Inspection technology of remote transmission towers based on a vertical take-off and landing fixed-wing UAV

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Abstract. Transmission towers in remote areas are located in a complex terrain, usually far away from roads, making it difficult for inspectors to approach to deploy auxiliary inspection equipment. Therefore, inspection tasks for such transmission towers have become a time-consuming and laborious hard bone. In response to this problem, this paper proposes a new, safe and efficient form of inspection operations based on a vertical take-off and landing unmanned aerial vehicle (VTOL) which is equipped with a strap-down lateral imaging module to assist in the inspection of electrical towers. Based on the known longitude and latitude information of transmission towers, the inspection route is pre-planned offline. When the VTOL reaches a certain transmission tower, it can be controlled to hover around the center point of the transmission tower at a fixed height. The strap-down lateral imaging module could obtain image information of the transmission tower to monitor the status of the transmission tower. In addition, line-of-sight angles of the center point of the transmission tower in the image can be extracted to help to adjust the height and radius of the VTOL hovering around the transmission tower, so as to achieve the most effective inspection of the transmission tower with a low-cost strap-down industrial camera. The algorithms of the scheme in this paper have been implemented in reliable hardware modules. The scheme has the capability of an actual flight inspection.

Keywords: Inspection of transmission towers, a vertical take-off and landing fixed-wing UAV, a strap-down lateral imaging module, loiter flight control.

1. Introduction

The high-voltage transmission lines of our country's power grid are distributed in a wide range, and a considerable part of the lines and transmission towers are erected in areas with a complex terrain and harsh weather environments. This situation continues to test the safe operation of transmission lines and related devices, and puts forward high requirements for the inspection, maintenance and management of high-voltage transmission lines. The use of UAVs to conduct regular inspections of high-voltage transmission lines has entered the industry as a new, safe and efficient form of inspection operations and has been used by some power companies and has shown a trend of replacing traditional operation methods [1].
The current electric power line inspection methods mainly adopt two methods: manual line inspection using telescopes and short-distance remote control UAVs line inspection. Both methods use people as the basic unit of action. Due to the limitation of observation methods and the control distance of multi-rotor UAVs, inspectors are required to be close to the transmission tower to have a good line patrol effect in areas that are easily accessible. The remote-control UAVs used for inspections are mainly divided into three types: multi-rotor UAVs, unmanned helicopters and fixed-wing UAVs [2-4]. Among them, multi-rotor UAVs are widely used because of their ability to hover to collect data. But their flight speed is slow, the covered transmission lines and transmission towers are limited under a certain endurance. In addition, for transmission towers that are distributed in the complex terrain and remote areas, it is very difficult for inspectors to approach the transmission towers, and it increases the time cost, personnel cost and capital cost. For this reason, there is an urgent need for a low-cost, high-reliability power line inspection method to realize the inspection of difficult-to-reach transmission tower groups.

This paper proposes an inspection method based on a vertical take-off and landing fixed-wing UAV [5-7] (a QuadPlane VTOL (standard plane plus quad) UAV, hereinafter referred to as VTOL) to conduct inspections on transmission towers in remote areas. The VTOL takes off from a vehicle-mounted platform, and uses the integrated navigation method of Inertial Navigation System (INS) and Global Position System (GPS) to realize a rapid inspection of multiple transmission towers with known positions within a radius of 20 kilometers. During the inspection process, the VTOL is controlled to fly around the transmission tower accurately in the fixed-wing state, and the lateral strap-down imaging device mounted on the VTOL is used to perform a 360° monitoring of the transmission line and the transmission tower. In addition, this paper verifies the proposed scheme in a hardware-in-loop simulation system [8].

2. Overall technical scheme
The VTOL inspection system for remote transmission towers consists of three parts: a VTOL flight platform, a side-view strap-down imaging module and a VTOL navigation control system.

The VTOL not only has the characteristics of a multi-rotor drone that can take off and land vertically, and hover at a fixed point, as well as the characteristics of a fixed-wing UAV with a fast-cruising speed and a wide coverage, but also is outstanding in the endurance and load capacity. We choose the fixed-wing state of the VTOL to fly in circles, and use a low-cost strap-down industrial camera to complete a long-term and effective inspection of the transmission tower. Under normal circumstances. The fixed-wing state reduces the power loss of the onboard power supply compared to the multi-rotor state. This is also the fundamental reason why we choose a VTOL state as the flight platform.
2.1. Inspection workflow of VTOL

In the overall technical scheme of this paper, the ground control station operator will write position coordinates of all the transmission towers involved in the inspection task as automatic flight waypoints of the flight task when performing the inspection task, and the VTOL will be lifted from the parked position, taking off vertically from a ground inspection vehicle, as shown in Figure 1. The VTOL switches from the multi-rotor state to the fixed-wing state after the take-off and then starts a waypoint flight, flying to the first transmission tower. The VTOL will judge the distance between itself and the transmission tower in real time during the process of flying to the next transmission tower. When it reaches the set safe distance, the VTOL will make a decision based on the relationship between the relative distance vector and the current speed vector to avoid intersection with the transmission tower, and then enter the circle route from one side of the transmission tower. The circle route is calculated with the location information of the transmission tower and the preset circle radius and height. The detailed inspection workflow is shown in Figure 2. In the second judgment link, if the preset height and circle radius are not appropriate, the height and circle radius can be adjusted within a safe range, so is the shooting angle and distance of the side-view strap-down camera.

![Figure 1. The schematic diagram of the inspection process of transmission towers based on the VTOL.](image-url)
2.2. Side-view strap-down imaging module

The side-view strap-down imaging module used in this paper is a visible light system and is fixedly installed on a side of the VTOL body. The optical axis is perpendicular to the axis of $O_bx_b$, and has an angle against the $O_bx_by_b$ plane in aircraft-body coordinate system $O_bx_by_bz_b$. The camera parameters

Figure 2. Work flow chart of inspection based on a side-view strap-down camera.
are shown in Table 1. The imaging module is responsible for real-time shooting of the transmission cable and the transmission tower during the inspection process. In this paper, we adopt NVIDIA Jetson TX2 as the image processing module. Limited by the operating performance of the image compression algorithm, the image frame rate in the proposed scheme can reach 25-30 frames per second.

Table 1. Hikvision Robot Industrial Camera Parameter Table.

| Item           | Parameter                                      |
|----------------|-----------------------------------------------|
| Model          | MV-CA020-10UC                                 |
| Name           | 200 million pixels 1/1.7” CMOS USB3.0 Industrial array camera |
| Sensor Type    | CMOS, Global shutter                          |
| Sensor Model   | IMX430                                        |
| Pixel Size     | 4.5 µm×4.5 µm                                 |
| Resolution     | 1624×1240                                     |
| Max Framerate  | 89.1 fps                                      |
| Dynamic Range  | 75.4 dB                                       |
| SNR            | 40 dB                                         |
| Gain           | 0 dB –24 dB                                   |
| Time of Exposure | 1 µs ~ 10 sec                                 |

The navigation control of the VTOL has no inputs of the terrain height information. The altitude used during the flight of the VTOL is based on a fused altitude of the air pressure altitude and the altitude of the satellite positioning, and the accuracy is about 3-5m. So, when flying around the transmission tower at a fixed height, the height will inevitably have a large deviation. According to the pixel coordinates of the main body of the transmission tower in the image coordinate system, the line-of-sight elevation angle can be calculated. Then, a required height compensation is calculated according to the line-of-sight elevation angle \( \lambda_p \), and the fixed height is corrected to ensure that the main body of the transmission tower is always in the middle of the side view, and a better inspection effect is achieved. In addition, the center of the circle can also be fine-tuned according to the line-of-sight azimuth angle \( \lambda_h \) of the main body of the transmission tower in the lateral image.

The calculation of the line-of-sight elevation angle and azimuth angle, image acquisition, compression and other functions are all implemented in NVIDIA Jetson TX2 image processing module.

2.3. The loiter flight control method

Under normal circumstances, according to the schematic diagram on the left in Figure 3, after specifying \( L \) and \( R \), a desired lateral acceleration can be calculated according to the real-time speed (the general cruising speed) of the VTOL to control the VTOL to fly in a circle around point O at a fixed height [9].

\[
L = 2R \sin \eta \tag{1}
\]

\[
a_{\text{centripetal}} = \frac{v^2}{R} = 2 \frac{v^2}{L} \sin \eta \tag{2}
\]

\[
\varphi_{\text{desired}} = \tan^{-1} \frac{a_{\text{centripetal}}}{g} \tag{3}
\]

Where, \( L \) is a reference distance, \( R \) is the radius, \( \eta \) is related to \( L \), \( a_{\text{centripetal}} \) is the centripetal acceleration, \( \varphi_{\text{desired}} \) is the desired roll attitude.

\[1 \text{https://www.nvidia.cn/autonomous-machines/embedded-systems/jetson-tx2/}\]
Figure 3. The two-dimensional schematic diagram of a VTOL hovering around point O at a fixed height.

The schematic diagram on the right in Figure 3 shows the situation where there is an error in the VTOL’s circled center, that is, the line-of-sight azimuth angle $\lambda_h$ of the main body of the transmission tower in the lateral image is not 0. It is possible to fine-tune the center through $\eta = \eta_0 + \lambda_h$. In general, because the fixed center is the measured longitude and latitude of the center of the transmission tower, the error is almost 0, so it is not recommended to use the line-of-sight azimuth angle to correct it for a long time. The compensation for the fixed height can be calculated by measuring the compensation height $\Delta h = R \cdot \tan^{-1} \lambda_v$ according to the line-of-sight elevation angle $\lambda_v$.

In this scheme, the open-source autopilot Pixhawk2² and PX4³ are selected as the navigation control system of the VTOL, and the secondary development is carried out. The control method mentioned above is implemented in the lateral flight control application layer of its fixed-wing control state.

3. Hardware-in-the-loop simulation

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3.1. Simulation method

² http://www.proficnc.com/content/13-pixhawk2
³ https://px4.io/
The software framework of the hardware-in-the-loop simulation platform are shown in Figure 4. The simulation system uses Xplane-10 flight simulation software, which supports adding custom landscapes, ground target models and aircraft models. Xplane-10 can simulate aircraft optical acquisition equipment for image acquisition and supports adjustment of image resolution. The open-source ground control station QGroundControl\(^4\) (QGC) is used to monitor aircraft data, and it supports hardware-in-the-loop simulation between Pixhawk and Xplane-10. In Figure 4, an UART serial communication in bottom layer works between the Pixhawk autopilot and image processing model, and the transmission protocol is FastRTPS\(^5\) protocol. Nuttx\(^6\) operating system runs in the autopilot, and uORB is used for message transfer management between applications. The image capture card obtains the image information of the flight simulation software’s interface in the visual flight simulation computer (the side image information of the simulated VTOL) and then transmits it to image processing module for processing. The image processing module, as one of the core modules in the simulation platform, installs an Ubuntu operating system and runs programs such as image acquisition, target tracking, image compression and transmission, data processing, and thread control. And the line-of-sight angles of the transmission tower are calculated in the target tracking software.

We select the airport’s control tower as the simulated target to be inspected, as shown in Figure 5(1), and perform a circle flight simulation on it. The circle track is shown by the yellow dotted circle in Figure 5(2), and there is a VTOL in the yellow solid circle.

3.2. Simulation results and analysis

\(^4\) http://qgroundcontrol.com/
\(^5\) https://www.eprosima.com/index.php/products-all/eprosima-fast-rtps
\(^6\) https://nuttx.apache.org/
In the hardware-in-the-loop simulation, the simulated VTOL flies in a circle around the tower with a relative height of 60m and a radius of 50m. The cruise airspeed of the VTOL is about 16m/s. During this period, the height of the VTOL was compensated by using the light-of-sight elevation angle of a certain position of the tower in the side image, so that the position of the tower could be in the middle area of the side image. The simulation data is shown in Figure 6.

![Figure 5](image1.png)  
(1) Control tower; (2) Schematic diagram of the circle route.

It can be seen from Figure 6 that the VTOL can fly around the tower in a circle with a radius of 50m at a set relative height of 60m with a roll angle of 27° and a pitch angle of 4°. It can be seen from Figure 6(2) and Figure 6(3) that the flight attitude is stable and the attitude control effect is good. The altitude in Figure 6(1) is the altitude above sea level, and the altitude of the simulation location is 28m, so when flying at a relative altitude of 60m, the displayed fusion altitude is about 88m.

In addition, Figure 6 also contains the test of flying height compensation using the elevation angle of the line-of-sight. It can be seen from Figure 6(1) that the expected height has jumped from 88m to 98m, and Figure 6(2) and Figure 6(3) shows that both the roll and pitch attitudes have been adjusted. In Figure 6(3), the VTOL heads up and climbs. During the climb, the roll attitude of the VTOL has been adjusted within 5° in order to maintain the circle radius. The simulation results show that the VTOL can accurately and stably fly around the fixed target in a fixed-wing state, and can effectively adjust the flight height through visual information.
Figure 6. (1) The altitude curve; (2) The roll attitude curve; (3) The pitch attitude curve.

4. Conclusions
This paper proposes a method of patrolling transmission towers in remote areas based on a VTOL. The multi-rotor state of the VTOL can be used to take off and land vertically and to detect a certain point
after hovering. When the VTOL is flying around the transmission tower in a fixed-wing state, the equipped lateral strap-down imaging model obtains lateral image information to realize the inspection of the transmission tower. In addition, the fixed-wing state of the VTOL can achieve large-scale coverage with less energy consumption and complete rapid inspections of multiple transmission towers. In this paper, the relevant algorithms have been implemented on a reliable hardware platform which is also tested in the simulation system, and the hardware platform could be equipped on a VTOL and have the ability to fly in the field and complete the inspection.

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References
[1] Lanbo C. Research on UAV patrol scheme of power line[J]. Technology and Innovation, 2020, No.155 (11): 42 - 44+47. (in Chinese).
[2] Wang B, Huang S, Huang Z. Development of New Unmanned Fixed-wings Aircraft Patrol to Power Transmission Line [C], 2013.
[3] Guanyu W. Application of UAV ranging in transmission tower Patrol inspection[J]. Electric Power System Equipment, 2019 (2): 92 - 92. (in Chinese).
[4] Bian J, Hui X, Zhao X, et al. A monocular vision-based perception approach for unmanned aerial vehicle close proximity transmission tower inspection [J]. International Journal of Advanced Robotic Systems, 2019, 16 (1).
[5] Van Cruyningen I J. UAV Inspection Flight Segment Planning [J]. 2016.
[6] Redia, Mohd, Redzuwan, et al. Transmission Tower Environment Monitoring Using UAV [J]. Iop Conference, 2013.
[7] Wang J, Wang G, Hu X, et al. Cooperative Transmission Tower Inspection with a Vehicle and a UAV in Urban Areas [J]. Energies, 2020, 13.
[8] Kamali C, Jain S. Hardware in the Loop Simulation for a Mini UAV [J]. Ifac Papersonline, 2016, 49 (1): 700 - 705.
[9] Deyst, John. A New Nonlinear Guidance Logic for Trajectory Tracking. In AIAA guidance, navigation, and control conference and exhibit. 2004.