Hindawi
Journal of Control Science and Engineering
Volume 2018, Article ID 7245872, 8 pages
https://doi.org/10.1155/2018/7245872

Research Article

Networked Closed-Loop Model for Smart On-Site Maintenance of Substation Equipment Using Mobile Networks

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Received 28 February 2018; Accepted 10 May 2018; Published 11 June 2018

Academic Editor: Cui-Qin Ma

This paper introduces a networked closed-loop model for smart on-site maintenance of substation equipment using mobile networks, which is composed of a field-side Smart Operation and Maintenance (SOM) box with its related APP and a centre-side system platform for Operation and Maintenance (OM). As a bridge to connect the operation sites and data centre, the networked equipment maintenance model enables bidirectional communication among the management, maintenance teams, and diversely located equipment. This model not only realizes the formal data uploading in real-time, but also can provide the workers on site with guidance from the data centre.

1. Introduction

To improve the performance of equipment and provide security assurances of power generation, power grid equipment maintenance has been paid more attention to the power industry. With the development of the modern industry, the power system becomes huge and complex. There are thousands of nodes that need to be controlled [1, 2]. What is more, the power grid equipment is normally diversely located, which makes great difficulties for their daily servicing and maintenance.

According to the responsibilities, the daily work of the substation is generally divided into Operation and Maintenance (OM) to ensure the safety of the power grid. However, this division of labor may also lead to lower production efficiency and insufficient human resources. The increasingly complex background of the grid makes the requirements for safety and reliability higher and higher [3, 4]. To realize the task of "major overhaul" system construction proposed by the State Grid of China, the research on enhancing the assets safety life management is urgently necessary, mainly by integrating operation, management, and maintenance [5–7]. However, for the conventional on-site maintenance procedures, there is a gap between the management and the on-site maintenance teams due to the lack of real-time communication. If bridges between the management centre and the maintenance site could be built using the network such as WIFI and 4G, the work efficiency and reliability will be greatly improved.

In order to break the limits on the physical location of space and simplify the system connection, based on the development of network and control technologies, Networked Control Systems (NCS) have been broadly applied in modern industry to address these problems [8–11].

NCS is designed to achieve the control loop in the serial network; that is, the signals are exchanged among the controllers, sensors, actuators, and other components through the serial network. The system uses the network to transmit feedback signals to form a closed loop. The control loops are closed through communication networks which connect the cyberspace to physical space, which enables several tasks to be executed from a long distance [12, 13]. A mobile network is a communication network where the last link is wireless. The mobile network has been widely used in daily and industrial applications in recent years together with the fast advancement of wireless communication technologies [14]. Using the mobile network and networked control technologies, distributed devices can be connected wirelessly and form complex systems.

Along with the advantages, new control strategies and data communication protocols and some other relative topics are studied in depth. A control system strategy designed for multivariable plants has been proposed by Goodwin et al. [15] from University of Newcastle. Through a digital, data-rate limited, communications channel, the controllers, sensors, and actuators of the control system are all connected. In Yang's survey on NCSs [16], a simple framework for the research on NCSs is presented, in which the impact of NCS on control methodologies of conventional large-scale system with a related application is also reviewed. Sala et al. [17] in Universidad Politécnica de Valencia presents a strategy for control on the basis of the retuning of the PID controller according to the variable delays in an NCS to avoid the decrease of control performance in her paper.

In the previous work in [18], a Smart Operation and Maintenance (SOM) system has been presented focusing on the online management of the substation maintenance work, covering the hardware/software design, online system design, and also the online maintenance routines. In consideration of the development of NCS and the issues of power grid equipment maintenance such as the communication between management centre and the maintenance site, this paper proposes a networked model for on-site maintenance of substation equipment. The new scheme is based on the mobile networks and wireless communication for substation OM [19, 20]. By developing an on-site SOM system, the management in the centre side and the equipment together with the maintenance teams on the field side are effectively connected through the mobile network. A closed-loop smart maintenance scheme is introduced to enable bidirectional communication among the management, maintenance teams, and diversely located equipment. Using a hand-held smart box, the real-time data on field side can be uploaded and checked in real-time. The workers can also call for help from experts on the centre side any time when they meet some difficulty during their work. Using the newly proposed system, both the efficiency and effectiveness of the on-site maintenance work can be significantly improved.

2. Architecture of Smart On-Site Maintenance Based on Mobile Network

2.1. The Architecture of Smart Maintenance System. The SOM system's whole structure is illustrated in Figure 1. It can be partitioned to the centre side and field side. The field-side system consists of a SOM box, working as the bridge between the two sides. There is also on-site SOM equipment that can be tested by many kinds of technologies. Through the mobile communication network, related guidance and support can be provided to field workers by an integrated OM platform in the centre of the power grid.

The OM work includes live detection, intelligent inspection, preventive test, major defect state monitoring, alarm for state assessment, and maintenance decision optimization. The work is completed with these devices such as ultrasonic testing, partial discharge detection, infrared temperature measurement, and spectral analysis. The SOM box is composed of data acquisition module, video conference module, 4G mobile communication module, power management module, etc. The OM platform includes data acquisition communication, decision support, data storage, centre side advanced application, and standardization advanced application framework. In the centre side of power grid company, the platform can communicate with the OM site through 4G mobile communication.

2.2. Networked Closed-Loop Smart Maintenance Model. Figure 2 shows the networked model for the substation equipment maintenance. In the centre side, the project managers assign the maintenance tasks online. When the new tasks are confirmed by the system, it would be pushed to the mobile device held by the corresponding maintenance teams using apps. After the maintenance teams receive the tasks, they carry the proper equipment to the specified substations. They can use a specially designed Smart Maintenance Box to carry out the routine work. Using the box, they can collect the data from all the sensors automatically. After the maintenance work is finished, the smart box can also generate the maintenance report and upload it to the data server on the centre side through the mobile networks. If the teams encounter any problems they cannot solve during the work process, they can call the centre side any time. The smart box is equipped with four high definition cameras. Video conference over the 4G mobile network can be established any time between the on-site personnel and the experts on the centre side.

After the maintenance work is finished, the smart box generates and uploads the report to the data server located on the centre side automatically. The management teams check the reports on the data server. If the reports are satisfactory, they can be proved online. Otherwise, feedback will be sent back to the maintenance team and guide them to redo part of the work.

Using the networked equipment maintenance model, the centre side and the field side are integrated by the mobile networks. The information can be shared and exchanged by both sides in real-time. From the task assignment, execution to the assessment, a closed-loop model through the network is established. With the help of the mobile network, the daily maintenance work can be carried out in an effective and efficient way, even though the power equipment is diversely located.

3. Design and Implementation of the SOM Box

Based on NCS technology, a networked closed-loop model has been applied to the SOM system. The kernel part of the SOM system is a SOM box which is connected to the on-site power detection equipment through a wireless network. The SOM box communicates with the on-site power detection

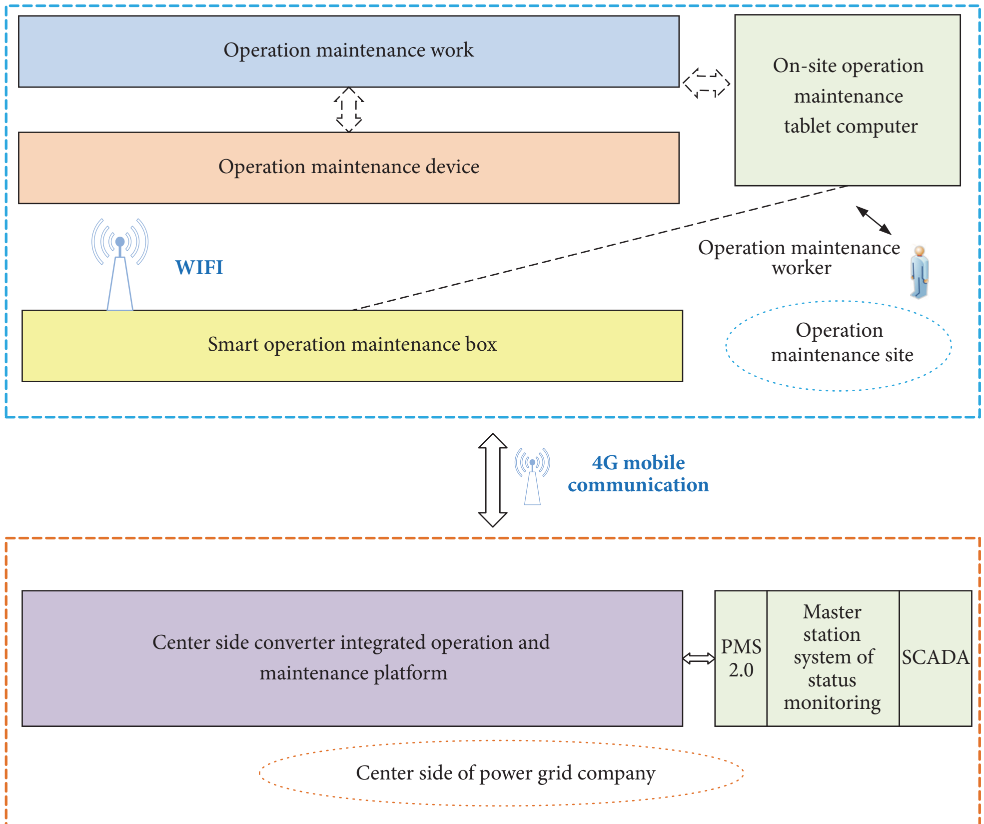

FIGURE 1: Architecture of the proposed system.

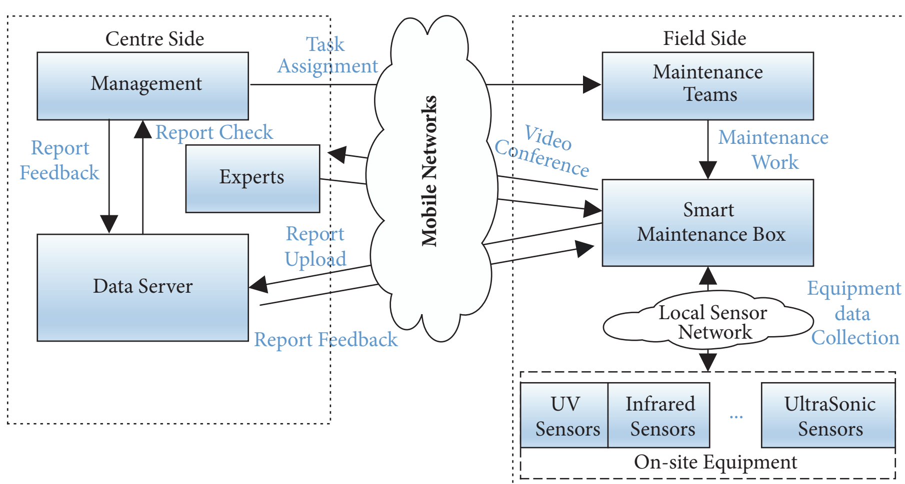

FIGURE 2: Structure of networked closed-loop smart maintenance model.

equipment using a unified protocol. The standardized box information can be used for intelligent assessment and detection, as long as it has been uploaded to and stored in the Power Grid Corp data centre.

The interactions between the centre-side source including big data analysis and calculation and the on-site maintenance work are achieved through the SOM box. For example, the senior application centre can analyse the data uploaded locally and match and analyse it through the built-in case library. In the event of abnormal data or emergency equipment failure, the maintenance team can be notified directly to intervene. When OM personnel face technical difficulties, professional on-site guidance can be obtained through the video conference call centre.

Figure 3: Hardware interface of the SOM box.

3.1. Hardware Design and Implementation. Considering the energy consumption and also the performance, the TI (Texas Instruments) OMAP5432 platform is adopted for the design of the SOM box, and Samsung's Exynos 5250 System-on-Chip (SoC) processor based on a dual-core ARM CorTex-A15 framework is also considered.

As shown in Figure 3, to support the data monitoring in real-time in this project, a TI 2D BitBLT graphics accelerator is adopted in the hardware interface. It can support four displays and three cameras simultaneously, enabling direct video conferencing. Embedded with an adaptive network communication module of Bluetooth, 4G, WIFI, and 10M/100M, the box is able to communicate with various on-site testing equipment and also the data centre.

3.2. Software Design and Implementation. Regarding the software, the Android 4.2.2 is used in the proposed system whose kernel is on the basis of Linux and the gcc 4.4.1 is used for cross-compilation. As for the file system, the combination of Ramdisk and Ext4 is adopted.

Figure 4 shows the multitier-structure software design of the SOM box. It can be seen that a variety of communication-driven management modules are integrated into the architecture, which can support various communication devices and protocol. Device drivers, for example, USB storage devices, cameras, and monitors, can also be deployed. The Android system provides the resource of kernel layer. In order to form a own special system, an open source operating system is applied and tailored to build up functionalities of the system.

The independently developed modules, including data processing, video conferencing clients, and data management, form the application tier module. Main functionalities, for example, data acquisition storage and uploading as well as interactions with the centre side can be realized by these modules supported by corresponding algorithms.

4. Communication Protocols for Data Collection

4.1. AMQP Based Communication Protocol. There are various maintenance devices which create all kinds of data such as charts, images, and data streams. Therefore, it is utterly important to unify the forms of the communication data between the smart box and maintenance devices. The communication protocol is based on an open standard application layer protocol, that is, Advanced Message Queuing Protocol (AMQP) that can be used for message-oriented middleware. There are many open source frameworks available in the market, such as Apache Qpid, Apache ActiveMQ, and RabbitMQ. Among them, RabbitMQ is a kind of light-weight AMQP supporting library which is suitable for embedded devices.

For the future maintenance devices, the new communication protocol can be embedded when they are designed and manufactured. However, there are many existing maintenance devices which were deployed before the networked smart maintenance project and may not support the newly proposed communication protocol. Therefore, they must be modified.

As most of the mainstream devices are equipped with the communication ports, the most convenient way is to add a plug-in module over the old communication ports. The module is a bridge between the old and new communication protocols. It is able to translate the data from old format into the new format, as shown in Figure 5.

4.2. Data Storage. During OM work, various forms of data are generated by the equipment. Some of the data are structured like numerical data and texts. Some of the data are unstructured like spectrum, videos, and images. The two different kinds of data should be stored in different ways.

4.2.1. Structured Data Storage. The structured data are stored in the XML format. Extensible Markup Language (XML) is used to define the rules for encoding documents in a format which is readable not only for human but also for the machine. Comparing with the conventional data storage model, it has an object-oriented structure which is much easier to transplant, with good scalability, compatibility, and portability. Algorithm 1 is a sample of the test data which is collected from a substation in Wuhan.

4.2.2. Unstructured Data Storage. The plain unstructured data like images and spectrum are hardly searchable in database. Their characteristics need to be extracted before they can be effectively stored in database. Figure 6 shows the normalization for the images of the power equipment. It is based on sparse coding and visual dictionary technologies.

For the unstructured data which can be normalized, they are converted and stored inside the XML structure directly. For the data which cannot be normalized such as images and videos, the original data are stored inside the database and their characteristics are extracted and marked inside the XML.

5. Work Procedure with SOM Box

By applying the proposed closed-loop model, the OM efficiency, as well as the data reliability, can be greatly raised. The work procedure of OM using intelligent transportation box is as shown in Figure 7. Two kinds of users are involved in this whole system according to the division of labor.

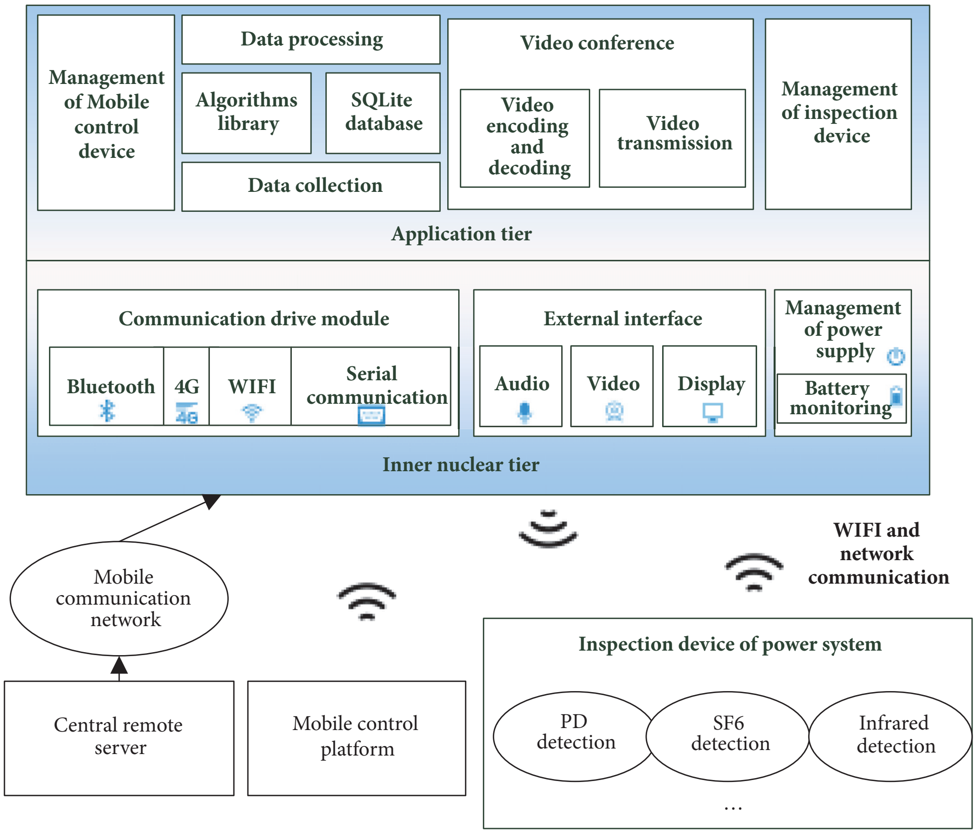

Figure 4: Software design of SOM box.

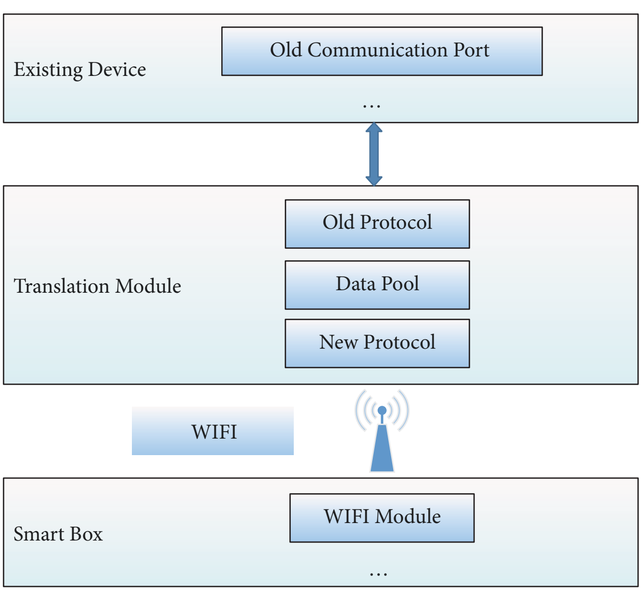

Figure 5: Modification of existing devices.

The project manager can comprehensively manage the substation inspection project. Firstly they assign and issue tasks for on-site OM personnel. Secondly, the data collected on site will be checked and they can supervise the completion of OM tasks. When the OM team encounters technical difficulties, they will respond to their call requests at any time and according to their needs arrange corresponding technical experts to conduct video conferences to solve their difficulties.

For the on-site OM team, under the supervision of the project manager, they can perform tasks through this APP, such as task downloading and data uploading on the live detection test to realize data interaction between the on-site and client-side. After that, live detection information will be displayed. With the networked closed-loop model, the team is also able to give the feedback of detection information to clients.

Seen from the work-flow, it can be concluded that the network closed-loop model greatly relieves the workload of the staff. The project manager is just responsible for management of the OM tasks through the web platform. In the on-site SOM, all devices are connected to the smart inspection box through the network, with unified management and unified data uploading. OM personnel do not need to manually record test data and can obtain real-time guidance through the network, which makes the entire OM work more efficient and reliable.

6. Conclusions

An on-site SOM system for substation equipment with a networked closed-loop model is proposed in this paper.

```
<TEST version="1.3">
        <DeviceInfo desc="Primary Device Information">
                <StationName>Wuhan Optical Valley East Substation</StationName>
         <Level desc="Voltage Level">500 kV</Level>
                ......
                <DeviceCode desc="Code">#12FF</DeviceCode>
        </DeviceInfo>
    <IED channelNum="2" desc="Partial Discharge Detection Device" vendor="Wuhan Nari" model="JFD-2000">
    ......
        </IED>
    <TestValue>
                <Channel chNo="1" sensorType="HFCT">
                        <Do name="AppDsch" desc="Apparent Discharge">
                                <Val>12</Val>
                                <t>2015-09-23 16:165:00.123</t>
                        </Do>
                </Channel>
                ......
    </TestValue>
    ...
    </TEST>
```


Algorithm 1

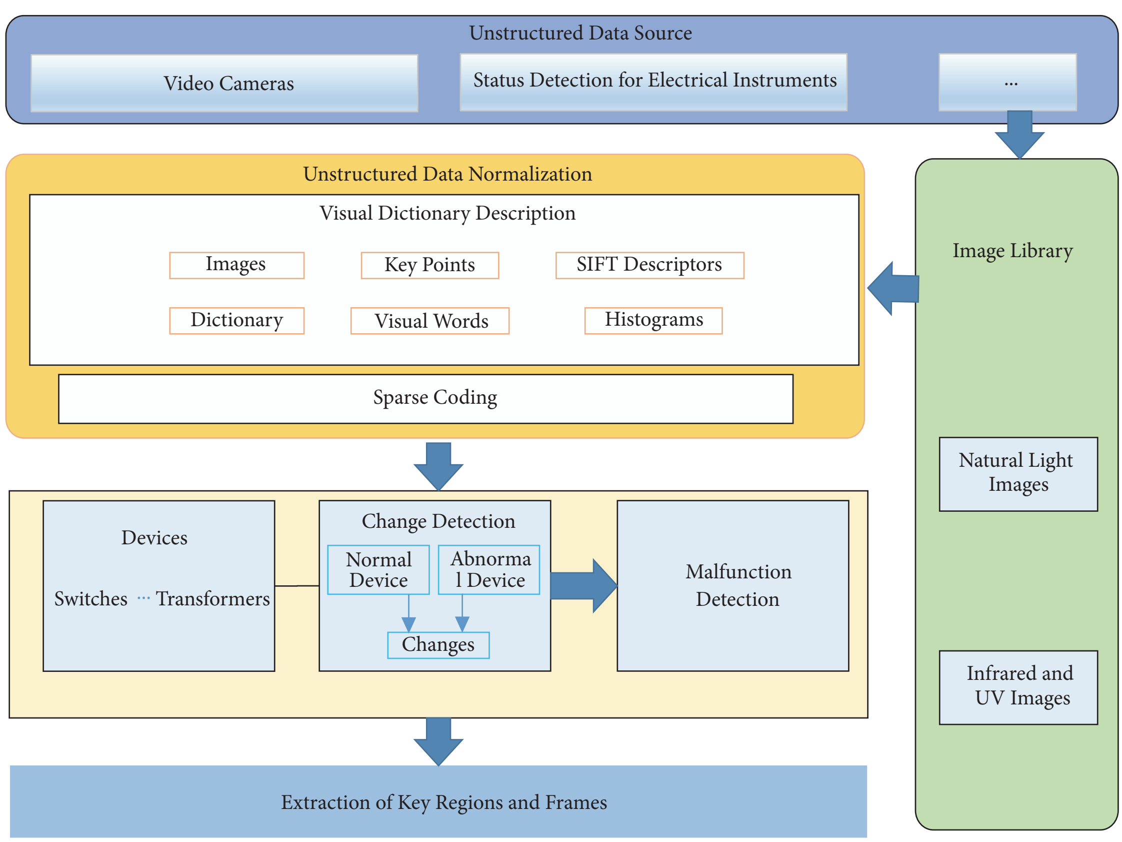

Figure 6: Transformation from nonstructural data to structural data.

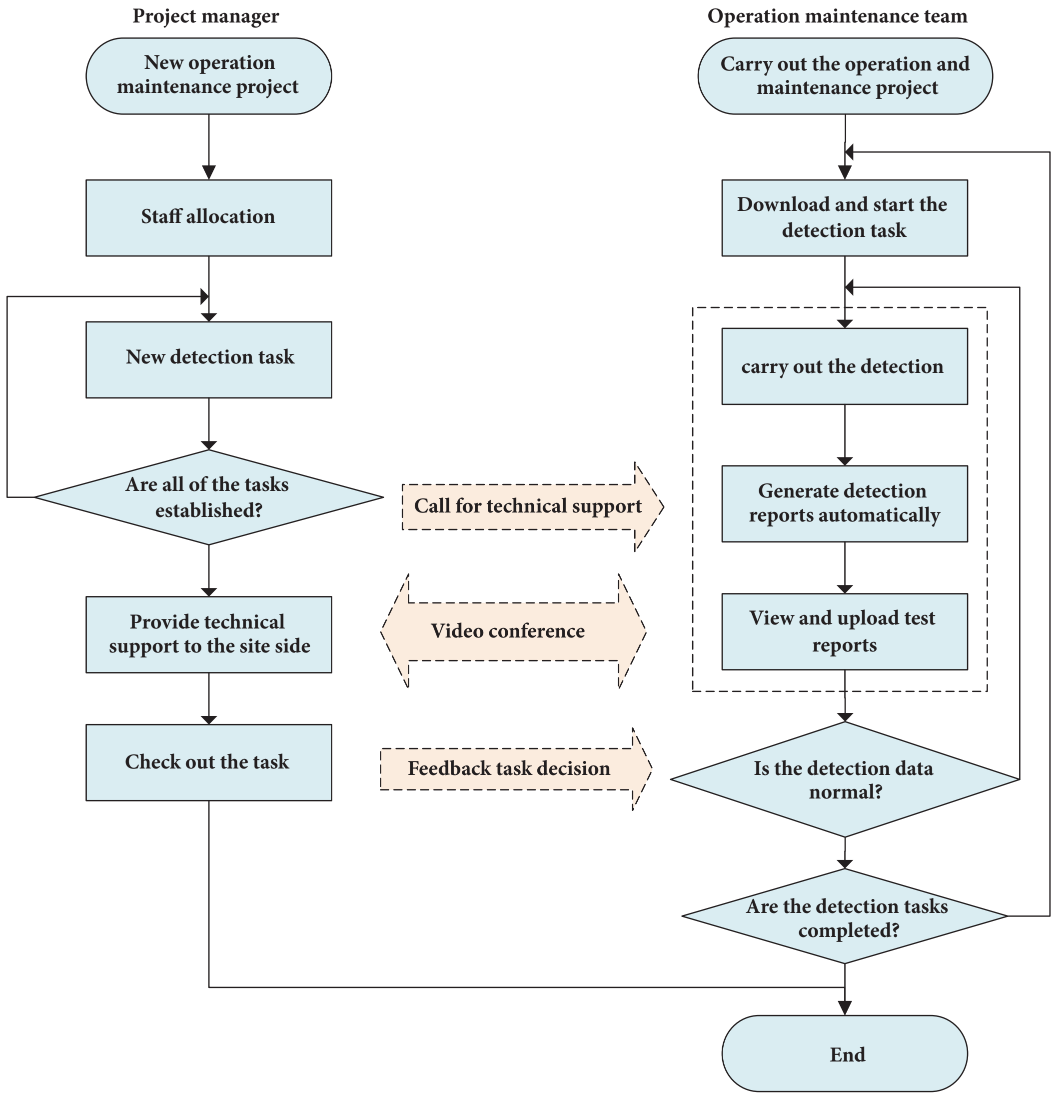

Figure 7: Workflow of OM work.

As a bridge to connect the communication with data, the networked closed-loop model based on an NCS integrates the control theory, communication technology, and computer technology together. It can be applied to a hugely complex system or remote control system because of its high information integration. In the proposed on-site SOM system, the networked closed-loop model takes intelligent field equipment as its material base and communicates high-speed Ethernet, to achieve the high efficiency and flexible operation, which in turn reduces the pressure on workers.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by State Grid Corporation of China Science and Technology Project (524625160017).

References

[1] W. Zhang, M. S. Branicky, and S. M. Phillips, "Stability of networked control systems," *IEEE Control Systems Magazine*, vol. 21, no. 1, pp. 84–99, 2001.

[2] Y. Zhao, G. Liu, Y. Kang, and L. Yu, "A Brief Tutorial of Networked Control Systems," in *Packet-Based Control for Networked Control Systems*, pp. 1–11, Springer, Singapore, 2018.

[3] B. S. Reddy and S. Ulgiati, *Adoption of Smart-Grid Technologies by Electrical Utilities in India: An Exploratory Study of Issues and Challenges*, Springer, New Delhi, India, 2016.

[4] C. E. Gilbert, K. W. David, and K. J. Gregory, "Final Report on the Operation and Maintenance Improvement Program for Concentrating Solar Power Plants," Office of Scientific & Technical Information Technical Reports, 1999.

[5] Y. Hayashi, H. Fujimura, M. Furukawa, K. Shimizu, and Y. Hayasaka, "Operation and maintenance planning aiding system for power generation installation," US, US 20030004659 A1, 2003.

[6] R. S. Atlason and R. Unnthorsson, "Operation and Maintenance in Icelandic Geothermal Power Plants: Structure and Hierarchy," in *Proceedings of the ASME 2013 Power Conference*, Boston, Mass, USA, article V001T05A007, 2013.

[7] R. Bayindir, E. Hossain, and S. Vadi, "The path of the smart grid -the new and improved power grid," in *Proceedings of the 2016 International Smart Grid Workshop and Certificate Program (ISGWCP)*, pp. 1–8, Istanbul, Turkey, March 2016.

[8] L. Wang, Q. Chen, H. Gao, Z. Ma, Y. Zhang, and D. He, "Framework of Fault Trace for Smart Substation Based on Big Data Mining Technology," *Automation of Electric Power Systems*, vol. 42, no. 3, pp. 84–91, 2018.

[9] N. Ivancevic, "Information technology communications cabinet for electrical substation communications," US, US20060269207, 2006.

[10] H. Zamanian, J. Ghaisari, and F. Sheikholeslam, "Robust networked control of load frequency in multi-area interconnected power system," in *Proceedings of the 25th Iranian Conference on Electrical Engineering, ICEE 2017*, pp. 1126–1131, May 2017.

[11] K. Nimma and S. Faraj, "Modeling Intelligent Control Switch IEC 61850 Based Substation Automation Communication," *Applied System Innovation*, vol. 1, no. 1, p. 7, 2018.

[12] Y. B. Zhao, G. P. Liu, Y. Kang, and L. Yu, "Stochastic Stabilization of Packet-Based Networked Control Systems," in *Packet-Based Control for Networked Control Systems*, pp. 77–85, Springer, Singapore, 2018.

[13] Y. Wang and S. Yu, "An improved dynamic quantization scheme for uncertain linear networked control systems," *Automatica*, vol. 92, pp. 244–248, 2018.

[14] L. Litz, T. Gabriel, M. Groß, and O. Gabel, "Networked Control Systems (NCS) – Stand und Ausblick (Networked Control Systems (NCS) – State of the Art and Future)," *at - Automatisierungstechnik*, vol. 56, no. 1, pp. 4–19, 2008.

[15] G. C. Goodwin, H. Haimovich, D. E. Quevedo, and J. S. Welsh, "A moving horizon approach to networked control system design," *IEEE Transactions on Automatic Control*, vol. 49, no. 9, pp. 1427–1445, 2004.

[16] T. C. Yang, "Networked control system: a brief survey," *IEE Proceedings Control Theory and Applications*, vol. 153, no. 4, pp. 403–412, 2006.

[17] A. Sala, Á. Cuenca, and J. Salt, "A retunable PID multi-rate controller for a networked control system," *Information Sciences*, vol. 179, no. 14, pp. 2390–2402, 2009.

[18] L. Cheng, W. Hu, Z. Liu, and W. Cai, "On-site Smart Operation and Maintenance System for Substation Equipment Based on Mobile Network," *International Journal of Online Engineering (iJOE)*, vol. 14, no. 3, pp. 66–80, 2018.

[19] S. P. Dulman, "Maintenance operations console for an advanced intelligent network," in *US 5802146 A*, 1998.

[20] B. Qian, Z. Liu, L. Zhang, and J. Chen, "Study on the supplementary VR visual platform for intelligent substation operation and maintenance," *Electrical Automation*, vol. 40, no. 1, pp. 30–32, 2018.