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Intelligent segment typesetting in shield tunneling based on artificial neural networks and transfer learning

Rui LIU[1], Quanyong ZENG[1], Haibo XIE[2,3], Guoli ZHU[1]

[1]*School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China*
[2]*Institute of Advanced Machines, Zhejiang University, Hangzhou 310014, China*
[3]*State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, Hangzhou 310058, China*

Section S1 Method for calculating the thrust cylinder stroke differences

According to the relevant reference (Szczotka and Wojciech, 2008), the homogeneous transformation matrix (HTM) for the conversion from coordinate system 2 to coordinate system 1 is determined by the relative position (*x*, *y*, *z*) and relative orientation (*α*, *β*, *γ*). The expression for the HTM is as follows:

$$
{}_2^1\boldsymbol{T}=\begin{bmatrix}1&0&0&x\\0&1&0&y\\0&0&1&z\\0&0&0&1\end{bmatrix}\times\begin{bmatrix}\mathrm{c}\gamma&-\mathrm{s}\gamma&0&0\\\mathrm{s}\gamma&\mathrm{c}\gamma&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}\times\begin{bmatrix}\mathrm{c}\beta&0&\mathrm{s}\beta&0\\0&1&0&0\\-\mathrm{s}\beta&0&\mathrm{c}\beta&0\\0&0&0&1\end{bmatrix}\times\begin{bmatrix}1&0&0&0\\0&\mathrm{c}\alpha&-\mathrm{s}\alpha&0\\0&\mathrm{s}\alpha&\mathrm{c}\alpha&0\\0&0&0&1\end{bmatrix}, \tag{S1}
$$

where c and s represent cosine and sine functions, respectively.

${}_B^A\boldsymbol{T}$ is the HTM from $O_B-X_BY_BZ_B$ to $O_A-X_AY_AZ_A$, derived using Eq. (S1). Likewise, the HTM ${}_C^B\boldsymbol{T}$, which represents the transformation from $O_C-X_CY_CZ_C$ to $O_B-X_BY_BZ_B$, and the HTM ${}_D^A\boldsymbol{T}$, which denotes the transformation from $O_D-X_DY_DZ_D$ to $O_A-X_AY_AZ_A$, can be derived.

Based on the design dimensions of the shield machine, we know the coordinates of the thrust cylinder mounting points in $O_B-X_BY_BZ_B$, denoted as ${}^BM_k\,(k=1,2,3,4)$. The mounting points can be expressed in $O_A-X_AY_AZ_A$ as follows:

$$
{}^AM_k={}_B^A\boldsymbol{T}\times{}^BM_k\,. \tag{S2}
$$

The thrust cylinders are all parallel to the axis of the front shield, and their direction vectors $\vec{v}$ in $O_A - X_A Y_A Z_A$ can be represented as follows:

$$^{A}\vec{v} = {}^{A}_{B}\boldsymbol{T} \times {}^{B}\vec{v} = {}^{A}_{B}\boldsymbol{T} \times \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}. \tag{S3}$$

The equations of the lines where the four cylinders are located can be represented as follows:

$$\overrightarrow{^{A}M_k \, ^{A}P_k} = t_1 \, ^{A}\vec{v}, \tag{S4}$$

where, $P_k (k = 1, 2, 3, 4)$ is an arbitrary point on the line, and t_1 is an arbitrary real number.

Let the normal vector and the center point of the front face of the previous segment ring in $O_D - X_D Y_D Z_D$ be denoted by $^{D}\vec{u}$ and $^{D}O_D$ respectively, where $^{D}\vec{u}$ is given as $\begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}$ and $^{D}O_D$ as $\begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix}$. In $O_A - X_A Y_A Z_A$, these can be represented as follows:

$$^{A}\vec{u} = {}^{A}_{D}\boldsymbol{T} \times {}^{D}\vec{u}, \tag{S5}$$

$$^{A}O_D = {}^{A}_{D}\boldsymbol{T} \times {}^{D}O_D. \tag{S6}$$

In $O_A - X_A Y_A Z_A$, the plane equation of the front face of the previous segment ring can be expressed as Eq. (S7):

$$\overrightarrow{^{A}O_D \, ^{A}P_5} \times {}^{A}\vec{u} = 0, \tag{S7}$$

where P_5 is an arbitrary point on the plane.

Combining Eqs. (S4) and (S7), the coordinates of the intersection points, $S_k (k = 1, 2, 3, 4)$, between the thrust cylinder and the front face of the previous segment ring in $O_A - X_A Y_A Z_A$ can be calculated. The thrust cylinder strokes on the upper ($U_{u,n}$), left ($U_{l,n}$), lower ($U_{d,n}$), and right ($U_{r,n}$) sides can be determined using Eq. (S8).

$$\begin{cases} U_{u,n} = \left| \overrightarrow{{}^{A}M_1 \, {}^{A}S_1} \right| - c_y \\ U_{l,n} = \left| \overrightarrow{{}^{A}M_2 \, {}^{A}S_2} \right| - c_y \\ U_{d,n} = \left| \overrightarrow{{}^{A}M_3 \, {}^{A}S_3} \right| - c_y \\ U_{r,n} = \left| \overrightarrow{{}^{A}M_4 \, {}^{A}S_4} \right| - c_y \end{cases}, \tag{S8}$$

where c_y is the length of the thrust cylinder when it is not extended.

Subsequently, the thrust cylinder stroke difference in the vertical direction, indicated as $U_{v,n}$, and the thrust cylinder stroke difference in the horizontal direction, denoted as $U_{h,n}$, can be calculated.

Section S2 Method for calculating the lower tail shield gap

The HTM from $O_D - X_D Y_D Z_D$ to $O_E - X_E Y_E Z_E$, denoted as ${}^{E}_{D}\boldsymbol{T}$, can be obtained using Eq. (S9).

$${}^{E}_{D}\boldsymbol{T} = \begin{bmatrix} \mathrm{c}\theta & -\mathrm{s}\theta & 0 & 0 \\ \mathrm{s}\theta & \mathrm{c}\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \tag{S9}$$

Let $\vec{w}$ be the direction vector of the segment ring's axis, and ${}^{E}\vec{w} = \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}$. With O_E as the origin of $O_E - X_E Y_E Z_E$, and ${}^{E}O_E = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix}$, the equation of the outer cylindrical surface of the segment ring expressed in $O_E - X_E Y_E Z_E$ can be expressed as:

$$\left| \overrightarrow{{}^{E}O_E \, {}^{E}P_6} \right| \times {}^{E}\vec{w} = \frac{D_g}{2}, \tag{S10}$$

where P_6 is an arbitrary point on the cylindrical surface, and D_g is the outer diameter of the segment ring.

The sensor mounting points in $O_C - X_C Y_C Z_C$ can be measured and are denoted as ${}^{C}H_k \, (k = 1, 2, 3, 4)$, and their coordinates in $O_E - X_E Y_E Z_E$ can be represented as follows:

$${}^{E}H_k = {}^{E}_{C}\boldsymbol{T} \times {}^{C}H_k, \tag{S11}$$

$$ {}_{C}^{E}\boldsymbol{T} = \left[{}_{C}^{A}\boldsymbol{T}^{-1} \times {}_{D}^{A}\boldsymbol{T} \times {}_{D}^{E}\boldsymbol{T}^{-1} \right]^{-1}, \tag{S12} $$

where ${}_{C}^{E}\boldsymbol{T}$ is the HTM from $O_C - X_C Y_C Z_C$ to $O_E - X_E Y_E Z_E$.

Let $\vec{r}$ be the direction vector of the laser emitted by the displacement sensor below, represented by ${}^{C}\vec{r} = [0 \quad 0 \quad 1 \quad 0]$ in $O_C - X_C Y_C Z_C$, which can be represented in $O_E - X_E Y_E Z_E$ as follows:

$$ {}^{E}\vec{r} = {}_{C}^{E}\boldsymbol{T} \times {}^{C}\vec{r}. \tag{S13} $$

The equation of the laser line can be expressed as:

$$ \overrightarrow{{}^{E}H_3 \, {}^{E}P_7} = t_2 \, {}^{E}\vec{r}, \tag{S14} $$

where P_7 is arbitrary points on the laser line, and t_2 is an arbitrary real number.

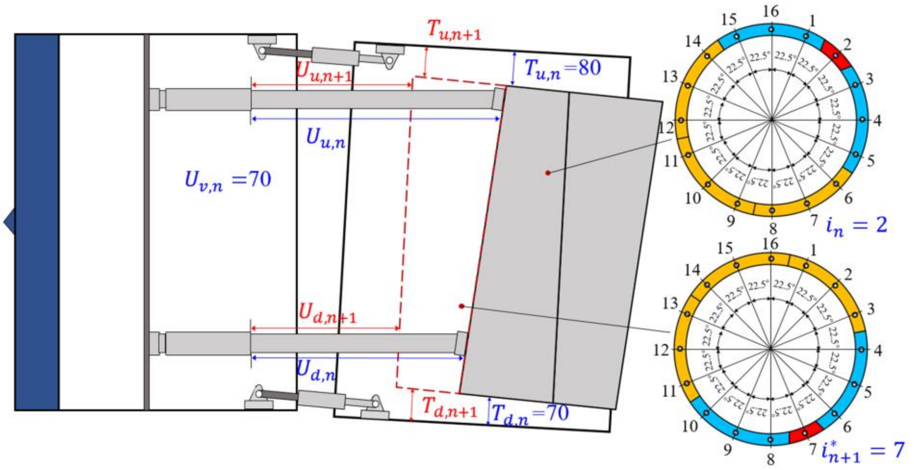
Combining Eqs. (S10) and (S14), the lower measurement point D_3 on the outer cylindrical surface of the segment ring can be calculated. The lower shield tail gap can be expressed as:

$$ T_{d,n} = \left| \overrightarrow{{}^{E}H_3 \, {}^{E}D_3} \right|. \tag{S15} $$

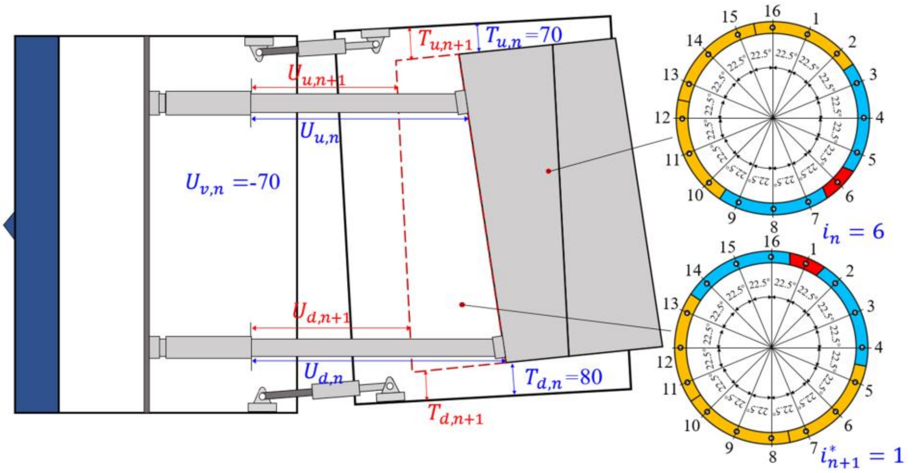
Section S3 Method for data augmentation

By applying a horizontally symmetrical transformation to the shield tail gaps and thrust cylinder strokes, the assembly points must also be adjusted symmetrically to maintain optimization. As shown in Fig. S1a, the original data shows a vertical thrust cylinder stroke difference $U_{v,n}$ of 70 mm, upper and lower shield tail gaps, $T_{u,n}$ and $T_{d,n}$, of 80 mm and 70 mm, respectively; the previous segment assembly point i_n at point 2, and the optimal current segment assembly point i_{n+1}^* at point 7. Applying a horizontal symmetrical transformation to this data yields Fig. S1b, where $U_{v,n}$ becomes -70 mm, $T_{u,n}$ and $T_{d,n}$ are transposed to 70 mm and 80 mm, respectively, and i_n is transformed to assembly point 6. Consequently, to achieve equivalent optimization, the optimal assembly point i_{n+1}^* should also be adjusted symmetrically, changing from 7 to 1.

Similarly, vertical and diagonal symmetrical transformations were applied, effectively increasing the dataset size by a factor of four. Table S1 presents a representative example to demonstrate this augmentation method. Ultimately, a total of 11,560 sets of example data were collected.



(a)



(b)

Fig. S1 Schematic diagram of example data augmentation: (a) original data; (b) horizontally symmetrical transformation

Table S1 Examples of data augmentation method

Data types	$U_{v,n}$	$U_{h,n}$	$T_{u,n}$	$T_{d,n}$	$T_{l,n}$	$T_{r,n}$	i_n	i^*_{n+1}
Original data	70	20	80	70	80	70	2	7
Horizontally symmetrical	-70	20	70	80	80	70	6	1
Vertical symmetrical	70	-20	80	70	70	80	14	9
Diagonal symmetrical	-70	-20	70	80	70	80	10	15