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An Effective Method for Submarine Buried Pipeline Detection via Multi-Sensor Data Fusion

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ABSTRACT Submarine pipelines are important resource delivery devices between land and ocean. For safety reasons, pipelines are often embedded beneath the seabed at a certain depth, to reduce the risk of direct damage to the pipeline. In the past, various kinds of detection equipment have been used for pipeline inspection, to ensure the normal operation of pipelines in practical applications. Acoustic detection technology is the dominant method to monitor buried submarine pipelines. Extracting and integrating the information in acoustic images, such as the route and burial depth, can help to monitor the status of a pipeline. However, most of the existing methods are based on limited parameters, and they cannot be used to precisely detect and locate a submarine pipeline under complex conditions. In this study, a multi-sensor surveying system was used, which integrates a sub-bottom profiler (SBP) and the Shipborne Over- and Under-Water Integrated Mobile Mapping System (SiOUMMS) on the same ship. The data acquired in this system include acoustic profile images and the over- and under-water topography of the pipeline route area. We also designed a position deviation correction method to improve the accuracy of the pipeline detection positioning, i.e., pipeline positioning correction in the real-time kinematic (RTK) positioning data and pipeline horizontal route correction in the integrated data. Compared with the uncorrected pipeline detection positioning result, the reliability of the pipeline inspection result is greatly improved, and the effectiveness and merit of the proposed method are clearly demonstrated. Finally, we conducted a buried pipeline safety assessment for the installation of newly designed wharf piles at Mawan Port of Shenzhen, China, where the results showed that one of the first rows of wharf piles would collide with the sewage pipeline.

INDEX TERMS Over- and under-water topography, submarine pipeline, acoustic profile images, buried pipeline detection.

I. INTRODUCTION

A submarine pipeline is a pipeline that is laid on the seabed for resource delivery between land and ocean. Submarine pipelines are primarily used to carry oil, gas, or water, and they can be regarded as the lifelines that ensure the safe and efficient transportation of different kinds of basic supplies [1]. The pipelines are usually buried beneath the seabed at a certain depth, to reduce the possibility of direct damage to the pipeline. When the seawater reaches a certain depth, the pipeline can be directly laid on the seabed [2]. However, pipelines are sensitive to a wide variety of damage and defects, such as corrosion and deformation [3]–[5]. Thus, to avoid potential disasters brought about by fracture or leakage, periodic surveying and inspection of a pipeline are adopted as the main maintenance tasks [2], [6].

Various types of equipment have been used to inspect pipelines and their surrounding environment. Inspection equipment can be divided into two categories according to the working principle of the sensor, i.e., visual inspection technology and acoustic detection technology. Both scuba diving inspection and its replacement of remotely operated

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vehicle (ROV) inspection involve the use of visual inspection to track and check the pipeline. These methods can intuitively show the status of a pipeline, without requiring processing or interpretation of the collected data. Therefore, the visual inspection methods are widely used in inspecting the external condition of pipelines and the status of pipelines on the seabed [2], [7]. However, even under the best water conditions, the under-water visibility range is often only a few meters. As a result, it is often difficult to determine the condition of pipelines in a wide area by the use of scuba diving or ROVs. In addition, although an ROV can realize the rough positioning of its body under water [8], it cannot transfer the coordinates to the pipeline. Acoustic detection of a pipeline or cable is usually carried out by generating a sequence of acoustic wave pulses by a submarine pulse transmitter. The acoustic waves reflected from the pipeline are then detected by a submarine wave receiver and displayed to show the position of the pipeline or cable with respect to the seabed [9]. Extracting and integrating the acoustic image information can help to monitor the status of a pipeline, such as the route and burial depth. At present, the most commonly used acoustic inspection systems include the side-scan sonar (SSS), the multibeam bathymetric system (MBS), and the sub-bottom profiler (SBP). The SSS uses the bathymetric echo principle to detect seafloor geomorphology and underwater objects. The transducer array is either installed in the hull of a surface vessel or towed behind the ship. By obtaining high-resolution topographic and geomorphological images of the seafloor, the route of an unburied pipeline can be identified intuitively [10], [11]. However, due to the separation of the towed transducer and the vessel hull, this can lead to poor positioning accuracy for the detected pipeline in the geomorphological imagery. The SBP uses the technique of reflection seismology to create a 2D picture of the geology beneath the seabed. In buried pipeline detection, compared with the other background signals, there is a great difference in the acoustic impedance between the strata and the pipeline, and diffraction waves are often produced at this interface. The diffraction waves caused by a buried pipeline are visible as obvious hyperbolic features in the acoustic profile images [12]. The MBS sends out a fan-shaped sound wave beneath the vessel's hull, and determines the water depth according to the return time of the sound wave. The size, route, and height variation of a pipeline can thus be measured when the ship travels along the survey line [13], [14]. The status of submarine pipelines can be revealed completely by integrating multiple detection methods and making full use of the respective characteristics of each method [14], [15]. MBS and SBP equipment is often installed as modules on ships or other vehicles, and their positioning parameters are calibrated with the use of a positioning and orientation system (POS). As a result, the positioning accuracy for a detected submarine pipeline is often better than that achieved by other methods. However, differing from land surveys, due to the complex sea surface environment and the limited accuracy of the inertial navigation systems, the location accuracy of these methods is often adulterated with system errors, and there are no fixed control point coordinates at sea to correct the system errors. In order to ensure the smooth progress of coastal engineering, detailed geophysical exploration is necessary, and pipeline exploration is one of the most important tasks. Coastal engineering department need to accurately detect the location of buried pipelines in construction area to avoid any damage caused by the coastal engineering operations. At present, the detection methods for buried submarine pipelines cannot meet the requirements of coastal engineering departments in positioning accuracy.

In recent years, the Shipborne Over- and Under-Water Integrated Mobile Mapping System (SiOUMMS) has become a key technique for collecting high-accuracy spatial information in coastal zones, islands, reefs, and channels [16]–[19]. The SiOUMMS system integrates advanced sensors, including an MBS, a laser scanner system (LSS), a Global Navigation Satellite System (GNSS), and an Inertial Measurement Unit (IMU). In the SiOUMMS system, the over-water spatial information can be easily verified by the use of a measuring system on land, such as real-time kinematic (RTK) positioning or a total station, which corrects the deviation of the over-water topographic survey, thus improving the accuracy of the under-water topographic survey [16], [17]. Shi *et al.* [18] applied the SiOUMMS system to the measurement of lakeshores, islands, and bridges, and achieved a high accuracy in the over- and under-water integrated measurement. Guan *et al.* [16] applied the SiOUMMS system to achieve a positioning accuracy for a pier pile of better than 10 cm. However, few studies have applied this new technique to the detection of submarine pipelines. Therefore, this study was aimed at integrating the SiOUMMS system into the conventional buried submarine pipeline detection methods, to improve the accuracy of the pipeline positioning.

In this paper, we conducted a buried pipeline safety assessment for the installation of newly designed wharf piles at Mawan Port of Shenzhen, China. The spatial information of the over- and under-water coastal topography, and the acoustic profile images of the buried pipeline were obtained by the SiOUMMS system and the SBP, respectively. Both of them are installed on the same ship and share the same GNSS and IMU data. With the data acquired from the different sensors, we extracted the crude positions of the pipeline outfalls and the buried pipeline route. Meanwhile, we extracted and corrected the systematic error from the compared results between the over-water point cloud positions and the RTK positioning data. We then established the pipeline route based on the corrected integrated system results. The experimental results were provided to the marine engineering department, who confirmed that there would be a collision between the newly designed wharf piles and the submarine pipeline.

II. METHOD

In this paper, we propose an effective method for submarine buried pipeline route detection in coastal areas based on multi-sensor data fusion. The proposed method can be

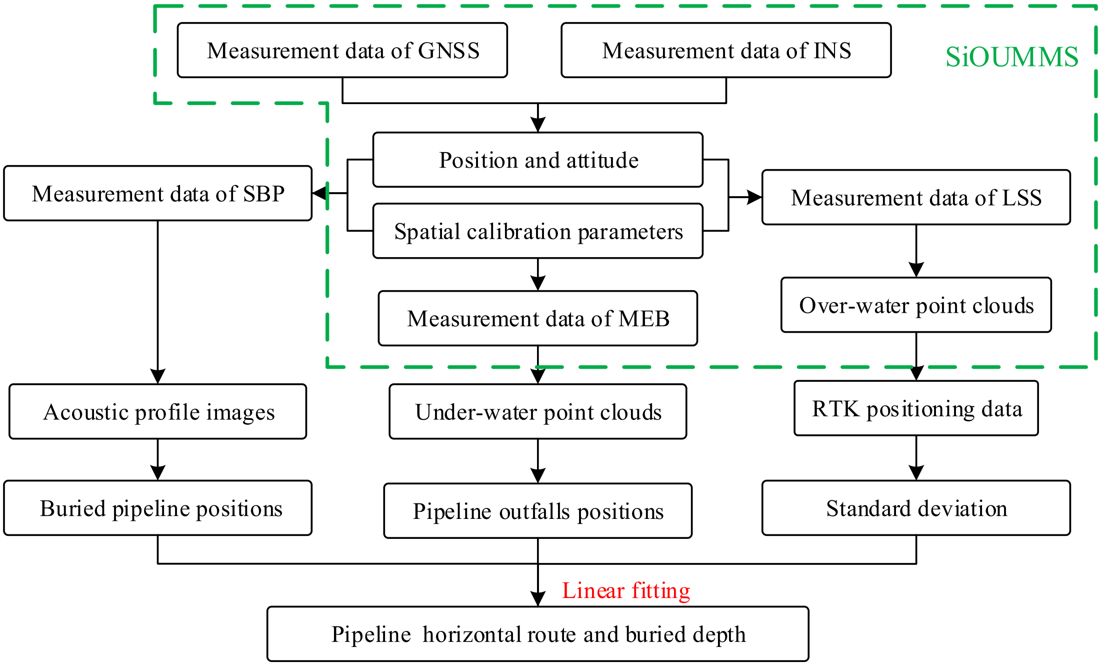


FIGURE 1. Flowchart of using muti-sensor fusion to acquire the buried submarine pipeine spatial information. The green dashed line represents the composition and workflow of the SiOUMMS system. The spatial calibration parameters include the caliration of the LSS, MBS and SBP, respectively.

divided into two parts. Firstly, we obtain the over- and under-water topography point clouds and the acoustic profile images around the buried pipeline route by the multi-sensor integrated system measurements. Then, a specially designed position deviation correction method is used to mitigate the systematic deviation components in the buried pipeline route established by the multi-sensor data fusion.

A. MULTI-SENSOR FUSION DETECTION

In the multi-sensor fusion detection, we integrate SiOUMMS system and an SBP system on a single ship, where the two systems share the same GNSS and IMU data. We can then obtain the over- and under-water topography point clouds and the acoustic profile images around the buried pipeline route through the multi-sensor surveying system. The integrated system is made up of an MBS, an SBP, an LSS, and a POS, as shown in Figure 1. The idea of this integrated surveying system is to ensure that the different equipment types become a rigid body by means of solid-state connection. The real-time positioning and orientation parameters of the ship are calculated by the use of the POS, and we can then set up the parameters in each sensor. The POS can obtain the external azimuth elements and attitude parameters, independent of the ground control points, and can provide direct geographical coordinate reference data for the integrated measurement system. Direct geo- referencing techniques can then be realized by using the precise time parameters. Finally, the acoustic profile images and the over- and under-water topography are obtained together in the same coordinate system.

In SBP detection, compared with background signals, there is a great difference in acoustic impedance between the strata and the pipeline, and diffraction waves are often produced at this interface. The diffraction waves are visible as obvious hyperbolic features in the acoustic profile images [12]. Based on this characteristic, we can extract the horizontal position and the burial depth of a pipeline using the SBP [14], [15]. A pipeline in a certain area can show an obvious difference with the surrounding topography, such as exposed pipeline parts, marine outfalls, and riprap protection. This different seabed topography information can be depicted by the high density point clouds generated with the data collected by the SiOUMMS system, where the characteristics can be more intuitively discerned than the features in the acoustic profile images. In this study, the buried pipeline outfalls could be quickly found using the SiOUMMS system. By analyzing the characteristics of the outfall locations, we set up a "measurement line scheme" for the vertical pipeline route, in order to obtain more obvious features of the pipeline in the acoustic profile images. We could then acquire seamless over- and under-water topography from the outfalls to land.

B. PIPELINE DETECTION POSITIONING CORRECTION

We designed a position deviation correction method. i.e., pipeline positioning correction in the RTK positioning data, and pipeline horizontal route correction in the integrated data. To improve the pipeline detection positioning accuracy.

1) PIPELINE POSITIONING CORRECTION IN THE RTK POSITIONING DATA

We can extract the crude position of the buried pipeline from the acoustic profile images and the position of the exposed pipeline from the under-water point clouds. However, as a result of the complex under-water environment, and the fact that there are no fixed control point coordinates at sea, it is difficult to evaluate the precision of the crude pipeline position obtained in this way. However, due to the different equipment becoming a rigid body, the positioning and orientation parameters are the same for each sensor. We can also reduce the measurement error of the multisensor integration by using RTK positioning data to calculate the systematic deviation of the over-water point clouds. We can therefore extract the coordinates of the feature points from the over-water point clouds measured by the LSS, and can then perform precision evaluation with the measured and accurate coordinates. To evaluate the precision of the over-water point clouds, we can acquire accurate coordinates of the feature points through the RTK positioning, and we can then extract the systematic deviation of these point clouds. Finally, we can use the systematic deviation to reduce the measurement deviation of the position of the buried pipeline obtained by the SBP and the exposed pipeline outfalls obtained by the MBS.

2) PIPELINE HORIZONTAL ROUTE CORRECTION IN THE INTEGRATED DATA

The data acquisition system includes the SiOUMMS system and an SBP deployed on the same ship. The spatial vectors between the individual sensor systems are determined precisely in the ship coordinate system by the geodetic measuring procedure, so that all the measurements can be transformed into the same coordinate system. The over- and under-water topography and the acoustic profile images are acquired synchronously. We obtain the coordinates of the pipeline outfalls from the under-water topography point clouds measured by the SiOUMMS system, and we extract the coordinates of the features of the pipeline from the acoustic profile images.

However, the working principle of the SBP itself often causes distortion of the images and multiplicity of the data under certain seabed sedimentation conditions [20]. As a result, the coordinates of the features extracted often contain inevitable errors. Because the buried marine outfalls have a vertical relationship with the pipeline route, they have the same horizontal coordinates. By integrating the horizontal route of the outfalls from the SiOUMMS system and the pipeline horizontal route from the SBP, we can use an appropriate linear fitting method to deduce the exact position of the submarine pipeline horizontal route. The commonly used least-squares fitting algorithm was used in this study:

$$\begin{aligned} &f(x_i) = a + bx_i \\ &\mathrm{a} = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{n\sum x_i^2 - \left(\sum x_i\right)^2}, b = \frac{\sum y_i - a\sum x_i}{n} \end{aligned} \tag{1}$$

where $f(x_i)$ is the fitting line in discrete pipeline coordinates; (x, y) is the coordinates of the detected pipeline; i is the serial number of the coordinates; and n is the number of coordinates.

III. EXAMPLE

A. FIELD EXPERIMENT DESCRIPTION

We chose a section of buried sewage pipeline, which runs perpendicular to Mawan pier in Mawan Port of Shenzhen, China, as the demonstration pipeline to verify the effectiveness of the proposed pipeline detection method. The water depths in this survey area range from 10 m to 17 m. The sedimentology of the seabed around the route of the pipeline is predominately medium- to fine-grained sand [21].

A steel structure sewage pipeline with a diameter of 2 m passes through the bottom of the wharf, with the axis of the sewage pipeline being vertical to the front of the wharf. The length of the sewage pipeline is 1609 m, with about 1000 m in the sea, and 10 vertical pipeline outfalls. In the surveying project for Mawan wharf, the construction department designed and proposed four rows of new piles. The elevation of the pile tips is from −25 to −32 m, and the diameter of the piles is 1.4 m. The spacing between the first row of piles and the second to the fourth row is 5 m and 10 m, respectively. The planar coordinate system used in the design is the Shenzhen independent coordinate system, and the elevation coordinate system is the Huang-Hai-56 national elevation system. It was necessary to measure the horizontal route and the burial depth of the sewage pipeline, so that the newly designed wharf did not collide with, and thus damage, the sewage pipeline.

B. BURIED SUBMARINE PIPELINE DETECTION

In this study, we used the integrated surveying system to detect the submarine pipeline route and the burial depth. The integrated surveying system included the SiOUMMS system and the SBP deployed on the same ship. The SiOUMMS system was equipped with a RIEGL VZ1000 laser scanner, a Reson SeaBat7125 multibeam echo sounder, and an Applanix POS MV WaveMaster [22]–[24]. The SBP was a Teledyne Chirp III [25]. Meanwhile, the POS MV also provided synchronous attitude and position information to the SBP. The technical parameters of each sensor are listed in Table 1.

We first quickly found the pipeline outfall locations from the under-water topography point clouds obtained through the SiOUMMS system, as shown in Figure 3. By analyzing the characteristics of the outfall route, we set up the measurement line scheme for the vertical pipeline route, as shown in Figure 2, to obtain more obvious features of the pipeline in the acoustic profile images, as shown in Figure 4. In the process of operation, with the change of strata and water depth, the field personnel were required to adjust the parameter settings of the integrated surveying system. Finally, we simultaneously acquired the seamless over- and under-water topography from the outfalls to the land.

C. RESULT OF THE SUBMARINE BURIED PIPELINE POSITIONING

After acquiring the data from the different sensors, the first step was to extract the crude positions of the outfalls from the

TABLE 1. Technical specifications of the RIEGL VZ1000 laser scanner, the reson SeaBat7125 multibeam echo sounder, the Applanix POS MV wavemaster, and the Teledyne Chirp III.

RIEGL VZ-1000		Reson SeaBat7125		Applanix POS MV WaveMaster		Teledyne Chirp III	
Distance range	2.5–1400 m	Frequency	200 kHz/400 kHz	Horizontal position	8 mm	Operating depth	200 m
Angle range	100°	Max range	500 m	Vertical position	15 mm	Signal resolution	16 bit
Precision	5 mm	Swath coverage	128°	Roll & pitch	0.02°	Ping rate	15 pings
Accuracy	8 mm	Number of beams	256 Hz /512 Hz	Heave	5 cm / 5%^{3}	-	-
Beam divergence	0.3 mrad	Depth resolution	5 mm	-	-	-	-

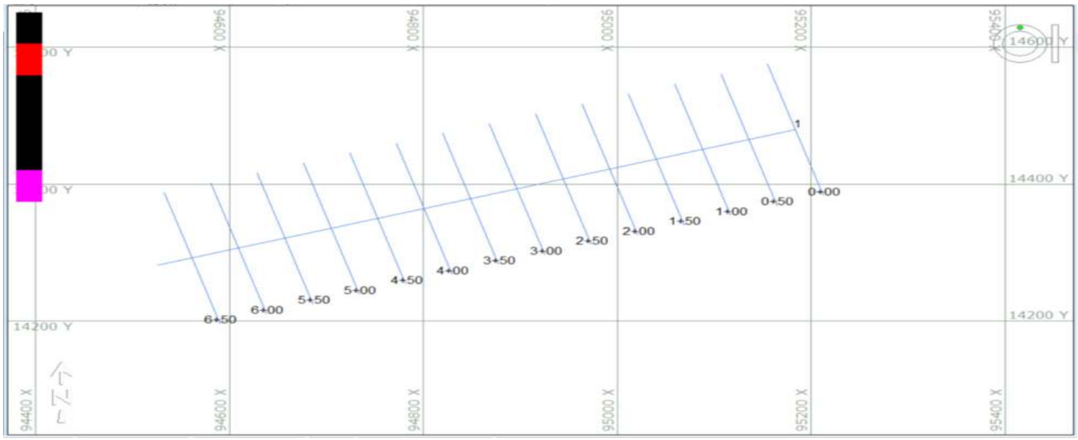


FIGURE 2. The measurement line scheme layout in hypack. We designed 14 measurement lines, with a spacing of 50 m between each line.

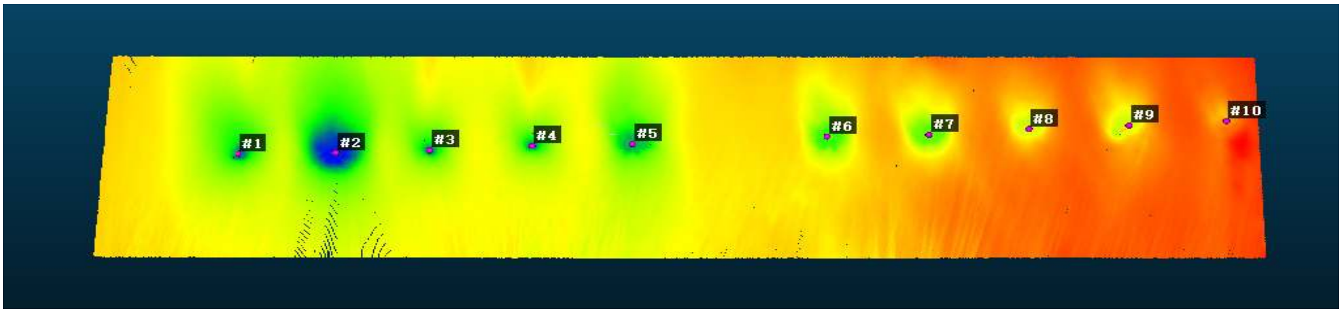


FIGURE 3. The cloud chart of the outfall of the buried pipeline produced by the multibeam bathymetric system. The hydrological effects of the outfalls result in the sedimentation around the outfalls being different from that of the surrounding environment. The purple points mark the centers of the outfalls.

under-water topographic point cloud maps and identify the pipeline horizontal route from the acoustic profile images.

From Figure 5, we can see that the burial depth of this pipeline is between −23 m and −23.5 m, and the mean burial depth is −23.22 m. The burial depth of the newly designed pile tips is from −25 to −32 m. Thus, the newly designed piles could collide with the buried pipeline.

The next step was to correct the crude pipeline positions in the RTK positioning. We extracted 10 groups of over-water point cloud positions from the edge of the wharf, and carried out RTK positioning on these 10 feature points. We then calculated the deviation between the point cloud positions and the RTK positioning data in these feature points, and set the mean deviation as the measurement systematic deviation. Table 2 lists the elevation and horizontal gap spacing statistics.

After correcting the systematic deviation of the integrated system results, we established the pipeline horizontal route using the buried pipeline positions using the fusion data of the buried pipeline positions and the pipeline outfall positions. The next task was to correct the crude pipeline positions in the RTK positioning. We extracted 10 groups of over-water point cloud positions from the edge of the wharf, and carried out RTK positioning on these 10 feature points, as shown

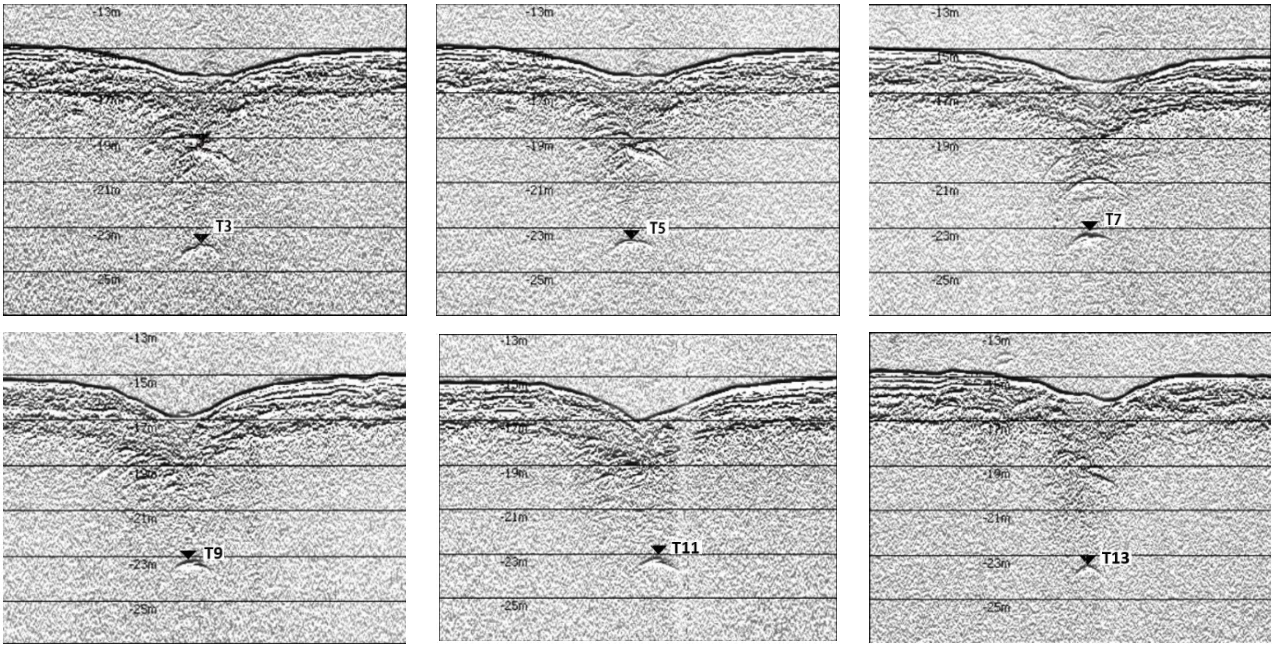


FIGURE 4. **Partial buried pipeline acoustic profile images collected by the SBP, with the black hyperbolic features representing the sectional view of the pipeline. In the acoustic profile images, the hyperbolic top of the buried pipeline is below the seabed surface. We obtained the horizontal coordinate and buried depth of the pipeline by extracting the position at the hyperbolic curve.**

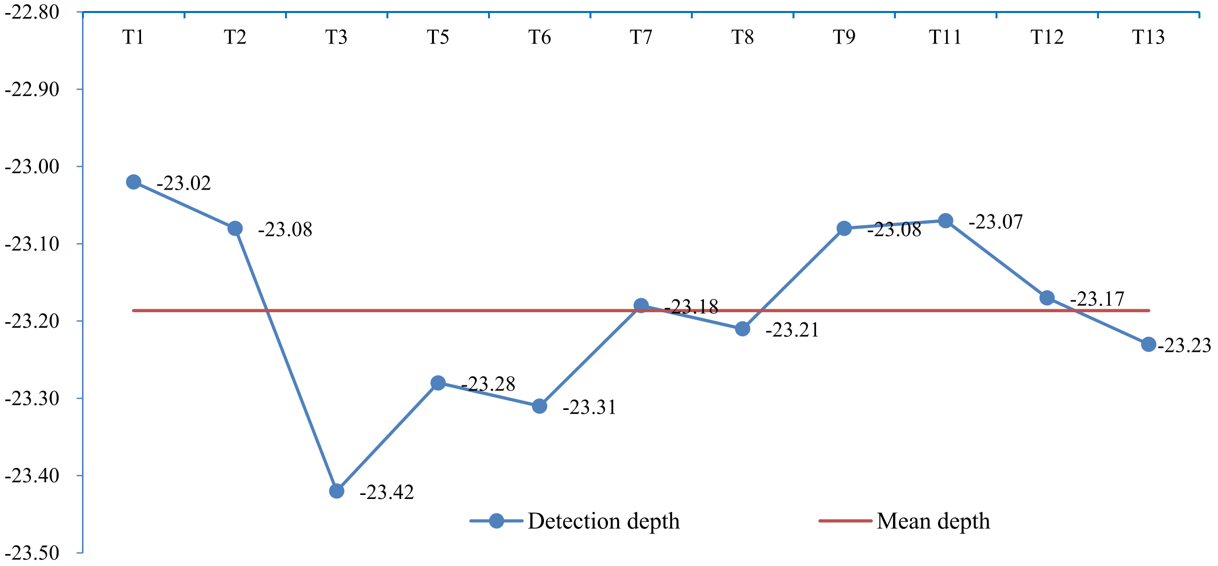
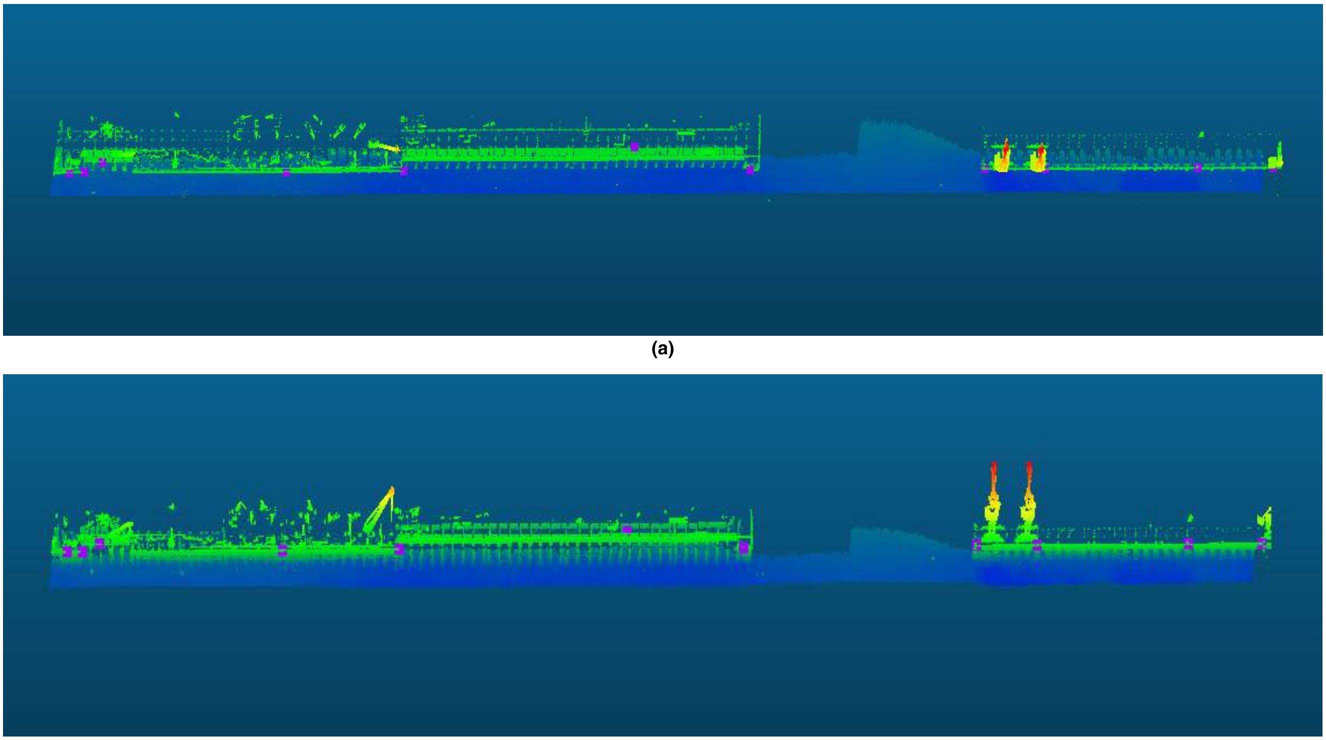


FIGURE 5. **The effective pipeline burial depths extracted from the acoustic profile images. The hyperbolic features in the T4 and T10 acoustic images are not obvious, and were not used in calculating the average buried pipeline depth.**

in Figure 6. We then calculated the deviation between the point cloud positions and the RTK positioning data in these feature points, and chose the mean deviation in the comparison result as the measurement systematic deviation to reduce the measurement error of the position of the detected buried pipeline. Table 2 lists the elevation and horizontal gap spacing statistics.

To better understand the RTK positioning data correction, it was necessary to design an appropriate verification scheme to evaluate the performance and characteristics compared with the uncorrected feature points of the over-water point clouds. We therefore designed a verification scheme, based on the feature points of the over-water point cloud positions and the RTK positioning data. The purpose of the verification scheme was to evaluate the performance and characteristics of the systematic position deviation correction method in reducing the measurement error of the over-water point clouds. Firstly, we chose one of the RTK positioning data



(a)

(b)

FIGURE 6. Results of the measurements in the Mawan wharf over- and under-water point clouds. (a) The vertical angle-of-view of the point clouds. (b) The horizontal angle-of-view of the of the point clouds, where the purple rectangles are the RTK positioning data.

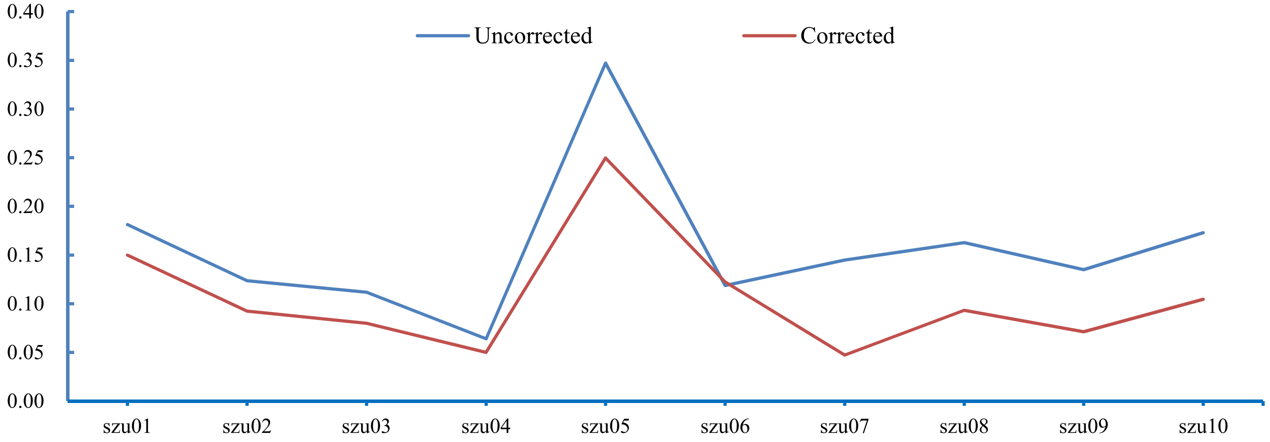


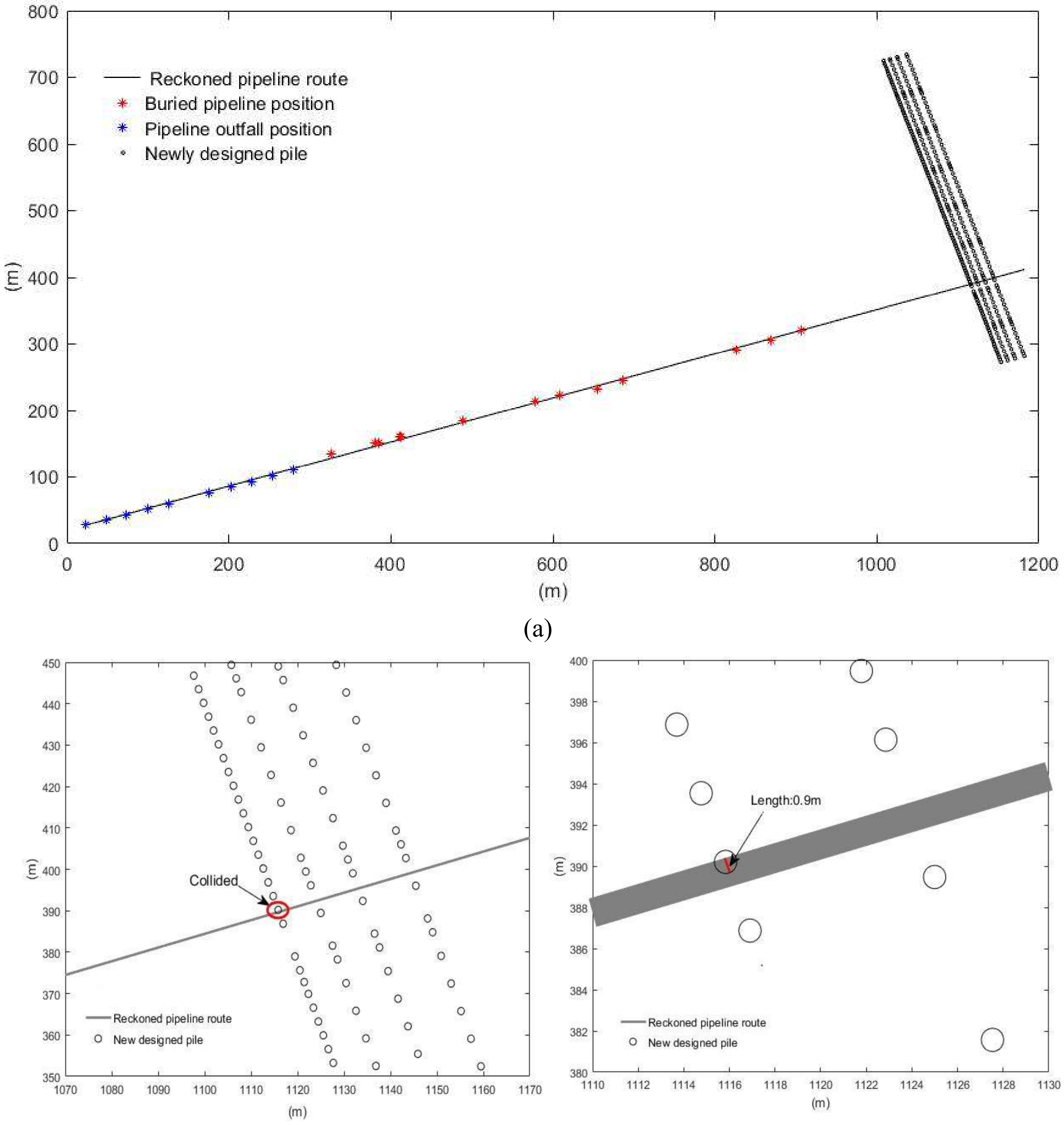
FIGURE 7. Comparison of the corrected and uncorrected over-water point cloud error in the outer precision.

points in the feature points as a known point, and the other RTK positioning data were used to calculate the systematic deviation for correcting the measurement error of the over-water point clouds. Secondly, we analyzed the outer precision of the corrected and uncorrected over-water point clouds. In this study, the outer precision was measured by the distance error, which was calculated by the deviations in the x, y, and z directions:

$$d = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} \tag{2}$$

where d is the distance error; Δx, Δy and Δz is the deviation in the x, y, and z direction, respectively.

From Figure 7, we can see that the error correction has an obvious effect, where the point error is reduced by more than 5 cm. After correcting the over-water point clouds by the RTK positioning data, we used the same correction parameters to correct the crude positions of the pipeline outfalls and the buried pipeline. We then used the least-squares fitting algorithm to deduce the exact position of the submarine pipeline horizontal route, based on the buried pipeline



(a)

(b) (c)

FIGURE 8. The spatial relationship between the calculated pipeline route and the newly designed piles.

positions and the pipeline outfall position fusion data. Finally, we compared the calculated pipeline route to the newly designed pile positions, to determine any potential collision of the piles with the pipeline.

As seen from Figure 8a, the pipeline route was calculated based on the marine outfall positions and the detected buried positions. From Figure 8b and c, it can be seen that one of the first rows of newly designed piles will collide with the sewage pipeline, with a length of collision area of 0.9 m, but the other piles close to the route are at a safe distance from the pipeline.

IV. DISCUSSION

Geological information under the seafloor can be depicted by the acoustic profile images generated with the data collected by the SBP at sample points in a vertical direction.

TABLE 2. The over-water point cloud position verification and the standard deviation correction. The red characters are the chosen systemmatic deviation; dx, dy and dh represent the horizontal and vertical deviation respectively; Δx, Δy and Δh represent the horizontal and vertical deviation after the deviation correction, respectively (unit: m).

	dx	dy	dh	$\triangle x$	$\triangle y$	$\triangle h$
szu01	0.11	−0.12	0.08	0.08	−0.16	−0.02
szu02	0.10	0.02	0.07	0.07	−0.03	−0.03
szu03	0.08	−0.05	0.06	0.05	−0.09	−0.04
szu04	−0.02	0.01	0.06	−0.05	−0.04	−0.04
szu05	0.09	0.10	0.32	0.06	0.06	0.22
szu07	−0.04	0.10	0.05	−0.07	0.06	−0.05
szu08	0.05	0.08	0.11	0.02	0.04	0.01
szu09	0.00	0.12	0.11	−0.03	0.08	0.01
szu10	−0.01	0.09	0.10	−0.04	0.05	0.00
szu11	−0.05	0.07	0.15	−0.08	0.03	0.05
Mean	0.03	0.04	0.10	0.00	0.00	0.01
RMSE	0.06	0.08	0.13	0.06	0.07	0.07

With an adequate resolution of the profile, small sedimentary structures or buried objects can be easily recognized [26]. The physical and mechanical properties of a buried pipeline are very different from those of the surrounding strata. As a result, the pipeline often produces diffraction waves at this interface. The diffraction waves are visible as obvious hyperbolic features in the acoustic profile images. The hyperbolic features of the pipeline are related to the water depth, ship speed, and signal source. The deeper the water, the more attenuated the signal. At the same depth, the slower the speed, the more obvious the hyperbolic features will be [27], [28]. In practical applications, because of the limitation of the resolution of the shallow-layer profilers, plus the burial conditions of the pipeline and the sea conditions, it is only possible to identify pipelines with a diameter greater than 0.3 m, or pipelines with a diameter of 0.2 to 0.3 m in a shallow water depth. Pipeline recognition is also improved when the sea conditions are calm. For pipelines with a diameter of less than 0.2 m, they can be difficult or even impossible to identify [29].

V. CONCLUSION

In this paper, we have proposed an effective method for the detection and positioning of buried submarine pipelines. To assess the safety of the buried pipeline at Mawan Port of Shenzhen, China, we used a multi-sensor surveying system to acquire the acoustic profile images and the over- and under-water topography of the pipeline route area. Moreover, we designed a position deviation correction method to improve the accuracy of the pipeline detection positioning. Using the refined multi-sensor data, the route of the buried pipeline was detected, and a safety assessment was then conducted to evaluate whether there would be collision between the newly designed wharf piles and the submarine pipeline. The data acquisition system included an SBP and the SiOUMMS system. We integrated the SiOUMMS system and the SBP on the same ship, and shared a set of GNSS and IMU data. Three main advantages of the integrated system are follows: 1) In the shipboard integrated system, each measurement sensor shares a set of GNSS and IMU data, which can reduce the influence of systematic deviation and avoid the decrease in accuracy caused by the data splicing process. 2) The characteristic points of over-water topography are easy to verify by the use of a measuring device on land, such as RTK positioning or a total station, and can be used to correct the deviation of the over-water topographic survey, thus improving the accuracy of the under-water topographic survey. 3) Because the data sources were collected via a multi-sensor approach, the poor quality of the data and the unstable inspection results can be improved by the designed position detection correction method.

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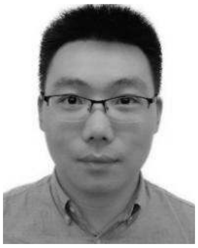

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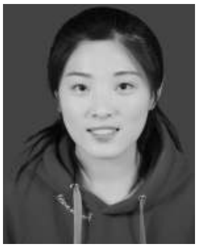

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