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Geometry-Corrected 360° Unfolded Surface Mapping for Defect Localization in Square and Octagonal Drainage Pipelines

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Underground drainage pipelines are extremely difficult and hazardous to inspect. In recent years, fatal incidents, including sudden road collapses and cases where workers entered pipelines and lost consciousness due to toxic gases, have highlighted the urgent need to prevent tragedies by eliminating human entry into confined spaces. Although robotic inspection has progressed, existing research mainly targets cylindrical pipes and focuses on detecting defects in the image domain without enabling practical localization on the physical pipe surface for maintenance planning. This paper introduces a geometry-aware framework for real-world square and octagonal drainage pipelines, such as box culverts, which are widely used in urban drainage networks, using image data collected by a commercially available quadruped robot equipped with a standard RGB camera. Unlike specialized pipeline robots that are costly and difficult to deploy, the proposed framework is low-cost and broadly accessible. The framework separates each wall surface, estimates individual perspective distortion, and reconstructs a continuous metric-consistent unfolded surface. This enables intuitive visualization of the pipeline interior and establishes the geometric foundation necessary for defect localization along the entire pipe length. By providing a spatially consistent surface representation, the proposed framework supports future AI-based condition assessment and can contribute to safer and more proactive maintenance of underground infrastructure while reducing the need for high-risk human entry and preventing further loss of life during inspection activities.

Keywords: Pipeline inspection, Underground infrastructure, Quadruped robot, Risk reduction, Image-based inspection, Box culvert, Maintenance planning.

1 Introduction

Underground drainage pipelines are a critical yet largely invisible part of urban infrastructure, and their deterioration poses serious risks to public safety. Despite their critical role, these systems are subject to progressive deterioration, a considerable proportion of sewer networks in developed countries have been assessed as being in poor condition, and the cost of remediation continues to place significant financial pressure on municipalities worldwide (Li et al., 2022). Regular inspection is therefore essential, but the confined spaces, poor visibility, water accumulation, and potential presence of toxic gases such as hydrogen sulfide (H_2S) make these environments life-threatening for workers. Recent incidents have made this danger impossible to ignore. In January 2025, a road collapse in Yashio City, Saitama, was traced to a deteriorated sewer pipe that caused underground cavity formation and eventual structural failure. In August 2025, four workers lost their lives in Gyoda City, Saitama, after inhaling H_2S gas during a routine pipeline inspection. These tragedies highlight the urgent need to substantially reduce human exposure to such hazardous environments through safer inspection alternatives.

Robotic inspection technologies have been widely explored as a safer alternative (Elankavi et al., 2020, Haurum and Moeslund, 2020, Li et al., 2022). Deep learning methods have shown strong performance in defect classification and detection, and more recent work has pushed toward multi-sensor systems and 3D reconstruction (Jung and Reiterer, 2024, Liu et al., 2024). Efforts toward spatial defect localization have also emerged, some studies estimate the longitudinal position of defects from CCTV data and monocular geometry (He et al., 2025, Tang et al., 2025), while others use visual odometry with specialized platforms (Fang et al., 2022). These approaches, however, share a common gap: localization is confined to the pipe axis, leaving unresolved where on the cross-section a defect actually sits, whether on the floor, a sidewall, or the top wall. For maintenance teams, that distinction matters. Field crews need to know not just that a defect exists, but exactly where on the pipe wall it is, in order to plan access and carry out repairs. Beyond this, existing work overwhelmingly targets cylindrical pipe geometries, leaving non-cylindrical structures such as box culverts, common in urban drainage networks, largely unaddressed.

This paper presents a geometry-aware unfolding framework for underground box culverts, reconstructing a continuous, metric-consistent surface map of the pipeline interior from images collected by a commercially available quadruped robot with a standard RGB camera. The framework corrects for perspective distortion on each wall face independently and stitches the results into a spatially coherent representation, establishing a 2D spatial reference on

the physical pipe surface that enables defect localization across both axial and cross-sectional dimensions. Video data from the same inspection pass were also used to generate a preliminary 3D reconstruction via structure-from-motion, offering a complementary view for remote assessment. Field experiments in a real underground drainage pipeline demonstrate the practical feasibility of the approach.

2 Quadruped Robot Inspection System

2.1 *Quadruped robot platform*

The inspection system is built around a commercially available quadruped robot, the Unitree Go2 Air. The inspected pipeline contained standing water throughout much of its length, conditions under which wheeled systems are prone to slippage, while legged systems offer the advantage of minimal slippage on irregular surfaces (Elankavi et al., 2020). Beyond traction, the quadruped's leg-based locomotion keeps the robot body at a stable height above the waterline, reducing the risk of water reaching onboard electronics. The platform also adapts naturally to uneven ground without requiring significant changes to the control strategy, and its stable movement directly benefits the quality of subsequent perspective correction and surface reconstruction.

The robot was operated manually via a dedicated controller with real-time visual feedback through a front-facing camera and a mobile application over a local wireless network. As this was an initial field deployment in a real underground environment, an operator accompanied the robot inside the pipeline to monitor its operation and respond to any unexpected conditions. Future deployments are expected to transition toward fully remote operation as system reliability is established. The use of a commercially available platform rather than a custom-built system significantly lowers the barrier to deployment, demonstrating that geometry-corrected surface mapping does not require specialized robotic hardware.

2.2 *Camera and lighting setup*

Three imaging devices were evaluated to identify the most suitable configuration for underground pipeline inspection: a smartphone camera (iPhone 17 Pro Max), a mirrorless RGB camera (Nikon Z30 with kit lens), and an action camera (DJI Action 3). The devices represent distinct imaging approaches, the iPhone 17 Pro Max for its computational photography capabilities and accessibility, the Nikon Z30 for its larger image sensor to assess whether a dedicated camera would offer advantages in this environment and the DJI Action 3 for its wide field of view and compact waterproof form factor suited to confined and wet environments. All devices were mounted on the robot body and operated remotely via dedicated applications. Based on preliminary visual evaluation under the same underground illumination conditions, the iPhone 17 Pro Max produced noticeably lower noise levels and greater surface detail retention than the other two devices and was adopted as the primary imaging device for the surface mapping framework.

The pipeline environment presented several illumination challenges. The robot is equipped with a built-in front-facing light, but this alone proved insufficient given the low-light conditions inside the culvert. One supplementary LED light source was therefore added, and each imaging device was equipped with its own built-in flash to further improve local surface illumination. The resulting setup, as shown in Figure 1, reflects the overall inspection configuration deployed during field experiments.

A handheld stabilizer was also employed during video capture to reduce motion-induced distortions caused by the robot's walking movement. This is particularly relevant for video-based applications such as structure-from-motion (SfM), discussed in a later section. For still image acquisition, stabilization was not a concern, as images were captured only when the robot was stationary — a strategy described further in Section 3.

Figure 1. The quadruped robot deployed inside the underground box culvert during field inspection, showing the inspection environment, water accumulation, and camera-lighting configuration mounted on the robot.

3 Data Acquisition

3.1 *Pipeline characteristics*

Field experiments were conducted in a real underground stormwater drainage pipeline in Japan, covering approximately 25 m of the pipeline length. The pipeline had been previously identified as containing structural defects, making it a practical and representative test environment for the proposed framework.

The pipeline has a rectangular cross-section with chamfered upper corners, giving it eight wall faces in total, as illustrated in Figure 2. This geometry is representative of box culverts commonly found in urban drainage infrastructure. The internal dimensions are approximately 1.8 m in width and 1.7 m in height. Due to standing water of approximately 5–10 cm throughout most of the pipeline length, the floor and lower diagonal faces were submerged and visually indistinct during the inspection. As a result, six wall faces were consistently observable — the top wall, two upper diagonal faces, and two sidewalls — and these form the basis of the surface reconstruction described in Section 4.

3.2 *Inspection environment*

The pipeline interior presented several environmental challenges typical of underground drainage infrastructure. Standing water was present along the floor throughout the inspection, and interior surfaces exhibited low texture with few distinguishable visual features. Illumination was severely limited due to the confined space and complete absence of natural light, a particularly critical factor in image-based inspection, as insufficient lighting directly compromises surface detail capture and the reliability of subsequent image processing.

The environment also raised safety concerns. Forced ventilation was applied through the manhole opening to maintain adequate air quality, and a gas monitor was deployed to track oxygen levels and detect toxic gases. These conditions highlight the practical risks of human entry into such environments and reinforce the motivation for robotic inspection as a safer alternative.

3.3 *Data collection strategy*

Image data were collected using a step-and-scan approach, in which the robot was manually advanced along the pipeline and brought to a full stop before each image was captured. This ensures that each image is taken from a stationary platform, avoiding motion blur and maintaining consistent image geometry, both of which are important for reliable perspective correction and surface reconstruction. Images were captured at approximately 50 cm intervals along the inspection path, though precise spacing could not always be maintained due to the manual nature of robot control. Additionally, wireless signal attenuation at greater distances from the operator introduced occasional control latency, making fine-grained movement adjustments more difficult in the deeper sections of the pipeline.

In addition to still images, video data were recorded along the same path using a handheld stabilizer to reduce motion-induced distortions. This video was collected to support structure-from-motion (SfM) reconstruction, which will be discussed alongside the main results in Section 5.

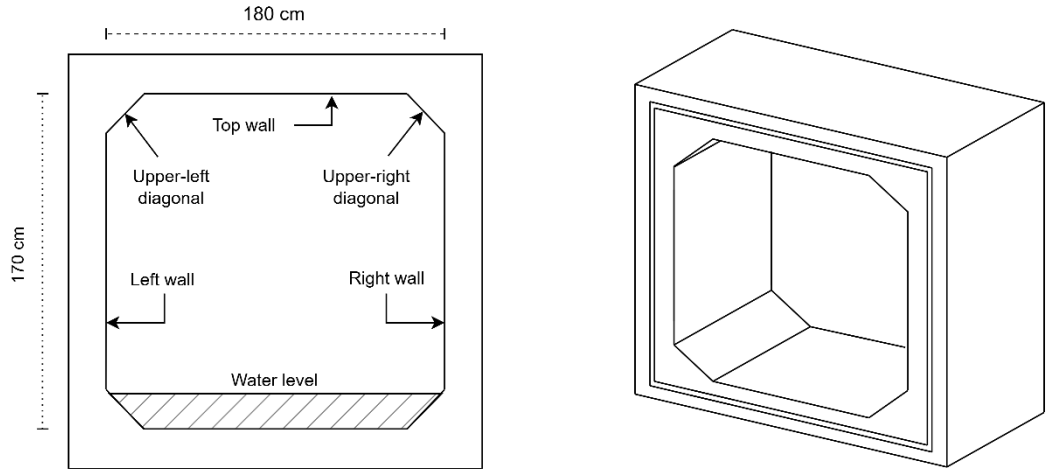


Figure 2. Internal geometry of the inspected pipeline: (a) cross-sectional view with wall face labels and water level, (b) 3D view.

4 Surface Mapping Framework

4.1 *Image unfolding*

Each image captured during the inspection contains multiple wall faces of the pipeline cross-section, all observed from a perspective viewpoint that introduces geometric distortion. Unlike cylindrical pipe inspection systems, which exploit rotational symmetry to perform unfolding through a fixed coordinate transformation, box culverts present a fundamentally different challenge, each flat wall face has its own perspective geometry that must be estimated and corrected independently.

Because the pipeline follows a straight, rectilinear trajectory, structural lines along the walls, ceiling, and floor naturally converge toward a common vanishing point when viewed in perspective. This geometric property is exploited to estimate the vanishing point from diagonal lines detected in the scene, which serves as a geometric anchor for the subsequent identification of the six principal structural lines defining the wall face boundaries, as illustrated in Figure 3a. As the lower diagonal faces are partially submerged, the water surface line is used in place of the lower structural edges, providing a stable lower boundary for the observable wall region. This substitution assumes that the water level remains approximately constant throughout the inspection, a reasonable assumption for enclosed drainage pipelines under normal dry-weather conditions, though it would not hold during or immediately after storm events. Similarly, the framework assumes a straight pipeline trajectory; curved or branching sections would disrupt the vanishing point geometry and would require a different treatment.

The boundary region of each wall face is then defined based on these lines, and a perspective warping transformation is applied to each face independently, producing a rectified planar representation that corresponds to a frontal view of that surface. This process is applied to all six observable wall faces per captured frame. The physical dimensions of the pipeline cross-section, 1.8 m in width and 1.7 m in height, serve as metric references, ensuring that the rectified representations correspond to real-world surface dimensions. Because the geometry-corrected face images are tied to known physical dimensions, the resulting map provides a basis not only for defect localization but also for defect sizing, once detection is integrated, the physical extent of any identified anomaly can be estimated directly from its position and size within the rectified image. As illustrated in Figure 3b, the unfolding process preserves the fine surface detail of the original image, including surface texture, staining, and structural features, demonstrating that geometric correction does not compromise the visual information available for subsequent inspection and defect analysis. It should be noted that perspective distortion increases with distance from the camera, and wall faces captured at longer ranges within a single frame tend to accumulate greater geometric error in the rectified output. This represents a practical limitation of the current approach, and closer image capture intervals are recommended to maintain reconstruction quality along the full inspection path.

4.2 *Image stitching*

The unfolded face images from consecutive frames are assembled into a continuous surface map through a stitching process applied independently to each of the six observable wall faces. Slices from successive frames are aligned using image correlation, accounting for both longitudinal displacement along the inspection path and minor lateral offsets from variations in camera position. An illumination normalization step is applied to reduce intensity discontinuities at slice boundaries, though complete correction is inherently limited in enclosed pipeline environments. Surfaces closer to the light source appear brighter, and without ambient reflected light the intensity gradient cannot be fully resolved through image processing alone. Capturing images at closer intervals would reduce this variation and improve visual continuity.

The output is a set of six continuous surface strips, one per observable wall face, forming a complete 2D surface map of the pipeline interior. Each strip is produced from geometry-corrected face images with known physical dimensions, providing a spatially consistent reference of the pipe wall surface that enables defect localization across both the longitudinal and cross-sectional dimensions.

(a) (b)

Figure 3. Wall face detection and unfolding result: (a) detected wall face regions with boundaries defined by the estimated vanishing point, (b) example of an unfolded wall face demonstrating that surface detail is preserved after perspective correction.

5 Surface Mapping Visualization and Defect Localization

5.1 *Unfolded surface map*

The proposed framework was applied to image data collected from the inspected pipeline, producing a continuous, geometry-corrected surface map covering approximately 25 m of the pipeline interior. The results presented here were obtained using the iPhone 17 Pro Max as the primary imaging device.

Figure 4 shows the resulting unfolded surface map. The vertical axis corresponds to the face index, representing the cross-sectional position of each wall face, F1 (left wall), F2 (upper-left diagonal), F3 (top wall), F4 (upper-right diagonal), and F5 (right wall), while the horizontal axis represents the longitudinal distance along the inspection path. The water-submerged region is split and placed at the top and bottom edges of the map, as this region contains no practically significant defects for maintenance purposes; this arrangement allows the five observable wall faces to remain spatially continuous and directly adjacent, preserving cross-sectional connectivity. This coordinate system establishes a 2D spatial reference on the physical pipe surface, in which any point on the map can be associated with a specific wall face and a specific distance along the pipeline. While finer angular resolution within each face is attainable, the face index representation is considered more practical for maintenance teams, as it directly indicates which wall face requires attention without requiring angular measurement.

Several locations of potential surface anomalies are highlighted with red boxes in Figure 4, exhibiting visual characteristics, including dark staining, surface irregularities, and crack-like features, consistent with known defect types in concrete drainage infrastructure. The map demonstrates that such anomalies are spatially resolvable and their locations directly identifiable within the 2D spatial reference, associating each anomaly with a specific wall face and longitudinal position. This coordinate system further enables a severity profile to be constructed, plotting damage intensity against longitudinal position and face index, allowing maintenance teams to identify the most critical sections and prioritize repairs accordingly.

5.2 *3D reconstruction via SfM*

In addition to the 2D unfolded surface map, video data recorded during the same inspection were processed using structure-from-motion (SfM) to generate a 3D reconstruction of the pipeline interior, providing a complementary spatial representation from the same data collection pass. Two video clips were recorded at 4K resolution and 120 fps, one traversing the pipeline in each direction and frames were extracted at a 40-frame interval, yielding approximately 3 frames per second of footage and a total of 1,310 frames submitted for reconstruction. The reconstruction was performed using Agisoft Metashape Professional with depth map quality and mesh reconstruction set to ultra high, producing a textured 3D model consisting of approximately 4.85 million faces and 47.9 million points.

Of the 1,310 frames, 423 were successfully aligned. The relatively low alignment rate reflects the step-and-scan data collection approach used during the inspection, the camera was periodically held stationary while images were captured, resulting in a high proportion of near-duplicate frames between which Metashape could not establish sufficient feature displacement for reliable alignment. Alignment failures were further concentrated in low-texture regions common to concrete drainage infrastructure, where feature matching is inherently limited regardless of frame spacing.

Despite these limitations, the model demonstrates a practical application that is difficult to achieve without dedicated equipment, enabling maintenance teams to remotely assess the internal geometry and condition of the pipeline before entering the site. Traditionally, such spatial awareness requires costly laser scanning systems; here, it is achieved using only the robot and a standard smartphone camera deployed during the same inspection pass. This suggests that even partial reconstructions of this kind can meaningfully support pre-inspection planning and access preparation. Looking further ahead, models of this type could serve as a basis for immersive inspection approaches such as VR-based remote walkthroughs, using data collected through the same practical workflow.

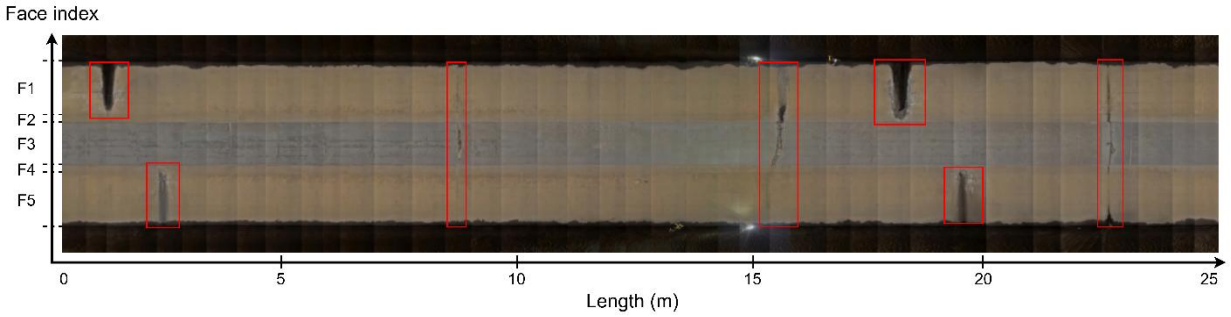
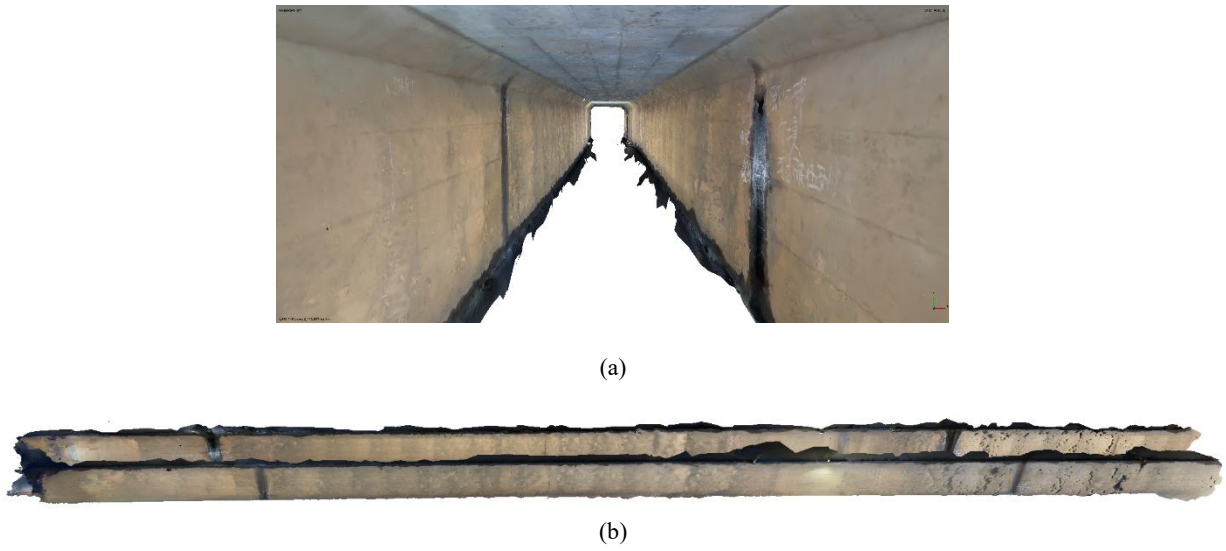


Figure 4. Geometry-corrected unfolded surface map of the inspected pipeline, providing a 2D spatial reference indexed by wall face and longitudinal distance that enables defect localization on the physical pipe surface. Red boxes indicate locations of potential surface anomalies.



(a)

(b)

Figure 5. 3D reconstruction of the inspected pipeline generated via structure-from-motion: (a) interior perspective view showing surface texture and geometry, (b) longitudinal view of the reconstructed pipeline model.

6 Conclusion

This paper presented a geometry-aware framework for unfolded surface mapping of underground box culverts using image data collected by a commercially available quadruped robot with a standard RGB camera. The framework addresses the geometric complexity of non-cylindrical cross-sections by estimating a vanishing point from the scene structure and applying independent perspective correction to each wall face, producing a continuous, metric-consistent surface map of the pipeline interior.

Field experiments in a real underground stormwater drainage pipeline in Japan demonstrated the practical feasibility of the approach under challenging conditions, including standing water, low texture surfaces, and limited illumination. The resulting surface map spans approximately 25 m and provides a 2D spatial reference, indexed by wall face and longitudinal distance. Potential surface anomalies are visually identifiable in the map, and their locations can be directly associated with a specific wall face and longitudinal position, enabling defect localization on the physical pipe surface. The level of detail retained is further sufficient to support future AI-based automated detection workflows. A 3D reconstruction of the pipeline interior was also generated from video data collected during the same inspection using structure-from-motion.

The current implementation is designed for straight pipeline sections under dry-weather conditions; curved or branching geometries and significant water level variations would require additional adaptation. As with any perspective-based approach, geometric accuracy decreases with distance from the camera, and closer image capture intervals are recommended for longer pipeline segments.

The proposed framework contributes to the broader goal of reducing human entry into hazardous inspection environments by enabling remote, spatially coherent visual assessment of pipeline interiors. Future work will focus on integrating automated defect detection with the established spatial reference, enabling quantitative condition assessment and severity-based maintenance planning.

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