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Review

The Development of the Pipe Jacking Guidance Technology

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Abstract: Pipe jacking is one of the most important construction methods in trenchless technology. Pipe jacking guidance technology acquires the jacking route by collecting the attitude and position information of the pipe jacking machine. It ensures that the deviation between the jacking route and the route designed in the engineering drawings during the construction is kept within the error range and prevents the damage to other facilities caused by the deviation of the construction route. It improves the construction efficiency and ensures the precision and safety of pipeline laying. In this paper, the basic principle and working mode of the pipe jacking guidance system are sorted out, and the current technical means are classified and organized. A systematic overview of the research on pipe jacking guidance methods is given, the development trend of pipe jacking guidance systems towards automation, intelligence and multi-source data fusion are discussed, and the challenges faced by pipe jacking guidance systems in complex scenarios are elaborated. This is to provide guidance and reference for the research and practice in related fields and to promote the further innovation and application of pipe jacking guidance technology.

Keywords: pipe jacking guidance systems; total station; prism; gyros

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1. Introduction

In recent years, the development and utilization of underground space have received more and more attention, and the construction of underground pipeline networks is crucial for urban construction [1,2]. Pipe jacking construction causes little damage to rivers, plants, buildings and traffic facilities, generates low noise, works efficiently and can complete the laying of underground pipelines with high quality [3]. In the jacking process, the cutter head has some problems such as uneven force, mechanical oscillation and uneven grouting, which lead to the jacking trajectory deviating from the design route [4]. Therefore, it is necessary to obtain the attitude and position information of pipe jacking in time to correct the current pipe jacking machine to avoid further deviation from the design route. The quality of guidance is contingent upon the pipe jacking machine's capacity to advance efficiently and safely according to the pre-designed plan line, and it is also pivotal to whether the pipe jacking machine can reach the receiving shaft smoothly and finally realize the penetration. With the densification of urban underground pipelines, the new pipeline lines are no longer just short-distance straight lines, and the construction of long-distance and curved lines has become one of the important requirements of pipe jacking construction, which has more stringent requirements for the guidance system of pipe jacking [5–7]. Especially in the long-distance curve jacking construction, as the pipeline needs to advance along the complex curve, the measurement path must be calculated accurately to ensure that the pipeline can be jacked in accordance with the radius and length of the curve required by the design. This not only ensures the construction quality of the pipeline but also avoids damage to the surrounding environment and underground pipelines during the construction process. By measuring the path accurately, the construction personnel can accurately grasp the attitude and position information of the pipe jacking machine, which can help the construction personnel find and deal with the potential safety hazards in time and ensure the construction safety.

At present, the traditional pipe jacking guiding methods include the manual visual inspection method, the prism method and the laser target method. In recent years, the inertial guidance method has been widely studied without considering the bending and distance of the construction pipeline. However, in practical engineering applications, when the construction conditions are more demanding, such as small diameters, curves and long distances, it is difficult for a single method to meet the accuracy and adapt to all construction environments in the research of pipe jacking guidance methods. Therefore, a hybrid method using the above methods is proposed. At the same time, the idea of multi-source data fusion based on multiple sensors has a remarkable effect on improving the guidance accuracy and has been paid attention to by many researchers.

The research of the pipe jacking guidance system is of great significance to the development and utilization of urban underground space. Therefore, this paper will summarize the current technical status of the pipe jacking guidance system in order to help researchers in the follow-up research in this field.

2. Manual Visual Inspection Method

The manual visual inspection method is a manually guided method of controlling the reverse deflection of the pipe jacking machine by the technician observing the deviation of the laser dot on the laser target. As shown in Figure 1, the laser launchers such as the laser theodolite or laser total station are set up in the ground of the starting shaft, and the laser receiving target is set up at the pipe jacking machine. During pipe jacking, the laser beam is kept parallel to the central axis of the design. During pipe jacking forward, the technician meticulously observes the change in the position of the laser point on the laser target. In the event that the laser point on the laser target deviates abnormally, the technician will precisely control the pipe jacking machine to correct the deviation in the reverse direction.

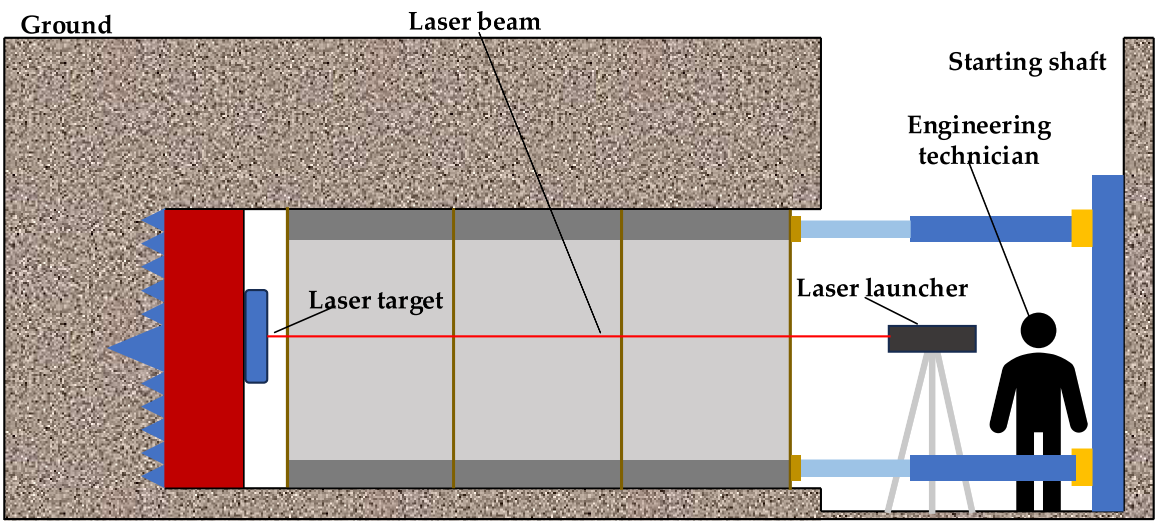

Figure 1. Schematic diagram of the manual visual inspection method.

3. Laser Target Method

3.1. System Configuration

The laser target method is a relative approach to the manual visual inspection method. It involves the implementation of a corresponding transformation by the laser target, thereby replacing the manual visual inspection. As illustrated in Figure 2, the laser target structure is composed of multiple components. The entire equipment for the laser target is placed in a hermetically sealed metal box, the interior of which consists of thin lenses, a CCD camera and a dual-axis inclinometer, among other things. Since the distance of the light-sensitive surface from the thin lens is the focal length f of the thin lens, the laser beam will form a spot with a certain uniform radius on the light-sensitive surface after passing through the thin lens. The CCD camera records the position of the laser spot noted as $P(x_f,y_f)$. The azimuth angle is calculated using spatial relationships, and the dual-axis inclinometer captures the pitch and roll angles.

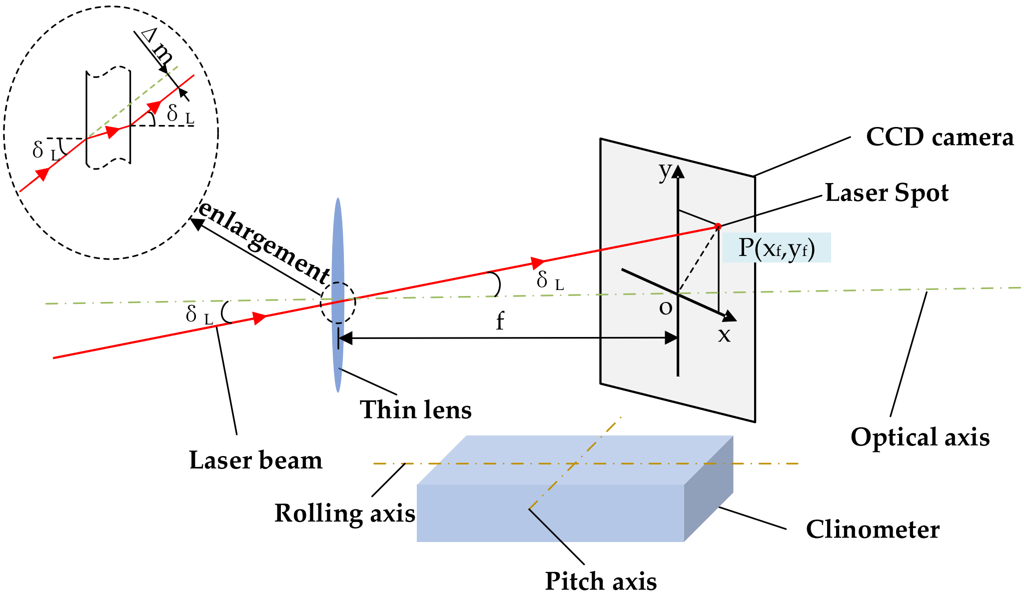

Figure 2. Structure composition of the laser target.

Given that the thickness of the thin lens is considerably less than the focal length f, the offset due to the refraction of the laser beam is neglected in the localized enlargement in Figure 2, i.e., Δm = 0. Since the optical axis of the laser target is parallel to the central axis of the pipe jacking machine, the angle δ_L between the laser beam and the optical axis is also the angle between the laser beam and the central axis of the pipe jacking machine. Based on the spatial geometry, δ_L is calculated as shown in Equation (1).

$$\delta_L = \arctan\left(\frac{1}{f}\sqrt{{x_f}^2 + {y_f}^2}\right) \quad (1)$$

The system composition of the laser target method is illustrated in Figure 3. The laser target is set up at the pipe jacking machine, and it is ensured that the optical axis of the laser target (shown in Figure 2) remains parallel to the central axis of the pipe jacking machine. The target prism is close to the laser target, and the laser total station is set up in the starting shaft, and the rear-view prism with a known coordinate is set up on the wall of the starting shaft. The ground control terminal is responsible for resolving the collected data to obtain the required guidance parameters.

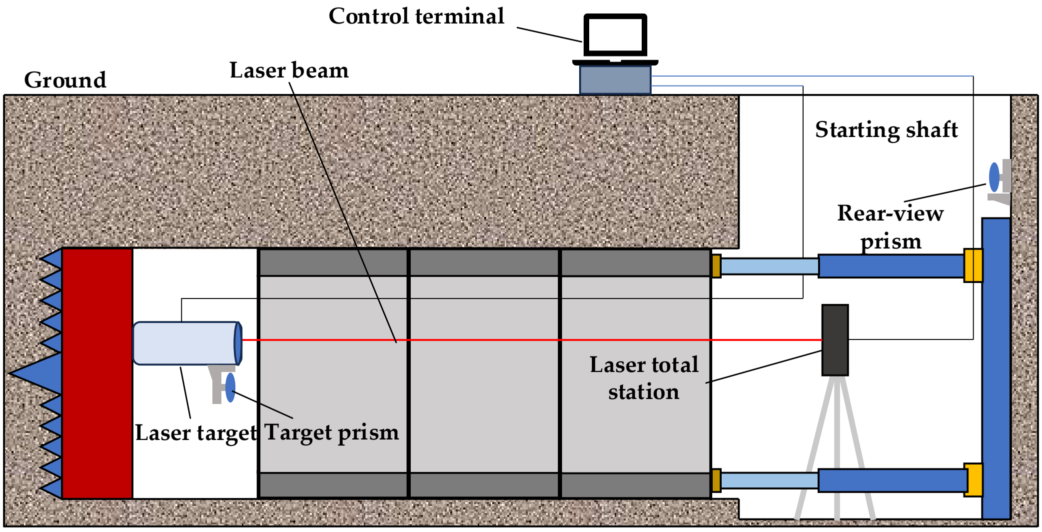

Figure 3. Schematic diagram of the laser target method.

3.2. Measuring Principle

The laser target method is to finally obtain the laser target position and the azimuth, pitch and roll angles of the pipe jacking machine by means of the laser beam and coordinate measurement function provided by the total station [8]. The total station emits a laser beam, which is illuminated onto the target prism below the laser target to obtain the absolute coordinates of the laser target. The laser beam is focused through a thin lens on the laser target to form a laser spot on the light-sensitive panel. The CCD camera collects the laser spot information and utilizes the horizontal and vertical position of the laser spot on the light-sensitive panel to obtain the azimuth of the current state. The laser target is equipped with a dual-axis inclinometer that is capable of measuring pitch and roll angles. Finally, the horizontal and vertical deviations between the central axis of the jacking pipe and the design route are calculated. The calculation process is as follows:

3.2.1. Definition of the Coordinate System

Assuming that the pipe jacking machine is placed horizontally in the space, establish the pipe jacking machine coordinate system, the laser target coordinate system and the absolute coordinate system to calculate the center coordinates of the head and tail of the pipe jacking machine, as shown in Figure 4.

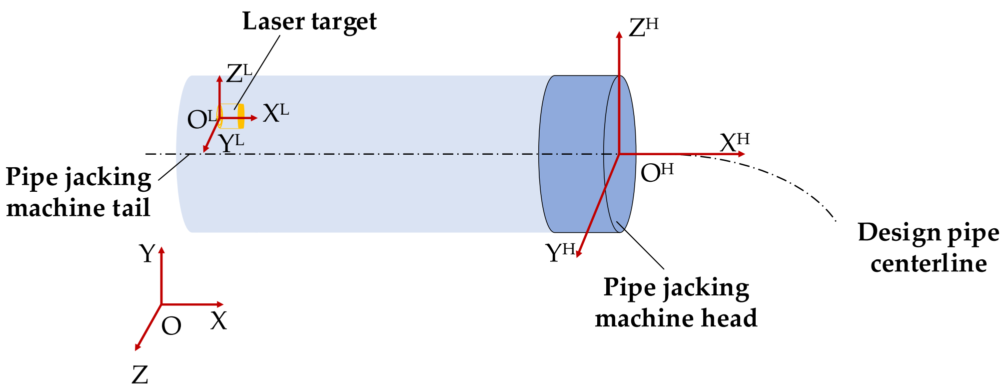

Figure 4. Diagram of the coordinate system.

Pipe jacking machine coordinate system (O^H-$X^HY^HZ^H$): The center of the pipe jacking machine head is designated as the coordinate origin, designated as O^H. The center axis of the pipe jacking machine is the X^H coordinate axis, and the direction from the center of the tail of the pipe jacking machine to the center of the head of the pipe jacking machine is the positive direction. The Z^H-axis is defined as being perpendicular to the horizontal plane and oriented in an upward direction. The direction of the Y^H-axis is determined by the left-hand rule.

Laser target coordinate system (O^L-$X^L Y^L Z^L$): The laser target position is defined as the coordinate origin O^L, and the three-axis direction is oriented parallel to the pipe jacking machine coordinate system.

Absolute coordinate system (O-XYZ): The setting of the absolute coordinate system must be based on the design route situation; for example, the coordinate of the rear-view prism at a known location is the coordinate under the absolute coordinate system. Finally, all the coordinates to be solved must be converted to the absolute coordinate system in order to participate in the calculation.

3.2.2. Angular Measurement

Angle measurements include the pitch angle λ, roll angle β and azimuth angle α of the pipe jacking machine. The dual-axis inclinometer built into the laser target provides the pitch angle λ and roll angle β of the pipe jacking machine. The azimuth angle α needs to be further calculated using the laser spot position inside the laser target.

The azimuth calculation is shown in Figure 5. A temporary coordinate system, O^t-$X^t Y^t Z^t$, is established, with point O^t representing the laser spot and the three axes being parallel to the three axes of the laser target coordinate system, respectively. In the arrangement of the laser target, it is imperative that the optical axis within the laser target is aligned parallel to the central axis of the pipe jacking machine. Therefore, the angle between the laser beam and the central axis of the laser target is equivalent to the angle between the laser beam and the central axis of the pipe jacking machine. The straight-line O^tA (translation axis O^tA) is parallel to both the central axis of the pipe jacking machine and the optical central axis of the laser target. The blue dashed line forms a horizontal plane ψ with the X^t-axis and Y-axis, and O^tA_1 and O^tB_1 are the projections of the straight-line O^tA and the laser beam O^tB on the horizontal plane ψ. The horizontal azimuth (ε) of the laser beam and the angle (λ_1) between the laser beam and the horizontal plane are measured by the total station. The angle between O^tA and its projection, O^tA_1, in the horizontal plane is the pitch angle (λ) of the pipe jacking machine.

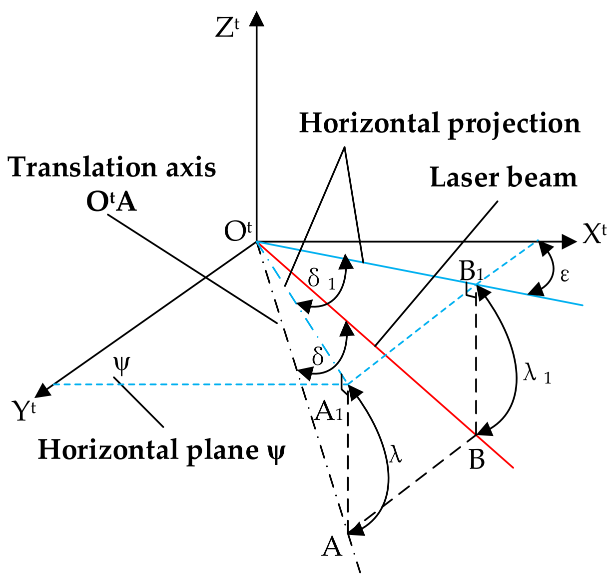

Figure 5. Schematic diagram of the azimuth calculation principle.

The angle δ between the laser beam O^tB and the line O^tA is equal to δ_L in Equation (1), which is shown in Equation (2):

$$\delta = \delta_L \tag{2}$$

δ_1 can be calculated according to the cosine theorem as shown in Equation (3).

$$\delta_1 = \arccos\left(\frac{\cos\delta - \sin\lambda\sin\lambda_1}{\cos\lambda\cos\lambda_1}\right) \tag{3}$$

The angle α between the horizontal plane projection O^tA_1 of the straight-line O^tA and the X^t-axis of the temporary coordinate system is the azimuth angle. According to the geometric relationship, the azimuth angle α is calculated in Equation (4).

$$\alpha = \varepsilon + \delta_1 \tag{4}$$

3.2.3. Absolute Coordinate Calculation

Absolute coordinate calculation means to convert the coordinates of the pipe jacking machine's center of the head and the pipe jacking machine's center of the tail in the laser target coordinate system to the absolute coordinates in the absolute coordinate system. This provides absolute coordinate information for subsequent calculations of horizontal and vertical deviation.

The total station is utilized to illuminate the prism at the lower end of the laser target, thereby enabling indirect measurement of the absolute coordinates of the laser target within the absolute coordinate system. These coordinates are recorded as $L(X_0,Y_0,Z_0)$. The pipe jacking machine and the laser target are relatively fixed in space, therefore, the positional parameters of the laser target at the pipe jacking machine are constant. As shown in Figure 6, according to the spatial position relationship, the coordinate information under the coordinate system of the pipe jacking machine can be obtained: the head center of the pipe jacking machine coordinates H(0,0,0), the tail center of the pipe jacking machine coordinates T(−A−B,0,0) and the laser target coordinates L(−B,D,C); coordinate information in the laser target coordinate system: the head center of the pipe jacking machine coordinates H(B,−D,−C), the tail center of the pipe jacking machine coordinates T(−A,0,−C) and the laser target coordinates L(0,0,0).

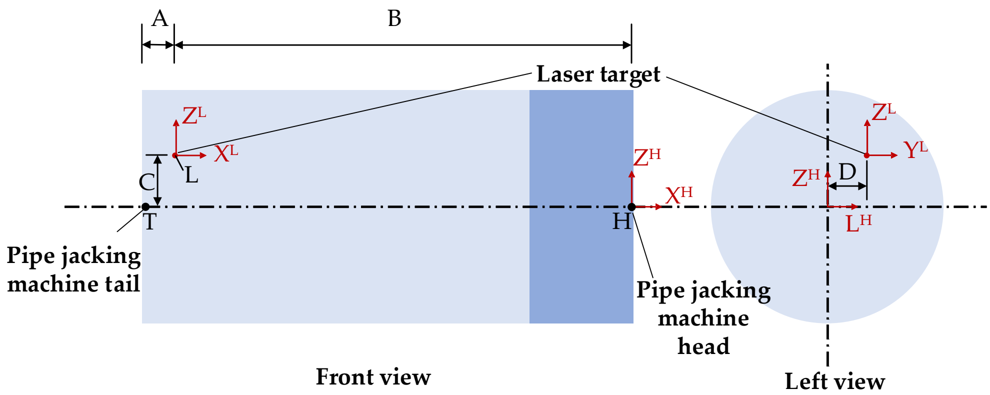

Figure 6. Spatial position diagram of the laser target.

The absolute coordinates (X_1,Y_1,Z_1) of the head center H of the pipe jacking machine are its coordinates (B,−D,−C) under the laser target coordinate system rotating β around the X axis, λ around the Y axis and α around the Z axis, and the translations of the three axes are (X_0,Y_0,Z_0), which can be calculated by the rotating matrix coordinate transformation Equation (5).

$$\begin{bmatrix} X_1 & Y_1 & Z_1 & 1 \end{bmatrix} = \begin{bmatrix} B & -D & -C & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta & 0 \\ 0 & \sin\beta & \cos\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \cos\lambda & 0 & \sin\lambda & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\lambda & 0 & \cos\lambda & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \cos\alpha & \sin\alpha & 0 & 0 \\ -\sin\alpha & \cos\alpha & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ X_0 & Y_0 & Z_0 & 1 \end{bmatrix} \quad (5)$$

In Equation (5), α, β and γ are the azimuth, roll and pitch angles of the pipe jacking machine, respectively. (X_0, Y_0, Z_0) are the coordinates of the laser target in the absolute coordinate system.

According to Equation (6), the absolute coordinates (X_2, Y_2 and Z_2) of the pipe jacking machine's tail center can be calculated.

$$\begin{bmatrix} X_2 & Y_2 & Z_2 & 1 \end{bmatrix} = \begin{bmatrix} -A & 0 & -C & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta & 0 \\ 0 & \sin\beta & \cos\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \cos\lambda & 0 & \sin\lambda & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\lambda & 0 & \cos\lambda & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \cos\alpha & \sin\alpha & 0 & 0 \\ -\sin\alpha & \cos\alpha & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ X_0 & Y_0 & Z_0 & 1 \end{bmatrix} \quad (6)$$

3.2.4. Calculation of Horizontal Position Deviation and Angular Deviation

The design of the pipeline route in the horizontal plane projection is a curve. The curve in the project is usually equidistant interpolation, in which the entire curve is approximated as a number of straight-line segments. The coordinates of point i on the designed route of the pipeline are a function of the corresponding mileage Li at that point as the independent variable. The functional relationship is illustrated in Equation (7).

$$\begin{cases} X_i = X(L_i) \\ Y_i = Y(L_i) \\ Z_i = Z(L_i) \end{cases} \quad (7)$$

In Equation (7), L_i denotes the mileage corresponding to point i, and X_i, Y_i and Z_i represent the absolute coordinates of X_i, Y_i and Z_i at point i.

The design pipe centerline is a curve. In order to facilitate the calculation to solve the horizontal and vertical deviation, the curve is inserted into a number of points at equal intervals for segmentation so that each segment can be approximated as a straight-line segment. The selection of the proximity straight-line segment is based on finding the nearest end point A and its next end point B to the pipe jacking head H, i.e., the straight-line segment AB is the proximity straight-line segment.

The horizontal deviation HC, the head mileage L_H and the vertical deviation P_H of the head center of the pipe jacking machine are solved by applying Equation (8) according to the relationship in Figure 7.

$$\begin{cases} HC = AH \cdot \sin\lambda_1 \\ L_H = L_A + AH \cdot \cos\lambda_1 \\ P_H = Z_H - [Z_A + (Z_B - Z_A) \cdot AH \cdot \cos\lambda_1 / AB] \end{cases} \tag{8}$$

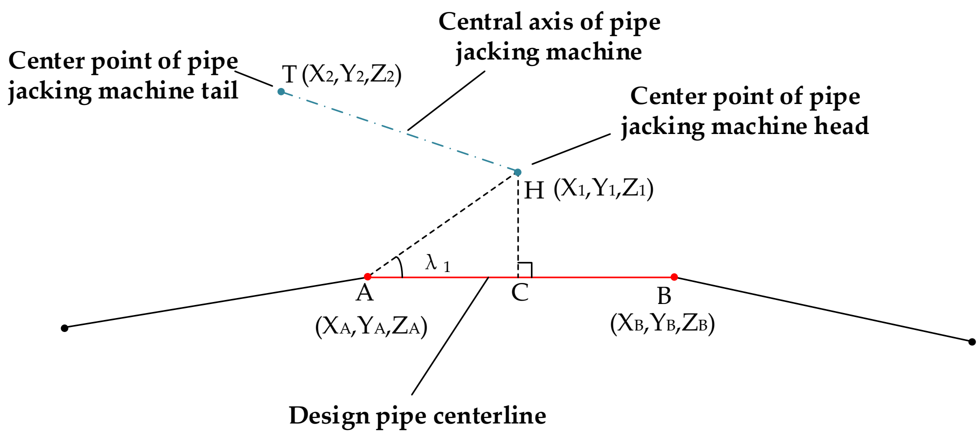

Figure 7. Schematic diagram of the horizontal and vertical deviation principle.

In Equation (8), L_A is defined as the mileage at point A, and Z_i is the elevation coordinate value of point $_i$ (i = A, B, H).

The horizontal angular deviation, designated as ΔH, and the vertical angular deviation, denoted as ΔP, at the center of the pipe jacking machine head are resolved through the application of Equation (9).

$$\begin{cases} \Delta H = \alpha - \arctan[(Y_B - Y_A)/(X_B - X_A)] \\ \Delta P = \lambda - \arctan[(Z_B - Z_A)/AB] \end{cases} \tag{9}$$

In Equation (9), X_i and Y_i represent the coordinate values on the X and Y axes at point i (i = A, B).

The horizontal position deviation and angular deviation of the center point of the pipe jacking machine tail are solved by Equations (8) and (9).

3.2.5. Control Corrections

Based on the above angular deviation and positional deviation information, the fitting correction algorithm is designed so as to control the jacking direction of the pipe jacking machine and reduce the deviation from the design curve.

3.3. Research Status

Lixin Measurement (Shanghai, China) Co., Ltd.'s RMS-D (linear) automatic guiding system adopts fully automatic measurement technology, ensuring high measurement accuracy. The instruments are characterized by their affordability, compact size, minimal pipe aperture requirements and wireless communication capabilities. See Table 1 for details. However, since the laser can only propagate along the straight line, and with the increase of distance, resulting in laser spot discoloration, it seriously affects the guiding accuracy, so the method is suitable for short-distance straight-line construction. The TUnIS Navigation MT^{Laser} from VMT Germany is suitable for short straight-line pipe jacking construction where the length of the pipe jacking is less than 250 m. TUnIS Navigation $MT^{HydrolLevel}$ adds a static leveling to TUnIS Navigation MT^{Laser}. It calculates the vertical position changes of the pipe jacking machine in real time during the jacking process and integrates the vertical position data information into the data of the laser target. This improves the guidance accuracy and the pipe jacking distance. The system can meet the requirements of straight pipe jacking guidance within 400 m.

Table 1. RMS-D automatic guidance system.

Product Advantages	Contents
Measurement accuracy	Guidance system with an accuracy of 2 mm
Measurement range	Total station and laser target measuring distance up to 300 m
Laser angle of incidence range	±25°
Convenient communication	Wireless communication, communication distance up to 500 m
Pipe Outer Diameter	2–15 m

In order to improve the guidance measurement accuracy of this method, the research focuses on laser targets. The ZED's laser target utilizes photoelectric sensor measurement technology inside. The laser target developed by Huazhong University of Science and Technology (HUST) and Shanghai Tunneling Engineering Company Limited (STEC) adopts a non-contact photoelectric detection method. It is inevitable that the laser spot will suffer from aberrations, lack of shape and other phenomena due to problems such as excessive distance during laser propagation, high humidity in the pipeline and deviations in the placement of the CCD camera. Wang [9] established a geometric transformation correction model to improve the laser spot perspective distortion caused by the skewed installation position of the industrial camera. The grayscale centroid algorithm was used to calibrate the center coordinate position, and the actual coordinate position was obtained through coordinate transformation. Experiments showed that the system accuracy of this method was better than 0.1°. Huang [10,11] proposed a dual-screen visual target system, which used a front and rear dual imaging screen, two industrial cameras arranged relative to each other and a built-in dual-axis inclinometer to measure roll and pitch angle information.

4. Prism Method

The prism method utilizes a total station to emit a laser, thereby aligning the three prisms at the pipe jacking machine and acquiring their absolute coordinates. This process is then used to deduce the absolute coordinates of the head and tail of the pipe jacking machine. Subsequently, the attitude angle information (azimuth, pitch and roll angle) of the pipe jacking machine is solved for using the spatial vector relationship. Finally, the horizontal and vertical deviations of the center of the head and tail of the pipe jacking machine from the designed route are calculated so as to provide guidance parameter information for subsequent pipe jacking correction [12].

4.1. Measuring Principle

4.1.1. Coordinate Measurement

Coordinate measurement uses the principle of three points to determine a plane to calculate the center coordinates of the pipe jacking machine's head and tail. As shown in Figure 8, target prisms are placed at target points A, B and C at the tail of the pipe jacking machine. The coordinates of the target prisms are obtained by the total station and are marked as (X_i, Y_i, Z_i) (i = A, B, C). The center coordinates of the pipe jacking machine head are set (X_{O1}, Y_{O1}, Z_{O1}) and the center coordinates of the pipe jacking machine tail are set (X_{O2}, Y_{O2}, Z_{O2}). The calculation of the head center coordinate of the pipe jacking machine is based on the same principles and formulae as the calculation of the tail center coordinate of the pipe jacking machine. Consequently, the following discussion will focus exclusively on the head center coordinate of the pipe jacking machine.

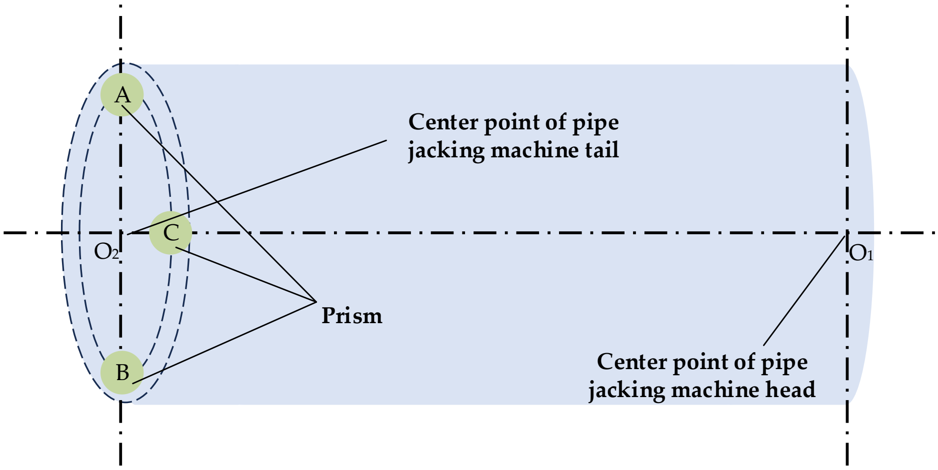

Figure 8. Schematic diagram of the prism method scheme.

The spatial positions of the three target prisms from the center of the pipe jacking machine head remain unchanged. Before the pipe jacking construction, the distances from prisms A, B and C to the center of the pipe jacking machine head O_1 can be measured based on the initial measurement, which are recorded as D_{AO1}, D_{BO1} and D_{CO1}. In the pipe jacking construction process, once the target prism coordinates have been obtained through the total station, the distance Equation (10) can be utilized.

$$\begin{cases} (X_A - X_{O1})^2 + (Y_A - Y_{O1})^2 + (Z_A - Z_{O1})^2 = D_{AO1}^2 \\ (X_B - X_{O1})^2 + (Y_B - Y_{O1})^2 + (Z_B - Z_{O1})^2 = D_{BO1}^2 \\ (X_C - X_{O1})^2 + (Y_C - Y_{O1})^2 + (Z_C - Z_{O1})^2 = D_{CO1}^2 \end{cases} \tag{10}$$

In Equation (10), (X_i, Y_i, Z_i) (i = A, B, C) denote the target prism coordinates, (X_{O1}, Y_{O1}, Z_{O1}) represent the head center coordinates of the pipe jacking head and D_{iO1} (i = A, B, C) are the known distance parameters.

Assume that the normal vector coordinates of the plane where the target prism is located are (X_{ABC}, Y_{ABC}, Z_{ABC}), and the calculation Equation (11) is as follows based on the target prisms A, B and C:

$$\begin{pmatrix} X_{ABC} & Y_{ABC} & Z_{ABC} \end{pmatrix} = \left(\begin{vmatrix} Y_A - Y_B & Z_A - Z_B \\ Y_A - Y_C & Z_A - Z_C \end{vmatrix} \quad \begin{vmatrix} Z_A - Z_B & X_A - X_B \\ Z_A - Z_C & X_A - X_C \end{vmatrix} \quad \begin{vmatrix} X_A - X_B & Y_A - Y_B \\ X_A - X_C & Y_A - Y_C \end{vmatrix} \right) \tag{11}$$

According to the plane normal vector coordinates (X_{ABC}, Y_{ABC}, Z_{ABC}), the equation for the plane is:

$$X_{ABC}x + Y_{ABC}y + Z_{ABC}z + D = 0 \tag{12}$$

In Equation (12), (x, y, z) are the coordinates of any point on the plane where the target prism is located.

Substituting the coordinates of any point of A, B and C into Equation (12) to obtain D, that is, Equation (13):

$$D = -(X_{ABC}X_A + Y_{ABC}Y_A + Z_{ABC}Z_A) \tag{13}$$

According to the point-to-plane distance Equation (14), the distance D_{ABC} from the center O_1 of the jacking machine head to the plane can be obtained:

$$D_{ABC} = X_{ABC}X_{O1} + Y_{ABC}Y_{O1} + Z_{ABC}Z_{O1} \tag{14}$$

The coordinates of O_1 (X_{O1}, Y_{O1}, Z_{O1}) at the center of pipe jacking head can be obtained by solving the above Equations (10), (11), (13) and (14).

In a similar manner, the center coordinates O_2 (X_{O2}, Y_{O2}, Z_{O2}) of the pipe jacking machine tail can be obtained.

4.1.2. Angular Measurement

According to the center coordinate values O_1 (X_{O1}, Y_{O1}, Z_{O1}) and O_2 (X_{O2}, Y_{O2}, Z_{O2}) of the pipe jacking machine's head and tail solved in Section 4.1.1, the angles between the coordinate axes can be calculated. For example, the angle δ with the *x*-axis is calculated and solved by Equation (15).

$$\delta = \arctan\left(\frac{\sqrt{(Y_{O2}-Y_{O1})^2+(Z_{O2}-Z_{O1})^2}}{X_{O2}-X_{O1}}\right) \quad (15)$$

The calculation principle of the space vector of the azimuth, pitch and roll angle of the pipe jacking machine is shown in Figure 9. Vector a is the direction vector of the designed trajectory route, the red dotted line is the projection of vector a on the horizontal plane and the angle between vector a and the horizontal plane is θ. The yellow local plane is defined as the plane coplanar with vector a and at an angle θ to the horizontal, denoted as plane m. Vector b is defined as the normal vector to plane m.

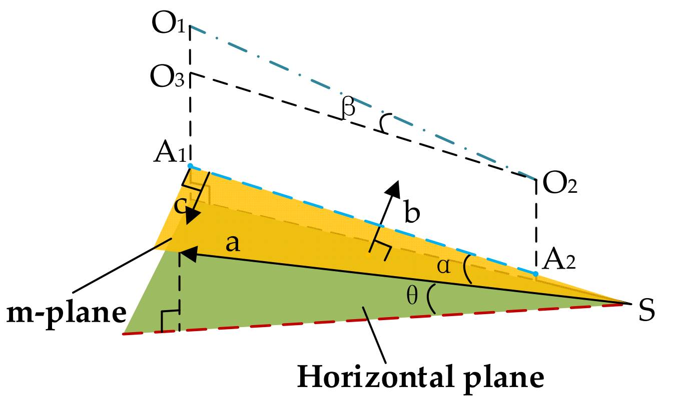

Figure 9. Schematic diagram of the Angle calculation.

Define the known vector a (X_a, Y_a, Z_a) and the normal vector b (X_b, Y_b, Z_b) to be solved of the plane m, where the vector a (X_a, Y_a, Z_a) is calculated before construction. Because vector a is in plane m, the normal vector b is perpendicular to vector a; since the angle between plane m and the horizontal plane is θ, we can know that the angle between the normal vector b of plane m and the normal vector (0, 0, 1) of the horizontal plane is θ. Therefore, according to the cosine theorem, the following Equation (16) can be obtained.

$$\begin{cases} X_aX_b + Y_aY_b + Z_aZ_b = 0 \\ \frac{Z_b}{\sqrt{X_b^2+Y_b^2+Z_b^2}} = \cos\theta \end{cases} \quad (16)$$

Normalize the vector b (X_b, Y_b, Z_b) to obtain Equation (17).

$$X_b^2 + Y_b^2 + Z_b^2 = 1 \quad (17)$$

The resolution of the joint Equations (16) and (17) results in the determination of the normal vector b (X_b, Y_b, Z_b) of the plane m.

In Figure 9, A_1A_2 is the projection of the jacking machine axis O_1O_2 on the plane m. The vector O_1O_2 is calculated according to Equation (18).

$$\begin{pmatrix} X_{O1O2} & Y_{O1O2} & Z_{O1O2} \end{pmatrix} = \begin{pmatrix} X_{O1} - X_{O2} & Y_{O1} - Y_{O2} & Z_{O1} - Z_{O2} \end{pmatrix} \tag{18}$$

(X_{O1O2}, Y_{O1O2}, Z_{O1O2}) are the coordinates of the vector O_1O_2.

In Figure 9, vector c (X_C, Y_C, Z_C) is in plane m and perpendicular to O_1O_2. According to the vector product formula, Equation (19) can be obtained:

$$\vec{c} = \overrightarrow{O_1O_2} \times \vec{b} = \begin{pmatrix} X_c & Y_c & Z_c \end{pmatrix} = \left(\begin{vmatrix} Y_{O1O2} & Z_{O1O2} \\ Y_b & Z_b \end{vmatrix} \quad \begin{vmatrix} Z_{O1O2} & X_{O1O2} \\ Z_b & X_b \end{vmatrix} \quad \begin{vmatrix} X_{O1O2} & Y_{O1O2} \\ X_b & Y_b \end{vmatrix} \right) \tag{19}$$

According to the vector product formula (Equation (20)), the coordinates of vector A_1A_2 can be solved:

$$\overrightarrow{A_1A_2} = \begin{pmatrix} X_{A1A2} & Y_{A1A2} & Z_{A1A2} \end{pmatrix} = \left(\begin{vmatrix} Y_c & Z_c \\ Y_b & Z_b \end{vmatrix} \quad \begin{vmatrix} Z_c & X_c \\ Z_b & X_b \end{vmatrix} \quad \begin{vmatrix} X_c & Y_c \\ X_b & Y_b \end{vmatrix} \right) \tag{20}$$

(1) Pitch angle β

As shown in Figure 9, O_2O_3 is parallel to A_1A_2. Therefore, the angle between vectors O_1O_2 and A_1A_2 is the pitch angle β. According to the vector angle Equation (21), β can be calculated:

$$\beta = \arccos\left(\frac{X_{O1O2}X_{A1A2} + Y_{O1O2}Y_{A1A2} + Z_{O1O2}Z_{A1A2}}{\sqrt{X_{O1O2}^2 + Y_{O1O2}^2 + Z_{O1O2}^2}\sqrt{X_{A1A2}^2 + Y_{A1A2}^2 + Z_{A1A2}^2}} \right) \tag{21}$$

(2) Azimuth angle α

The angle α between line segment A_1A_2 and vector a represents the azimuth angle, as shown in Equation (22).

$$\alpha = \arccos\left(\frac{X_aX_{A1A2} + Y_aY_{A1A2} + Z_aZ_{A1A2}}{\sqrt{X_a^2 + Y_a^2 + Z_a^2}\sqrt{X_{A1A2}^2 + Y_{A1A2}^2 + Z_{A1A2}^2}} \right) \tag{22}$$

(3) Roll angle γ

As shown in Figure 10, the coordinates of point D in plane G are calculated using the principle of calculating the center coordinates of the pipe jacking machine head in Section 4.1.1 and are recorded as (X_D, Y_D, Z_D). The normal vector g (X_g, Y_g, Z_g) of the G plane is calculated based on the coordinates of points D, O_1 and O_2. The normal vector h (X_h, Y_h, Z_h) of the vertical plane H is calculated based on the coordinates of the O_1O_2 vector of the pipe jacking machine and the plumb line vector (0, 0, 1). The specific solution process of the two vectors can be found in [13]. The angle between the normal vector h and the normal vector g is the rolling angle γ, and the solution Equation (23) is as follows:

$$\gamma = \arccos\left(\frac{X_gX_h + Y_gY_h + Z_gZ_h}{\sqrt{X_g^2 + Y_g^2 + Z_g^2}\sqrt{X_h^2 + Y_h^2 + Z_h^2}} \right) \tag{23}$$

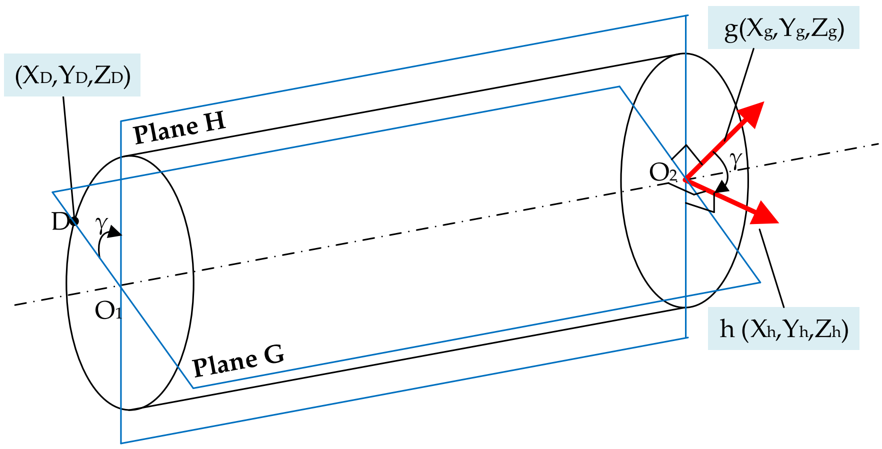

Figure 10. Schematic diagram of the rolling Angle calculation.

4.2. Research Status

At present, the MTG-P3 pipe jacking guidance system of Shanghai MIDU Measurement Technology Co., Ltd. (Shanghai, China) realizes the measurement of the position and posture information of the pipe jacking machine through a high-precision total station and three prisms. The high-precision laser total station and prisms are installed on the wall of the starting shaft and on the top of the pipeline with a bracket. Three prisms are installed at the tail of the pipe jacking machine and placed in a triangle, namely the target prisms. The prisms with known coordinates are placed on the wall of the starting shaft and are used for aiming at the orientation in front of the target prisms, namely the rear-view prism. During operation, the control terminal is used to control the total station to aim at the rear-view prism. After completing the rear-view orientation, the target prisms should be aimed at sequentially to obtain the coordinate information of the three target prisms in the absolute coordinate system. Therefore, the coordinates of the center of the tail of the pipe jacking machine are deduced, and the coordinates of the center of the head of the pipe jacking machine are deduced by using the structural relationship of the pipe jacking machine. Consequently, the attitude information of the position of the pipe jacking machine can be obtained. During the construction process, as the pipe jacking machine moves forward, the total station and the target prisms move together. The total station measures the positional coordinates of the prisms in real time and transmits the measurement data back to the control terminal. This results in the real-time position information of the pipe jacking machine. The ROBOTEC automatic guidance system of Japan's ENZAN company (Kyoto, Japan) has the same principle. Through professional software data processing, the plane deviation, elevation deviation, slope and other information between the center axis of the pipe jacking machine and the design axis of the pipeline are displayed in real time on the screen.

For dynamic measurement during pipe jacking construction, the total station cannot aim at three prisms at the same time, and each prism needs to be searched and measured in turn. As the pipe jacking machine keeps moving forward, it causes the measurement position of each prism to be out of synchronization. Secondly, the confined space within the jacking pipe, coupled with inadequate spacing between prisms, led to suboptimal calculation accuracy and constrained viewing conditions.

In response to the above problems, relevant research has been carried out to design prediction algorithms to reduce the errors caused by unsynchronized measurement times for the problem of unsynchronized prism measurements. In response to the problem of not being able to install three target prisms, the "Two prisms—Inclinometer" scheme was adopted, which reduces the number of prisms and adds a smaller inclinometer with fewer placement restrictions to complete the guided measurement.

4.2.1. Algorithmic Research

By constructing an algorithmic prediction model, the collected data is passed through the prediction model to compensate for the positional error and improve the accuracy. Huang [14] employed the Kalman filtering algorithm to measure and predict prism coordinates in real time. Experimental evidence has demonstrated that the utilization of the attitude solution algorithm in conjunction with the Kalman filter algorithm results in a reduction of error when compared to the conventional prism method of attitude measurement. However, this method exclusively considers smooth motion in establishing the equation of state and makes predictions exclusively for prism coordinate observations, without considering the effects caused by objective factors such as curved pipes. He [15] adopted a coordinate prediction and a coordinate fusion scheme. A Kalman filter prediction model was established for straight segments and curved segments. Through coordinate prediction and data fusion, the influence of prism measurement time asynchrony on measurement error was further improved.

4.2.2. "Two Prisms—Inclinometer" Scheme

In the three-prism scheme, the coordinates of the head and tail centers of the pipe jacking machine must be calculated according to the position coordinates of the three prisms. If the distance between the three prisms is too close, it will lead to low data accuracy and poor positioning effect. This is not applicable to small-diameter pipe jacking. In addition, during the pipe jacking process, the internal measuring instruments will move with the pipe jacking machine, and the three prisms are installed in a triangle [16]. This will cause the total station to fail in the process of searching for the prisms, making it difficult to aim at the prisms, and the coordinates of the three prisms need to be measured one after another, which has poor real-time performance. Even if the above problems can be improved by using algorithms to predict the coordinates, the essence of the error caused by the three prisms has not changed. Therefore, in order to overcome the shortcomings of this scheme, the "two prisms + inclinometer" scheme is proposed. Compared with the three-prism solution, the "two prisms + inclinometer" solution reduces the number of prisms to two and adds a dual-axis inclinometer. The dual-axis inclinometer can be used to directly obtain the pitch angle and roll angle, making up for the problem of insufficient solution parameters caused by the lack of a prism.

The computational principles underlying the "two prisms + inclinometer" method are primarily the spatial geometry method and the rotation matrix method. The spatial geometry method is a process of the coordinate solution. According to the spatial geometric relationship of the pipe jacking machine, the angle information provided by the dual-axis inclinometer is used as the spatial angle parameter, and the coordinates of the head center and the tail center of the pipe jacking machine are solved using the coordinates of the prisms. The rotation matrix method utilizes the real-time output of pitch and roll angles from the dual-axis inclinometer to construct a rotation matrix to describe the attitude and determine the spatial position and attitude information. The method has good real-time performance and meets the requirement of real-time orientation. Chen [17] employed a 3D coordinate transformation model with a 7-parameter model and directly incorporated the inclinometer data as observations in the solution. The researcher constructed a joint leveling method for joint data processing and jointly processed two types of observations from the spatial geometry method and the rotation matrix method to take the redundant observations into account. This methodological improvement enhanced the reliability of the system. This method involves the direct introduction of the data obtained from the inclinometer as the Euler angles corresponding to the rotation matrix [18]. The rotation matrix serves to approximate the biaxial inclination data as equivalent to the Euler angles, accounting for modeling errors. Pan [19] addressed this issue by developing a 13-parameter spatial coordinate transformation model, introducing tiltmeter equivalent observations and constructing a model for leveling computation.

5. Inertial Guidance Method

5.1. Principle

The inertial guidance method, which is predicated on inertial navigation technology, is of particular significance in the context of underground space development [20]. The inertial guidance method utilizes equipment such as inertial measurement units (gyroscopes and accelerometers), odometers and static leveling, in addition to control terminals, as illustrated in Figure 11. The inertial measurement unit (IMU) is responsible for the collection of attitude and velocity information, while the odometer quantifies the distance increment of the pipe jacking process. Additionally, the static leveling provides elevation data of the pipe jacking machine, as illustrated in Figure 12. The data presented herein has been aggregated and processed to calculate the deviation distance between the pipe jacking route and the designed route. This information will be used to provide further feedback to control the jacking direction of the pipe jacking machine and reduce the deviation.

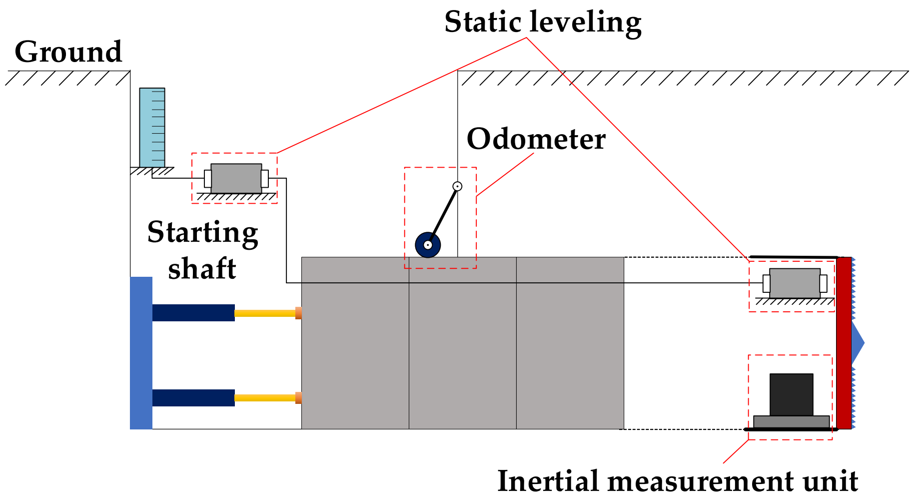

Figure 11. System composition of the inertial guidance method.

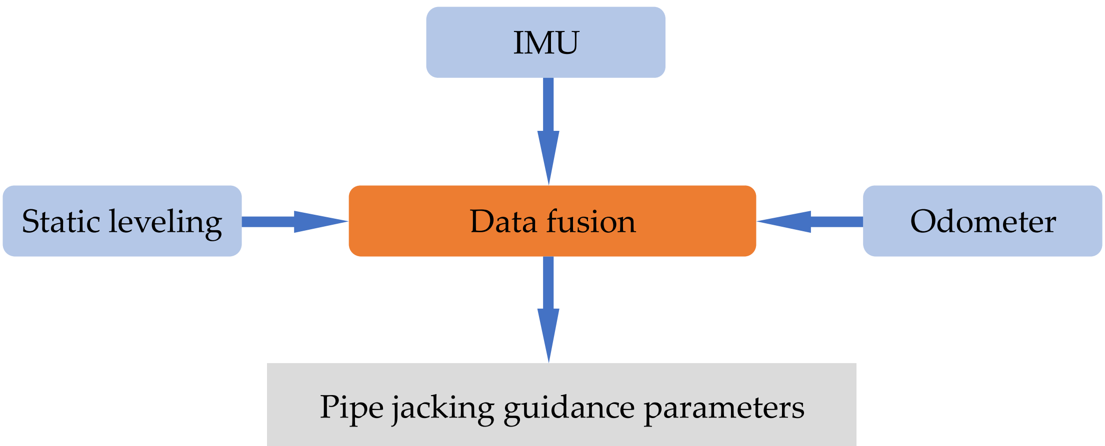

Figure 12. Sketch of the data fusion.

The horizontal position measurement of the pipe jacking machine can derive the position coordinates in the horizontal plane through the attitude angle information output from the inertial measurement unit and the distance increment information from the odometer, using the Dead Reckoning (DR) [21]. As shown in Figure 13, the equation for calculating the position coordinates of Q_i is shown in Formula (24):

$$\begin{cases} X_n = X_0 + \sum_{i=1}^{n} \Delta L_i \cdot \cos \alpha_i \\ Y_n = Y_0 + \sum_{i=1}^{n} \Delta L_i \cdot \sin \alpha_i \end{cases} \tag{24}$$

where the initial horizontal position coordinate of Q is set to be Q_0 (X_0, Y_0) and ΔL_i is the distance increment of Q_i in the direction of horizontal azimuth angle α_i (i = 1, 2, 3).

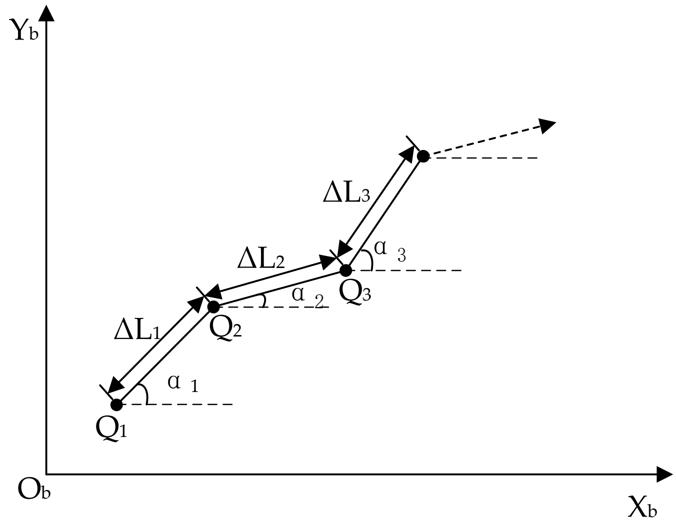

Figure 13. Schematic diagram of Dead Reckoning.

The position is updated through the application of Dead Reckoning, with the eastward offset ΔL_E and northward offset ΔL_N, both before and after the update, being related to the displacement increment, azimuth α, and pitch angle β. The eastward offset ΔL_E and northward offset ΔL_N are calculated as shown in Equation (25):

$$\begin{cases} \Delta L_E = \Delta L_i \cos \beta \cos \alpha \\ \Delta L_N = \Delta L_i \cos \beta \sin \alpha \end{cases} \tag{25}$$

According to Equation (26), the latitude and longitude information can be calculated.

$$\begin{cases} L = L_0 + \sum_{j=1}^{i} \Delta L_{Ej} / (R_M + h) \\ \lambda = \lambda_0 + \sum_{j=1}^{i} \Delta L_{Nj} / \{(R_N + h) \cdot \cos L\} \end{cases} \tag{26}$$

where L and λ are longitude and latitude, L_0 and λ_0 are the longitude and latitude information of the initial position, R_M is the radius of the local earth's meridian circle and R_N is the radius of the local earth's prime unitary circle. h is the current height.

By obtaining the water plane coordinate information above, combined with the height measurement of the static leveling, we can obtain the pipe jacking position information under the spatial coordinate system and calculate the deviation compared with the ideal design pipeline route.

5.2. Research Status

Theoretically, the pipe jacking machine posture can be measured without human intervention by using only the inertial navigation theory. However, due to the integration process in the inertial guidance algorithm, there is a non-integrable error term. This error term can be ignored under a limited degree of time accumulation, but as the error accumulates to a certain limit, it will seriously affect the navigation accuracy. Consequently, the implementation of inertial guidance technology necessitates the suppression of errors to ensure compliance with the stipulated requirements. There are three primary categories of error suppression for inertial sensors. The first category is compensating correction of inertial sensors by multiple sensor measurement parameters. The second category is the design of error compensation algorithms [22]. The third category is the use of redundant devices to increase the number of inertial sensors [23]. The fourth category is self-compensating errors by rotational modulation techniques [24]. Presently, research endeavors are directed towards enhancing the precision of inertial sensors in pipe jacking. This objective is pursued by augmenting the number of sensor devices and refining optimization algorithms to ensure enhanced accuracy.

The TMG-32B inertial guidance system from TOKYO KEIKI Co. Ltd. in Tokyo, Japan, contains gyroscopes and inclinometers internally. The dual-axis inclinometer measures pitch and roll angles, thereby improving the accuracy of attitude measurements through redundant gyroscope angle data information. The PN-200 system incorporates an odometer that facilitates the calculation of the pipe jacking distance. The azimuth of the pipe jacking machine is determined by the north-pointing function of the gyroscope. The position of the pipe jacking machine is calculated by integrating the odometer readings with the calculated waypoints and utilizing the attitude updating algorithm. Presently, the company's TMG-32F and PN-S1 guidance systems are considered to be in a relatively mature state. The RMS-D (Curve Type) automatic guidance system of Lixin Measurement (Shanghai, China) Co., Ltd. is predicated on an in-house developed elevation measuring instrument, the purpose of which is to provide elevation information. An odometer is placed at the starting shaft to detect the jacking distance of the pipe sheet. The odometer's readings are then combined with gyroscope data to calculate the pipe jacking machine's position information. The principle of this system is analogous to that of the products of the Japanese company.

Based on the idea of multi-source data fusion, that is, fusing data information from different sensors to improve accuracy, Zu [25] proposed a pipe jacking guidance scheme for a fiber optic gyro inertial navigation system. The Fiber Optic Gyro Inertial Measurement Unit (FOG-IMU) is situated in close proximity to the pipe jacking machine, with a static leveling configured above it. An odometer is positioned at the wall of the starting shaft to quantify the length of pipe jacking. A multi-sensor data fusion algorithm based on fiber optic gyro/odometer/static leveling is proposed, and a 15-dimensional Kalman filter is established. A horizontal position projection model is constructed based on odometry and a fiber optic gyro-inertial measurement unit (FOG-IMU). An elevation measurement model is also constructed based on static leveling. These models are used to obtain external gauging information for combined navigation. Finally, the guiding parameters for pipe jacking construction are derived, and the feasibility of the program is proved through experiments. Zhang [26] proposed a zero-speed detection algorithm to address the problem that the zero-speed update error compensation algorithm cannot accurately distinguish between motion and stationary states. Experimental results show that the zero-speed detection accuracy reaches 99.18%.

6. Hybrid Method

Since the laser propagates in a straight line and the dispersion of the laser spot formed by the laser affects the accuracy as the distance increases, the total station is too far away from the prism and cannot aim at the prism. In long-distance, curved pipe jacking construction, a single method is difficult to meet the guidance requirements. Therefore, the company that developed the pipe jacking guidance system proposed a hybrid guidance system with different schemes, which improved the guidance accuracy by combining multiple methods.

Since a single prism mounted on the tail of the pipe jacking machine can only obtain the center coordinates of the tail of the pipe jacking machine, it cannot obtain the 3D orientation of the pipe jacking machine, which can be provided by an inertial device for orientation. Pan [27] proposed a single prism and inertial measurement unit scheme. A prism is set up at a fixed distance above the center of the tail of the pipe jacking machine, a total station is placed inside the pipeline for coordinate measurement and a prism is set up on the top of the total station for elevation measurement with the prism at the tail of the pipe jacking machine. Since a single prism mounted on the tail of the pipe jacking machine can only obtain the center coordinates of the tail of the pipe jacking machine, it cannot obtain the 3D orientation of the pipe jacking machine, which can be provided by an inertial device for orientation. This solution realizes long-distance and curved pipe jacking guidance.

The prism method and the laser target method are used in the TUnIS Navigation MT$^{\text{LaserTotalstation}}$ of VMT and the MTG-L pipe jacking guidance system of Shanghai MIDU Measuring Technology Co. The guidance system is divided into two working modes: short-distance, straight-line operating mode and long distance, curved-line operating mode (as shown in Figures 14 and 15). During pipe jacking construction, the total station installed in the starting shaft aims at the laser target that moves with the pipe jacking machine. The system is based on the laser target guidance principle and incorporates an odometer to provide distance information for the laser target method. As the distance increases or when encountering a bend, the laser is unable to be aimed at the laser target. At this time, the total station is set up in the pipeline and moves with the pipe segment. Two prisms are added, and a rear-view prism is set up in the starting shaft. The prism method and the laser target method are combined to guide the pipe jacking.

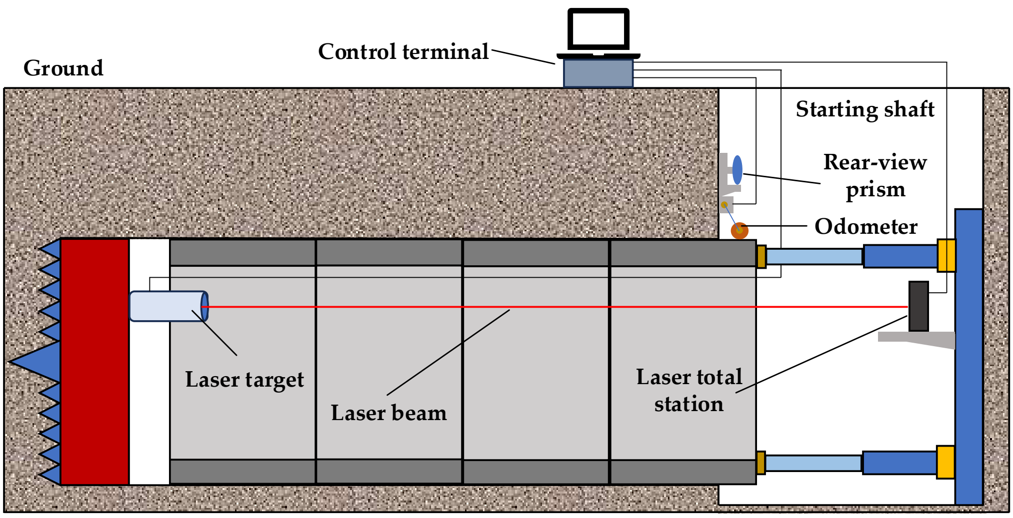

Figure 14. Short-distance, straight-line operating mode.

Since the total station is used in long-distance pipe jacking, the total station must be placed inside the pipe according to the jacking distance and advanced with the pipe. For narrow pipes, the total station cannot enter the inside of the pipe. Therefore, VMT's TUnIS Navigation MT$^{\text{Gyro}}$ uses a combination of laser target, odometer, static leveling and gyroscope measurements (as shown in Figure 16). The odometer and static leveling provide distance and elevation information. In the initial phase, the laser target method is employed to facilitate pipe jacking guidance. When the laser emitted from the starting shaft is unable to reach the target, the inertial guidance method is utilized in replacement. Ultimately, curved and long-distance pipe jacking guidance is achieved.

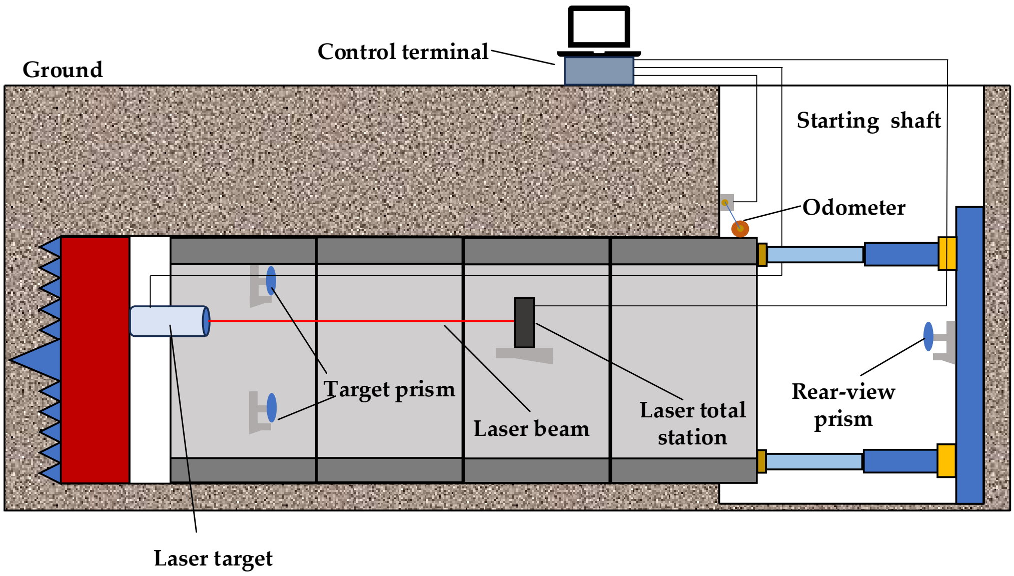

Figure 15. Long-distance, curved-line operating mode.

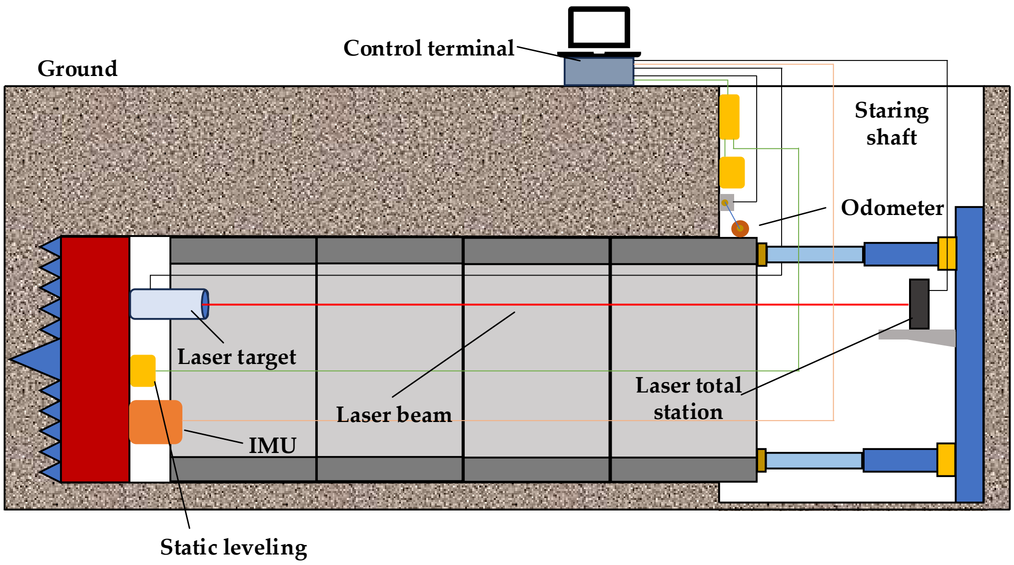

Figure 16. Schematic drawing of TUnIS Navigation MT$^{\mathrm{Gyro}}$.

In addition, the TUnIS Navigation MT$^{\mathrm{GyroEMS}}$ system developed by VMT based on gyroscopes and magnetic sensors is suitable for small-diameter, inaccessible long-distance and curved pipelines with high position accuracy. For construction conditions where visibility is not possible, the system uses an optical gyroscope as the main system and a magnetic sensor based on an electromagnetic probe as an auxiliary measurement system to perform comprehensive measurements. The optical gyroscope is responsible for providing continuous relative position data, and the magnetic sensor based on the electromagnetic probe maps itself to a reference line on the surface to improve the relative position data.

7. Analysis of Pipe Jacking Projects

7.1. Cases of Projects

As shown in Table 2, the prismatic method has been used for a long time and is suitable for larger pipe diameters due to the space limitations of the prismatic method. The pipe jacking project of the Yanqiao branch line of the Qingcaosha water source from Shanghai is divided into two sections, consisting of a starting shaft and two receiving shafts, so as to realize the simultaneous jacking of two rows of pipelines in close proximity [28]. The project adopted the RMS-TV system. Six prisms were placed on the wall of the starting shaft for precise orientation of the total station both above and below the shaft. During operation, the communication power supply was turned on, the total station was leveled and roughly aimed at one of the prisms and the start function key on the manual operation console was pressed, and the system would automatically and continuously perform measurements.

Table 2. Prism method engineering projects.

Time	Project Name	Content	Guidance Accuracy
2010	Pipe jacking project of Yanqiao branch line	Pipe diameter: 3.6 m; Distance: 1119 m and 1004 m	Horizontal and vertical deviation: ±75 mm Mileage deviation: 40–80 mm
2013	Pipe jacking project of Jianxin-Shennong transmission line	Pipe diameter: 3.2 m; Distance: 412 m Radius of curvature: 300 m	Horizontal and vertical deviation: <100 mm
2020	Yangcheng Lake Diversion Project	Pipe diameter: 2 m; Distance: 2670 m	Horizontal deviation: ±50 mm vertical deviation: ±70 mm

Pan [29] developed a pipe jacking guidance system based on the prism method for the Jianxin-Shennong transmission line pipe jacking project in Fuzhou City, Fujian Province, China. Since the radius of curvature reaches 300 m, a single total station cannot complete the measurement work. It is necessary to add a total station in the pipeline, and the control terminal drives the total station in turn to complete data collection, transmission and processing.

In the Yangcheng Lake diversion project, the second water source of Suzhou City, China, the single jacking distance reached 2670 m. As the jacking distance of the pipe jacking machine increases, the total station cannot aim at the prism at the pipe jacking machine. The total station fixed in the working well is placed in the pipeline at a position where it can aim at the prism and move with the pipeline. During the measurement process, the rear-view prism in the starting shaft is repeatedly aimed for orientation. When the rear-view prism cannot be aimed, the rear-view prism is installed in the pipeline and moved with the pipeline, thereby achieving long-distance pipe jacking [30].

As shown in Table 3, the MTG series and TUnIS Navigation MT series developed by Shanghai MIDU Measurement Technology Co., Ltd. and VMT Germany have been applied in long-distance and curved-pipe jacking projects. At close distances, the prism method is used. When the distance is too great or the pipeline is curved, the laser target method is used for guided measurements, in which the laser total station is placed inside the pipeline. In recent years, long-distance and curved-pipe jacking projects have developed towards smaller diameters, which makes it impossible to deploy the total station inside the pipeline. Therefore, for smaller pipe diameters, such as the Power Tunnel project in Taiwan, China, and the Drainage Services Department's sewer pipe project in Hong Kong, China, the TUnIS Navigation MT^{Gyro} system, based on the inertial guidance method, was used to complete the measurements.

Table 3. Long-distance and curved-pipe jacking projects.

<table>
<tr><th>System Name</th><th>Project Name</th><th>Content</th><th>Method</th></tr>
<tr><td>MTG-P3 System</td><td rowspan="2">Singapore Phi Tongshen Line Project</td><td rowspan="2">-</td><td>Prism method</td></tr>
<tr><td>MTG-L System</td><td>Hybrid method</td></tr>
<tr><td>MTG-L System</td><td>Singapore Murnane Pipeline Project [31]</td><td>Pipe diameter: 1.6 m;
Distance: 600 m</td><td>Hybrid method</td></tr>
<tr><td>SLS system</td><td rowspan="3">Sewage treatment pipeline project in Herne, Germany</td><td>Distance: 350 m;
Minimum radius of curvature: 480 m;</td><td>Laser target method</td></tr>
<tr><td rowspan="2">TUnIS Navigation MT^{LaserTotalstation}</td><td>Distance: 900 m;
Minimum radius of curvature: 450 m;</td><td rowspan="2">Hybrid method</td></tr>
<tr><td>Distance: 700 m;
Minimum radius of curvature: 450 m</td></tr>
<tr><td rowspan="2">TUnIS Navigation MT^{Gyro} system</td><td>Power Tunnel project in Taiwan, China</td><td>Pipe diameter: 1 m;
Distance: 394 m (Curved pipeline length 70 m);
Radius of curvature: 500 m</td><td rowspan="2">Inertial guidance method</td></tr>
<tr><td>Drainage Services Department's sewer pipe project in Hong Kong, China</td><td>Pipe diameter: 1.2 m;
Distance: 210 m (Curved pipeline length 30 m);
Radius of curvature: 111 m</td></tr>
</table>

7.2. Analysis of Costs and Selection Experience

The merits and demerits of the different methods of pipe jacking guidance systems are different, and they are closely related to the costs. As shown in Table 4, the manual visual inspection method utilizes a lesser quantity of measuring instrument hardware and exhibits the lowest cost, yet it demands a high level of operator skill. The laser target and prism methods for short-distance and straight pipe jacking construction conditions have reached a state of technological maturity and offer a reliable degree of accuracy. However, the laser target and prism methods for long-distance and curved pipe jacking construction conditions necessitate the augmentation of instrumentation within the pipeline, which in turn increases costs. The gyroscope used in the inertial guidance method is mature and has a relatively high cost. The hybrid method improves system accuracy based on the idea of redundancy, but the increase in measuring instruments increases the cost of the system.

Table 4. Analysis of different methods.

<table>
<tr><th>Methods</th><th>Merits</th><th>Demerits</th><th>Cost</th></tr>
<tr><td>Manual visual inspection method</td><td>Low amount of hardware</td><td>Limited construction conditions</td><td>+</td></tr>
<tr><td rowspan="2">Laser target method</td><td rowspan="2">Reliable precision;
Mature technology</td><td rowspan="2">Deformation and dispersion of Laser spot;
Limited pipe diameter</td><td>++
(Short distance straight pipeline)</td></tr>
<tr><td>++++
(Long distance curved pipeline)</td></tr>
<tr><td rowspan="2">Prism method</td><td rowspan="2">Reliable precision;
Mature technology</td><td rowspan="2">Out-of-sync error;
Limited pipe diameter</td><td>++
(Short distance straight pipeline)</td></tr>
<tr><td>++++
(Long distance curved pipeline)</td></tr>
<tr><td>Inertial guidance method</td><td>Small pipe diameter;
Continuous measurement</td><td>Error accumulation</td><td>+++</td></tr>
<tr><td>Hybrid method</td><td>High precision;
Few construction restrictions</td><td>Multiple hardware</td><td>++++</td></tr>
</table>

The symbol "+" is used to denote the cost level. An increased numerical value of '+' is indicative of a higher cost.

In the context of pipe jacking construction, the selection of a pipe jacking guiding system is a decision that must be made taking into consideration a number of factors. These include the construction conditions, cost and construction efficiency.

Regarding construction conditions, the soil layers in engineering geology are divided into soft soil, mucky soil, sandy soil, loess and rock. Among them, the rock has high hardness. The soil layer has a serious impact on pipe jacking, such as ground settlement [32–36]. Additionally, no matter what kind of soil layer it is, it will affect the operation of the pipe jacking machine, and the higher the hardness, the greater the impact [37,38]. The influence of the soil layer on the pipe jacking guide system is that vibration will be generated when the pipe jacking machine is advancing. For the manual visual inspection method, the engineering technicians are required to manually operate the laser equipment at the starting shaft or in the pipeline. The stability and stable support of the soil layers on the pipe segment must be ensured to prevent technical personnel from operating errors [39]. In addition, the target located at the pipe jacking machine will vibrate, affecting manual observation. The automation of the laser target method and the prism method avoids the influence of vibration on manual operation and observation. The laser total station is placed on the automatic leveling base at the pipeline where the pipe segments have been laid. The influence of vibration can be ignored. However, the laser targets or prisms located at the head of the pipe jacking machine are affected by vibration, which makes it impossible to fix the laser spot on the laser target or makes it difficult to aim the prism, affecting the measurement accuracy. Although the measuring instruments of the inertial guidance method are still affected by vibration, the impact of vibration can be reduced by increasing the sampling rate, optimizing the algorithm, etc. The hybrid method can reduce that impact by adding redundant sensors.

It is imperative to consider the construction requirements when formulating a strategy to minimize the costs and enhance working efficiency. In the domain of large-diameter, short-distance and straight-line pipe jacking construction, manual visual inspection, laser target and prism methods are preferred due to their low hardware cost, mature technology and reliable accuracy. In the case of large-diameter, long-distance and curved pipe jacking, the following methods are available: the laser target method, the prism method, the inertial guidance method and the hybrid method. Although the cost disparity of the both laser target method and prism method are not immediately apparent compared to that of the both inertial guidance method and hybrid method, the implementation of the laser total station within the pipeline is not as efficient or accurate as the inertial sensor. Therefore the inertial guidance method and the hybrid method are better. For small-diameter, long-distance and curved pipe jacking, it is impossible to erect a total station and prism in the pipe, so the inertial sensor method is selected at this time.

8. Discussion

The accelerating pace of new city construction necessitates the development of innovative solutions to address the challenges posed by recurrent road excavations, the intricate underground pipeline network and the frequent occurrence of pipeline accidents. In this context, pipe jacking construction has emerged as a promising approach, offering a range of advantages, including low noise and vibration, high precision, environmental sustainability, a short construction period and reduced economic costs. This research area holds significant promise for the future of underground pipeline construction, offering a promising avenue for addressing the pressing issues associated with urban infrastructure development. Pipe jacking construction is no longer only for short-distance and straight-line pipe jacking construction but also for long-distance and curved pipe jacking construction, which reduces the construction cost and improves the overall construction efficiency at the same time. However, how to realize the guiding accuracy of long-distance and curved pipe jacking construction has put forward higher requirements to the research institutions.

Multi-source data fusion is complementary and redundant. In the field of engineering applications, a single measuring instrument cannot fully meet engineering requirements, so additional measuring instruments are often used to meet the design requirements of engineering applications. Adding different kinds of measuring instruments can fully complement the defects between different instruments, and adding the same kind of measuring instruments or the same kind of functional measuring instruments can improve the system's stability and measurement accuracy through redundancy. The future development of pipe jacking guidance systems will be characterized by a shift towards the integration of multi-source sensors. This approach will leverage the complementarity of different sensors and the redundancy of similar sensors. The implementation of these systems will adapt to the complex pipe jacking construction conditions, thereby enhancing the guidance accuracy.

9. Conclusions

(1) With the development of pipe jacking construction, pipe jacking construction develops in the direction of small-diameter and long-distance curved pipe jacking construction, which puts forward higher requirements for pipe jacking guiding technology.

(2) Current guiding methods can be divided into four categories, namely, the manual visual inspection method, the laser target method, the prism method, the inertial guidance method and the hybrid method. The manual visual inspection method has a high degree of dependence on the technical level of technical personnel, but it is one of the important guiding means in the field of short, straight-line construction of pipe jacking. The laser target method is an upgrade from the manual visual method. This method is widely used in short, straight-line construction. However, since the laser can only propagate along a straight line and the laser spot dispersion increases with distance, it affects the guidance accuracy. Therefore, it cannot be applied in long-distance, curved construction, and it is necessary to add laser equipment for laser relay, which has a high cost and low reliability. The prism method is suitable for large-diameter pipe jacking construction, which can be applied to long-distance and curved projects by increasing the number of prisms and erecting new total stations, but the accuracy is limited by space and visibility conditions. The inertial guidance method can achieve independent guidance without the help of other equipment and has been widely studied in the application of long-distance and curved pipe jacking. However, due to the problem of error divergence accumulated over time, multiple sensors are often used to fuse data to improve accuracy. The hybrid method is based on the combined application of the above methods.

(3) As can be seen from the classification of pipe-jacking guidance technologies, each method has its own problems. Multi-source data fusion can use multiple sensors to collect the same or complementary types of data, build data fusion models and improve guidance accuracy.

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