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Study on the Construction and Application of Digital Twins on High Voltage Transmission Line Live Working Scenes

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ABSTRACT Affected by electric field generated in power transmission line, live worker on the high-voltage transmission line is in dangerous working environment. In this paper, posture perception, numerical simulation, and risk assessment are adopted to realize the deep fusion of physical trajectory and spatial virtual electric field distribution of live worker, and digital twin bodies of live worker in different live working scenarios are constructed. Firstly, posture trajectories and 3D model of living worker in typical operation conditions are captured and reconstructed by full-body inertial action capture technology and this technology use motion capture unit which include 3-axis accelerometer/gyroscope/magnetic field sensors. The length of complex gap and body workspace under various live work scenes are also calculated. By static electrical field finite element (FE) numerical modeling, surface electrical field distributions of live worker under different posture trajectories are then calculated. Finally, interactive mechanism between “body-information-physical environment-virtual environment” is introduced, and potential risk of live worker is on-line assessed by live work guide rules. This work develops a new assessment and protection method for virtual training and field operations of high-voltage live worker. Which is of great significance for enhancing operation level and ensuring living workers’ safety.

INDEX TERMS Live work, data twin, intelligence.

I. INTRODUCTION

In the process of living working on power transmission lines, workers will be affected by high-voltage lines and electric fields on the surface of the human body is induced when they enter the charged space of high-voltage power transmission line. Electric field distribution characteristics are closely related to the personal safety of live workers [1], [2]. Thus, effective protective measures must be taken to ensure live workers’ safety. At present, many researches have been carried out to protect live worker who are work on high-voltage transmission lines. Numerical calculations of the electric field on the surface of the human body were carried out at different position of high-voltage transmission line and different entry modes [3]–[5]. Current distributions of human body under

different live working scenarios are calculated in [6]. A gap discharge model for living working on UHV lines is established in [7], the electric field distribution on human body surface under different voltage levels, positions, and human postures are obtained by the finite element method. Related protective measures by electrical field analysis are widely used for live workers [8]–[12]. However, the real operating conditions and the numerical model parameters (geometry profiles and boundary conditions) could not be synchronized. Thus, the conventional electrical calculation methods have the limitation of real-time performance.

With the development of virtual reality (VR) technology, sensor technology, and computer vision technology, the virtual training and safety protection monitoring of live-work has made significant progress. The typical application scenarios of VR technology in training and safe operation evaluation of new power company employee is

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shown in [13]; A safety monitoring method of live working on high-voltage line by time-of-flight (ToF) depth imaging technology is raised in [14]. A live-working safety assessment and protection system which integrates the sensor data and micro-meteorological data is proposed in [15] and [16]. However, the current VR training considers the modeling including physical features such as electric fields, the on-line monitoring methods and systems are all based on the actual physical model of live worker. The features of virtual scene such as the spatial electric field distribution are not considered, and the relationship between the monitoring data and the physical model is not direct enough.

Digital Twin (DT) is a kind of mathematical virtual mapping technology to the physical model. Through the construction of virtual digital twin model, operating characteristics and behavior of the corresponding physical model could be illustrated. Besides control and evaluation of the physical model could be realized through the two-way flow of information between the digital twin and the physical model. In recent years, DT technology has received increasing attention and applications in the industrial field. The application of DT technology in the reconstruction and control of traffic scene is described in [17]. A visual monitoring and control system to operate a five-axis friction machine tool based on DT technology, thus improving the virtual-real interaction capability and monitoring efficiency of the machine tool [18].

This paper focus on virtual training and safety assessment of live worker who work in high-voltage power transmission line. Physical trajectory and spatial virtual electric field distribution of live worker are connected by posture perception, numerical simulation, and risk assessment. Then the DT model of different live operation scenarios of live worker is constructed. The actual scene actions of live working can be mapped into virtual scenes. Virtualized training and standardized evaluation of high-voltage live working could be realized through the virtual scenes provided by DT model. Research results will help improve the operation level of live worker in complex working scenes and ensure live workers' safety.

II. APPLICATION FRAMEWORK OF DIGITAL TWIN SYSTEM IN LIVING WORKING SCENE

The application framework of the DT model for live working scenes is shown in Fig. 1.

The DT model mainly includes live worker posture trajectory, geometric model, electrostatic field calculation model, and safety operation risk assessment model. The constructed DT model interacts with the external physical environment by geometry reconstruction, posture capture and material properties. Thus, safety assessment and risk prediction of live worker can be carried out, and early warning of live working status can be obtained.

III. MODELING OF LIVE WORKERS' POSTURE

In this paper, a 3-D human body model with main movable joints is constructed to obtain the geometric models of live workers in different live working scenarios, and whole-body

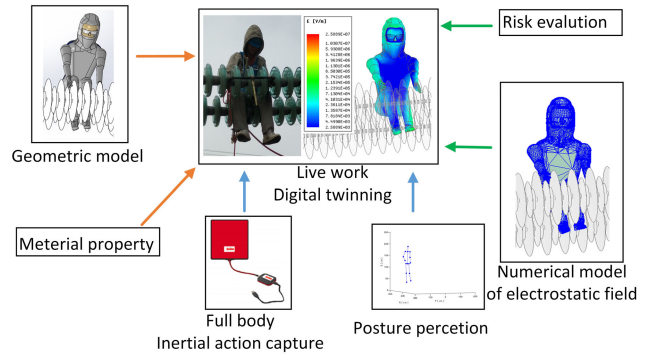


FIGURE 1. Application framework of DT model in hot-line working.

inertial action capture technology which arrange inertial capture units on the human body to measure the relative displacement information of each joint of the human body in different working scenarios. Information acquired will interact with the information of the initial human body 3-D model posture to realize reconstruction of the geometric model of human body.

A. GEOMETRIC MODEL OF LIVE WORKING PERSONNEL

The geometric model of live workers wearing shielding suits is built-in Solidworks as shown in Fig.2. The height of the human body is set to 1.75m. According to the regulations of live work, the live workers wear shielding suits except for their exposed faces [19]–[22]. In the modeling process, to facilitate the interaction with the acquisition of human body posture information to achieve geometric reconstruction, the movable parts of the human geometric model such as the neck, shoulders, elbows, wrists, crotches, knees, and ankles are provided with rotatable. Based on the posture information of the joints, the geometric model is reconstructed, and the Boolean operation is used to finally establish a geometric model that can be used for finite element analysis of the electrostatic field.

B. FULL-BODY INERTIAL ACTION CAPTURE TECHNOLOGY

Full-body inertial action captures technology uses motion capture sensors. The capture sensors bound to multiple joints of the human body to obtain information including the rotation angle and offset between bones and limb joints during human movement. The displacement-posture transformation algorithm is used to realize the real-time perception and reproduction of human posture. Based on this technology,

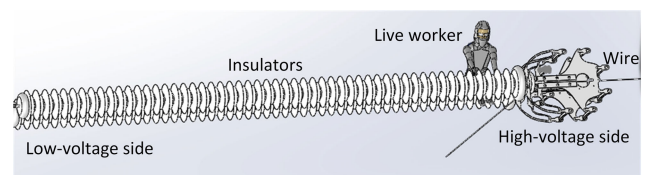


FIGURE 2. Geometric model of live worker.

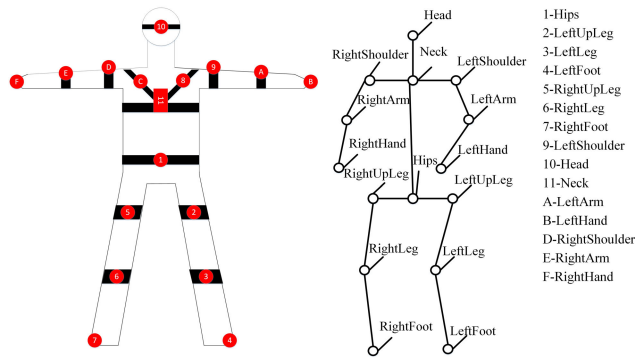


FIGURE 3. Action capture sensors adoption and human joints model of live worker.

joint motion information is acquired with a sensor array worn by the human body, and the information of joint motion will combine with the geometric dot-line human skeleton model to obtain the posture of the live worker. Based on the sensor layout of the full-body inertial motion capture system, the key translation and deflection information of the human body’s neck, shoulders, limbs, etc. are acquired, and the geometric point-line model of the human body is constructed again based on the geometric point-line human skeleton model (joint tree). As shown in Fig.3.

The Bounding Volume Hierarchies data structure is used to express the mapping relationship of the human joint tree. After the device is initialized and calibrated, the information obtained by the motion capture sensor is converted into corresponding posture data, the posture data associate with the information of the initial posture position and the human bone structure to generate the transformation matrix of the joints, and the position data obtained by the motion capture sensor is converted into the corresponding human posture by coordinate transformation, the mathematical formula can be described as:

$$\mathbf{v}' = \mathbf{M}\mathbf{v} \tag{1}$$

where \mathbf{v}' is the posture position of the human body, \mathbf{v} is the original point, \mathbf{M} is the coordinate system transformation matrix of adjacent bones which connected by joints. and \mathbf{M} is a combination of translation \mathbf{T} , rotation \mathbf{R} , and proportion \mathbf{S} . So the local conversion matrix \mathbf{M}_i of a single joint i can be described as:

$$\mathbf{M}_i = \mathbf{T}\mathbf{R}\mathbf{S} \tag{2}$$

where \mathbf{T} is the translation of the movement of a single joint which convert to relative coordination system, and \mathbf{T} can be expressed as:

$$\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & x \\ 0 & 1 & 0 & y \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

where \mathbf{x} , \mathbf{y} , and \mathbf{z} represent the relative offset between coordinate systems.

The rotation matrix \mathbf{R} can be expressed as:

$$\mathbf{R} = R_x R_y R_z \tag{4}$$

$$R_x(\alpha) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \alpha & -\sin \alpha & 0 \\ 0 & \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

$$R_y(\beta) = \begin{bmatrix} \cos \beta & 0 & \sin \beta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin \beta & 0 & \cos \beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

$$R_z(\gamma) = \begin{bmatrix} \cos \gamma & -\sin \gamma & 0 & 0 \\ \sin \gamma & \cos \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{7}$$

where α , β , and γ are the rotation angles of the coordinate system around the \mathbf{x} , \mathbf{y} , and \mathbf{z} axes respectively.

The scaling matrix \mathbf{S} can be expressed as:

$$\mathbf{S} = \begin{bmatrix} s_x & 0 & 0 & 0 \\ 0 & s_y & 0 & 0 \\ 0 & 0 & s_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{8}$$

where s_x , s_y , and s_z are the scaling ratio of \mathbf{x} , \mathbf{y} , and \mathbf{z} axes respectively. With the fixed bone state and matching human body model, the scale is set to 1.

According to the human joints model given in Figure 3, the global transformation of human posture is affected by the local transformation of a single joint and the local transformation of adjacent joints (parent skeleton) in the hierarchy. Therefore, the global transformation matrix \mathbf{M} can be described as:

$$\mathbf{M} = \prod_{i=0}^n \mathbf{M}_i \tag{9}$$

where $\mathbf{i} = 0, 1, 2, \dots, n$, $\mathbf{M}_0(\mathbf{i} = 0)$ represents the transformation matrix of the human root bone position in the global scene. The others $\mathbf{M}_i(\mathbf{i} = 1, 2, \dots, n)$ represent the local transformation matrix of the corresponding number of joints.

C. PERSONNEL POSTURE ACQUISITION AND RECONSTRUCTION IN DIFFERENT LIVE WORKING SCENARIOS

In this paper, the True action inertial motion capture system is used to obtain the motion data of live workers. The system mainly consists of a motion capture sensing unit, signal acquisition and transmission unit, and a processing unit. The motion capture sensing unit includes a three-axis accelerometer, a three-axis gyroscope, and a three-axis magnetometer, which can complete the posture analysis of different parts of the human body. The posture data obtained by the sensor unit is sent to the processing unit through the signal acquisition and transmission unit, and the processing unit processes the joint points’ signal in real-time to calculate the relative offset of each joint of the body, thereby achieving the acquisition of the human posture. Parameters of motion sensor are listed

TABLE 1. Motion capture sensor parameters.

parameters	Value
Range of Gyroscope	±2000dps
Range of Accelerometer	±32g
Accuracy of Static Attitude	Roll 0.7°, Pitch 0.7°, Yaw 2°
Data Calculation Frame Rate	800Hz
Data Output Frame Rate	240Hz

in Table 1. The signal transmission method is wireless transmission at 2400MHz-2483MHz. The body motion calculation time is 1.25ms and body motion data transmission speed is 4.16ms. Thus, the signal transmission delay is 5.41ms or 184 frame rate.

The skeleton pattern acquisition and geometric reconstruction process of live worker are shown in Figure 4. The movement information such as the rotation angle and offset of each joint of the human body obtained by the sensor unit, the human skeleton pattern is obtained through the coordinate conversion of the hierarchical bounding box data structure (Fig.4(a)). The translation operation is performed by the relative position between the gravity center of the human body and the gravity center of the line. The relative rotation angle of each joint calculated by the human joint model is used to rotate the corresponding joints of human body. The geometric model of the human body is reconstructed through Boolean operations (Fig.4(b)).

IV. CALCULATION OF HUMAN BODY SURFACE ELECTRIC FIELD UNDER TYPICAL LIVING WORKING SCENES

When a live worker enters the high-voltage space electric field, the human body, which can be regarded as a conductor, can cause the space electric field distortion. In this paper, the electrostatic field finite element theory apply to obtain the virtual electric field distribution on the surface of the human body under different live working scenes, and a finite element solution domain containing the reconstructed 3-D geometric model of the human body in different postures and high-voltage transmission lines is constructed. The electric field distribution on the human body surface obtained by 3-D electrostatic field finite element analysis, The FE analysis

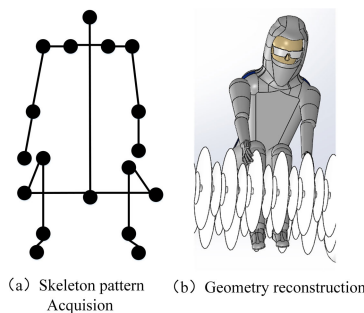


FIGURE 4. Skeleton pattern acquisition and geometric reconstruction of live worker.

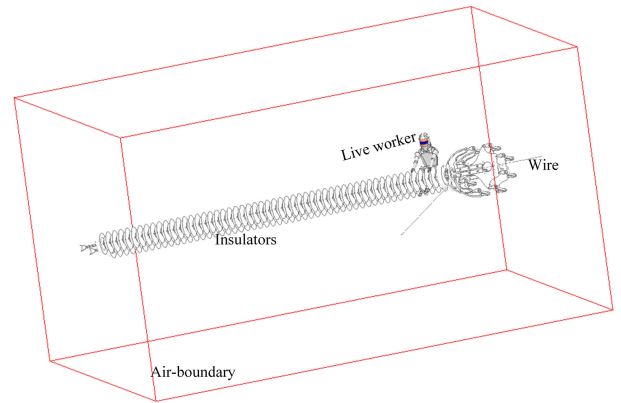


FIGURE 5. Electric field solution region division.

can provide a basis for analyzing and assessing human body safety in typical operating scenes.

A. SOLUTION DOMAIN SETTING

The solution domain of the numerical calculation model of the human body surface electric field in a typical live working scene is shown in Fig.5. The high-voltage line’s material is steel-cored aluminum stranded wire, the live workers wear shielding protective clothing and glasses, and the face of the live worker is bare. There is air space between high-voltage lines and live worker. To simulate the distribution and attenuation of the electric field in space, the size of the air domain is set to 3 times the characteristic size of the human body during the modeling process. The material properties of different solution domains are presented in Table 2.

B. MATHEMATICAL MODEL AND BOUNDARY CONDITIONS OF ELECTROSTATIC FIELD

Under normal working conditions, the power frequency electric field around the overhead line changes with time. due to the electric field changes slowly at the power frequency, it can generally be considered that the electric field distribution around the overhead line obeys the law of the electrostatic field. Equations of electrostatic field can be expressed as:

$$\nabla \times \mathbf{E} = 0 \tag{10}$$

$$\nabla \cdot \mathbf{D} = \rho \tag{11}$$

where \mathbf{E} is the electric field intensity; where ρ is the charge density; where \mathbf{D} is the electric flux density.

For a linear medium, the relationship between the electric flux density \mathbf{D} and the electric field intensity \mathbf{E} can be

TABLE 2. Material properties of different solution region.

Name	Conductor	Shielding clothing	Face	Air
conductivity (S/m)	1.67e7	0.27e3	0.1	-
relative dialect	1	1	10 ⁵	1

expressed as:

$$D = \epsilon E \quad (12)$$

where ϵ is the material's dielectric constant.

Since the electrostatic field is a non-rotating field, the scalar potential φ is introduced as an auxiliary quantity to simplify the numerical calculation. The relationship between the electric field intensity E and the scalar potential φ can be expressed as:

$$E = -\nabla\varphi \quad (13)$$

Substituting the scalar potential into the electrostatic field governing equation, the Poisson equation in the electrostatic field is expressed as:

$$\nabla^2\varphi = -\frac{\rho}{\epsilon} \quad (14)$$

The boundary conditions for the surrounding electrostatic field distribution of overhead transmission lines containing live workers are as follows:

The boundary Γ of the high-voltage line, the grounding end of the insulator, and the calculation domain which contain live workers on the ground potential of the tower should meet with the Dirichlet boundary condition with known voltage:

$$\varphi|_{\Gamma} = g(\Gamma) \quad (15)$$

$g(\Gamma)$ is the voltage function, when the voltage function is the transmission line voltage, it indicates live worker with high-voltage, and when the voltage function is zero, it indicates live worker with ground potential.

When the human is not at ground potential, the surface of the human body should meet with floating potential boundary condition:

$$\oint_s \frac{\partial\varphi}{\partial n} ds = Q \quad (16)$$

where n is the outer normal vector of the human surface s , Q is the surface charge of the floating conductor, and $Q = 0$.

C. CALCULATION RESULTS AND ANALYSIS OF THE ELECTRIC FIELD ON THE SURFACE OF THE HUMAN BODY

When a worker wears shielding clothing and enters a high-voltage live working zone, an induced electric field will be generated on the surface of the human body. The electrostatic field numerical modeling is used to calculate the surface electric field distribution of the worker under a typical operating posture. Fig.6 shows the electric field in the surrounding space and the electric field intensity distribution on the body surface of the live worker when the worker is working on a tensile insulator string with a voltage of 500 kV (the minimum distance between the worker and the high-voltage transmission line is 0.6m). It can be seen from the results that when a live worker wearing a shielding suit enters a high-voltage space electric field, an induced electric field is generated on the surface of the body and causes the space electric field distortion, what's more, electric field concentration occurs in the hands and feet of the body.

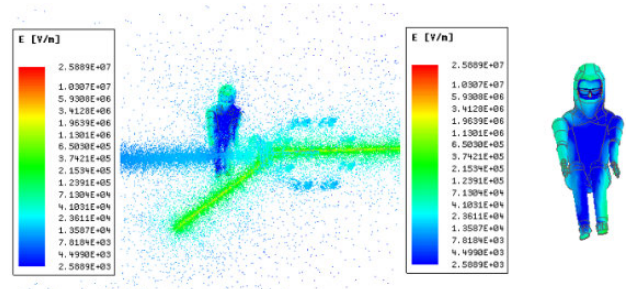


FIGURE 6. Distributions of electric field under 500kV live scene.

V. SAFETY RISK ASSESSMENT OF TYPICAL LIVE WORKING PROCESS

In the digital twin of live working, Based on the human body posture captured, 3-D geometric model can be reconstructed, combing with the boundary of electric field distribution, the workers' location and the unified model in the virtual environment, the complex gap in the real live working environment can be calculated in real-time, as well as the data of safety actions of workers can be represented and evaluated.

A. POSITIONING OF LIVE WORKING SCENE AND CALCULATION OF COMPLEX GAP

When workers work on high-voltage lines, a complex gap is generated among the high-voltage boundary, the grounding boundary, and live workers who wear shielding clothing. The length of the complex gap will directly affect the safety of live workers [23]. The calculation of the length of the complex gap in the live working scenario is shown in Fig.7. It is assumed that at any time t , the normal distance between the working boundary of the worker and the high-voltage boundary is $d1(t)$, and the normal distance between the working boundary of the worker and the grounding boundary is $d2(t)$. The complex gap length $D(t)$ can be expressed as:

$$D(t) = d_1(t) + d_2(t) \quad (17)$$

In the DT project of high-voltage live working scenes, the mapping relationship between the real environment and the virtual reality environment's spatial position is firstly established. On this basis, the full-body inertial motion capture unit is used in the real environment to capture the human's posture and spatial position in real-time. Then posture and

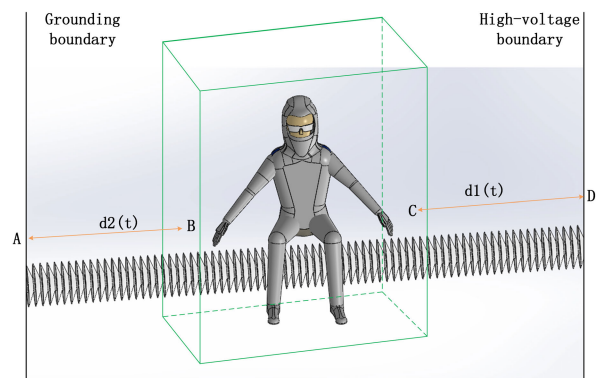


FIGURE 7. Complex gap calculation of live work.

spatial position map to the virtual reality environment. Geometric characteristics of the human model are combined to calculate the working boundary of the worker in real-time (the boundary is green rectangular box in Fig.7), calculate the distance between the working boundary of the worker and the high-voltage boundary, calculate the distance between the working boundary of the worker and the grounding boundary. According to the mapped relationship, the working boundary of the worker and the length of the complex gap calculated in the virtual reality environment must be completely consistent with the real environment. For convenience, the relevant calculations in this paper are all performed in the virtual reality environment.

B. LIVE WORK SPECIFICATION EVALUATION

Before applying the DT to evaluate the safety of live working, the relative position, direction, and other parameters of the real space and virtual space should be calibrated firstly to determine the spatial transformation relationship. Motion capture sensors are used to obtain the relative position and posture transformation of the human body in real-time. According to the reconstructed geometric model of the human body to calculate the body motion boundary and the current length of the complex gap in real-time, and the length of complex gap will compare with the minimum complex gap required by the regulations, the operation safety risk assessment is carried out by the formula:

$$\text{sign}(t,\sigma) = \begin{cases} 1, & \text{if } D(t) \leq D_s \\ 0, & \text{if } D(t) > D_s \end{cases} \quad (18)$$

where D_s is the minimum complex gap required by the operating regulations.

During the live working, the complex gap $D(t)$ calculated in the virtual reality environment at any time is compared with the minimum complex gap D_s specified in the live-working regulations. When the value of the function is 1, it indicates that there is a safety risk in the current live working; When the value of the function is 0, it indicates that there is no safety risk in the current live working.

VI. APPLICATION EXAMPLES AND ANALYSIS

In this paper, the DT model is applied to operation safety assessment of high-voltage live worker under different working scenarios. Through the full-body inertial motion capture system which worn by the live worker, the real-time human skeleton pattern of live worker corresponding to different operation behavior in the real scene is obtained. Through 3-D geometric model reconstruction and electric field calculation, the real live working scene is mapped to virtual reality scenes. The length of the complex gap, the working boundary of the worker, and the electric field distribution on the human body during the live working will be full-process monitored in real time, and the safety risk of the operation behavior of the live worker is assessed.

A. PROCESS OF ENTERING 500KV EQUIPOTENTIAL

Fig.8 shows an application example of DT, a live worker enters the 500kV equipotential for living working. The scenario can be described as: a live worker moves along the 500kV tensile insulator string from the side of the grounded power tower to the high-voltage transmission line to enter the equipotential zone. According to live working regulations, the minimum complex gap distance required for 500kV live working is 3.9m [23]. In the correct operation scenario in Fig.8(a), the moving posture of the live worker is correct and the movement action is standardized. In the whole process of moving, the minimum complex gap distance is 4.63m, meeting the requirement of 3.9m complex gap distance for 500kV live working. In the incorrect operation scenario in Fig.8(b), the live worker has a large foot span during the movement, the minimum complex gap distance is 3.89m, which does not meet the requirement of a complex gap distance of 3.9m for 500kV live working. There is an electric field concentration on the feet side, and the maximum field strength is 1.3 times than that of the standard operation, which may cause the insulation strength of the complex gap to change. Discharge occurred between the feet of the live worker and the high-voltage line in the virtual scene. It would be evaluated as an incorrect operation.

B. PROCESS OF ENTERING 220KV EQUIPOTENTIAL

Fig.9 shows an application example of a DT, a live worker enters the 220kV equipotential for living working. The scenario can be described as: a live worker moves along the insulating flexible ladder to approach the metal ladder connected with the high-voltage transmission line to enter the equipotential zone, and another live worker who is grounded stands on the tower to cooperate. In the correct operation scenario shown in Fig.9(a), the moving posture of the live worker is correct, and the distance between the bare head and the high-voltage line is 0.38m, which meets the minimum complex gap distance of 0.3m for 220kV live working [23] and no discharge occurs. In the incorrect operation scenario shown in Fig.9(b), a live worker has a incorrect posture that

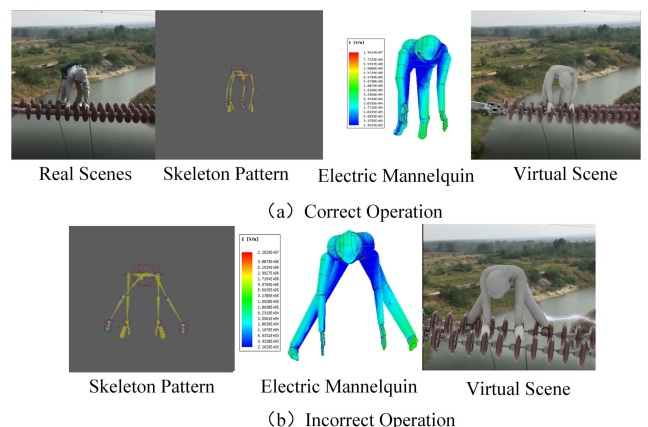


FIGURE 8. Application of DT on 500kV entry equipotential live working scene.

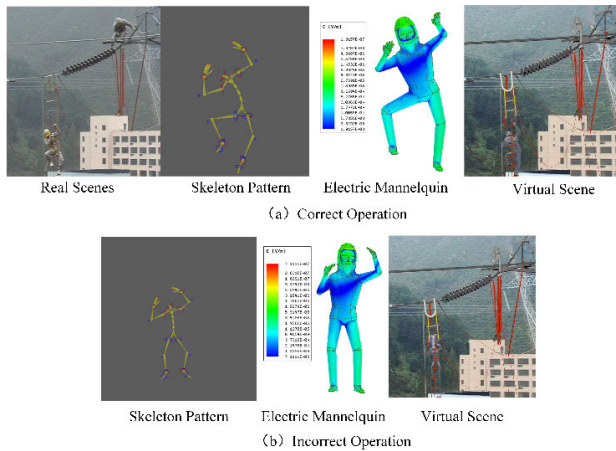


FIGURE 9. Application of DT on 220kV entry equipotential live working scene.

his face is too close to the high-voltage line. The distance between the exposed part of the head and the high-voltage line is 0.25m, which does not meet the minimum complex gap distance of 0.3m for 220kV live working. The electric field concentrated on exposed part of the face, discharge occurred between the head of the live worker and the high-voltage line in the virtual scene. It would be evaluated as an incorrect operation.

C. REPLACEMENT OF THE 110KV INSULATORS

Fig.10 shows an application example of DT, a live worker replaces 110kV insulators. The live working scenario of replacing 110kV insulators includes high-voltage live worker and grounded live worker who stands on the tower. According to relevant regulations, the minimum distance between the exposed part of the live worker’s head and the insulator is 0.3m [23], and the height of the head should not exceed two insulator pieces. The scenario can be described as: high-voltage live worker enters equipotential along the ladder, and the grounded live worker stand on the tower to cooperate. In the correct operation scenario shown in Fig.10(a), the movement posture of the live worker is standardized, the distance between the head and the insulator is 0.39m, and the head height of live worker not exceeds two insulator

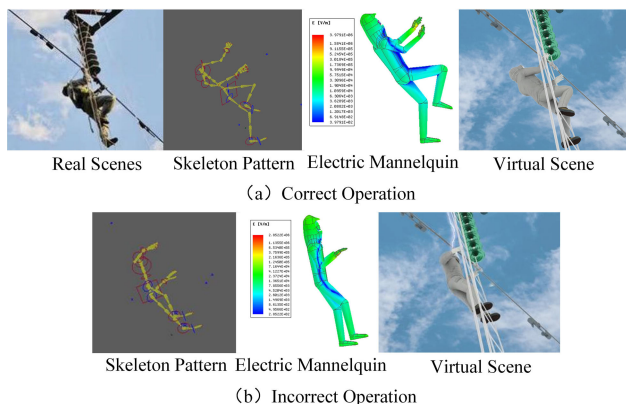


FIGURE 10. Application of DT on insulator replacement in 110kV live work scene.

pieces. The minimum distance of 110kV live working is more than 0.3m. No discharge occurs. In the incorrect operation scenario in Figure.10(b), the height of live worker’s head exceeds two pieces of insulators. The distance between the bare head and the high-voltage line is 0.21m, which is less than the minimum distance of 0.3m required for 110kV live working. Electric field concentrated on exposed parts of head and face of live worker. Discharge occurs between the head of the live worker and the grounded tower in the virtual scene. It would be evaluated as incorrect operation.

The above-mentioned typical application examples show that the use of DT technology can map the action behaviors of live workers in the real environment to the virtual environment. In the virtual environment, the working boundary of the live worker and complex gap distance from the high-voltage line to live worker can be calculated in real-time, the complex gap distance is compared with regulated safety distance, the real-time evaluation of the operation risk of the live worker under various operation scenarios could be conducted.

VII. CONCLUSION

Focused on problem of lack of virtual-reality interaction ability, single geometry presentation and insufficient real-time operation risk evaluation in training and safety assessment of live worker. In this paper, the construction and application of DT models of various live working scenarios are studied. Following conclusions could be obtained from this work:

1) Using full-body inertial action captures technology, skeleton patterns of live worker under different operation scenarios are captured, and 3-D geometry model of live worker are constructed. Real-time mapping from real scene to digital virtual scene is realized, and the working boundary of live worker, complex gap distance, and the distance between the human body and high-voltage line under different live working scenes are obtained.

2) Through the 3-D geometric reconstruction of the live working virtual scene, the numerical solution domain is confirmed. Through the electrostatic field FE calculation, the electric field distribution on the body surface of live worker under different operation scenarios is obtained. The visualization of the electric field in the virtual space of live worker under the typical live working scenarios is realized

3) The interaction between human skeleton pattern and space virtual electric field and the changing of complex gap distance are captured by full-body inertial action capture sensors in real time. Based on live working regulations, the safety risk of live worker is assessed under different working scenarios. The application results show that DT technology could assess the safety risk of live works in real time through the calculation of complex gap distance and required safety distance.

In this paper, the research results provide a new method of safety risk assessment for virtual training, maneuver, and guidance for live workers, which can be used as a reference

for improving the operating level and ensuring the safety of live workers.

REFERENCES

- [1] *Method of operation of live working*, Electric Power Press, State Grid Corp. China, Beijing, China, 2009, pp. 26–30.
- [2] T. Hu, Y. Hu, J. Li, and L. Long, “Safety protection for live working on transmission line,” *High Voltage Eng.*, vol. 32, no. 5, pp. 22–25, 2006.
- [3] M. Yu, J. Wang, and J. Li, “The experimental study on the human body influence on measurement of high voltage power frequency electric field,” *Electr. Meas. Instrum.*, vol. 50, no. 570, pp. 24–27, 2013.
- [4] M. Talaat, “Calculation of electrostatically induced field in humans subjected to high voltage transmission lines,” *Electr. Power Syst. Res.*, vol. 108, pp. 124–133, Mar. 2014.
- [5] B. Zemljarić, “Calculation of the connected magnetic and electric fields around an overhead-line tower for an estimation of their influence on maintenance personnel,” *IEEE Trans. Power Del.*, vol. 26, no. 1, pp. 467–474, Jan. 2011.
- [6] W. B. Kouwenhoven, C. J. Miller, H. C. Barnes, J. W. Simpson, H. L. Rorden, and R. J. Burgess, “Body currents in live line working,” *IEEE Trans. Power App. Syst.*, vol. PAS-85, no. 4, pp. 403–411, Apr. 1966.
- [7] L. Wang, Q. Zhang, J. Hu, K. Liu, T. Wu, and J. Wang, “Research on complex gap discharge model of live working on EHV and UHV high-voltage transmission lines,” *Can. J. Electr. Comput. Eng.*, vol. 37, no. 1, pp. 11–18, 2014.
- [8] Y. Hu, K. Liu, J. Hu, T. Liu, and B. Xiao, “Analysis on safety protective equipments for live working on ± 800 kV UHV DC transmission line,” *High Voltage Eng.*, vol. 36, no. 10, pp. 2357–2361, 2010.
- [9] F. Huo, W. Lu, D. Huang, J. Nan, Z. Qiu, and C. Huang, “Study on electric field distribution characteristics of live-working and protection for crossing project of 1000 kV-over-500 kV AC transmission lines,” *Power Syst. Technol.*, vol. 43, no. 1, pp. 349–355, 2019.
- [10] Z. Su, Y. Peng, K. Liu, T. Liu, B. Xiao, T. Wu, and T. Pan, “Simulation analysis of electric field protection for live-working on 1000 kV and 500 kV AC four-circuit transmission lines on one tower,” *Electr. Power*, vol. 47, no. 2, pp. 78–83, 2014.
- [11] Y. Hu, H. Jianxun, K. Liu, T. Liu, B. Xiao, T. Wu, and J. Hu, “Field strength of body surface during the live working on the UHV AC and DC transmission lines,” *High Voltage Eng.*, vol. 36, no. 1, pp. 13–18, 2010.
- [12] X. Liu, D. Wu, H. Li, W. Li, X. Tang, and R. Luo, “Research on electric field distribution characteristics of body surface with live working in compact 500 kV same tower double circuit transmission lines,” *High Voltage App.*, vol. 53, no. 7, pp. 87–94, 2017.
- [13] N. Wang, L. Shen, and S. Deng, “Application of VR virtual reality in electric power safety education training,” *Telecom Power Technol.*, vol. 34, no. 5, pp. 166–169, 2017.
- [14] D. Zou, Y. Yan, W. Wang, Z. He, and H. Ruan, “Method of live working safety inspection for high voltage transmission lines based on ToF technology,” *High Voltage Eng.*, vol. 46, no. 7, pp. 2570–2577, 2020.
- [15] R. Luo, M. Fang, Z. Li, W. Li, D. Zou, and Z. Li, “Sensor based information integrated safety protection system for live working,” *China Saf. Sci. J.*, vol. 28, no. 10, pp. 73–77, 2018.
- [16] S. Bai, K. Liu, L. Song, Y. Peng, Y. Du, G. Wu, and X. Zhang, “Study on the method of real-time monitoring of microclimate and live working safety evaluation for ± 800 kV ultra high voltage DC transmission line,” *High Voltage App.*, vol. 55, no. 6, pp. 198–204, 2019.
- [17] T. Xiao, H. Jiang, G. Ding, L. Jiang, and S. Ma, “Research on digital twin-based modeling and monitoring of five-axis grinder,” *J. Syst. Simul.*, 2020. [Online]. Available: <https://kns.cnki.net/kcms/detail/11.3092.V.20201029.1655.002.html>
- [18] Z. Wu, Z. Liu, K. Shi, L. Wang, and X. Liang, “Review on the construction and application of digital twins in transportation scenes,” *J. Syst. Simul.*, vol. 33, no. 2, pp. 295–305, 2021.
- [19] Q. Li, W. Liao, Y. Ding, and J. Fan, “Shielding protection for live working on ± 800 kV DC transmission line,” *Proc. CSEE*, vol. 39, no. 34, pp. 96–101, 2009.
- [20] *Screen Clothes for Live Working*, Standard DGB 6568-2008, 2008.
- [21] E. Subcomitte, “Minimum number of good (healthy) porcelain or glass insulator units in a string for live work,” *IEEE Trans. Power Del.*, vol. 17, no. 3, pp. 806–814, Jul. 2002.
- [22] *Guide of Insulation Co-Ordination for Live Working*, Standard DL/T 876-2004, 2004.
- [23] *China Southern Power Grid Company Limited Working Regulations of Power Safety*, Standard Q/CSG510001-2015, 2015.



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