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B2 Overhead Lines
PS2 Latest Techniques in Asset Management, Capacity Enhancement, Refurbishment

The Next-Generation Intelligent Maintenance for Over-head Electric Power facilities using Edge Cloud Collaboration

Hua WU* wuhua@ncepu.edu.cn, Xiaojing BAI* baixiaojing@ncepu.edu.cn, Zengguang OU ouzhengguang@huawei.com, Qi ZHANG zhangqi21@huawei.com
North China Electric Power University, China
Huawei Cloud, China.

SUMMARY

Regular inspections and timely maintenance of the over-head electric power facilities are crucial to national security. As pioneers of intelligent maintenance with UAV based inspection, we have gained insight into the industrial revolution and find the trend of the technology development from IMLocal(Intelligent Maintenance by the local application) to IMCloud(Intelligent Maintenance by Cloud). IMCloud architecture is reported with several shortcomings. In this paper, a next-generation intelligent maintenance system - IMEdge(Intelligent Maintenance using edge-cloud collaboration) is proposed to overcome the shortcomings by 4 primary architectures: edge cloud security, autonomous inspection, collaborative inferencing, and edge collaborations between robots. Further, 3 general latent collaboration cores hidden in the architectures are found in the IMEdge. A vast range of edge-edge collaboration is constructed taking the advantages of the collaboration cores for the electric power industry. Finally, a cross-industry architecture is proposed based on the IMEdge.

KEYWORDS

Edge cloud collaboration, intelligent maintenance, UAV inspection, architecture

I Introduction

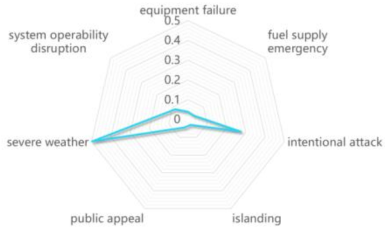

Figure 1 Major causes of outages in different states in the continental U.S. during January 2000–July 2016 in percentage.

Electric power grid safety directly leads to national security. Figure 1 shows the major causes of outages in different states in the continental U.S. during January 2000–July 2016 [1]. Obviously, the major power outages attribute to the severe weather and intentional attach. Power outage affects millions of people and cost billions of dollars in economic losses each year around the world. As a result of power outage, the blackouts can completely hinder production at companies and critical infrastructures such as electronics manufacturing, telecommunication networks, financial services, water supplies, and hospitals [2]. Regular inspection and emergency inspection methods for the power consist of the human patrol(shown in Figure 2), helicopter-assisted inspection, climbing robot inspection, and UAV inspection. Moreover, UAV with on-board sensors is the most promising method due to its advantages in low-cost inspection facilities, diverse sensors[3], and fast evolution ecosystem [4]. According to the [5], the inspection drones market reaches a value of USD $ 23 Billion by 2027.

Figure 2 Human inspectors walking on the power transmission lines.

However, human have deeply participated in the entire procedure of UAV inspection, including data acquisition, transferring and analysis. Similar to most of the infrastructure visual inspection[6], human in the inspection loop (HITL) suffers from steep learning curves, bias and errors. During the data acquisition, skilled workers know the inspection techniques for various electric power facilities beforehand. They go to the site and carefully select the best viewpoints during the flight. Then, camera parameters should be carefully tuned in different illumination conditions. In the meantime, they were qualified experts to pilot the UAV to avoid obstacles and keep a certain distance to the inspection target during the flight beyond the visual range. During the data transfer, data encryption is not considered which may result in revealing protected information or unreliability of the data. During the data analysis, experts with knowledge of defects review the captured photos and make further decisions for field repair. Therefore, to mitigate HITL inspection of the electric power infrastructures and to increase the efficiency of defects detection, an intelligent maintenance system can standardize the entire workflow and meet the requirements of unbiased, accurate, and timely.

The intelligent maintenance system is under rapid iterative research and development in the decade. New methods have been proposed to reduce the time of flight using reinforcement learning[7] and increase the quality of inspection photo by viewpoints planning [8][9]. A native software was developed to assist the analysis of the data acquired during inspection flights[10][11][12]. To release the experts from a large amount of photo reviewing, machine learning is adopted to solve such laborintensive work[13][14]. It can be regarded as the first stage towards inspection automation - Intelligent Maintenance by the local application (IMLocal). These automation procedures are independent from the network and they were not invented for the entire inspection process. They solve the partial problems of inspection while bringing more data preparation effort, more undermined parameters, and more cross-domain knowledge. Since each procedure of inspection does not interconnect, they cannot share other procedures information to upgrade original methods.

The first Intelligent Maintenance by Cloud (IMCloud) was developed by Hua WU's team. It is the state of the art intelligent inspection system which was built on top of several national industry standards. We also contribute our expertise to the IEEE P2821 standard. The architecture of the system is shown in Figure 3. Inspection devices are in the perceptive layer, which provides diverse data acquisition capabilities and facilitates multi-modality data gathering when the inspection devices equipped with various sensors. The field data can be uploaded to the cloud via various channels, e.g., 4G LTE, virtual private networking, or even manual transferring. Thus, the cloud layer processes the inspection data with multiple VMs using vCPUs or GPUs. Based on the architecture, the application layer can reorganize resources and algorithms and connect every inspection procedure into a complete automation data processing line. There are 5 major resources at the bottom of the application layer. The power line resource contains the towers and lines physical, structural and temporal parameters. The inspection devices management provides standardized utilization flow for the inspection teams to access their inspection devices, warranties, and accessories. Flying qualification regulates the scheduling within legal airspace and qualified workers. Once the inspection task is allowed and scheduled to specific groups, their entire operation footprints are recorded for further inspection knowledge mining. Experts' experiences of the flights and photo analysis are digitized and correlated with several aspects. It improves the smart flight module to better inspection viewpoints. It helps others to learn the inspection technique faster. It enables the quantitative measurement of the workers' workload and lifetime of the inspection devices. The inspection results management feed defects to further repair scheduling and add obtained samples for the intelligent analysis. The system depends on the cloud infrastructure to simplify the platform design, software deployment, service upgrade and reduction of the hardware investment for GPU computation. Consequently, IMCloud is a Software as a Service (SaaS) platform for inspection automation.

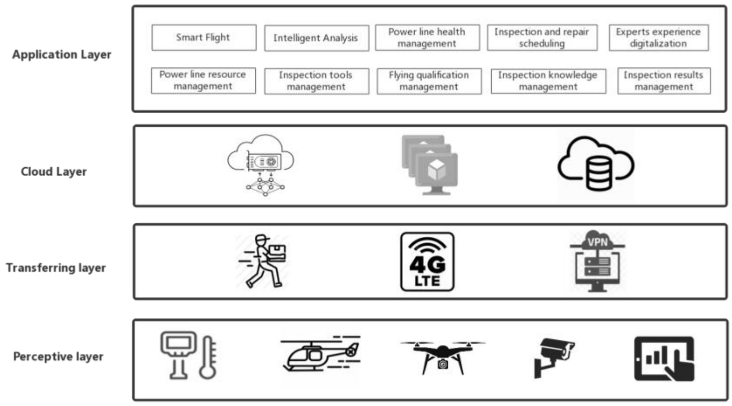

Figure 3 IMCloud: 4 layers architecture for inspection automation.

Though the SaaS platform extends the IMLocal abilities and boost the evolution of inspection with the huge computation and PaaS level intelligence, IMCloud completely depends on a large amount of data transferring, mobile networking aided accurate positioning, samples-dependant defects recognition, etc. In the field application, more than 10 gigabytes data are needed to upload every day in each UAV after inspection. Nevertheless, the power line cannot be fully covered by the valid signal range of the communication tower. Furthermore, the situation may affect the positioning system. Additionally, sometimes the ultra-high voltage DC grids would interference the flight stability. Thus the UAV cannot be accurately controlled near the electric power facilities. The data would cost much computation resources after inspection, though the results are not really accurate especially most of the defects are rare. Under such circumstances, the accuracy of the inspection cannot be guaranteed. The SaaS platform is limited to small scenarios.

The inspection automation keeps pace with the industrial UAV hardware and the cloud computation development to the new era - Edge AI. To plan the viewpoint with less time and better adaption, the on-board computation can largely enhance the UAV localization and mapping accuracy in diverse environments [15]. With the edge-cloud collaboration, the data transferring with edge security protection, the inspection viewpoints can be planned and edge-cloud AI recognition can be further achieved in versatile autonomous inspection systems which fit for more autonomous robots.

Intelligent Maintenance using edge-cloud collaboration (IMEdge) is proposed to conduct the aforementioned shortcomings in IMCloud from a systematical point of view. Several edge-cloud collaboration paradigms are established to tackle specific issues. They are finally assembled into a universal architecture of edge-cloud collaboration for cross-industry applications, which enlarges the range of the inspection systems. Finally, the academic and commercial value of the IMEdge can be inspired.

II IMEdge Characteristics

2.1 Security between edge and cloud

The security from edge to the cloud is regarded as data collaboration in the IMEdge. Several security issues are raised because of sensitive data has been exchanging with the cloud in the IMEdge. Among all sorts of information transferred on the Internet, the coordinates and images are the most sensitive properties of the national grid. Thus, the edge reduces the most network traffic by prepossessing in the edge device. An edge computing device used to run edge applications, process data, and collaborate with cloud applications securely and conveniently. Most of the intelligent applications such as navigation, viewpoint planning, defects recognition, or even human-machine interaction are shifted from cloud to edge, which are functional modules that run on edge nodes. By deploying the required applications, they build ones own edge computing capabilities. In Figure 4 shows the 3 levels of security in the IMEdge. The cloud security and Identity and Access Management (IAM) certification protect sensitive information communication in the cloud. The sensitive information is protected during edge cloud communication. The characteristics of security schemes are:

- Edge cloud communication is safe. Intelligent EdgeFabric (IEF) and IEF-Edge establish a Websocket+TLS encrypted bidirectional channel. IEF-Edge initiates from the bottom up. Bidirectional message sending and receiving are authenticated and encrypted through certificates [16].
- Cloud security, pre-DDos network security protection, anti-malicious attacks.
- IAM certification, AK/SK assignment through IAM roles allows access to cloud resources.
- The node certificate issues a unique access certificate for each edge node and the two-way communication passes certificate authentication and encryption.
- Application certificate, which is used to access IEF-Edge by issuing certificates for edge applications.
- Device certificates. Edge devices use certificates for identity authentication.

The node, device, and applications using the certificates to avoid the attacks of the malware injection, the side-channel and the authentication, and authorization [17].

The security issues can be solved by the multi-level protection. The edge computation substitutes the human operation with edge-device security communication and edge-cloud security collaboration. Furthermore, block-chain can be adopted. It is a way to make drones more secure and easier to regulate and monitor. The block-chain features decentralization, immutability, secure communications [18].

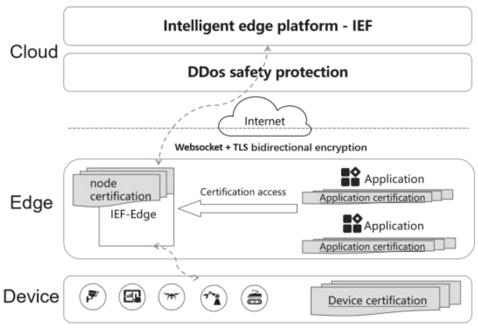

Figure 4 Information security in the IMEdge.

2.2 Autonomous inspection

The quality of intelligence maintenance is mainly defined by the ability of autonomous inspection. The environment perception, UAV positioning, and viewpoint planning are the key techniques for the autonomous inspection. In the environment perception, the environment digital models are reconstructed for closed-loop control and viewpoint planning [20] [21]. It can be regarded as data collaboration in the IMEdge. To plan the accurate absolute positions of the viewpoints for the UAV relative to the inspection targets is limited by the Real-Time Kinematic (RTK) technology. We leverage the management collaboration in the IMEdge to overcome the limitations. The data collaboration and the management collaboration can further serve the environment perception refinement, inspection experience sharing, navigation algorithms update, etc.

Figure 5 indicates the state-of-the-art autonomous inspection through edge-cloud collaboration. Assisted by the IEF agents, the onboard edge node can easily deploy docker containers. Inside the docker, ROS, deep learning frameworks, hardware mapping, etc. established the middleware of the autonomous inspection systems. The flight controller is connected to the onboard edge node. Though there are different flight controllers with heterogeneous hardware, the docker container handles the different protocols with a common middleware layer. The apps layer provides a robust navigation stack and captures inspection data through the IMEdge's data collaboration and management collaboration.

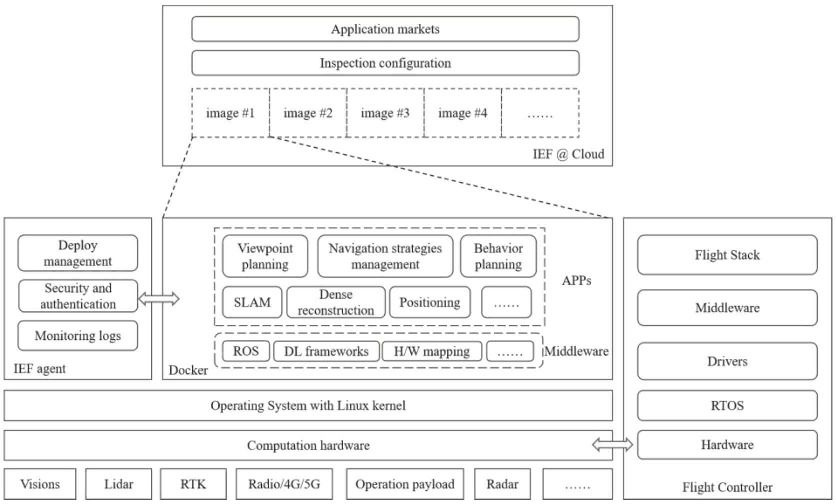

Figure 5 Autonomous inspection in the IMEdge.

The cloud redefinition module manages different images for different scenarios in an inspection. Ones can publish their latest dockerized applications to the application markets. By the inspection configuration layer, different inspection requirements can be satisfied and reconfigured to images. The images are used to build the working containers in the edge device.

2.3 Collaborative inferencing

The defect recognition for the inspection images is large training sample scale-dependent [22], which is confronted with the drawbacks of few-shot samples per edge for training,non-I.I.D data across edges, the performance of universal AI model degraded on edge, resource-constrained on edge. These challenges coexist with several advantages, i.e. data privacy which reduces data transfer by human, lower latency than cloud processing, reduce the cost of the transfer to the cloud.

We establish a collaborative AI service based on IEF in the IMEdge, including a global coordinator on the cloud, a local controller at the edge, workers to run inferencing or training, and libraries for interoperability with existing ML frameworks. The edge-cloud collaborative ML features, including joint inferencing, incremental learning, and collaborative training (aka federated learning). We can build and publish edge-cloud collaborative AI services/functions easily.

Under the condition of limited edge resources, the collaborative inferencing of the edge cloud models improves the accuracy of conferencing, and deploy on-demand according to resources, adapt to different edge devices. Multiple defects recognition models collaborate to form a model group, but how to design and train the edge model and the cloud model can achieve the best collaboration effect (taking into account accuracy, recall, and edge resource constraints), there are challenges. Several methods have been proposed to cope with the challenges, i.e. multi-objective-oriented model group training method, cooperative defects recognition algorithm, and incremental update algorithm for defects recognition.

There are nested inference and refinement strategies of intelligence collaboration in the IMEdge. Figure 6 demonstrate the 3 major components of the intelligence collaboration. The edge defects recognition model focus on recall (preferable more false-negative results), the cloud accepts some low-confidence results. The defects recognition model can run on various resource constraint edges. The inspection applications take advantage of the low latency of the defects recognition model to improve the UAV inspection behaviors and the defect recognition can also utilize the real-time flight information to improve the recognition accuracy. The cloud back cloud judgment communicates with the defects recognition refinement in the cloud. Hard samples with low confidence is fed into the training pipeline for edge model refinement. The intelligence collaboration management monitors the process, updates the edge model and integrates the experience of the defects recognition experts by the manual refinement of the experts. The experts' knowledge and standards are adopted into the training procedure in the IMEdge

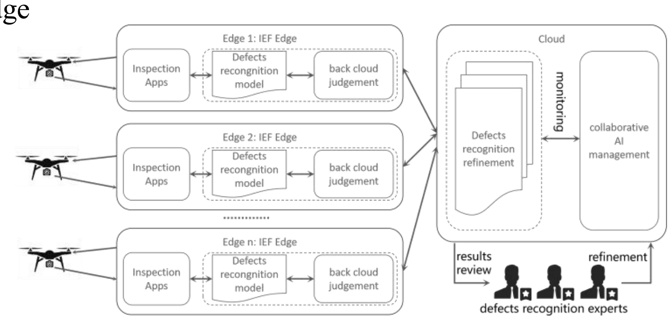

Figure 6 Collaborative inferencing and cloud-edge refinements in the IMEdge.

2.4 Collaboration with more devices and services

In the journey to the predictive maintenance of the power transmission and distribution facilities, diverse functional robots, online surveillance devices and sensors installed on the lines can be used to obtain more data and accomplish more works without risking the life of line workers [23] [24] [25] [26]. Based on EdgeMesh in IMEdge, robots, devices and sensors collaboration is illustrated in Figure 7. Though the appearance inspection by UAV only covers one part of the health parameters of the power transmission and distribution facilities, the online operating robot can finish the repair work after urgent defects detected. Additionally, on-line monitoring devices and sensors enrich the modalities of the inspection, which may lead to more accurate and objective results. The collaboration is regarded as the IEF's edge-edge collaboration.

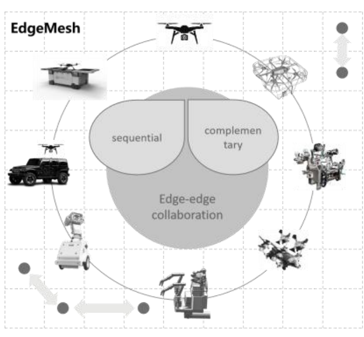

Figure 7 Edge devices collaboration.

During the rapid development of 5G infrastructure and technology, the edge nodes would extend their abilities using more online services and expose their capabilities to the large ecosystem of the IMEdge. The cloud employs an API gateway to provide the services. The API Gateway is a high-performance, high-availability, and high-security API hosting service that builds, manages, and deploys Application Programming Interfaces (APIs) at any scale and open up capabilities with minimal costs and risks. The APIs for API callers can be provided using offline channels or released to the API marketplace. In the IMEdge, a large amount of APIs provided by different providers would consolidate their ecological position and promoting the positive development of the ecosystem.

III Collaborative IMEdge

3.1 Collaboration cores

By solving the key problems in building IMEdge for power line inspection, we can summarize 3 major collaboration cores: management collaboration, data collaboration, and Intelligence collaboration. The cores are the soul of the IMEdge. The role of each core listed below.

- Data collaboration. It is the basic building blocks of the IMEdge, since the system communication and security guarantee the control commands, video streaming, private data, etc. under traceable management and authorized access. In the upcoming 5G epoch, these robots and devices will widely work with each other with less time delay in IMEdge. They respond to the control data base on the feedback of the sensor data from others.
- Intelligence collaboration. Since the edge capabilities become more powerful and offload the cloud inferencing time and resource consumption, the collaboration decouples a large amount of data transmission and inferencing jobs in the cloud. Meanwhile, human experts can take part in the training stage for better supervising the quality of the results in an efficient way. In the IMEdge, most of the inspection UAVs with onboard computing device enable them to be more than a single function. They evolve with the cloud to achieve better performance and accuracy.
- Management collaboration. There are 2 levels in the management collaboration: business management collaboration and application management collaboration. In business management collaboration, applications can be orchestrated with respect to the requirements in a timely manner. It enables cross-industrial applications by the orchestrating original building blocks and with less time in the development of new functions. In the application management collaboration, the application life cycle management reduces the UAV upgrading time and simplifies the field operation monitoring for improving software and hardware iteration.

As shown in Figure 8, the 3 collaboration cores augment existing systems and can be directly applied to other industries.

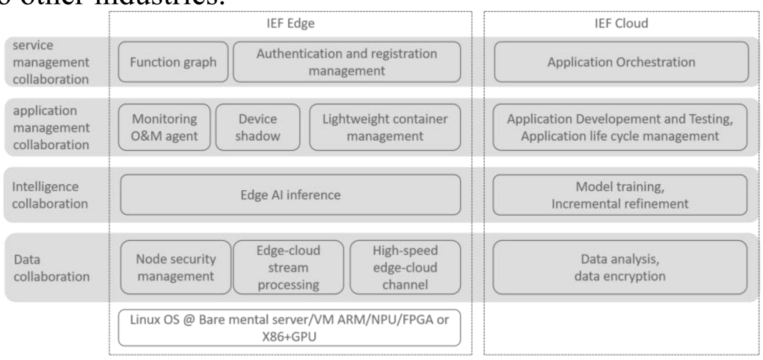

Figure 8 Collaborative IMEdge.

3.2 Edge-Edge Collaboration

IMEdge is born to be the eye in the sky, but with the help of other robots, the entire job can be finished and continued using robots and devices. Therefore, the robots are collaborated with each other in 2 modes in IMEdge. The first mode is a complementary mode. Robots or devices with different sensing capabilities can work together to provide more abundant data modalities for the facility's health evaluation. Second mode is a sequential mode. Robots or devices with different operation functions can work in a pipeline to achieve a certain goal.

The edge-edge and edge-cloud collaboration adopte EdgeMesh. It provides the answer to the requirements: micro-services discovery and communication across edge-cloud, governance capabilities, typical gray-scale release processes such as canary and blue-green release. Therefore, a unified service discovery across edge-cloud can be created. It supports the edge-cloud Overlay network channel of multiple edge access methods. It is a highly integrated service discovery and edge implementation of service routing. The traffic management is unified in the system. The network penetration is possible across sub-nets.

IV IMEdge Architecture for cross-industries

The power line inspection can be regarded as a most sophisticated instance of the UAV inspection in comparison with the inspection of the petroleum pipeline, wind/solar power plant, 5G base station, etc. We have built a practical and elegant architecture of IMEdge in Figure 10. The cross-industry applications might be orchestrated in the cloud by some building blocks. Their functions are enriched by the APIs. The ModelArts provides training and refinement services for the IEF [27]. The IEF markets enhance and establish an ecosystem for different devices and robot providers. The edge robot or device actively collaborates with the cloud and other edge nodes. The collaborative cores have extended the cloud services to the edges with high security and quality.

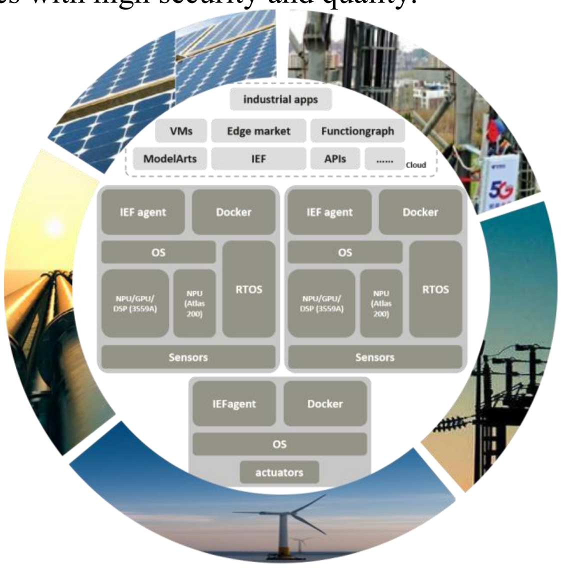

Figure 10 IMEdge architecture.The Atlas is an AI Accelerator Module integrates the Ascend 310 AI processor to implement inferencing on the edge [28]. The 3559A is an efficient heterogeneous computing platform with neural network inference engine.[29]

V Conclusions

The next-generation intelligent maintenance system - IMEdge is proposed to overcome the shortcomings by 4 primary architectures: edge cloud security, autonomous inspection, collaborative inferencing, and edge collaborations between robots. Further, 3 collaboration cores are summarized with respect to the IMEdge and enable a vast range of edge-edge collaboration. Finally, the cross-industry architecture of intelligent maintenance is proposed based on the IMEdge.

Rome was not built in a day. The IMEdge still has a long way to be a great deal of benefits to the industries. It opens a new era for predictive maintenance using edge-cloud collaboration and edge-edge collaboration. It also opens up a new paradigm for robotics perception and navigation, edge computing architecture, and edge-cloud machine learning, etc. researches and applications.

BIBLIOGRAPHY

[1] Mukherjee, Sayanti, Roshanak Nateghi, and Makarand Hastak. "Data on major power outage events in the continental US." Data in brief 19 (2018): 2079.

[2] Castillo, Anya. "Risk analysis and management in power outage and restoration: A literature survey." Electric power systems research 107 (2014): 9-15.

[3] Nguyen, Van Nhan, Robert Jenssen, and Davide Roverso. "Automatic autonomous vision-based power line inspection: A review of current status and the potential role of deep learning." International Journal of Electrical Power & Energy Systems (2018): 107-120.

[4] Giones, Ferran, and Alexander Brem. "From toys to tools: The co-evolution of technological and entrepreneurial developments in the drone industry." Business Horizons 60.6 (2017): 875-884.

[5] Transparency Market Research. "INSPECTION DRONES MARKET TO REACH A VALUE OF US$ 32 BN BY 2027: TRANSPARENCY MARKET RESEARCH". www.transparencymarketresearch.com. https://www.transparencymarketresearch.com/pressrelease/inspection-drones-market.htm(accessed June 23, 2020).

[6] Agnisarman, Sruthy, et al. "A survey of automation-enabled human-in-the-loop systems for infrastructure visual inspection." Automation in Construction 97 (2019): 52-76.

[7] H. Wu, et al. "Planning efficient and robust behaviors for model-based power tower inspection." 2012 2nd International Conference on Applied Robotics for the Power Industry (CARPI). IEEE, 2012.

[8] Liu, Changan, Ruifang Dong, and Hua Wu. "Flying Robot Based Viewpoint Selection for the Electricity Transmission Equipment Inspection." Mathematical Problems in Engineering (2014): 1-10.

[9] Liu, Changan, et al. "A safe flight approach of the UAV in the electrical line inspection." International Journal of Emerging Electric Power Systems 16.5 (2015): 503-515.

[10] Martinez, Carol, et al. "The Power Line Inspection Software (PoLIS): A versatile system for automating power line inspection." Engineering applications of artificial intelligence 71 (2018): 293-314.

[11] Zhang, Yong, et al. "Automatic power line inspection using UAV images." Remote Sensing 9.8 (2017): 824.

[12] Zhou, Zhenyu, et al. "Energy-efficient industrial Internet of UAVs for power line inspection in smart grid." IEEE Transactions on Industrial Informatics 14.6 (2018): 2705-2714.

[13] V. N. Nguyen, R. Jenssen and D. Roverso, "Intelligent Monitoring and Inspection of Power Line Components Powered by UAVs and Deep Learning," in IEEE Power and Energy Technology Systems Journal, vol. 6, no. 1, pp. 11-21, March 2019.

[14] X. Tao, D. Zhang, Z. Wang, X. Liu, H. Zhang and D. Xu, "Detection of Power Line Insulator Defects Using Aerial Images Analyzed With Convolutional Neural Networks," in IEEE Transactions on Systems, Man, and Cybernetics: Systems, vol. 50, no. 4, pp. 1486-1498, April 2020.
[15] Aggarwal, Shubhani, and Neeraj Kumar. "Path planning techniques for unmanned aerial vehicles: A review, solutions, and challenges." Computer Communications 149 (2020): 270-299.
[16] HUAWEI CLOUD International website. "What Is Intelligent EdgeFabric?". support.huaweicloud.com/intl/en-us. https://support.huaweicloud.com/intl/en-us/productdesc-ief/ief_productdesc_0001.html(accessed June 23, 2020).
[17] Xiao, Yinhao, et al. "Edge computing security: State of the art and challenges." Proceedings of the IEEE 107.8 (2019): 1608-1631.
[18] McGovern, Seamus. Blockchain for Unmanned Aircraft Systems. No. DOT-VNTSC-20-04. John A. Volpe National Transportation Systems Center (US), 2020.
[19] Alhassan, Ahmad Bala, et al. "Power transmission line inspection robots: A review, trends and challenges for future research." International Journal of Electrical Power & Energy Systems 118 (2020): 105862.
[20] J. Bian, X. Hui, X. Zhao and M. Tan, "A Novel Development of Robots with Cooperative Strategy for Long-term and Close-proximity Autonomous Transmission-line Inspection," 2019 International Conference on Robotics and Automation (ICRA), Montreal, QC, Canada, 2019, pp. 1898-1904.
[21] Hamelin, Philippe, et al. "Discrete-time control of LineDrone: An assisted tracking and landing UAV for live power line inspection and maintenance." 2019 International Conference on Unmanned Aircraft Systems (ICUAS). IEEE, 2019.
[22] Jenssen, Robert, and Davide Roverso. "Intelligent monitoring and inspection of power line components powered by UAVs and deep learning." IEEE Power and Energy Technology Systems Journal 6.1 (2019): 11-21.
[23] Richard, P-L., et al. "LineRanger: Analysis and Field Testing of an Innovative Robot for Efficient Assessment of Bundled High-Voltage Powerlines." 2019 International Conference on Robotics and Automation (ICRA). IEEE, 2019.
[24] É. Barrett et al., "Autonomous Battery Exchange of UAVs with a Mobile Ground Base," 2018 IEEE International Conference on Robotics and Automation (ICRA), Brisbane, QLD, 2018, pp. 699-705
[25] Menendez, Oswaldo, et al. "Robotics in power systems: Enabling a more reliable and safe grid." IEEE Industrial Electronics Magazine 11.2 (2017): 22-34.
[26] F. Passerini and A. M. Tonello, "Analysis of High-Frequency Impedance Measurement Techniques for Power Line Network Sensing," in IEEE Sensors Journal, vol. 17, no. 23, pp. 7630-7640, 1 Dec.1, 2017.

[27] HUAWEI CLOUD International website. "What Is ModelArts?". support.huaweicloud.com/intl/en-us. https://support.huaweicloud.com/intl/en-us/productdesc-modelarts/modelarts_01_0001.html(accessed June 23, 2020).
[28] Yeo, Candy, et al. "Technology Advancement and Growth: A Case Study of Huawei." Journal of the community development in Asia 3.1 (2020): 82-91.
[29] HISILICON International website. "Hi3559A's Neural Network Inference Engine drives the development of Multi-Object Categorization and Identification System". www.hisilicon.com/ens. http://www.hisilicon.com/en/Media-Center/News/CES2018_hisilicon_hi3559a_AI(accessed June 23, 2020).