Mechanical System Design and Motion Space Analysis For Transmission Line Insulators Laser Deicing Robot

Jie Niu\textsuperscript{1,2}, Wei Jiang\textsuperscript{3}, Dehua Zou\textsuperscript{1,2}, Jianghua Kuang\textsuperscript{1,2}, Lanlan Liu\textsuperscript{1,2} and Xiaoguang Qiao\textsuperscript{1,2}

\textsuperscript{1} Live Inspection and Intelligent Operation Technology State Grid Corporation Laboratory (State Grid Hunan Transmission Maintenance Company), Changsha, Hunan, 410100 China
\textsuperscript{2} Hunan Province Key Laboratory of Intelligent Live Working Technology and Equipment (ROBOT) (State Grid Hunan Transmission Maintenance Company), Changsha, Hunan, 410100 China
\textsuperscript{3} Wuhan Textile University, Hubei Engineering Research Center of Industrial Detonator Intelligent Assembly, Wuhan 430073, China
Email: jiangwei2013@whu.edu.cn

Abstract. In the cold winter, it is a routine task to deicing on transmission lines in severe cold climate so as to ensure the safety and stable operation of transmission lines. Compared with the traditional contact deicing method for transmission line insulators, the using of laser for transmission line deicing has the advantages of sound deicing effect, no damage to the lines, clean and efficient energy utilization, et al. As the laser energy gradually decays with the increase of distance, this paper proposes a new method to realize laser deicing of short-range transmission line insulator by using UAV equipped with laser. In responds to the dispersion problem of traditional control, this paper fully integrates UAV control and laser control platform, the double have been integrated into one, in the new control platform, the UAV control and laser control can be realized simultaneously, the kinematics model of the laser has been established and its forward and inverse solutions have been solved and analyzed. Finally, simulation experiments verify the validity of the model. Compared with the traditional mode, this deicing mode not only realizes the control integration, but also it is easy to operate. It is especially suitable for the operation in the transmission line field environment, which greatly enhances the robot operation efficiency. At the same time, the simulation of laser head sweeping space and deicing operation motion planning based on the kinematic model show that the system designed in this paper can realize the suspension insulators deicing without blind area. The implementation and promotion of this study has important theoretical significance and practical application value for the practicability of intelligent operation and transmission lines maintenance management.

Keywords: Laser deicing; Robot; Integrated control; MFC; Human-computer interaction

1. Introduction
Insulators are important fittings on high-voltage transmission lines, the insulator string [1-4] is a string of insulators which are connected end to end and suspended between the transmission tower and the transmission conductor, it can not only ensure the insulation between the tower and the conductor but also play the role of supporting the tower. In the severe cold weather in winter, the insulator string located in the high-altitude field environment which is often severely iced. The icing not only
increases the load on the tower, but also causes the loss of the insulation performance of the insulator strings. Especially the ice formation between the insulators on the insulator strings [5-6] will cause the occurrence of insulator short-circuit accidents, which seriously threaten the safe and stable operation of transmission lines in winter. Therefore, deicing of transmission line insulators is a routine task of electric workers. At present, the most commonly used deicing methods at home and abroad are thermal ice melting [7-8], mechanical ice breaking [9-10], wherein, thermal ice melting requires power-off operations, which will cause huge economic losses in power outages. The ice falling off during mechanical deicing is a great threat to the personal safety of operators. At the same time, the vibration generated during mechanical deicing may have a certain potential impact on the transmission line structure. In addition, most of these deicing methods have some significant shortcomings, such as low operation efficiency and high safety risks. As a clean energy source, laser [7-11] can not only achieve non-contact deicing but also flexible control, which is particularly suitable for deicing of transmission line insulators in complex field environments. The key to laser deicing is the accumulation of laser energy, as the laser energy gradually attenuates as the distance increases, this is a key bottleneck restricting the long-distance laser deicing operation [12-15]. Conventional vehicle platforms equipped with lasers cannot meet the requirements of long-distance deicing on transmission lines. Therefore, seeking a new laser mounting method is the key to the deicing operation of transmission lines.

Based on the above analysis, this paper proposes a new method to realize the deicing of transmission line insulator strings by using the UAV equipped with lasers, and realize the laser deicing of the insulator string through the coordinated control of the UAV and the laser. Aiming at the control dispersion problem caused by the physical independence of the UAV system and the laser system, based on the implementation plan of the laser deicing system, this paper deeply integrates the UAV control and the laser control and proposes a deep integration of the UAV and the laser. Based on the MFC platform, the integrated human-computer interaction platform of the laser deicing system has been designed and developed, which realizes the integrated control of the UAV-laser system. This control platform is simple to operate, compared with traditional decentralized control, it is especially suitable for laser deicing of insulator strings on transmission lines in complex field environments. Laser deicing of insulator strings is a new attempt and new exploration for the deep integration of laser technology and power systems. Its research and implementation are essential for the safety, stability, intelligent operation and maintenance management of transmission lines. In particular, it has important theoretical significance and practical application value for advancing the practical process of deicing operation methods on transmission lines.

2. Basic Composition of Insulator String Laser Deicing System
The energy of the laser continuously attenuates with the increase of distance, in order to ensure the efficiency and effect for the laser deicing of the power line insulator and to reduce the laser energy loss. Using UAV equipped with lasers, through flight control, to ensure the effective distance between the laser and the insulator ice is the key to achieve insulator laser deicing. Figure 1 shows the overall implementation scheme of the laser deicing robot system, wherein, figure 1(a) is a quad-rotor and figure 1(b) is a laser system. The mechanical connection and separation of the quad-rotor UAV and the laser system can be easily realized through the connection device between the UAV chassis and the laser top. The complete robot laser deicing system after the combination of the UAV and the laser is shown in figure 1(c). The deicing operation of insulators on transmission lines can be achieved through laser equipment carried by quad-rotor UAV as shown in figure 1(d). The key to the laser deicing robot to achieve no blind area deicing on the transmission line is the flight control of the quad-rotor UAV and the two-degree-of-freedom motion control of the rotation and pitch of the laser. Since the two are electrically independent, the integration motion control of the UAV and the laser system is the key to the coordinated operation control of the two.
Figure 1. The overall realization of the laser deicing system.

3. Kinematic Model and Trajectory Planning of Laser Deicing Robot

3.1. Kinematics Model of Laser Deicing Robot

The mechanical structure of the insulator laser deicing robot is shown in figure 2, which has four degrees of freedom. The rotation joint 1 is used to control the rotation of the horizontal plane of the laser head, the rotation joint 2 is used to control the pitching movement and stretch movement of the laser head. The joint 3 is used to control the front end of the gear to reach the ice and the rotation joint 4 is used to control the gear to rotate at high speed after contacting the ice and cut the ice. Using the D-H modeling method to establish the kinematics model of the laser equipment, in order to facilitate the correspondence with the simulation in MATLAB, the laser equipment system is displayed upside down and then a Z axis and X axis are assigned to each kinematic joint as shown in figure 3. With the established laser kinematics model, the D-H parameter table for the kinematic analysis of the laser system can be obtained as shown in table 1.

Figure 2. Mechanical structure diagram of laser equipment.
3.2. Simulation Experiment of Laser Head Scanning Space

The laser head scanning space experiment is the key to achieve no blind zone operation. In order to prevent the motion space from interfering with the UAV body, the joint 1 is restricted to rotate 90° left and right based on the forward direction of the fuselage, rotate 90° downward from the horizontal plane, using the Monte Carlo method and the D-H parameters in Table 1 to simulate the laser's reachable scanning space effect diagram in MATLAB software, as shown in figure 4 (a), (b), (c), (d) respectively. It is a x-y-z three-dimensional space point cloud diagram and a point cloud diagram in the three plane directions of x-y, x-z, y-z respectively. It can be seen from the point cloud diagram that the manipulator end of the robot's operation can effectively cover the deicing operation space and realize the deicing operation of transmission line insulators without blind spots.

| #   | \(\theta\) | d     | a     | \(\alpha\) |
|-----|-------------|-------|-------|------------|
| 0-1 | \(\theta_1\) | \(d_1=125\) | 0     | -90°       |
| 1-2 | \(\theta_2\) | 0     | \(a_2=15\) | -90°       |
| 2-3 | \(\theta_3\) | \(d_3=200\) | 0     | 90°        |
| 3-4 | \(\theta_4\) | 0     | 0     | 0          |

Figure 3. D-H kinematic coordinate model of laser equipment.

Table 1. D-H parameter table of laser equipment.

```markdown
3.2. Simulation Experiment of Laser Head Scanning Space

The laser head scanning space experiment is the key to achieve no blind zone operation. In order to prevent the motion space from interfering with the UAV body, the joint 1 is restricted to rotate 90° left and right based on the forward direction of the fuselage, rotate 90° downward from the horizontal plane, using the Monte Carlo method and the D-H parameters in Table 1 to simulate the laser's reachable scanning space effect diagram in MATLAB software, as shown in figure 4 (a), (b), (c), (d) respectively. It is a x-y-z three-dimensional space point cloud diagram and a point cloud diagram in the three plane directions of x-y, x-z, y-z respectively. It can be seen from the point cloud diagram that the manipulator end of the robot's operation can effectively cover the deicing operation space and realize the deicing operation of transmission line insulators without blind spots.
```
4. Conclusion and Future Work

Aiming at the decentralization problem of the software control platform for the UAV-laser insulator deicing system on the transmission line, this paper proposes an integrated human-computer interaction control solution. The UAV control and laser control have been integrated on the same control interface, based on the MFC platform, a human-computer interaction control system has been developed, which has a friendly interface and convenient operation. It is especially suitable for portable laser deicing operations in the field environment, and realizes the innovative application of laser technology in power systems. At the same time, the laser deicing system and the new deicing method proposed in this article need to be further tested to explore the optimal control parameters of the laser and UAV movement, so as to further realize the automation and intelligent operation of the laser deicing system to improve the engineering practicality of its power system application.

Acknowledgement
This article was funded by the Science and Technology Project of State Grid Hunan Electric Power Company Limited. (No: 5216AJ20000T)
Reference

[1] Pouliot N, Richard P L and Montambault S 2015 LineScout technology opens the way to robotic inspection and maintenance of high-voltage power lines IEEE Power & Energy Technology Systems Journal 2(1): 1-11.

[2] Seok K H and Kim Y S 2016 A state of the art of power transmission line maintenance robots Journal of Electrical Engineering & Technology 11(5): 1412-1422.

[3] Alhassan A B, Zhang X, Shen H, et al. 2020 Power transmission line inspection robots: A review, trends and challenges for future research International Journal of Electrical Power & Energy Systems 118: 105862.

[4] Jalal M F A, Sahari K S M, Fei H M, et al. 2018 Design and development of three arms transmission line inspection robot Journal of Robotics, Networking and Artificial Life 5(3): 157-160.

[5] Kalani H, Malayjerdi M and Dehnavi M H 2019 H2M robot: a new prototype robot for insulation of high voltage transmission International Journal of Intelligent Robotics and Applications 3(1): 87-98.

[6] Wang H, Yan B, Pu Z, et al. 2019 Optimal design and stress analysis of the transmission line inspection robot along the ground line The Journal of Engineering 20(16): 3088-3091.

[7] Lima E J, Bomfim M H S and Mourão M A M 2018 POLIBOT–power lines inspection robot Industrial Robot: An International Journal 45(1): 98-109.

[8] Wang W, Wu G, Bai Y, et al. 2014 Hand-eye-vision based control for an inspection robot’s autonomous line grasping Journal of Central South University 21(6): 2216-2227.

[9] Shruthi C M, Sudheer A P and Joy M L 2019 Optimal crossing and control of mobile dual-arm robot through tension towers by using fuzzy and Newton barrier method Journal of the Brazilian Society of Mechanical Sciences and Engineering 41(6): 245-270.

[10] Sun C, He W and Hong J 2017 Neural network control of a flexible robotic manipulator using the lumped spring-mass model IEEE Transactions on Systems Man & Cybernetics Systems 47(8): 1863-1874.

[11] Hu Y Z, Yu S F, Zhang L, et al. 2014 Research and validation on melting ice of overhead transmission line Applied Mechanics and Materials 543-547: 653-657.

[12] Wei Sh N, Wang Y N, Yin F, et al. 2012 Line-grabbing control of deicing robot based on K-nearest neighbor classification reinforcement learning Control Theory and Application 29(4): 470-476.

[13] Chiddarwar S S and Babu N R 2012 Optimal trajectory planning for industrial robot along a specified path with payload constraint using trigonometric splines International Journal of Automation & Control 6(1): 39-65.

[14] Ayyildiz, Mustafa Z and Etinkaya K 2016 Comparison of four different heuristic optimization algorithms for the inverse kinematics solution of a real 4-DOF serial robot manipulator Neural Computing & Applications 27(4): 825-836.

[15] Jiang G, Luo M, Bai K, et al. 2017 A precise positioning method for a puncture robot based on a pso-optimized bp neural network algorithm Applied Sciences 7(10): 969.