HIGH PRECISION GPS AIDED IN-PIPE DISTANCE CALIBRATION FOR SATELLITE IMAGE-BASED PIPELINE MAPPING

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ABSTRACT

Asset management and pipe condition assessment (CA) activities in the water industry usually require locating buried pipes accurately to minimise inspection and maintenance costs. A typical challenge in practice is locating an anomaly detected by an in-pipe inspection tool from above-ground in order to dig up a pipe for replacement. Accumulated in-pipe errors over longer distances in particular can easily lead to selecting the wrong pipe section for further investigation or exhumation. In fact, some in-pipe CA providers suggest utility personnel dig up a number of sections of pipe around the suggested location so as to ensure finding the target section. In this paper we propose a mechanism to accurately correlate a 3D pipeline profile built from GPS surveying results of above-ground pipeline features with in-pipe chainage distances, so as to establish an accurate link between above-ground GPS coordinates and in-pipe distance measurements. This approach naturally characterises and corrects for some of the most prominent in-pipe chainage measurement errors that can lead to uncertainties about the reported location of a buried pipeline from above-ground. The detailed pipeline information can then be projected onto satellite imagery as an accurate easy-to-understand reference for efficient decision making.

INTRODUCTION

A large proportion of the infrastructure a water utility owns and maintains is their buried assets. Scheduled inspections of their underground pipelines are essential in developing effective renewal programs and reducing the incidence of catastrophic failures. In this regard, increasing numbers of in-pipe inspection tools have been developed for the purpose of pipeline condition assessment, Liu *et al.* (2013), Stroebele *et al.* (2015), Valls Miro *et al.* (2013). However, the recorded distance of a tool along a pipeline, generally based on the tool's reported odometry, inevitably accumulates error as odometers drift with increasing distance. Moreover, given varying buried depths and the geometries of the terrain a pipe is buried in, locations reported by in-pipe distances are not directly projectable to accurate above-ground locations. Therefore the localisation of reported features or anomalies from above-ground, and subsequent decision making around the location of the buried assets is affected by significant uncertainties. This paper provides a solution to calibrate the in-pipe distance measurement and improve the above-ground localisation certainty using high precision GPS. Centimetre-accurate GPS measurements on a limited number of above-ground features and pipeline apparatus are employed as anchors to efficiently build a 3D profile of the pipeline. Corresponding reported in-pipe features and distances are matched with these apparatus to calibrate the in-pipe distance measurement.

For easier reference and to further facilitate the asset manager's decision making process, this project also proposes to plot the calibrated pipeline map on top of satellite images, such as those obtained from the satellite view in Google Maps®. Several evaluation examples are provided to demonstrate how the refined above-ground location information assists in producing an accurate targeted dig-up plan taking into consideration ground terrain conditions like driveways, plants and roads. The proposed approach has the potential to aid inspection service providers in delivering more accurate condition reports, and thus facilitating planning renewal programs for the utilities.

The procedure generally holds for a multitude of in-pipe inspection tools as long as the required pipeline apparatus are detected, and their in-pipe locations are reported. Examples include tethered and free-flowing pigs, CCTV platforms, as well as acoustics based screening tools, such as those described in Robbins *et al.* (2014) and Gong *et al.* (2015), which report chainage distances along the pipe.

METHODOLOGY/ PROCESS

Distance Representation and Sources of Error

A buried pipeline has a 3D profile, meaning that any single location along the axis of the pipeline has three dimensions. However, in practice, locations could be highly simplified by one dimensional distance measurements. As shown in Figure 1, distances along a pipeline may be reported in different ways: pipeline drawings based on 2D GIS maps generally reflect a projected 3D profile and report the so-called map distance, while in-pipe Non-Destructive Testing (NDT) tools or CCTV inspections platforms usually provide distance measurement along the pipe (referred to as “in-pipe distance” thereafter). A map distance ignores terrain elevation changes while the reported in-pipe distance associated with a tethered tool is usually subject to drift over distance and could be significantly affected by pipe elbows. Therefore, accurately locating features or anomalies reported on the pipeline from above-ground is a challenging task. Although inspection companies put effort towards tracking in-pipe tools from above-ground when they are in operation, factors like inaccurate reference coordinates, inaccessible areas, close-by pipelines, and human error render the localisation accuracy less reliable.

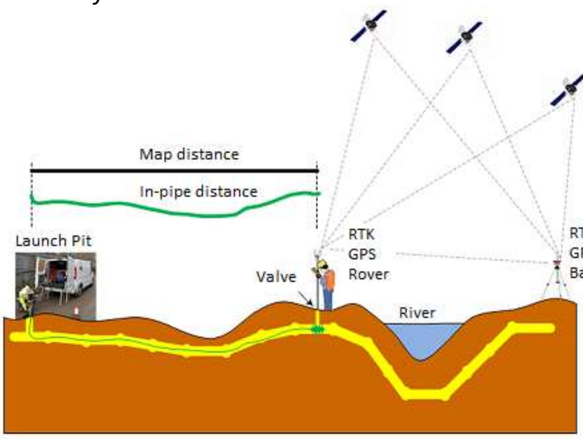


Figure 1: Different ways to report distances as descriptions of a pipeline.

Efficient High Precision GPS Surveying

Without Satellite-based augmentation systems (SBAS) – currently not available in Australia, consumer-grade GPS measurement in reality provides horizontal accuracy of about 5 ~ 10 metres, (depending on landscape settings), Wing *et al.* (2005). Vertical accuracy is always worse, generally at least 1.5 times worse than the horizontal error specification, Satirapod *et al.* (2001). This level of accuracy is clearly insufficient in aiding localisation of above-ground features.

To accomplish the task, a centimetre-accurate real-time kinematic (RTK) GPS system is suggested, Bouvet *et al.* (2000). A typical single-based RTK GPS consists of a stationary base, a moving rover, and the data link (e.g. RF) between them. Both base and rover unit antennae receive their own GPS signals, while the base also broadcasts the necessary correction information to achieve the higher accuracies. The base’s GPS coordinate is fixed and accurately set. The rover unit calculates its location using the received GPS signal and exploit the received correction information to improve its localisation accuracy. Setting up the base is usually a time consuming task as the GPS receiver requires hours of observations to achieve the convergence necessary for the highly accurate GPS base location reference required to exert effective GPS corrections. An alternative approach proposed in this paper, in order to efficiently set up a single-based RTK GPS, is to make use of the readily available highly accurate GPS coordinates provided by established Survey Marks, such as those maintained by the New South Wales Land and Property Information, and use them as the base location. Examples of two typical survey marks are shown in Figure 2. The diameter of the survey mark is about 5 cm.

Figure 2: Survey marks on a road curb in Sydney.

Please note that commercial RTK GPS solutions are available in Australia. By subscribing to the service, an end user with only a rover can expect even higher accuracies than those obtained in this work, Janssen *et al.* (2011), Roberts *et al.* (2007).

3D Profile Building for Buried Pipelines

The proposed strategy of solving distance discrepancies from the various sources is done to establish an accurate 3D profile of the buried pipeline and associate all measurements to said profile. Therefore, we propose to first building a 3D pipe profile based on the selected above-ground GPS measurements (longitude, latitude, and elevation). The buried pipeline is assumed located at a constant depth - except for some special areas, e.g. where pipe elbows are used, a situation depicted in Figure 5 for the case of a pipeline situated underneath a river crossing. The real elevation profile of the pipeline is thus assumed to be closely approximated by measuring the terrain elevation along the vicinity of the pipeline at a reasonable interval (utilities generally keep records of a pipeline’s nominal buried depth), taking into account the profile of areas with obvious elevation changes (e.g. a river). The end result is a close-to-reality 3D profile of the pipeline, described mathematically by a piecewise-linear continuous function representation, as described by equation (1):

$$f(P)=\begin{cases} \dfrac{x-x_1}{x_2-x_1}=\dfrac{y-y_1}{y_2-y_1}=\dfrac{z-z_1}{z_2-z_1} & \text{between } P_1 \,\&\, P_2 \\ \dfrac{x-x_2}{x_3-x_2}=\dfrac{y-y_2}{y_3-y_2}=\dfrac{z-z_2}{z_3-z_2} & \text{between } P_2 \,\&\, P_3 \\ \vdots & \vdots \\ \dfrac{x-x_{n-1}}{x_n-x_{n-1}}=\dfrac{y-y_{n-1}}{y_n-y_{n-1}}=\dfrac{z-z_{n-1}}{z_n-z_{n-1}} & \text{between } P_{n-1} \,\&\, P_n \end{cases} \qquad (1)$$

where $P_i(x_i, y_i, z_i)$ are the coordinates of a point on the pipeline. P_1 and P_n end points are generally the entry and exit points of the in-pipe tool and therefore their coordinates are often directly measurable.

Longitude and latitude measurements from locations of known apparatus (e.g. valves and manholes) belonging to the target pipeline are collected to derive the above profile. The conversion from GPS coordinate (longitude and latitude) to the local coordinate is achieved by using two constants – the length in metres of one degree latitude and longitude. The x-axis of the local coordinate is a straight line from one end of the pipeline to the other end, and the y-axis is perpendicular to the x-axis. If the terrain profile between two above-ground features varies significantly, extra ground elevation measurements along the two features may be required to further constrain the 3D profile.

Typical above-ground features which can be directly related to the location of a target pipeline are depicted in Figure 3. The difficulty here lies in identifying the apparatus that belong to the target pipeline. Utilities usually keep good records of these externally accessible apparatus, e.g. from their geographic information systems (GIS), but on site identification of these features is non-trivial. There exists for instance, confusion as to when features could belong to adjacent pipelines, or which assets are not managed by the water utilities. Thus, in addition to encouraging utilities to keep accurate records of the GPS locations of these features in their GIS system for regular asset management and maintenance tasks, utilities are also encouraged to do so for the purpose of better above-ground localisation of their buried assets from in-pipe inspections.

An example of how a 3D pipeline profile is derived is given in the next section in the context of how this representation is then employed for in-pipe measurement calibration.

It is worth noting that there are also geographic mapping tools that can provide 3D terrain profiles, as needed by the work proposed here (e.g. Google Earth® and other commercial ventures). These could have also been incorporated into the in-pipe mapping framework instead of the RTK GPS measurement. This could have significant implications in the overall accuracy due to the precision and resolution of the measurement provided by these maps. A recent study has shown that when using Google Earth®, the vertical root mean squared error (RMSE) could be as high as 4.77 metres in some instances, Salinas-Castillo *et al.* (2014). This can compromise its reliability for building accurate 3D pipeline profiles as described in this work.

Figure 3: Typical above-ground pipeline features, also depicting the rover antenna used in this work.

In-pipe Distance Calibration

Given the constructed 3D pipeline profile, as described by equation (1), all known apparatus and their calculated in-pipe distances are regarded as accurately calibrated references for any measured in-pipe distances of these features.

It is now assumed that in-pipe CA providers are able to detect and report features' locations in the chainage, and relate these to the above-ground apparatus (more coarsely or finely depending on the nature of the in-pipe measurement technique and on-board localisation sensing). To the author's best knowledge this is generally the case, as most in-pipe CA measurement techniques are sensitive to substantial changes in the condition of the pipe such as those exhibited by features such as off-takes or valves.

In-pipe distance calibration can then be accomplished through linear interpolation. A simplified example of the procedure is illustrated in Figure 4.

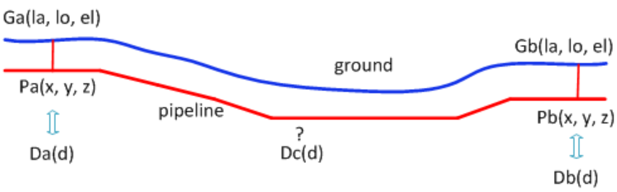


Figure 4: An example of in-pipe distance calibration.

1. Two above-ground features G_a and G_b are identified as belonging to the target pipeline and their centimetre accuracy GPS coordinates (latitude, longitude and elevation) are obtained by RTK GPS.

2. If the crown of the pipeline is not directly accessible from these two features, given the assumption of constant depth the 3D locations P_a and P_b (in local coordinate) of the in-pipe features corresponding to G_a and G_b can be

calculated. A coarse piecewise linear pipeline profile can be built from P_a and P_b.

3. As there is a visible large variation between the two above-ground features, as shown in Figure 4, RTK GPS coordinates of a small number of ground control points between G_a and G_b are measured to provide more accurate ground elevation profile, as described earlier, which also applies to the buried pipeline assuming a constant depth offset, so as to refine the coarse pipeline profile.

4. Given P_a, P_b and the pipeline elevation profile, the in-pipe distance between P_a and P_b can be accurately calculated.

5. If an in-pipe condition assessment tool reports features G_a and G_b in terms of chainage distance D_a and D_b, as well as an anomaly D_c, then the distance between D_a and D_b can be calibrated and a linear scale factor can be applied to all distance measurements (including D_c) between D_a and D_b. Therefore, the reported anomaly at D_c can be accurately located above ground - and visualised in an above-ground satellite map as described below. It can thus be readily associated to an (above-ground) GPS coordinate for personnel to easily find it on site.

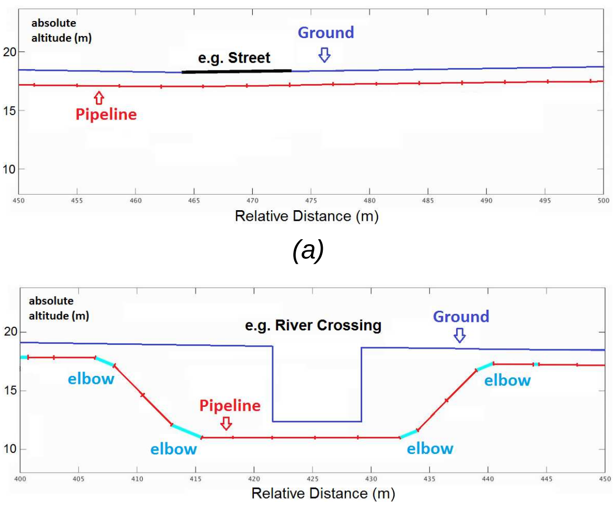
As most in-pipe CA techniques have, to varying degrees of accuracy, the capability of providing pipe chainage locations, accurate calibration of this information as described above, easily leads to a validated description of a pipeline asset down to the minimum pipe segment level (generally a pipe segment as defined between two joints). Two examples of the attained 3D profile for the test-bed pipeline described below in the results section are shown in Figure 5, depicted as a 2D side view for easier understanding. The x-axis represents in-pipe distance and the y-axis reflects the elevation.

From the point of view of asset management the proposed in-pipe distance calibration effectively becomes an interesting and efficient mechanism to update pipeline records and add certainty to pipeline replacement and maintenance decision-making.

Satellite Image-based Pipeline Mapping

The constructed 3D profile of the buried asset can be projected onto 2D satellite images for a more easily recognised and user-friendly representation. The end result (shown in Figures 9 and 10) is for pipe chainage to be displayed similarly to the way GIS pipeline maps are presented, with the notable exception that satellite maps are able to provide more detailed and relatively up-to-date above-ground information. Most of the high resolution satellite imagery on Google Earth® for instance is between 6 months and 5 years old, and since the actual imagery date is available to the user, Taylor (2014), the validity of the satellite imagery for the pipe of interest can be easily assessed by the asset manager just based on this temporal aspect. Furthermore, by simply walking along the pipeline to examine any notable changes above ground in relation to the imagery available would suffice to appreciate whether the exercise of referencing the buried asset with the above ground imagery might be rendered unhelpful.

As the 3D profile is a close-to-reality representation of the pipeline and described mathematically by a piecewise-linear continuous function, the framework allows projecting any in-pipe distance value to an above-ground location, effectively allowing a utilities' asset manager to accurately visualise pipe features, anomalies and joint locations as reported by in-pipe tools on satellite imagery. Various examples of how these projections look like can be seen in the results given in Figures 9 and 10, as described in the following section.



(a)

(b)

Figure 5: Examples of the 3D pipeline profile (2D side view) for a) a relatively flat area, and b) the river crossing area.

RESULTS/ OUTCOMES

Test Bed and GPS Equipment

A 1.5 km long DIN600 cement lined cast iron (CICL) pipe at Strathfield, Sydney, has been provided by Sydney Water as a test-bed in the scope of the Advanced Condition Assessment and Pipe Failure Prediction Project, Valls Miro *et al.* (2013). The pipeline was laid in 1922 and recently decommissioned due to poor condition. The following experiment was conducted on 1 km of this test bed. The reported pipe section segment is about 3.6 metres long with a bell-and-spigot joint configuration. The nominal pipe wall thickness is 30 mm. As is often the case for older pipes no data was collected during pipe lay commissioning, hence no further comparisons with respect to the real chainage can be established. It would however be an interesting exercise to compare the proposed strategy with verified pipe lay data to further validate the framework when such data is available. In its absence, dig-ups, in-pipe CCTV and above ground features, as used in this work, provide the validation mechanism.

The RTK GPS system (the base) used in this experiment is shown in Figure 6. The rover has exactly the same hardware, the only difference being the firmware configuration. The GPS receiver and antenna in both base and rover are NovAtel® products, while the license-free data radio is from RF Innovations®. Both units are powered on-site by portable 12V sealed lead acid batteries. A laptop is then required on-site: the firmware requires a one-off configuration via a serial link, and for data collection (which is needed only on the rover side).

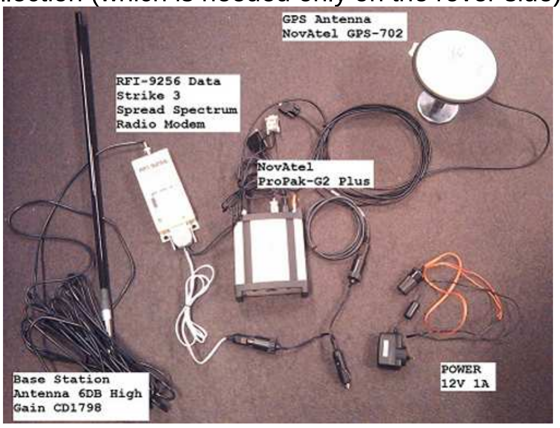


Figure 6: The RTK GPS system (the base) used for accurate above-ground location measurement.

3D Profile Building

As described earlier, for the experimental work we set up an RTK GPS system using a State Survey mark location at the system base. We then took 30 measurements along a 1 km length of the pipeline, as shown in Figure 7 (at the end of this paper) and built its 3D profile. The altitude measurements of all these points were utilised to establish the elevation profile of the area, as well as that of the pipeline. The pipeline profile in the other two dimensions (local x and y in metres converted from latitude and longitude measurements) are constrained by the coordinates of 10 above-ground features, located immediately above the crown of the buried pipeline. Following equation (1), all these points serve as known local coordinates of points on the pipeline. The accuracy of the RTK GPS system reported by the receiver has typically 2 ~ 3 cm horizontal uncertainty and 8 ~ 10 cm vertical uncertainty.

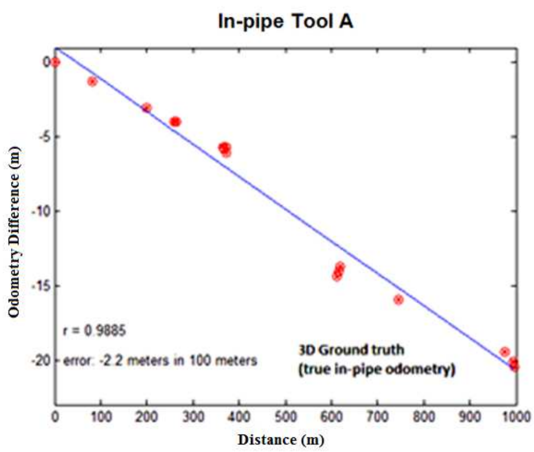
CCTV surveying, confirmed by utility information, indicate that when the pipeline was laid under a river a ~45° pipe elbow configuration (four of them as shown in Figure 5 (b)) was adopted to conform to the terrain. Therefore, the 3D profile in this area has been adjusted accordingly to the known pipe structure information.

In-pipe Distance Calibration

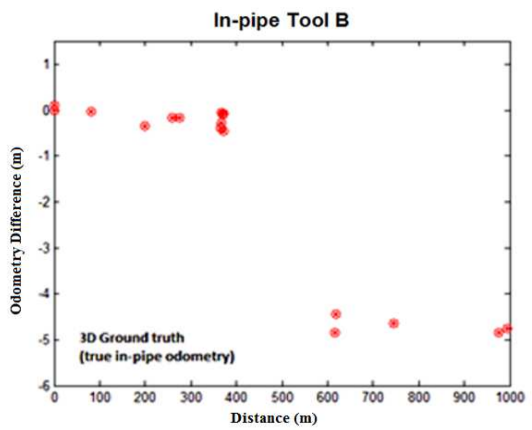
In the scope of the Advanced Condition Assessment and Pipe Failure Prediction Project, several inspections with different CA techniques have been conducted on this test bed. Two of these are in-line tools which have provided chainage distances of detected in-pipe features and pipe joint locations for the 1 km section depicted in Figure 7. Using the approach proposed in this work, we characterised the in-pipe distance measurements provided by these two in-pipe inspection tools. The calibration charts are shown in Figure 8. The x-axis represents in-pipe distance derived from the proposed 3D pipeline profile, and the y-axis reflects the calculated distance difference when compared with the distance measurements reported by the tool's odometer. The red points correspond to matched pipe features; hence, providing reference in-pipe distance error at those locations.

Figure 8 (a) shows that in-pipe tool A (tethered) reports on average 2.2 metres less per each 100 metres along the length of the inspected pipeline (1km) - when assuming a linear pattern from the data, shown in blue. The maximum odometer error is about 20 metres towards the end of the 1 km pipeline.

Figure 8 (b) collects the results for tool B (free flowing). Unlike tool A, the inspection with in-line tool B was carried out accompanied by an above-ground tracking device, as it is customary for that technique, so that odometer drift and slippage can be manually attenuated. The reported distance data, when post-processed, exhibits relatively small distance errors when compared to in-pipe tool A, with a maximum odometer error of about 5 metres. However, also clearly visible, is how between the 400m and 600m mark the reported distance error suddenly increases. This is where a river crossing is located. Due to the inaccessibility of the river area, the odometer cannot be properly corrected and the error therefore accumulates.



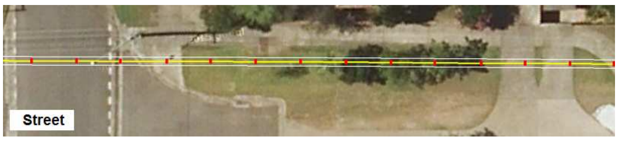
(a)



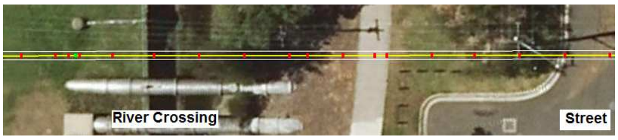
(b)

Figure 8: Characterisation of in-pipe reported distance for two in-pipe tools.

Satellite Image-based Pipeline Mapping
The calibrated and detailed 3D pipeline profile can also be associated with the above-ground satellite image to provide a top-down view of the target area. Examples of satellite image-based test-bed pipeline mapping are shown in Figure 9. The thick yellow line represents the centre of the pipeline, while the two thin while lines either side reflect the pipe boundaries. Red dots indicate pipeline bell-and-spigot joints. This level of detail can better assist water utilities in accurately locating reported anomalies directly above-ground, to the benefit of the asset manager, civil works crews and general public as it would likely minimise unnecessary disturbance due to uncertain diggings.



(a)



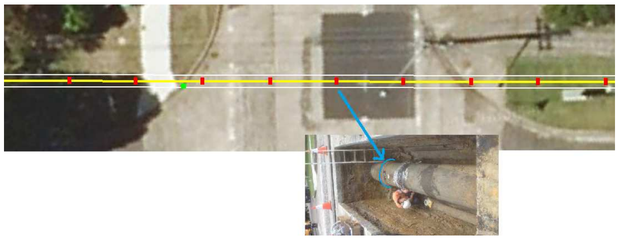
(b)

Figure 9: Satellite image-based pipeline mapping (top-down view) corresponding to the 3D pipeline sections depicted in Figure 5 as a) relatively flat, and, b) river crossing area.

The proposed framework has been qualitatively evaluated at various locations on the test bed where there was a need to dig up the pipeline. Figure 10 (a) shows an example where access to the pipeline was required in an area in the middle of a road. The calibrated 3D profile derived with RTK-GPS and measurement from the two in-pipe CA tools indicated that there were two joints in this dig-up area, and both of them were correctly located (the joint on the right is not visible in this picture due to the angle of the picture)

Figure 10 (b) shows an excavation which exposed a pipe unit from an area between the road and the footpath. The 3D profile indicated that there was a joint in this dig-up area which was correctly identified.

Figure 10 (c) depicts a scenario where it was required to extract a 2.0 metre pipe segment from the indicated joint (assumed as located where the 3D profile indicates), which is located towards its left in the image. The whole pipe segment is about 3.6 metres long, and thus according to the derived profile and corresponding satellite mapping the left joint was supposed to be located just under the unpaved driveway seen in the image. Given the accuracy of the data available a decision could be taken that minimises disturbance to the local resident as it could be accurately be established that the section of interest was safely located away from the right edge of the driveway; hence, the driveway did not need to be excavated. Dig-up results supported the correctness of the information, with the right joint located as expected, and the left joint located beyond the dug up area under the driveway, as seen by the picture insert. CCTV inspection data also confirmed this.



(a)

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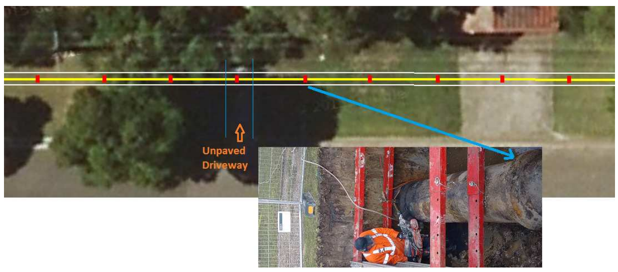

(c)

Figure 10: Evaluation of the derived calibrated 3D pipeline profile.

CONCLUSION

An efficient procedure for building the 3D profile of a buried pipeline using accurate above-ground locations derived from high precision GPS measurements is proposed in this paper. The resulting continuous mathematical representation of the pipeline can then be employed to calibrate the error-prone distance measurements provided by in-pipe CA tools. This is accomplished through above-ground and in-pipe feature matching. Moreover, the technique can readily map the calibrated buried pipes on satellite imagery for ease of reference and aid above-ground referencing of the underground asset. The proposed work establishes a novel accurate procedure for in-pipe CA technology providers to report their findings in a more manageable way for asset managers, and also for the utilities to better exploit the information collected from in-pipe CA activities towards more efficient decision making about targeted pipeline inspections, replacements and maintenance in general.

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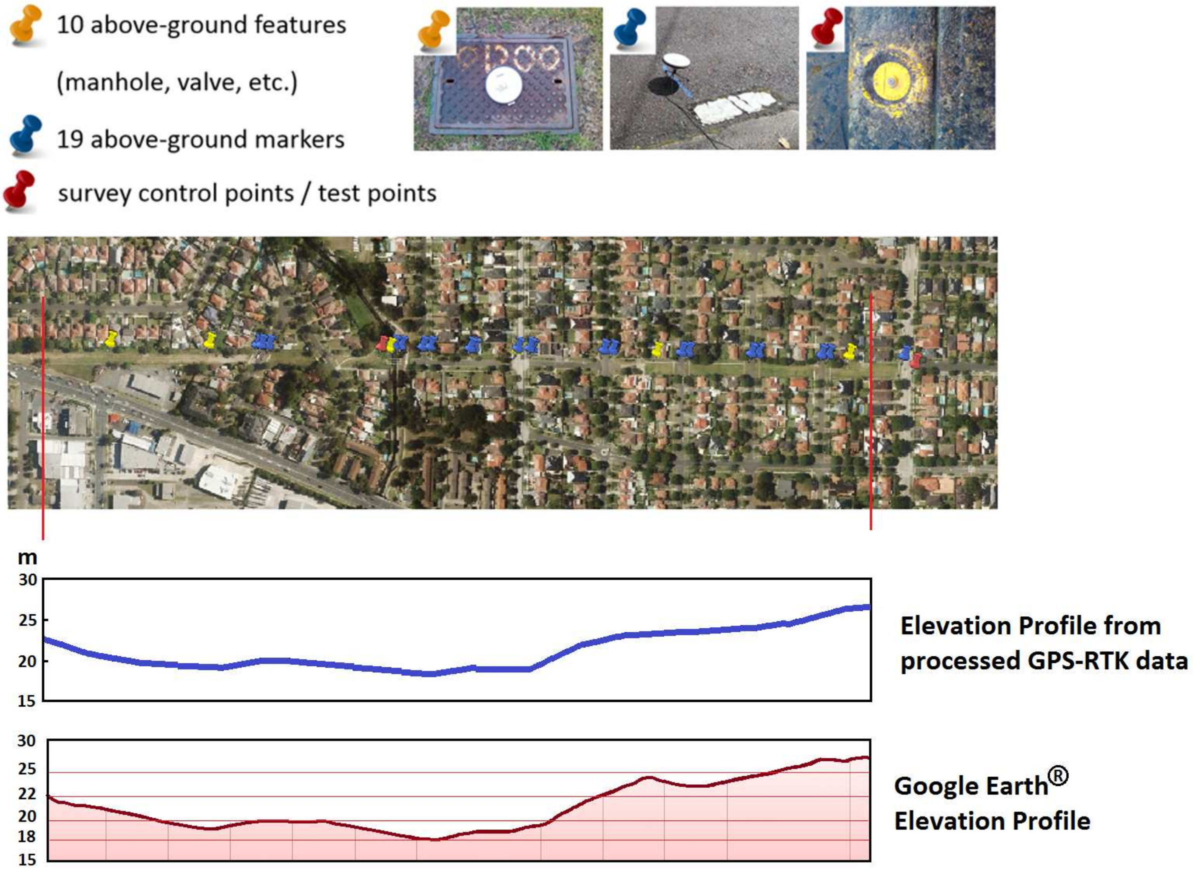

Figure 7: Measurements taken on a 1 km pipeline.