the pipeline elevation profile and pressure delta due to hydrostatic pressure changes.

Figure 1: Top: measured change in pressure relative to the start of the pipeline ($\Delta P = P - P_0$) in blue and change in pressure due to the weight of the fluid ($\Delta P = \rho g h$). Bottom: Elevation profile of pipeline. Note, the gradual divergence of the measured pressure from that predicted by the fluid weight is due to the head loss, H_L.



This allows analysts to identify inspection tool locations based on known pipeline elevation changes. Elevation profiles may be provided directly by the pipeline owner/operator but can also be deduced (albeit with higher uncertainty) from third party geospatial altitude databases or, where roads and rivers are present, from satellite imagery. For example, note the change in pressure as the pipeline crosses the rivers in Figure 2. Risers will also result in changes in the hydrostatic pressure and their position, if not provided directly, can often be identified via satellite imagery.

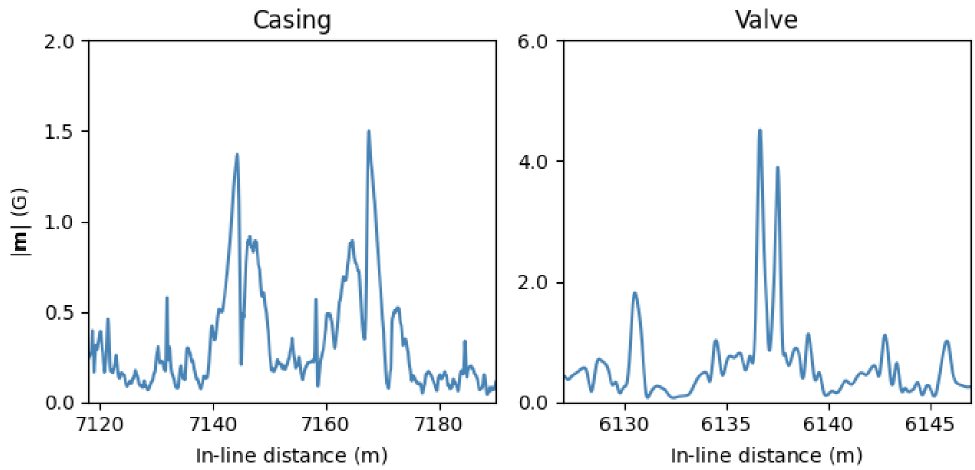
Figure 2: Pipeline path segment in cyan overlaid on satellite imagery showing two major river crossings (top) and the measured pressure as the inspection device passes each river (bottom).



4.2 Known Hardware and Fixtures

As discussed in section 3, the remnant magnetic field is affected by the pipeline material properties, quantity and additional material or hardware. Because magnetic field strength decays at $1/_{r^3}$, the effects of changes in material or hardware, such as a valve or change to non-metallic piping, fall off quickly. Therefore, the inspection tool's location can be determined with the magnetometer by identifying when it measures a known piece of hardware on the pipeline. Figure 3 shows an example of the total magnetic flux density measured as the inspection tool passes a casing (left) and a valve (right). With knowledge of the inline distance of these features, the inspection tool's position can be specified at the time it passes these features.

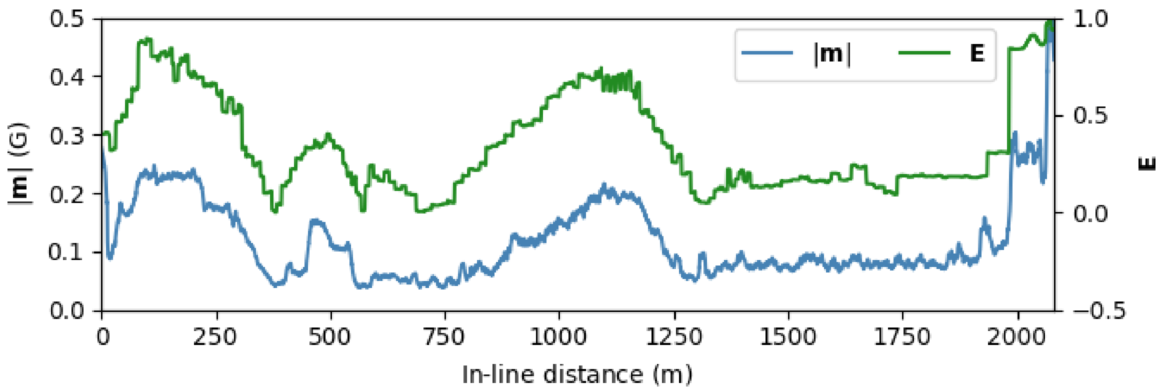
Figure 3: The total magnetic flux density measured as the inspection tool passed a casing (left) and a valve (right).



4.3 Geometric Information

When a drawing of the pipeline path is provided, the inspection tool's location can be determined from changes in the pipeline direction. This can be done in two ways: identify when the tool passed a particular bend by an associated signature in the remnant magnetic flux (Section 4.2); or correlate the alignment of a segment of pipeline with Earth's magnetic field, $\boldsymbol{E}$, with changes in the total magnetic flux density, $|\boldsymbol{m}|$. Figure 4 shows the total magnetic flux density in a pipeline, filtered to highlight gradual changes, in blue and the associated pipeline's alignment with Earth's magnetic field in green. The pipelines alignment ranges from -1 to 1, where -1 represents the situation when Earth's magnetic field and the pipeline are pointed in opposite directions and +1 represents the case where they are pointed in the same direction.

Figure 4: The measured total magnetic flux density (blue, left axis) through a pipeline and that pipelines alignment with Earth's magnetic field (green, right axis).

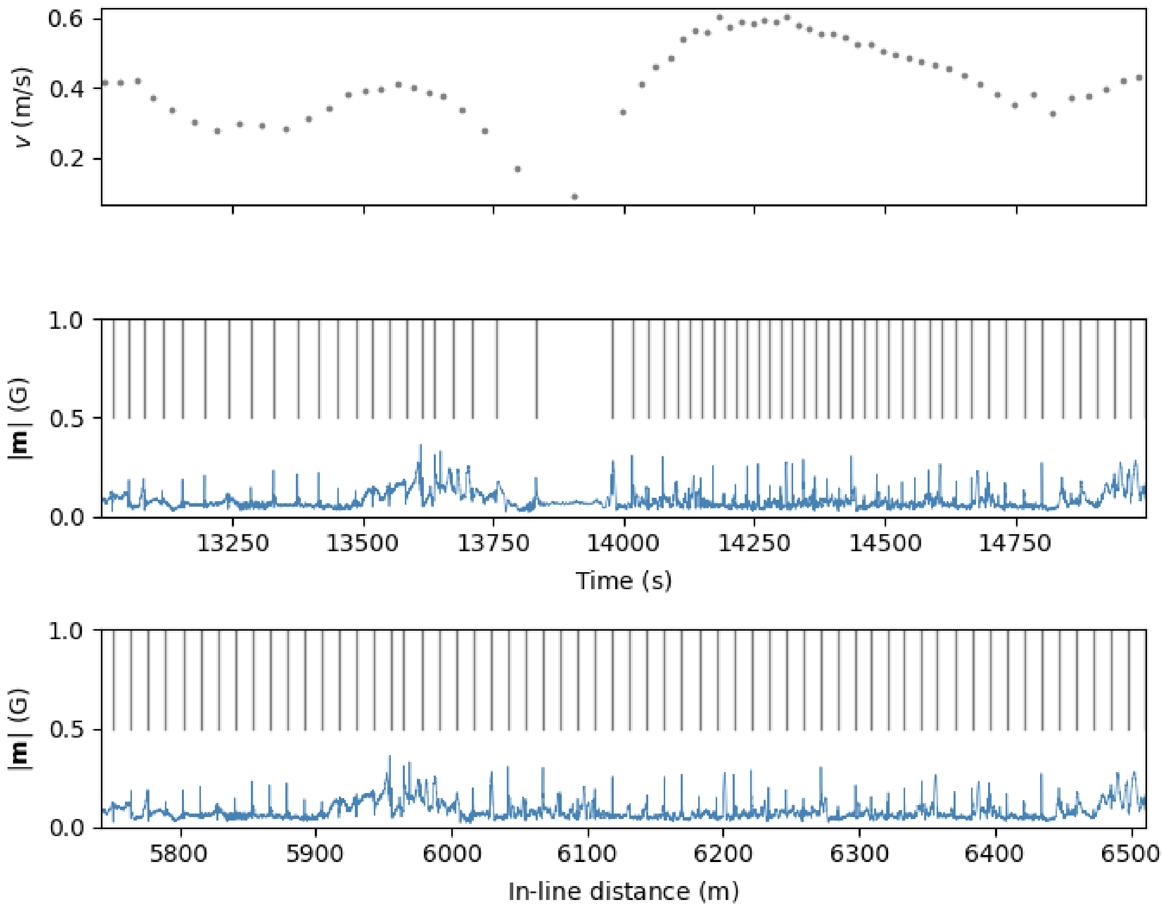


4.4 Joints and Spools

Pipelines are typically constructed by welding together lengths of pipe manufactured to a common standard. These welds produce a readily identifiable signature in the magnetic field so that, even without knowing the precise location of each weld, useful information about the distance travelled by the inspection tool and its speed through each pipe can be inferred. If a pipeline segment of known length (such as between two identified changes in elevation) is expected to be constructed of pipe spools of equal but unknown length, then the spool lengths and changes in tool speed can be estimated.

For example, Figure 5 shows the average inspection tool speed vs. time through each spool for a segment of pipe with a known length. In this case, the tool speed is highly variable. Below is the total magnetic flux density with welds marked by vertical gray lines, also plotted in time. Lastly, the bottom plot shows the same magnetic flux density and selected welds after converting to distance. The level of variability in flow speed shown here is unusual. In a deployment where the flow speed varies little, it is possible to instead use a sequence of pipe spools to estimate the distance travelled by assuming a typical manufactured spool length.

Figure 5: Average velocity through each spool (top), total magnetic flux density (blue) with welds (vertical gray lines) vs. time (middle) and distance (bottom).



5 Case Study

DTS Construction requested a leak detection on a critical water main owned by the Provincial Waterworks Authority of Surat Thai province in Thailand using Pipers®. The Pipers® are equipped with acoustic sensors that allow them to detect the presence of leaks as they pass by. Inspection of the 50 km long pipeline using the methods described in this paper resulted in the confirmation of 24 leaks (see Figure 7) located by the Pipers® with a maximum location error of 5 m.

Provided was a map of the pipeline with the location of HDPE pipe segments, diameter changes, and places where the pipeline elevation increased or decreased. Figure 6 shows examples of several locations where the provided information was correlated with Pipers® measurements. In the top row, a segment of HDPE pipe was identified. Since HDPE does not interact with Earth's magnetic field, the Piper measures a stable magnetic field through these spools. In the middle row, a diameter change was located using the magnetic flux density. Since a diameter change will correspond with an increase in flow speed, this feature was confirmed by comparing the Pipers® velocity before and after the diameter change. The third row shows two elevation changes in the measured pressure. For this project a full elevation profile was not provided, but the location of significant elevation changes (such as where the pipeline crosses a major road) were provided. Thus, the location of the Piper was identified when it passed these regions. Lastly, the pipeline path's alignment with Earth's magnetic field was compared to the large-scale changes in the measured magnetic flux density through the steel parts of the pipeline. This confirmed that the existing position estimates were accurate.

Figure 6: Data showing several features measured by the Pipers® that were correlated to provided information about the pipeline. Top, magnetic flux density around a material change. Top-middle, magnetic flux density around a diameter change. Bottom-middle, Pressure changes at provided locations of elevation changes. Bottom, magnetic flux density (blue) filtered to highlight large scale changes and pipeline alignment with Earth's magnetic field (green). Vertical, yellow lines indicate locations where the Piper position was identified.

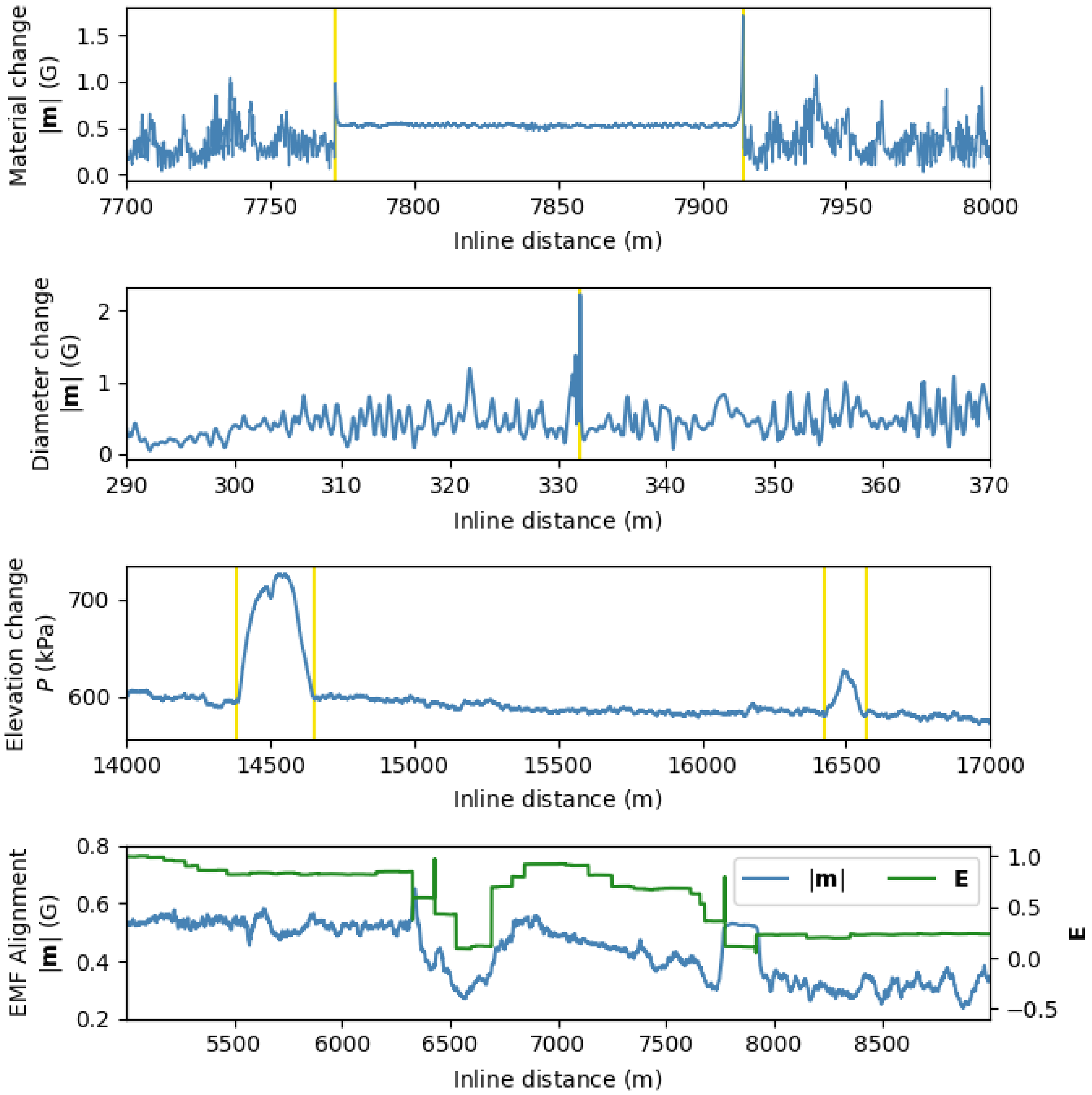


Figure 7: Pictures of two leaks located by the free-floating Pipers® and repaired by DTS at 8942 m (left) and 9001.8 m (right).

6 CONCLUSION

A method to estimate the inline position of a neutrally buoyant, free-floating inspection tool was described and demonstrated with a case study. The method relies on correlating known information about a pipeline with measurements taken by the free-floating device. Local pressure measurements were related to changes in pipeline elevation and measurements of remnant magnetic flux density were related to pipeline hardware, such as valves, pipe material and diameter changes, welds and changes in the overall pipeline direction. Together these relationships were used to locate 24 out of 27 leaks (the remaining 3 locations were not verified by the client) on a 50 km pipeline in Thailand to within 5 m without the use of above ground markers or specialized hardware like odometer wheels.