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Multi-machine collaborative positioning method for rapid excavation complete equipment

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Abstract. A multi-machine collaborative positioning method is proposed to meet the high-precision positioning needs for multi-machine collaborative operations of rapid excavation equipment, including the bolter miner, crusher, and conveyor belt. This method uses a laser locator to measure the absolute pose of the bolter miner as the primary reference and deploys laser ranging and ultrasonic ranging sensor groups on subsequent equipment. Through spatial coordinate transformation and data fusion, the system gets the absolute positions, relative positions, and attitudes of all three machines at the same time. The system setup and collaborative positioning algorithms are explained in detail, and experimental verification is conducted. The results show that the laser ranging subsystem achieves a standard deviation of 4.7–7.3 mm for distance measurement within the range of 0.5–1.5 m, and a standard deviation of less than 0.16° for attitude angle measurement. The ultrasonic ranging subsystem achieves a standard deviation of 10.5–13.6 mm for lateral offset measurement. The positioning accuracy of the proposed method meets the requirements for collaborative operations and can provide technical support for intelligent collaborative control of tunnel excavation equipment.

Keywords: rapid excavation; multi-machine collaboration; laser positioning; ultrasonic ranging; pose measurement.

1. INTRODUCTION

Complete rapid excavation equipment, consisting of a bolter miner, a crusher, and a conveyor belt, is widely used in mines, tunnels, and other engineering projects. The collaborative operation of these three machines can significantly enhance excavation efficiency, reduce labor costs, and promote the development of tunnel excavation towards automation and intelligence [1]. Accurate, reliable, and low-cost positioning technology forms the foundation for achieving multi-machine collaborative operations, ensuring efficient coordination and safe operation between the equipment.

Positioning technologies are categorized into active and passive positioning based on whether an external reference is required [2]. Active positioning includes laser positioning, ultra-wideband positioning, total station positioning, and visual positioning. Li Rui improved the light source for laser positioning by replacing the point laser of conventional laser locators with fan-shaped structured light. A laser target was installed on the excavation equipment to measure the coordinates of the projected laser spot, and the lateral offset and yaw angle of the equipment were calculated from these coordinates [3]. Chen Hongyue further refined this method by fusing the measurement data from inclination sensors with the spot coordinates, improving the accuracy of pose detection [4]. Zhang Xuhui used parallel lasers to provide a positioning reference, installed a camera on the excavation equipment to capture laser images, and then solved for the roadheader pose using visual geometry methods [5, 6]. Fu Shichen applied ultra-wideband positioning methods to roadheader localization and analyzed and experimentally verified its positioning accuracy in narrow and long tunnel scenarios [7, 8]. Tao Yunfei proposed a single-station, multi-point, time-sharing method based on iGPS, using rotating lasers as a positioning reference. Multiple receivers were installed on the excavation equipment to measure distances and angles relative to reference, enabling the calculation of the roadheader pose [9]. Du Yuxin employed dual cross lasers as a positioning reference, installed a screen on the roadheader to capture laser projections, and derived the roadheader pose from the projected shapes obtained through image acquisition [10]. Measurement and accuracy of these technologies heavily relies on external references and is susceptible to occlusion or interference in complex environments. Furthermore, their environmental adaptability is poor, as factors like dust and vibration can affect laser or visual signals.

Passive positioning includes Inertial Navigation Technology [11] and Simultaneous Localization and Mapping [12], which measure the motion state of the equipment using accelerometers and gyroscopes. Their advantage lies in not relying on external signals, making them easy to deploy. However, inertial navigation suffers from error accumulation; its position and attitude errors increase over time, leading to significantly reduced accuracy, especially during prolonged operation. In tunnel environments, equipment often operates at low speeds with high-frequency vibrations, which exacerbate noise interference in inertial sensors and further degrade positioning accuracy [13]. Therefore, inertial navigation is unsuitable as the sole solution for positioning tunnel equipment and needs to be combined

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with other positioning technologies through multi-sensor fusion to compensate for its shortcomings. SLAM builds an environmental map in real-time by combining sensor data while simultaneously estimating the device position. Its high complexity and strong dependence on environmental features make it prone to failure in repetitive environments like tunnels [14, 15].

Proximity sensors are core components in equipment positioning systems. Currently, a wide variety of proximity sensing technologies are available on the market. Based on their working principles, they are mainly classified into inductive sensors, capacitive sensors, photoelectric sensors, ultrasonic sensors, and laser ranging sensors. Representative manufacturers of high-performance laser ranging sensors include Baumer, wenglor, KEYENCE, Banner Engineering, and SensoPart. In the field of industrial ultrasonic ranging, products from manufacturers such as Migatron, Monnit, and SICK are known for their ruggedness and reliable operation in dusty and humid environments. It should be noted that no single sensor technology or manufacturer's product can be universally applied to all scenarios. When selecting a sensor, factors such as detection distance, measurement accuracy, environmental conditions, power consumption, and system integration complexity must be considered comprehensively. Laser ranging sensors offer high measurement accuracy but have poor adaptability; ultrasonic sensors have lower accuracy but better adaptability to rough surfaces. In the multi-machine cooperative positioning scenario of rapid excavation equipment studied in this paper, sensor selection follows the principles below: For lateral distance measurement between the equipment and the tunnel sidewall, due to the rough surface of the coal wall where laser sensors are prone to diffuse reflection, resulting in unstable signals and reduced reliability, ultrasonic sensors are adopted to improve adaptability to harsh environments. For longitudinal distance measurement between front and rear equipment, since a dedicated ranging target is installed on the rear equipment and the measurement distance is relatively short, laser ranging sensors are selected to ensure measurement accuracy.

The aforementioned positioning technologies are mostly targeted at single pieces of underground equipment. However, to achieve collaborative operations between the bolter miner, crusher, and belt conveyor, it is essential not only to know their absolute positions but, more critically, to obtain the real-time relative positional relationships between the machines. Therefore, developing a set of multi-machine collaborative positioning systems that are adaptable to complex underground working conditions, easy to deploy, and exceptionally reliable holds significant practical importance.

This paper proposes a multi-machine collaborative positioning method specifically designed for the complete set of rapid excavation equipment. In contrast to existing studies that mainly focus on single-machine absolute pose measurement, the core innovation lies in establishing a unified framework that integrates absolute positioning, relative positioning, and lateral offset measurement. The main contributions are as follows:

1. A multi-level collaborative positioning architecture for the three-machine serial scenario. This paper proposes hierarchical architecture consisting of a main positioning system, a laser ranging subsystem, and an ultrasonic ranging subsystem. It enables the joint solution of absolute and relative poses within a unified reference frame, offering a novel systematic solution for multi-mobile-equipment collaborative positioning.
2. A least-squares relative pose estimation method based on four-point laser ranging. To overcome the susceptibility of vision, UWB, and other methods to dust, vibration, and occlusion in excavation faces, four laser ranging sensors are installed on the rear side of the preceding vehicle. Through spatial plane fitting and least-squares optimization, the relative distance and yaw angle of the following vehicle are simultaneously solved. This method extends point-to-point range to a multi-point-to-plane geometric constraint and exploits information redundancy to significantly enhance noise immunity and robustness.
3. A lateral offset measurement method based on a redundant ultrasonic sensor array. To address the unreliability of single-point ultrasonic or laser sensors caused by rough coal walls, four ultrasonic sensors are deployed on each side of the equipment. Through redundant measurement and data fusion, the lateral offset of the equipment centerline relative to the tunnel centerline is calculated, substantially improving engineering reliability in harsh underground environments.

In summary, the proposed method achieves synchronous acquisition of absolute positions, relative positions, and attitudes for all three machines, providing comprehensive pose information for intelligent collaborative control of rapid excavation equipment.

2. MULTI-MACHINE POSITIONING SYSTEM

The main components of the rapid excavation multi-machine collaborative positioning system proposed in this paper include the main positioning system, the laser positioning subsystem, and the ultrasonic positioning subsystem, as shown in Fig. 1.

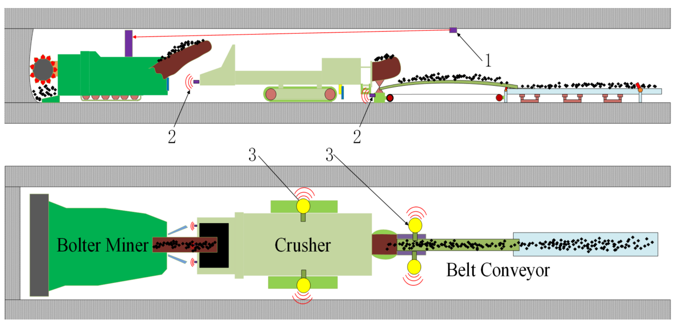


Fig. 1. Multi-machine collaborative positioning system. 1 – Main positioning system, 2 – Laser positioning system, 3 – Ultrasonic positioning system

The main positioning system is used to accurately measure the position and attitude of the bolter miner, providing the primary reference for the entire measurement system. It consists of a laser locator, a laser target, and inclination sensors. The laser locator is fixed above the tunnel to provide a precise reference for detecting the pose of the bolter miner. The laser target is fixed on the body of the bolter miner to receive signals from the laser locator. The pose of the bolter miner body is obtained by fusing the measurement signals from the laser target and the inclination sensors.

The laser positioning subsystem is arranged at the rear end of the equipment and is used to measure the attitude and front-rear distance of the subsequent equipment relative to the preceding machine. The laser positioning subsystem consists of multiple laser ranging sensors. Each laser ranging sensor can measure the distance from itself to a target on the subsequent equipment. By using the front-rear distances measured at multiple points, the pose of the subsequent equipment relative to the preceding equipment is calculated.

The aforementioned measurement methods cannot obtain the complete position and attitude of the equipment, as they lack the measurement of the lateral position of the equipment. The ultrasonic positioning subsystem consists of multiple ultrasonic ranging sensors installed on both sides of the equipment and is used to measure the relative position of the equipment within the tunnel. By measuring the distances from multiple points to the two sidewalls of the tunnel, the pose of the equipment within the tunnel is calculated.

3. MULTI-MACHINE POSITIONING ALGORITHM

This section presents the pose calculation algorithms for the main positioning system, the laser positioning subsystem, and the ultrasonic positioning subsystem, respectively, and provides the data fusion method under a unified reference frame.

3.1. Main positioning system algorithm

This algorithm is used to precisely determine the position and attitude of the bolter miner within the tunnel, with its principle illustrated in Fig. 2 [4]. The laser locator emits mutually perpendicular laser planes forward, which contain complete reference information. The laser targets measure the coordinates of the spots projected by the laser locator. By using multiple laser targets, the coordinates of multiple spots can be obtained.

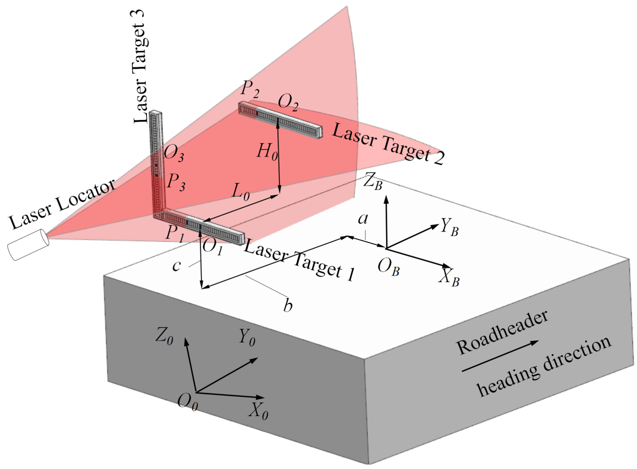
Define $O_0X_0Y_0Z_0$ as the reference coordinate system. Point O_i is the center of the laser receiver, and point P_i is the center of the laser spot. Let $\mathbf{r}_{O_i}$ and $\mathbf{r}_{P_i}$ be the coordinate vectors corresponding to points O_i and P_i, respectively, and let $\mathbf{r}_{O_iP_i}$ be the relative coordinate vector from point O_i to point P_i. Then, we have

$$\mathbf{r}_{P_i} = \mathbf{r}_{O_i} + \mathbf{r}_{O_iP_i} \quad (i = 1, 2, 3). \tag{1}$$

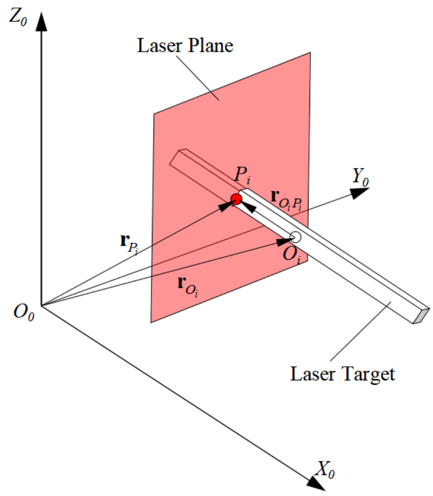
Using the spatial vector equation, the heading angle of the fuselage, as well as its lateral and vertical positions, can be obtained as follows [4]:

$$\alpha = \arctan \frac{(d_2 - d_1)\cos\gamma + H_0 \sin\gamma}{(d_2 - d_1)\sin\beta\sin\gamma + L_0\cos\beta + H_0\sin\beta\cos\gamma}, \tag{2}$$

$$\begin{aligned} d_x = & -d_1(\cos\alpha\cos\gamma - \sin\alpha\sin\beta\sin\gamma) \\ & + a(1 - \cos\alpha\cos\gamma + \sin\alpha\sin\beta\sin\gamma) \\ & + b\sin\alpha\cos\beta - c(\sin\gamma\cos\alpha + \sin\alpha\sin\beta\cos\gamma), \end{aligned} \tag{3}$$



(a) Installation of sensors



(b) Chains of coordinate vector

Fig. 2. Principle diagram of positioning algorithm

$$\begin{aligned} d_z = & -d_3\cos\beta\cos\gamma + a_3\sin\gamma\cos\beta \\ & - b_3\sin\beta + c_3(1 - \cos\beta\cos\gamma). \end{aligned} \tag{4}$$

In the formula, a, b, and c represent the installation positions of laser receiver 1 on the fuselage; L_0 is the longitudinal distance between laser receiver 1 and laser receiver 2; H_0 is the height difference between the two sensors; $d1$, $d2$, and $d3$ are the measurement values of the laser receivers; and β and γ are the pitch angle and roll angle measured by the inclination sensors. The longitudinal distance d_y is obtained using the rotating laser measurement method, as detailed in the reference.

3.2. Laser positioning algorithm

This algorithm is used to measure the attitude and distance of the crusher relative to the bolter miner, as well as the attitude and distance of the belt conveyor relative to the crusher. Four laser ranging sensors are arranged at the rear of the bolter miner to measure the distances to the corresponding target surfaces on the crusher located behind. Based on these measured values, the pose of the crusher is inferred. The pose measurement of the conveyor belt relative to the crusher is performed in the same way. This can be abstracted into the following mathematical problem: given four points arranged on a plane A, and the distances from these four points to another plane B are measured, if the position and attitude of plane A are known, determine the position and attitude of plane B, as illustrated in Fig. 3.

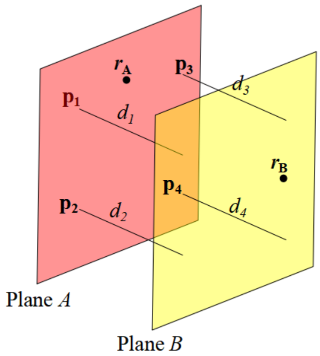


Fig. 3. Four-point distance measurement positioning principle

The equations of plane A and plane B can be expressed as

$$\mathbf{n}_A \cdot (\mathbf{r} - \mathbf{r_A}) = 0, \tag{5}$$

$$\mathbf{n}_B \cdot (\mathbf{r} - \mathbf{r_B}) = 0, \tag{6}$$

where $\mathbf{n}_A$ and $\mathbf{n}_B$ are the normal vectors of planes A and B, respectively, and $\mathbf{r}_A$ and $\mathbf{r}_B$ are known points on planes A and B, respectively. Plane A is attached to the bolter miner in front; therefore, $\mathbf{n}_A$ and $\mathbf{n}_B$, as well as the four points on plane A, specifically the coordinates $\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3$, and $\mathbf{p}_4$ of the laser ranging sensors, are known. Additionally, the distances d_1, d_2, d_3, and d_4 from these four points to plane B are also known.

The distance from point $\mathbf{p}_i$ to plane B is

$$d_i = \frac{|\mathbf{n}_B \cdot (\mathbf{p}_i - \mathbf{r}_B)|}{\|\mathbf{n}_B\|}. \tag{7}$$

Assume $\mathbf{n}_B$ is the unit normal vector. Then

$$d_i = |\mathbf{n}_B \cdot (\mathbf{p}_i - \mathbf{r}_B)|. \tag{8}$$

The system of equations can be established as follows:

$$\begin{aligned} |\mathbf{n}_B \cdot (\mathbf{p}_1 - \mathbf{r}_B)| &= d_1, \\ |\mathbf{n}_B \cdot (\mathbf{p}_2 - \mathbf{r}_B)| &= d_2, \\ |\mathbf{n}_B \cdot (\mathbf{p}_3 - \mathbf{r}_B)| &= d_3, \\ |\mathbf{n}_B \cdot (\mathbf{p}_4 - \mathbf{r}_B)| &= d_4, \end{aligned} \tag{9}$$

Expanding the plane equation yields

$$\mathbf{n}_B \cdot \mathbf{p}_i - \mathbf{n}_B \cdot \mathbf{r}_B = d_i. \tag{10}$$

Let $\mathbf{n}_B = (a, b, c)$, $\mathbf{r}_B = (x_0, y_0, z_0)$, and $\mathbf{p}_i = (x_i, y_i, z_i)$. Then equation (10) can be written as

$$a x_i + b y_i + c z_i \,(a x_0 + b y_0 + c z_0) = d_i. \tag{11}$$

It can be rearranged as

$$a x_i + b y_i + c z_i = k, \tag{12}$$

where k is

$$k = a x_0 + b y_0 + c z_0 + d_i. \tag{13}$$

Then the system of equations can be written as

$$\mathbf{A}\,\mathbf{x} = \mathbf{b}, \tag{14}$$

$$\mathbf{A} = \begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \\ x_4 & y_4 & z_4 \end{bmatrix}, \quad \mathbf{x} = \begin{bmatrix} a \\ b \\ c \end{bmatrix}, \quad \mathbf{b} = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ d_4 \end{bmatrix}. \tag{15}$$

The equations are redundant. To minimize the influence of measurement errors and noise, the least squares method is used to find the optimal solution

$$\mathbf{x} = \left(\mathbf{A}^T \mathbf{A}\right)^{-1} \mathbf{A}^T \mathbf{b}. \tag{16}$$

After solving for a, b, and c, the normalized unit vector can be obtained.

$$\mathbf{n}_B = \frac{(a, b, c)}{\sqrt{a^2 + b^2 + c^2}}, \tag{17}$$

where $\mathbf{n}_B$ represents the attitude of the rear equipment relative to the front equipment. In addition, the distance from $\mathbf{r}_B$ to plane B is

$$d_{AB} = |\mathbf{n}_B \mathbf{r}_B + \mathbf{n}_A \mathbf{r}_A|. \tag{18}$$

Since the positions of $\mathbf{r}_A$ and $\mathbf{r}_B$ relative to the equipment center are determined, the distance between the front and rear equipment can be obtained. This method alone cannot obtain the lateral position deviation, and additional auxiliary measurements using other methods are required. The above least-squares solution process is essentially a multi-sensor data fusion method, which fuses the distance measurements from the four laser ranging sensors to solve for the distance and attitude angle of the rear vehicle relative to the front vehicle.

3.3. Ultrasonic positioning algorithm

This algorithm is used to measure the lateral offset of the crusher and the conveyor belt within the tunnel. Ultrasonic ranging sensors are arranged on both sides of the equipment body to measure the distances from these positions to the two sidewalls of the tunnel. Due to the relatively low accuracy of ultrasonic ranging sensors, the susceptibility of the measurement data to occlusion interference, and the fact that the tunnel width is not ideally uniform, a significant redundancy in the number of sensors is arranged, exceeding the minimum number required for determining the pose.

The pose calculation can be abstracted as the following mathematical problem: Given that there are four points on the left side of a rectangular solid (the equipment) with known distances to plane A, and four points on the right side of the rectangular solid with known distances to plane B, which is parallel to plane A, and the distance between plane A and plane B is known as W, determine the distance from the center of the rectangular solid to plane A and its orientation. Let the equation of plane A be $z = 0$; then the equation of plane B is $z = d$, where d is the distance between the two planes, i.e., the width of the tunnel. The distances from the left side of the rectangular solid to plane A are h_1, h_2, h_3, and h_4, respectively, and the distances from the right side of the rectangular solid to plane B are h_5, h_6, h_7, and h_8, respectively.

The coordinates of the four points on the left are (x_i, y_i, h_i), where $i = 1, 2, 3, 4$; the coordinates of the four points on the right are $(x_i, y_i, W-h_i)$, where $i = 1, 2, 3, 4$. The distance from the equipment center to the tunnel centerline can be easily obtained as

$$d_{\text{offset}} = \frac{1}{8}\left(\sum_{i=1}^{4} h_i - \sum_{i=1}^{8} h_i\right). \tag{19}$$

Take the crusher as an example. Assume the filtered distances of the four left-side sensors are 380 mm, 382 mm, 379 mm, and 381 mm, giving an average of 380.5 mm; the filtered distances of the four right-side sensors are 480 mm, 478 mm, 481 mm, and 479 mm, giving an average of 479.5 mm. Then the center deviation of the crusher is $(479.5 - 380.5)/2 = 49.5$ mm.

3.4. Reference unified

The reference datums of the above three pose monitoring algorithms are different. For instance, the datum for the bolter miner pose measurement is the tunnel coordinate system established by the laser locator; the datum for the algorithm based on laser ranging sensors is the rear side surface of the preceding equipment; and the datum for the algorithm based on ultrasonic ranging sensors is the two sidewalls of the tunnel. To integrate the measurement results under a unified reference frame, data fusion is required. Let the position and attitude of the bolter miner be $\mathbf{p}_{\text{I}} = (x_{\text{I}}, y_{\text{I}}, z_{\text{I}})$, $\mathbf{R}_{\text{I}}$; the relative position and attitude of the crusher with respect to the bolter miner be $\Delta\mathbf{p}_{\text{I}-\text{II}}$, $\mathbf{R}_{\text{I}-\text{II}}$, and its offset relative to the tunnel centerline be $d_{2\text{offset}}$; the relative position and attitude of the belt conveyor with respect to the crusher be $\Delta\mathbf{p}_{\text{II}-\text{III}}$, $\mathbf{R}_{\text{II}-\text{III}}$, and its offset relative to the tunnel centerline be $d_{3\text{offset}}$.

The displacement of the crusher relative to the bolter miner is

$$\mathbf{p}_{\text{II}} = \mathbf{p}_{\text{I}} + \mathbf{R}_{\text{I}}\Delta\mathbf{p}_{\text{I}-\text{II}}. \tag{20}$$

Define the normal vector of the attitude $\mathbf{n} = \left[-r_{21}, r_{11}, 0\right]$. Considering its offset relative to the tunnel centerline, the result is corrected as

$$\mathbf{p}_{\text{II}} = \mathbf{p}_{\text{I}} + \mathbf{R}_{\text{I}}\Delta\mathbf{p}_{\text{I}-\text{II}} + d_{2\text{offset}} \cdot \frac{\mathbf{n}_{\text{II}}}{\|\mathbf{n}_{\text{II}}\|}. \tag{21}$$

The attitude is

$$\mathbf{R}_{\text{II}} = \mathbf{R}_{\text{I}}\,\mathbf{R}_{\text{I}-\text{II}}. \tag{22}$$

The position of the conveyor belt can be obtained using the same method

$$\mathbf{p}_{\text{III}} = \mathbf{p}_{\text{II}} + \mathbf{R}_{\text{II}}\Delta\mathbf{p}_{\text{II}-\text{III}} + d_{3\text{offset}} \cdot \frac{\mathbf{n}_{\text{III}}}{\|\mathbf{n}_{\text{III}}\|}. \tag{23}$$

The attitude is

$$\mathbf{R}_{\text{III}} = \mathbf{R}_{\text{II}}\,\mathbf{R}_{\text{II}-\text{III}}. \tag{24}$$

4. EXPERIMENT AND RESULT ANALYSIS

This experiment aims to eliminate the coupling interference during multi-system collaborative operation and independently verify the ultimate measurement accuracy and basic working performance of each positioning subsystem, providing a benchmark reference for subsequent integration tests. Given that the accuracy of the main positioning system of the bolter miner has been fully verified in previous studies, this experiment focuses on the independent performance evaluation of the laser ranging subsystem and the ultrasonic ranging subsystem. On this basis, further multi-machine collaborative overall performance tests are conducted to verify the comprehensive positioning capability of the system under actual excavation conditions.

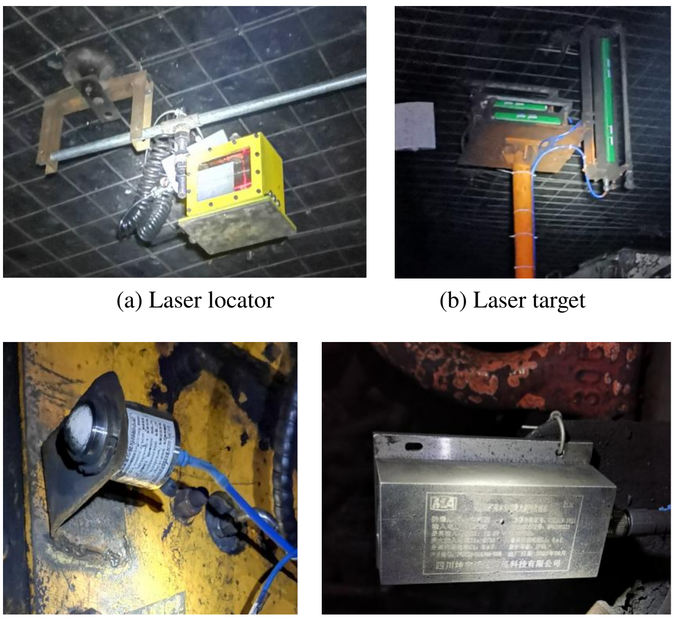
4.1. Experimental platform and design

This section describes the composition of the experimental platform, the sensor arrangement, and the accuracy test schemes for each positioning subsystem.

4.1.1. Experimental platform

In the multi-machine system consisting of the bolter miner, crusher, and conveyor belt, the sensors were arranged as shown in Fig. 1, and the experimental site is shown in Fig. 4.

The tunnel width $W = 5.6$ m, the body width of the bolter miner $B_I = 4.6$ m, the body width of the crusher $B_{II} = 4.2$ m,



(a) Laser locator (b) Laser target (c) Ultrasonic ranging sensor (d) Laser ranging sensor

Fig. 4. Experimental site

and the head width of the conveyor belt $B_{III} = 2.2$ m. The sensor parameters are as shown in Table 1.

Table 1
Sensor parameters

Sensor type	Measurement parameter	Values
Laser ranging sensor	Measuring range	0.2 m ~ 1200 m
	Accuracy	$\pm(1\ \text{mm} + 1\times10^{-6}\times \text{D})$
	Resolution	1 mm
	Laser wavelength	905 nm
	Mounting distance	50 mm
	Mounting angle	0°
Ultrasonic ranging sensor	Measuring range	0.4 m]*sim* 8 m
	Accuracy	±6 mm
	Resolution	1 mm
	Beam angle	8°
	Mounting distance	50 mm
	Mounting angle	90°

In terms of data acquisition and processing, a moving average filter in the time domain is applied to the continuous sampling sequence of each laser ranging sensor and ultrasonic sensor, with a window width of five sampling points (i.e., the arithmetic mean of the current point and the previous four points is taken as the effective value at that moment) to suppress random noise, while the effective sampling frequency is reduced to some extent. Regarding the calibration procedure, static linear calibration was performed on all laser ranging sensors and ultrasonic sensors before the experiments. In addition, the installation coordinates of all sensors (including the three-dimensional coordinates of the four laser ranging sensors on the rear side of the front equipment, as well as the mounting positions of the ultrasonic sensors on the left and right sides of the equipment) were precisely calibrated using a total station after installation to avoid systematic errors caused by installation deviations.

A total station was used to measure the true pose values of each piece of equipment. To comprehensively evaluate the positioning performance, the following evaluation indicators are defined in this paper: absolute positioning error, which refers to the position error of the bolter miner in the tunnel coordinate system; relative positioning error, which refers to the pose error of the crusher relative to the bolter miner and the belt conveyor relative to the crusher; lateral offset error, which refers to the distance error of the equipment center relative to the tunnel centerline; and attitude angle error, which refers to the measurement errors of the yaw angle, pitch angle, and roll angle.

4.1.2. Accuracy test scheme

1. Laser positioning subsystem test

This test aims to evaluate the accuracy of the four-point laser ranging-based algorithm for measuring the pose of the crusher relative to the bolter miner (or the conveyor belt relative to the crusher). The bolter miner (or the preceding equipment) is fixed on a horizontal reference surface, with four laser ranging sensors installed at its rear side. The crusher (or the subsequent equipment) is mounted on a precision displacement-angle adjustment platform, ensuring controlled distance movement and attitude deflection.

The subsequent equipment is controlled to move to distances of 0.5 m, 1.0 m, and 1.5 m from the preceding equipment. At each distance point, the attitude angle of the subsequent equipment is maintained at zero, and the readings of the four laser ranging sensors are recorded. The relative distance between the front and rear equipment is calculated using the algorithm described in Section 3.2. The calculated results are compared with the true values measured by a total station.

With the subsequent equipment positioned at a standard distance of 1.0 m from the preceding equipment, the platform is adjusted to produce yaw angle changes of −3°, 0°, and +3°, respectively. The four laser ranging values are recorded again, and the relative attitude angle is calculated. These results are compared with the true values measured by a high-precision inclinometer.

For each operating condition, the measurement is repeated 30 times. The calculated relative distances and attitude angles are recorded, and their mean errors and standard deviations are statistically analyzed.

2. Ultrasonic positioning subsystem test

This test aims to verify the accuracy of the ultrasonic sensor array in measuring the lateral offset of the equipment (i.e., the distance from the equipment center to the tunnel centerline) and to investigate the influence of tunnel width variations on the measurement results. The crusher (or the conveyor belt) is fixed on a laterally movable guide rail platform. 16 ultrasonic ranging sensors are installed on both sides of the equipment according to the designed positions.

In the standard width section of 5.6 m, the equipment is moved to positions of −0.3 m, 0 m, and +0.3 m from the tunnel centerline, respectively (simulating lateral offset). The distance data from the 16 ultrasonic sensors to the two sidewalls are collected, and the lateral offset of the equipment center relative to the tunnel centerline is calculated using the algorithm in Section 3.3. Each operating condition is repeated 30 times. The raw distance values of each sensor and the final calculated lateral offset are recorded and compared with the true lateral displacement values provided by the guide rail platform to analyze the error distribution.

3. Multi-machine collaborative overall performance test

Based on the completion of independent accuracy verification for each subsystem, this test aims to simulate actual excavation operating conditions and evaluate the overall positioning performance of the complete equipment consisting of the bolter miner, crusher, and conveyor belt under multi-machine collaborative operation. The focus is on examining the capability of the system to synchronously solve for the absolute poses, relative poses, and lateral offsets of the three machines during dynamic operation, verifying the effectiveness of the unified reference fusion algorithm, and analyzing the propagation pattern of chain errors during actual motion. Experiments were conducted in a straight tunnel test section with a length of 50 m to verify the consistency of multi-machine pose calculation under static conditions. A total station was used to track and measure the three-dimensional coordinates of key feature points on the three machines as the true pose values. The raw data and calculation results of the laser positioning subsystem, laser ranging subsystem, and ultrasonic ranging subsystem were recorded synchronously.

4.2. Analysis and discussion

This section sequentially analyzes the test results of the laser positioning subsystem, the ultrasonic positioning subsystem, and the overall multi-machine collaborative performance, and discusses the error propagation characteristics.

4.2.1. Analysis of laser positioning subsystem test results

The measurement results of the laser positioning subsystem under different distance and attitude conditions are statistically shown in Table 2.

Table 2
Laser positioning subsystem measurement error statistics

Measurement parameter	True value	Mean error	Standard deviation	Maximum error
Distance measurement	0.5 m	3.2 mm	4.7 mm	11.3 mm
	1.1 m	5.1 mm	5.9 mm	14 mm
	1.5 m	6.0 mm	7.3 mm	15.3 mm
Attitude measurement	−3.2°	−0.1°	0.14°	0.31°
	0.4°	0.06°	0.09°	0.2°
	2.9°	0.15°	0.16°	0.4°

1. Distance measurement accuracy analysis

As shown in Table 2, the standard deviations of the laser ranging system at the three distance points of 0.5 m, 1.1 m, and 1.5 m are 4.7 mm, 5.9 mm, and 7.3 mm, respectively. The overall error level is inferior to the nominal accuracy of the sensors. The following patterns can be observed:

(1) The error shows an increasing trend with distance. When the measurement distance increases from 0.5 m to 1.5 m, the standard deviation increases from 4.7 mm to 7.3 mm. This phenomenon is mainly attributed to two factors. First, the laser spot diverges as the distance increases, leading to decreased accuracy in spot center positioning. Second, during long-distance measurements, the ranging errors caused by slight changes in the laser incidence angle are amplified.

(2) The error distribution exhibits symmetry: The error distribution at each distance point is basically normal, with no obvious skewness characteristics, indicating that the system has no systematic bias. The mean errors range from +3.2 mm to +6 mm, with an overall positive bias, which may be related to minor deviations in the zero-point calibration of the laser sensors.

2. Attitude measurement accuracy analysis

(1) Higher accuracy is achieved at small angles: the measurement error is minimal near 0°, i.e., when the equipment is in aligned state; as the yaw angle increases, the error increases slightly. This is because, under large yaw angles, the distance differences among the four laser ranging points become larger, making the least squares solution more sensitive to sensor noise.

(2) Good symmetry between positive and negative yaw: the error levels under −3° and +3° conditions are basically consistent, indicating that the system has symmetrical measurement performance in both left and right directions without obvious directional bias.

(3) Accuracy meets collaborative control requirements: calculated with an attitude angle error of 0.2°, the lateral position deviation caused by the attitude error at the end of a 10-meter-long equipment chain is approximately 35 mm, which remains within an acceptable range.

The measurement errors of the laser positioning subsystem mainly originate from the following aspects: first, the measurement noise of the laser sensors themselves, manifested as random errors; second, calibration errors in the installation positions of the sensors, introducing systematic bias; third, the fitting residuals of the least squares method applied to multi-point data in the solution algorithm. Experimental results indicate that the current system design has controlled the aforementioned errors within a reasonable range.

4.2.2. Analysis of ultrasonic positioning subsystem test results

Analysis of ultrasonic positioning subsystem test results is statistically shown in Table 3.

Table 3
Ultrasonic positioning subsystem measurement error statistics

Measurement parameter	True value	Mean error	Standard deviation	Maximum error
Standard width	−0.3 m	−8.5 mm	12.3 mm	38.5 mm
	0 m	3.4 mm	10.5 mm	32.1 mm
	0.3 m	+9.8 mm	13.6 mm	42.3 mm

The analysis reveals the following:

(1) The highest accuracy is achieved at the centerline position. The measurement error is minimal when the equipment is positioned at the tunnel centerline. This is because the distances from both sides of the equipment to the two sidewalls are equal, and the incident angles and reflection characteristics of the ultrasonic waves are symmetrical, which helps to offset some systematic errors.

(2) The error increases with larger offsets. When the equipment is offset to −0.3 m and +0.3 m, the error increases significantly. Analysis suggests that when the equipment approaches one sidewall, the distance between the sensors on that side and the sidewall decreases, and the ultrasonic inci-

dent angle increases, leading to reduced ranging accuracy. Simultaneously, the measurement distance of the sensors on the far side increases, resulting in greater signal attenuation and a lower signal-to-noise ratio.

(3) Asymmetry in left and right offsets. The error at +0.3 m is different from that at −0.3 m. Upon examination, this was found to be related to the higher surface roughness of the right sidewall, indicating that the accuracy of ultrasonic measurement is significantly influenced by the surface characteristics of the tunnel walls.

4.2.3. Analysis of overall performance test results

Table 4 presents the statistical results of the absolute positioning errors of the three machines under the constant speed following condition.

Table 4
Absolute positioning error statistics

Equipment	Measurement parameter	Mean error	Standard deviation	Maximum error
Bolter miner	Y-direction (Longitudinal)	5.8 mm	6.2 mm	25.3 mm
	X-direction (Lateral)	4.2 mm	5.1 mm	12.1 mm
Crusher	Y-direction (Longitudinal)	8.7 mm	8.9 mm	32.5 mm
	X-direction (Lateral)	12.3 mm	14.2 mm	35.6 mm
Belt conveyor	Y-direction (Longitudinal)	12.5 mm	13.1 mm	42.8 mm
	X-direction (Lateral)	16.8 mm	18.5 mm	48.3 mm

As can be seen from Table 3, the bolter miner, serving as the main reference, exhibits the highest absolute positioning accuracy, with a standard deviation of 6.2 mm in the longitudinal direction and 5.1 mm in the lateral direction, which is consistent with the unit test conclusions. As the equipment chain lengthens, the positioning error shows a significant cumulative effect. The longitudinal error of the crusher is 43.5% larger than that of the bolter miner, and that of the conveyor belt is 111.3% larger than that of the bolter miner. The lateral error is significantly greater than the longitudinal error and accumulates at a faster rate, indicating that the ultrasonic positioning subsystem is the current accuracy bottleneck of the system.

Relative pose is a key parameter for collaborative control. Table 5 presents the measurement errors of the relative pose between adjacent equipment under constant speed conditions.

Table 5
Relative positioning error statistics

Equipment	Measurement parameter	Mean error	Standard deviation	Maximum error
Crusher relative to bolter miner	Relative distance	4.8 mm	6.5 mm	13.2 mm
	Relative attitude angle	0.08°	0.12°	0.25°
Belt conveyor relative to crusher	Relative distance	6.2 mm	8.7 mm	17.5 mm
	Relative attitude angle	0.11°	0.16°	0.32°

The analysis indicates the following:

(1) The measurement accuracy of the two stages is essentially comparable. The standard deviation of the distance measurement for the crusher relative to the bolter miner, and that for the belt conveyor relative to the crusher, are within the same order of magnitude. The differences mainly arise from objective conditions such as sensor installation positions and target surface reflection characteristics.

(2) The requirements for collaborative control are met. Taking the crusher as an example, the lateral deviation caused by a 0.12° attitude angle error at the end of a 10 m equipment chain is approximately 21 mm. Combined with the distance error of 6.5 mm, the overall deviation is controlled within 30 mm. This level of accuracy satisfies the alignment requirements for the transfer point between the crusher and the bolter miner, as well as the material connection needs between the belt conveyor and the crusher.

(3) The attitude angle error is slightly larger relative to the distance error. The standard deviations of the relative attitude angles for the two stages are 0.12° and 0.16°, respectively. This is partly because attitude calculation requires fusing information from four laser ranging points, making it more sensitive to sensor noise. Additionally, minor pitch and roll variations of the equipment during dynamic operation also increase the complexity of the attitude calculation.

Due to the three-stage serial structure of the complete set of rapid excavation equipment, the positioning errors of the crusher and the conveyor belt originate from the superposition of the absolute error of the preceding equipment and the relative measurement error of the current stage. Under the assumption that the measurement errors at different stages are independent, the total error of the downstream equipment can be regarded as the combination of the preceding error and the relative measurement error. The experimental data show that the measured total errors of the crusher and the conveyor belt are generally consistent with the above combination rule, indicating that the errors of each subsystem contribute significantly to the final accuracy. Among them, the accumulation effect of the lateral error is more pronounced than that of the longitudinal error, which is related to the fact that the error level of the ultrasonic ranging subsystem is higher than that of the laser ranging subsystem. Therefore, the overall collaborative positioning accuracy should take the measured error of the downstream equipment (especially the terminal belt conveyor) as the main evaluation indicator, while the subsystem-level individual errors can be used to diagnose performance bottlenecks of each module and to guide subsequent optimization.

To evaluate the performance level of the proposed method, a qualitative and quantitative comparison is made with several typical positioning solutions reported in the literature. Vision-based positioning methods [6] achieve high accuracy under ideal conditions but are susceptible to dust and illumination variations, with reported positioning errors of approximately 21 mm in underground environments. UWB positioning methods [7] offer large coverage, but multipath effects are significant in narrow and long tunnels, resulting in a lateral error of about 35 mm at a distance of 30 m. Total stations [8] provide the highest accuracy but require manual point-by-point measurement and cannot achieve real-time continuous positioning. Pure inertial navigation [16] has no external dependency, yet its error accumulates rapidly over time, with a lateral drift of approximately 42 mm over typical operating durations. In contrast to the above methods, the proposed laser-ultrasonic collaborative positioning method meets the accuracy requirements for multi-machine collaborative control while offering comprehensive advantages, including robustness against dust and vibration, no need for a large number of base stations or artificial targets, and the ability to simultaneously acquire absolute and relative poses in real time. It is therefore better suited for the actual working conditions of rapid tunnel excavation.

5. CONCLUSIONS

This paper proposes a multi-machine collaborative positioning method for rapid excavation complete equipment. This method uses a laser locator to measure the absolute pose of the bolter miner as the primary reference, integrates laser ranging and ultrasonic ranging sensor groups deployed on subsequent equipment, and achieves synchronous acquisition of the absolute positions, relative positions, and attitudes of the three machines through spatial coordinate transformation and unified reference fusion. Through systematic experimental research, the following conclusions are drawn:

1. The laser ranging subsystem performs well within the measurement range of 0.5–1.5 m, with a standard deviation of 4.7–7.3 mm for distance measurement and 0.09°–0.16° for attitude angle measurement, meeting the accuracy requirements for relative pose measurement in multi-machine collaborative operations.
2. The ultrasonic ranging subsystem achieves a standard deviation of 10.5–13.6 mm for lateral offset measurement under standard operating conditions, with the highest accuracy achieved when the equipment is positioned at the tunnel centerline. Measuring accuracy is significantly influenced by the lateral offset amount and the surface characteristics of the tunnel walls, verifying the necessity of redundant sensor configuration.
3. Overall performance tests show that the system can effectively acquire the pose information of the three machines. The bolter miner achieves an absolute positioning standard deviation of 6.2 mm in the longitudinal direction and 5.1 mm in the lateral direction. The crusher relative to the bolter miner achieves a distance measurement standard deviation of 6.5 mm and an attitude angle of 0.12°. The positioning accuracy meets the basic requirements for rapid excavation collaborative operations. Future research will focus on optimizing ultrasonic ranging data processing and multi-sensor fusion strategies to further enhance the reliability and environmental adaptability of the system.

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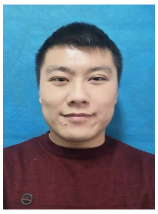

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