A Novel Intelligent Working Monitoring and Guarding System of Smart Substations Based on UWB Positioning and Aerial LiDAR Data

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Abstract —This paper analyzes the current status of power production safety, introduces the realization principle of intelligent working guarding system in substations, and delves into the technologies of positioning and intelligent video analysis based on ultra wideband (UWB) technology and high resolution digital spatial data of the substations. Based on the acquired data, an intelligent working monitoring and guarding system with various functions, including task management, real-time monitoring, alarm warning, region division, and replaying of historic data, has been developed by utilizing the technologies of 3-Dimension (3D) modeling of the substation by using aerial light detection and raging (LiDAR) and virtual reality (VR) for practical implementation.

Index Terms—guarding power safety, UWB positioning, intelligent video analysis, LiDAR

I. Introduction

Safety production is always the key ideology development and construction in power industry. As an important field of safety production, the safety of electrical power serves as the rule of thumb in power production and construction. According to the regulations of power safety accident emergency management, power accidents mainly include power system accidents, personal injury accidents and electrical device accidents. Based on the principle of human life privilege, the personal safety is of the most priority in all these kinds of accidents.

Although the power industry safety production situation remains stable in recent years, the number of personal injury or death accidents is still increasing by every year [1]-[3]. In 2015, 37 people died in 22 power production accidents and 24 power construction accidents caused the death of 42 persons. During the period of the 12th national five-year plan, 136 electric power production casualties happened in nationwide and caused 134 people death [3]. Personal accident will cause power outage and threaten the safety of power grid. The exemplified reasons include the coexistence of weak links and management flaws in some work crew, the weak safety awareness of operational staff, the failure to observe the power safety rules and regulations, illegal commands and operations, weak safety management, and careless operation organization. In order to solve these problems, various electric power enterprises have established safety standards, laws and regulations for organization, management, and technical operation. However, either domestic or abroad enterprises take little effort in technical guarding systems, while most of the guarding measures are with the scope of management, protocol and literal standards.

In view of this, the present paper proposes to study such information technologies as intelligent video analysis [4], UWB positioning technologies [5]-[6] and high resolution 3D spatial data of the substations from LiDAR data [7] to achieve the automatic monitoring and guarding of the onsite operational behavior. The utilizing of these technologies will effectively avoid the possible illegal operation of the staffs and substantially improve safety environments of works at the substations.

II. System Principle

The system mainly adopts the technologies of positioning and intelligent video analysis to achieve data acquisition and to analyze and transmit the timely information of illegal operation to both operators and monitoring staff concurrently. Fig. 1 illustrates the basic principle of the proposed system.

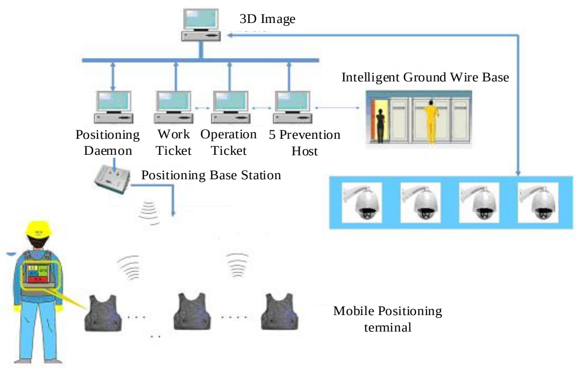

Fig. 1. Diagram of system principle

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A. Position Data Acquisition

Data acquisition mainly refers to the acquisition of location information and image data. The positioning tag of operational staff can help to collect location information by communicating the four positioning base stations around the substation with the data acquisition servers, which then generates the operator's position information after time difference of arrival (TDOA). The calculation is within the 3D rectangular coordinate system. Based on the existing video monitoring system deployed at the transformers, circuit breaker, bus wires or control room in smart substations, video analysis server can preprocess video data via background reduction and optical flow calculation, which can detect a moving target and help to generate the target object in the data acquisition server. Fig. 2 presents the data flow of data acquisition system.

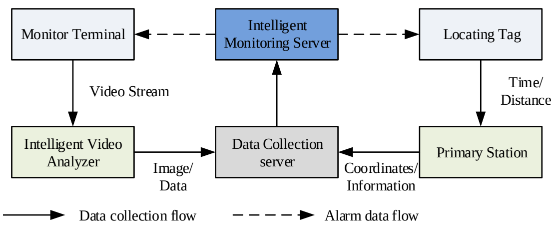

Fig. 2. The flow of data acquisition and processing

B. Alarm Information Generation

Any device in a transformation substation has a fixed three-dimensional coordinates after the simulation modeling of the three-dimensional panorama. Whenever the distance between an operational staff and a charged device is shorter than a preset safety distance, the system will generate a position alarm, i.e.,

$$\|\mathbf{u}-\mathbf{c}_i\|_2 < r \tag{1}$$

where $\mathbf{u}=[x,y,z]^{\mathrm{T}}$ represents the position coordinate of an operational staff, $\mathbf{c}_i=[x_i,y_i,z_i]^{\mathrm{T}}$ the position coordinate of a charged device, and r the preset safety distance. The position alarm includes a too short distance to the charged device, a wrong operational margin distance, an unsafe operation, or other illegal alarms.

Another alarm information is the video alarming. When a data acquisition system generates an object target though video stream, the system will compare the generated target with the source target in the unsafe operations in regulation database. Once these two targets match, the object target will be identified as an illegal one. For example, if a staff does not wear a helmet, then the object target generated by the acquisition server will identify the staff. Once the regulation database includes the staff without wearing any helmet, the image match between the two targets will be established. Normally, video alarm includes a staff without wearing a helmet, the lack of a responsible staff in working area, a staff going out of safety area, and a staff crossing over a preset picket line.

C. Video Positioning Linkage

In order to obtain the video of operation staffs accurately, we can utilize the relationship between a positioning system and a video monitoring system and design a corresponding scheduling algorithm. The algorithm should calculate and analyze the position information of operational staffs, determine the tracking angle for video camera by imposing the recent observations with higher priority, and transmit the order to intelligent video server via communication systems in the smart substation, which will finally forward scheduling command to the camera for adjusting the tracking angle. Fig. 3 depicts this relationship between video and positioning.

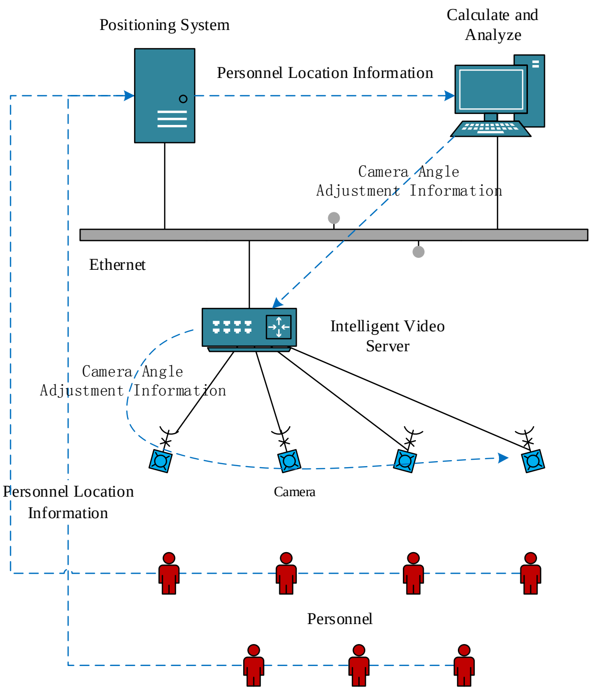

Fig. 3. The relationship between video and positioning

D. Alarm Reminder

The intelligent monitoring server will send alarm information to both onsite illegal operational staff and the crew leader based on concurrent sound and image data transmission. At the same time, the alarm information will be sent to the on-duty staff in working site by the means of sound and light. The system will also keep the alarm information into the database for future analysis and statistics.

III. Key Technologies of Implementation

A. UWB Positioning Technology

The positioning system utilizes the UWB technology, which is an emerging wireless communication technology [8] with high speed, low cost and low power consumption. As a pulse signal with a bandwidth greater than 500MHz or the ratio of baseband bandwidth and carrier frequency greater than 0.2, a UWB signal has a wide bandwidth range. In fact, the FCC sets UWB bandwidth from 3.1GHz to 10.6GHz and limits the transmission power of a UWB signal to be less than -41dBm [9]. The UWB positioning technology can meet the requirements of a high precision positioning of the transformation substation range, achieves a positioning accuracy within 30cm, and has the advantages of low cost, strong anti-interference ability, and strong penetration ability. A UWB positioning system is normally composed of positioning stations and tags.

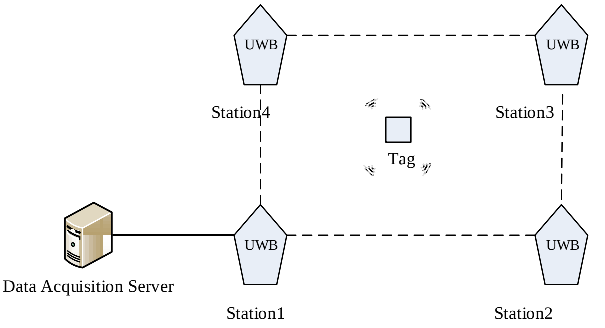

Fig. 4. UWB positioning system

As shown in Fig. 4, each positioning unit is composed of four or more positioning stations. Assume that n receiving stations are arbitrarily distributed within a 3D space the position coordinates of the i^{th} station is $\mathbf{s}_i = [x_i, y_i, z_i]^{\mathrm{T}}$, $i = 1, 2, ..., n$, and the position coordinates of the tag is $\mathbf{u} = [x, y, z]^{\mathrm{T}}$. The distance from tag $\mathbf{u}$ to station $\mathbf{s}_i$ then can be expressed as

$$d_i = \|\mathbf{u} - \mathbf{s}_i\|_2, \quad i = 1, 2, \cdots, n \tag{2}$$

By selecting $\mathbf{s}_1$ as the reference station and omitting the influence of non-line-of-sight propagation, we obtain the following equation according to the principle of TDOA

$$\tilde{t}_{i1} = t_{i1} + \Delta t_{i1} = C^{-1}(d_i - d_1) + \Delta t_{i1}, \quad i = 2, 3, \cdots, n \tag{3}$$

where $\tilde{t}_{i1}$ is a TDOA measurement, t_{i1} the real-time difference of received tag signal from secondary station to primary station, C the propagation speed of electromagnetic wave in a vacuum, and Δt_{i1} the error of TDOA measurement.

Thus the distance difference equation can be expressed as

$$\tilde{d}_{i1} = C\tilde{t}_{i1} = d_i - d_1 + e_{i1}, \quad i = 2, 3, \cdots, n \tag{4}$$

where $e_{i1} = C\Delta t_{i1}$ is the corresponding measurement error of distance. Let $a_{i1}(\mathbf{u}) = d_i - d_1$, then we have

$$\tilde{\mathbf{D}} = \mathbf{A}(\mathbf{u}) + \mathbf{E} \tag{5}$$

where

$$\tilde{\mathbf{D}} = [\tilde{d}_{21}, \tilde{d}_{31}, \cdots, \tilde{d}_{n1}]^{\mathrm{T}}$$

$$\mathbf{A}(\mathbf{u}) = [a_{21}(\mathbf{u}), a_{31}(\mathbf{u}), \cdots, a_{n1}(\mathbf{u})]^{\mathrm{T}}$$

$$\mathbf{E} = [e_{21}, e_{31}, \cdots, e_{n1}]^{\mathrm{T}}$$

Assume that the measurement error $\mathbf{E}$ follows the zero mean Gaussian distribution with its covariance matrix being $\mathbf{Q}$. The TDOA passive location problem based on multiple stations is then converted into the solution of the nonlinear equation (5) for obtaining an optimal estimate of $\tilde{\mathbf{u}}$.

B. Substation 3D Spatial Information Acquisition

The prerequisite of accurate UWB positioning and alarming is to establish the accurate spatial information a smart substation. The 3D spatial position of every apparatus, including the transformers, transmission line, the insulator, the circuit breakers and the control boxes, have to be accurately measured in a space coordinate. Due to the large amount of apparatuses in a single smart substation, the traditional manual measuring and modeling method is time wasting and workload intensive. With the progress of the aerial light detection and range (LiDAR) technology [10], we can now obtain the substation spatial information in a very efficient way by scanning the substation using an aerial LiDAR system.

The laser light emitting from the aerial LiDAR system travels to the ground and is reflected by the object being scanned. A point cloud can be obtained from the scanning as shown by Fig. 5. By detecting the distance between the LiDAR system and the ground object with other sensor data like GPS location and posture of the system with a set of computation algorithms, the accurate position in space coordinate of the every point of the object can be obtained.

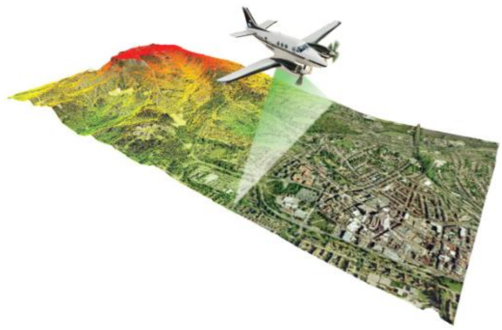

Fig. 5. Illustration of LiDAR scanning

The LiDAR system structure is shown in Fig. 6. The laser scanner uses 16 laser emitters in a line on a rotating shaft to obtain a 360° range of scanning space with a 300kHz scanning speed and 2cm in distance resolution and a point cloud density over 200 points per square meter, which is sufficient able to depict the details of the apparatuses in substations. The data acquired from the laser scanner, global positioning system (GPS), inertial measurement unit and digital colored photo are fused together by the to obtain a space coordinate position in a high accuracy by using the algorithms in the abovementioned software. As the positions of the every point of the substation obtained, the alarming strategy can be arbitrarily set in accordance to various working tasks under safety guarding codex.

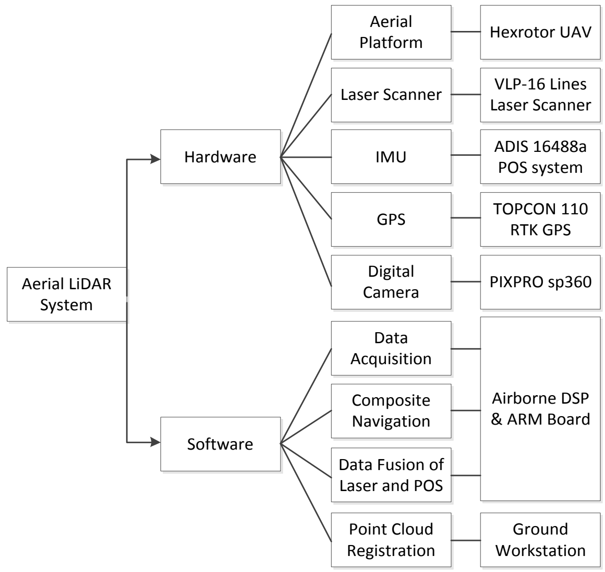

Fig. 6. System architecture of the LiDAR system

C. Intelligent Video Analysis

Intelligent video analysis comes from the computer vision technology, which is a branch research area of artificial intelligence [11]. Making use of the powerful data analysis ability of modern computers to analyze huge amount of video data in a high speed, this technology can automatically analyze and extract important information from video source, filter out irrelevant information to find abnormal contents from monitoring screen, and provide the useful information in a fast and effective way. In smart substations, a large amount of high-resolution surveillance cameras are deployed to ensure the visibility of every corner of the substation, covering the transformers, high voltage cables, circuit breaker, insulators and controlling boxes etc. Therefore, these cameras can reliably record the operations of on-site working staffs. The intelligent video analysis can then applied to detect if these operations have any potential unsafe risks.

In this project, the intelligence video analysis is mainly used to detect the working personnel sufficiently who is a moving object in a stationary background. The long established optical flow method is very suitable to detect the moving object from the background. In substations, each camera focuses on a certain area and the distance between the target area and the camera lens is normally known. In this scenario, the working personnel keeps a constant size in video frames and the simple block matching algorithm like sum of squared difference (SSD), Mean Absolute Difference (MAD) and minimum square error(MSE) can be applied to obtain the optical flow vector field [12], [13]. As long as the personnel image being detected, an image matching between the captured image and the template images in database to find if there is any unsafe operations [14].

IV. System Design

A. Technology Framework

In order to guarantee its scalability, reusability and maintainability, the system should adopt the idea of layered design. That is, the system can be divided into the equipment layer, the supporting layer, the operation layer, and the presentation layer. Among these layers, the equipment layer includes positioning information and a front-end data capture device for equipment information and hence provides the basic equipment data for the supporting layer. The supporting layer then includes data acquisition, processing, storage, and other underlying software platform. The operation layer should realize the main functions of intelligent monitoring and control system. The presentation layer is responsible for outputting and displaying alarm information, including the warning for operational staff to wear mobile terminal, flashing light source and mobile phone alarm, and monitoring terminal for on-duty personnel. Fig. 7 shows this system architecture.

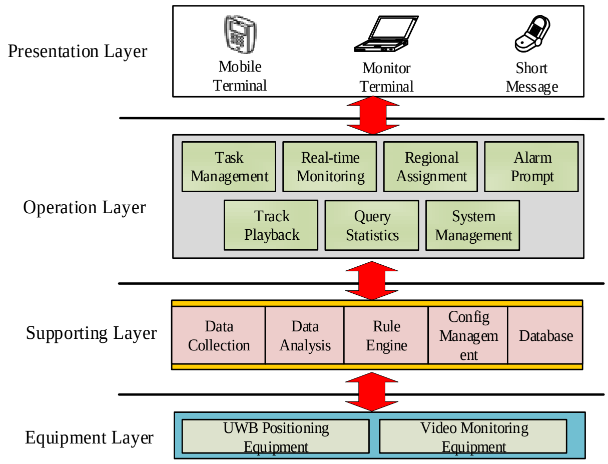

Fig. 7. The system technical architecture

B. Functional Design

The main functions of an intelligent monitoring and control system include the work management of operational personnel, real-time monitoring, working area delineation, alarm prompt, track playback, statistical inquiry, system management, and other related functions. Fig. 8 shows this architecture.

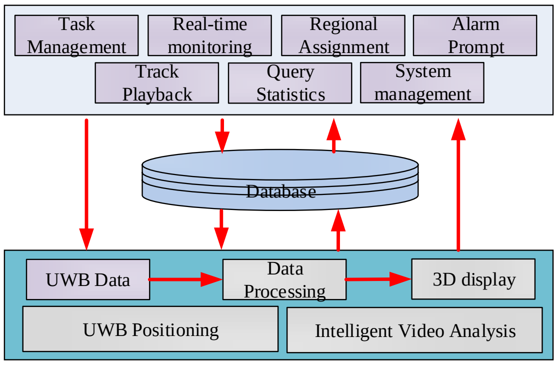

Fig. 8. The system function architecture

1) Task management function

The task management functions are mainly aimed to manage the operation process, the scene of personnel information, the working permit, and the operational permit information. With the function of task setting and dynamic management, the staff and the label could be quickly assigned and distributed under appropriate work record management and other functions.

2) Real time monitoring function

The function of real-time monitoring is to monitor the staffs in real-time who wear the positioning label. When operation personnel enter the working area, the system will be updated with the name and number of the personnel in the 3D spatial data space and store the basic and coordinate information of the movement into the database to prepare for query. The administrator can edit and change various virtual characters by clicking on a 3D simulation scene.

3) Regional assignment function

Regional assignment allows the guarding staffs to delineate the restricted operating area in substation. The label has the function of setup vertex points of the 3D working space by automatically input the vertex coordinate from the UWB positioning system to generate the restricted working areas.

4) Alarm prompt function

The alarm prompt function could automatically send out alarm when the operation personnel trespass the safety area or other illegal behaviors. There are three formations of alarms

- Voice alarm function in wearing tags.
- Voice alarm function and virtual monitoring area to highlight the display function (voice can be selected to disable) in management end.
- Alarm function by sending a short message.

5) Track playback function

The track playback has the function of playback the moving tracks of operational staff during the operation time. The playback modes include high-speed (e.g., 1 times, 4 times, 6 times, and 10 times), low-speed (e.g., 0.05 times, 0.1 times, 0.25 times, and 0.5 times), normal-speed. A quick exit function and video export function are also supported.

6) Query statistics function

The query statistics function has the ability of querying statistics in a certain period of time or alarms in a certain period, to remind the number of times, the number of people and work duration. It can export and print tithe query conditions including the crew name, job number, the name of the staff, and the specific date or time of work.

7) System management function

The system management function has the function of managing the basic data, user information, authority distribution, and system parameter. It is the basic support module of the application system.

V. System Implementation

A. 3D Spatial Data Modeling

A light and small Unmanned Aerial Vehicle (UAV) LiDAR system in Fig. 9 is used to quickly obtain the accurate high-density point clouds of the substation. The use of UAV can significantly reduce the traditional LiDAR scanning process which relies on a large manned plane. The whole acquisition time could reduce to less than 60 minutes compared to 2~3 days of conventional method. The generated point cloud of the substation is shown in Fig. 10.

Fig. 9. Unmanned aerial vehicle and LiDAR system

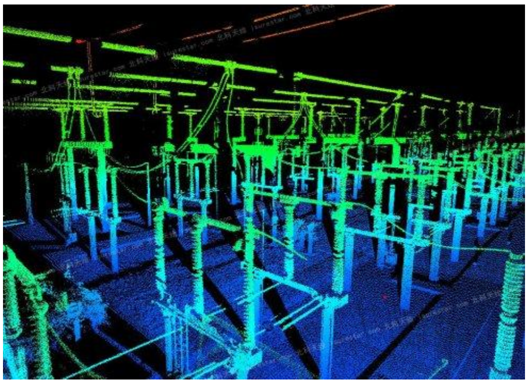

Fig. 10. Point clouds of the substation from LiDAR data

The colored pictures with spatial position tags of the digital cameras are used to automatically add the texture to the substation point clouds. The auto-triangulation measurement will be performed and generate the colored point clouds of the substations [15]. These point clouds from the pictures are then registered to the point clouds of the LiDAR to obtain the higher spatial accuracy up to 5cm per pixel [16]. The 3D mesh model are then established and the texture from the pictures are added to the point cloud model to obtain the final real 3D substation model with high spatial accuracy as shown in Fig. 11. The whole process is fully automatic and substantially reduces the human labor compared to conventional manual 3D Max modeling.

Fig. 11. Textured substation 3D model registered to LiDAR data

B. Intelligent Monitoring System to Achieve Protection

The system then uses the 3D model described above to establish the substation intelligent monitoring and guarding system so as to enable the personnel to roam within the job scene, perform real-time operation monitoring, and execute both alarm and alarm query. Moreover, the system can also seamlessly connect to the job allocation and safety check system.

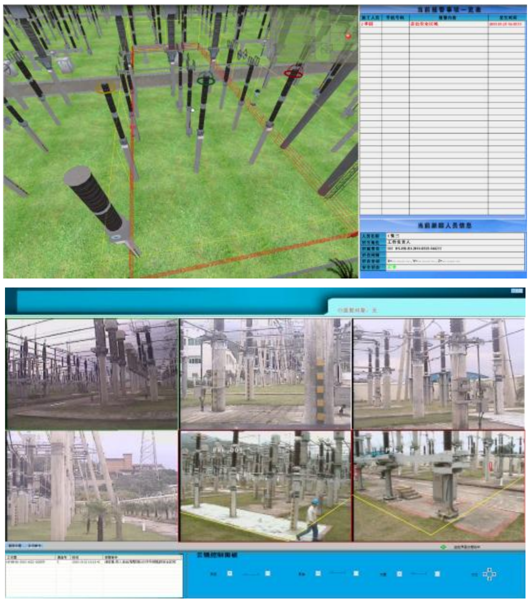

Fig. 12. The system interface. The red rectangle shows a virtual restricted area delineated by guarding staffs.

VI. Conclusion

In this paper, a novel intelligent working monitoring and guarding system of smart substations has been proposed. The system architecture, the data acquisition method, the intelligent analysis algorithm and the system functions are fully described in the paper. The application of UWB and LiDAR technology ensure a very high accuracy in 3D spatial positioning of the workers. The automatic alarming system is then put into using for preventing unsafe behavior during the operation. In conclusion, this intelligent system can provide an effective tool for safety monitoring and worker guarding function and can greatly improve the safety operation in substations.

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