Construction Process of Continuous Unreeling and Setting of Leading String Based on Trajectory Theory

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Abstract. The increasing construction of power transmission line promotes the development of construction technology of overhead power transmission line in our country into a brand-new era; while the paving of leading string of traditional overhead power transmission line is still to be completed by climbing the iron tower and manual operation of construction personnel. Therefore, it has been extremely urgent to implement research on the construction process of the power transmission line’s leading string threading into pulley, thus reducing the frequency of operation at height of construction personnel. This paper aims to introduce the ejection construction technology of UAV based on trajectory theory to reconstruct the line tackle device, states the construction process flow of multi-rotor UAV utilizing ejection technology to conduct continuous unreeling and setting of leading string with ejection technology in detail, summarizes the full process of construction, conducts contrastive analysis with traditional construction process, and summarizes the social benefit and economic benefit of new type of construction process.

Key words: power transmission line, multi-rotor UAV, pulley reconstruction, leading string

1. Introduction
At present, during the stringing construction process of power transmission line in our country, the UAV is gradually taking the place of dynamic parachute and helicopter to conduct unreeling and setting of leading string by virtue of its small volume, light weight and good manipulation performance, and has been applied into multiple projects. The construction enterprises have accumulated abundant using experience. However, the paving of leading string still needs to be completed by climbing iron tower and manual operation of construction personnel. The construction personnel need operating at height, with high safety risk, many uncontrollable factors, high labor intensity and low construction efficiency.

The UHV power transmission line project applies UAV to conduct unreeling and setting of leading string widely. The UAV is adopted as traction equipment to cooperate with dedicated small-sized
tension machine, so as to implement the tension unreeling and setting of “one traction and one tension”. During the process of unreeling and setting, the primary leading string is led by the UAV to pass through the top of tower at the unreeling and setting section base by base, and the personnel on the tower will place the primary leading string into the tackle wheel groove which faces upward via dedicated tool, thus completing the operation of each tower successively. After completion of unreeling and setting, through remote control on the ground, the UAV will cut off the primary leading string and then return to the take off site for landing. [1-7]

This paper proposes new assumption innovatively: utilize UAV to carry the ejection device, eject the leading string via pneumatic ejection, so as to make sure that the leading string can thread into the pulley exactly, so as to realize continuous unreeling and setting. The detailed content is shown as below:

- Reconstruct the receiving device of line tackle pulley, make sure that the leading string can enter the middle wheel groove exactly and under control.
- Research the construction scheme of threading leading string into the line tackle, verify the reliability, exactness and manoeuvrability of utilizing UAV leading string ejection device to eject leading string at height thus threading into the tackle.

2. Introduction to Unreeling and Setting of Leading String

2.1. Introduction to Construction Environment

This paper mainly introduces a construction for the transmission line with crossing barriers including railway, other power transmission lines, and trees. As shown in Figure 1, the line tackle is directly hung on the suspended composite insulator.

![Figure 1. Schematic Diagram of Suspension of Straight-line Tower Single Tackle](image)

2.2. Analysis on the Forces of Primary Leading String for UAV to Handle

At present, the selected rope projectile is 18.7mm in internal diameter, about 22mm in external diameter and about 198mm in length, and the weight of rope projectile is 140g. In case of researching the law of shooting off trajectory of rope projectile, to simplify the computation, we assume the following conditions:

- The shape and mass distribution of rope projectile are of axial symmetry;
- The gas thrust vector of rope projectile coincides with the center shaft of rope projectile;
- Under standard meteorological conditions, the influence of Coriolis inertial force and the change of acceleration of gravity along with latitude are not taken into consideration;
- Do not consider the influence of wind disturbance.

Based on above conditions and assumptions, we can obtain the longitudinal motion equation set of rope projectile:

\[
\begin{align*}
\frac{m}{dt} dV &= P \cos \alpha - X - mg \sin \theta \\
\frac{d\theta}{dt} &= \frac{P \sin \alpha + Y - mg \cos \theta}{m}
\end{align*}
\]

\begin{align*}
J_\tau \frac{dw_\tau}{dt} &= Mt_1 \\
\frac{\alpha}{dt} &= \frac{w_\tau}{d_{\tau}} \cos \theta \\
\frac{dx}{dt} &= V \cos \theta \\
\frac{dy}{dt} &= V \sin \theta \\
\frac{dm}{dt} &= -m \\
\alpha &= v - \theta
\end{align*}

Wherein

- \(X\) refers to resistance, \(X=CxqS\), and \(Cx\) refers to non-dimensional proportional coefficient, which is called resistance coefficient.
- \(Y\) refers to rising force, \(Y=CyqS\), \(Cy\) refers to non-dimensional proportional coefficient, called lift coefficient.

According to above theory, the relationship between flight speed and time of rope projector is simulated as shown in the Figure 2:

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Figure2.png}
\caption{Relationship between Flight Speed and Time of Rope Projectile}
\end{figure}

From the Figure above, it can be known that after the rope projectile is ejected, the maximum initial flight speed in theory is 17.5m/s, and before 0.5s, the rope projectile is at the acceleration stage; at this time, the gas thrust is greater than the leading string and air resistance; however, after this, the resistance of traction rope is greater than the gas thrust (or the thrust is 0), and the rope projectile is at the deceleration stage.

2.3. Analysis on Stress of Utilizing UAV to Conduct Unreeling and Setting of Leading String

According to existing matured theory [8-9], the sag of leading string in the midpoint of span:
\[ f = \frac{l^2W}{8H_1 \cos \phi} = \frac{l^2W}{8T \cos^2 \phi} \]  

Sag at any point of span:

\[ f_x = \frac{x(l-x)W}{2H_1 \cos \phi} = \frac{x(l-x)W}{2T \cos^2 \phi} = \frac{4x(1-u)}{l} \]  

Initial tension of overhead line (rope):

\[ H_1 = \frac{l^2W}{8f \cos \phi} = T \cos \theta \]  

As shown in Figure 3(a), when the suspension point A is higher:

\[ Y_0 = Y_B - \frac{W_0 X (l-X) + 2H_1 X \sin \phi}{2H_1 \cos \phi} \]  

As shown in Figure 3(b), when the suspension point A is lower:

\[ Y_0 = Y_B - \frac{W_0 X (l-X) - 2H_1 X \sin \phi}{2H_1 \cos \phi} \]  

In the formula:
- T - Average tension of overhead line, N;
- H_1 - Horizontal tension of overhead line, N;
- Y_A - Height difference from suspension point A to ground (or object), m;
- Y_B - Height difference from suspension point B to ground (or object), m;
- L - Line span distance, m;
- x - Horizontal distance from crossed object or near-ground span ground to the suspension point A, m;
- X - Horizontal distance from crossed object or near-ground span ground to the suspension point B, m;
- W - Dead weight of unit length of overhead line, N/m;
- h - Height difference of suspension point, m;
- f - Sag of midpoint line (rope) of span, m;
- \phi - Height difference angle of suspension point of conductor, degree;
- f_x - Sag of crossed object, m;
- Y_0 - Vertical clearance from rope (line) to ground (or object), m

(a) When the suspension point A is higher  
(b) When the suspension point A is lower

Figure 3. Overhead Line Suspension Curve when Two Suspension Points are not at the Same Height
In case of conducting unreeling and setting of leading string with UAV, the construction cannot be conducted unless the wind speed reaches fresh breeze, and the influence of wind pressure when the wind speed is 10m/s shall be taken into consideration. The wind pressure refers to the pressure of wind which the plane vertical to the air flow suffers from; the influence of wind pressure which the nylon thread suffers from within a short time period during the unreeling and setting can be neglected; according to the Bernoulli equation, we can obtain the relationship between wind and pressure, and the dynamic pressure of wind is:

\[ \wp = 0.5 \times \gamma_0 \times V^2 = 0.5 \times \gamma \times \frac{V^2}{g} \]  

In the formula:
- \( \wp \) - Wind pressure, kN/m²;
- \( \gamma_0 \) - Air density, kg/m³;
- \( V \) - Wind speed, m/s; under the standard status (the atmospheric pressure is 1,013hpa, and the temperature is 15°C), the unit weight of air is \( \gamma = 0.01225 kN/m^3 \), and the acceleration of gravity at the dimension of 45° is \( g = 9.8 m/s^2 \).

It should be pointed out that the air unit weight and the acceleration of gravity are changed along with the dimensionality and altitude. Generally speaking, the \( \gamma/g \) on the plateau is smaller than that on the plain, i.e. at the same temperature, the wind pressure on the plateau generated by the same wind speed is smaller than that on the plain;

If the length is one meter and the diameter is 2mm, then the stressed area for Dubond silk or Deenyma rope is calculated as below:

\[ S = \pi \times r \times l = 3.14 \times 0.02 \times 10^{-3} \times 1 = 6.28 \times 10^{-5} \]  

Then, calculate the horizontal tension for the leading string using software and get results as shown in Figure 4.

\[ F = \wp \times S = 0.5 \times 0.01225 \times 10 \times \frac{10}{9.8} \times 6.28 \times 10^{-5} = 3.925 \times 10^{-6} kN = 3.925 \times 10^{-3} N \]  

(a) Calculation of Tension for Unreeling and Setting of 2mm Dubond Silk after Considering Wind Pressure

| T(N) | I(m) | YA(m) | YB(m) | x(m) | X(m) | W(N/m) |
|------|------|-------|-------|------|------|--------|
| 21.36 | 279  | 32    | 33    | 164  | 115  | 0.02195 |
| H(N) | h(m) | \( \varphi \) (°) | f | fx(m) | higher(\( \gamma_0 \)) | lower(\( \gamma_0 \)) |
| 21.36 | 1    | 0.00  | 10    | 9.69 |      | 22.90  |

(b) Calculation of Tension for Unreeling and Setting of 2mm Dyneema Rope after Considering Wind Pressure

| T(N) | I(m) | YA(m) | YB(m) | x(m) | X(m) | W(N/m) |
|------|------|-------|-------|------|------|--------|
| 52.47 | 279  | 32    | 33    | 164  | 115  | 0.053925 |
| H(N) | h(m) | \( \varphi \) (°) | f | fx(m) | higher(\( \gamma_0 \)) | lower(\( \gamma_0 \)) |
| 52.47 | 1    | 0.00  | 10    | 9.69 |      | 22.90  |

Figure 4. Analysis on Stress in case of Unreeling and Setting of Leading String
Based on the calculation of the traction force, the UAV selected as shown in Figure 5 has following technical data:

- Rising limit of altitude: in case of routine power unit: ≥ 2,000m
- Power battery: 22,000 mah
- Maximum flight speed: 10m/s
- Duration of flight: 40min
- Flight radius: 8km
- Full load flying weight: 15.0kg
- Wind resistance capability: grade V (wind speed 8.0-10.7m/s)
- Working temperature: -10 to +40 ℃

![Figure 5. Picture of Multi-rotor UAV](image)

Characteristics of utilizing UAV to conduct unreeling and setting of leading string includes:

- The flying precision is relatively high, and it can realize the RTK positioning and automatic obstacle avoidance function, and is able to have a cruising flight to the pre-set position exactly, thus meeting the demands for distance of line tackle and safety of iron tower itself;
- It can complete hovering easily, and can realize the posture adjustment via stabilized gyro.

3. Reconstruction of Line Tackle which Utilizes UAV to Conduct Unreeling and Setting of Leading String

To realize the continuous operation construction of utilizing UAV to conduct unreeling and setting of leading string, it is necessary to reconstruct relevant equipment of stringing, make sure that the leading string can thread into the line tackle exactly and then enter the tackle wheel groove selectively; in addition, the pulley after reconstruction will not influence the subsequent tension stringing. The reconstruction scheme of line tackle is shown in Figure 6.
Prior to unreeling and setting of leading string with UAV, hang the line tackle below the cross arm of iron tower. At this time, for the steel wire rope wheel doesn’t suffer from any stress, the line tackle is in the status in Figure 6(a).

When the UAV utilizes ejection device to eject the leading string to the triangular zone between two guide plates, the leading string will slide into the steel wire rope wheel groove automatically along with the guide plate.

With the unreeling and setting of leading string, the vertical load which the steel wire rope wheel suffers from will be increased gradually. The spring in the self-adjustment mechanism will be deformed due to stress; the rack of line tackle, steel wire rope wheel, guide rope wheel and main shaft will have displacement downwards as a whole; and the guide plate will be raised gradually.

After completion of unreeling and setting of leading string, the root of leading string is connected with traction rope for traction unreeling and setting. At this time, the vertical load which the steel wire rope wheel of line tackle is further increased, and the spring is further compressed, till that the spring pressure plate contacts the upper surface of sleeve at the roof plate of spring. The spring will not be compressed any longer, the overall position of rack of line tackle, steel wire rope, guide rope wheel and main shaft will reach the lowest point. Meanwhile the guide plate will be raised to the highest position, as shown in the Figure 6(b).

At this time, the distance between the lower edge of guide plate and the steel wire rope wheel & upper edge of guide rope wheel is relatively large, which will not influence the threading of machines and tools such as subsequent traction plate and splicing sleeve protection device into the line tackle.

4. Continuous Operation Construction of Utilizing UAV to Conduct Unreeling and Setting of Leading String Based on Trajectory Theory
4.1. Operating Procedure
The operating procedure for using UAV to conduct the unreeling of leading string is shown in Figure 7.

![Diagram of operating procedure]

Figure 7. Operating procedure for using UAV to conduct the unreeling of leading string

4.2. Construction Preparation
- Conduct detailed investigation to the construction site and its environment, master the terrain, landform and crossing span situation on the site clearly, and sort the coordinate and elevation of tower position in the crossing span. Pay attention to the disturbance problem of electromagnetic wave.
• Investigate and implement situations and relevant agreements & treatment measures about crossed objects such as farmland, orchard, house, power line, railway, highway, etc. in the corridor channel, and gather the detailed technical constraints.
• To arrange the unreeling and setting of leading string of tension stringing reasonably, make full use of personnel and time, it is required to allocate personnel for the construction shift of unreeling and setting of leading string.
• Conduct technical training, learn relevant technical and process rules meticulously, master the operation characteristics and operation methods. Organize all construction personnel to conduct technical safety and technical disclosure meticulously.

4.3. Introduction to Continuous Operation Construction Flow of Leading String

4.3.1. UAV Carrying Leading String for Flying and Ejection Device Control. The UAV utilizes the GPS module which is mounted on itself to set target position, and then flies to the target position under the control of autonomous navigation program; in addition, it is allowed to be intervened by acting beyond the authority to guarantee the safety of flight during the flight process.

This system adopts portable ground control terminal to control the UAV to start operation by one key, and is able to observe the flight status of UAV in a real-time way; in addition, it is allowed to adopt multiple ground control terminals to control the same UAV. The multi-rotor UAV is provided with automatic obstacle avoidance functional module to enhance the safety of UAV flight, so as to avoid error during the planning of flight route or prevent the UAV from colliding the surrounding object due to wrong artificial flight control and intervention, thus guaranteeing that the UAV can conduct deceleration and hovering before the tackle.

The UAV utilizes the laser ranging and high-precision solid gyroscope to measure the distance from ejection system to the tackle and the angle of pitch exactly, and then work out the aim-taking system of aiming point accurately according to measurement parameters and trajectory theory. Research and develop double-spring damping type impulse absorption and release device, and then absorb the recoil impulse at the moment of ejection.

4.3.2. Construction Process of Threading Leading String into Tackle. Utilize the onboard leading string ejection device of multi-motor UAV; the core component for ejection takes the CO2 compressed gas which is released at a high speed as the power source of ejection of rope projectile, pushes the rope projectile to tract primary leading string (nylon thread) to move forward and separate away from the launching tube; after separation, the gas cylinder will release gas continuously to continue to push the rope projectile to fly forward and to drag the nylon thread to conduct motion of a free falling body after crossing the tackle span. After the projectile falls to the ground, separate the rope releaser away, so as to realize the unreeling and setting of leading string of tower base. Through the artificial traction, replace the nylon thread to φ2mm Dubond silk at the projectile falling point.

4.3.3. Utilizing Multi-motor UAV to Tract Secondary Leading String for Unreeling and Setting Level by Level. After the multi-motor UAV continues to fill rope projectile and rope releaser, connect it with the φ2mm Dubond silk at the falling point of rope projectile nearby the tower base, rise slowly and vertically, adjust the flight direction of UAV according to wind direction on the site, and then tract the φ2mm Dubond silk to fly to the next base of iron tower.

Control the tension of Dyneema leading string, adjust the flight height appropriately if necessary, make the Dyneema leading string pass the obstacle smooth, and in case of being close to the tackle of next base of iron tower, utilize the ejection construction technology of UAV based on the trajectory theory repeatedly, and at this time, the unreeling and setting of leading string in this crossing span is completed, and it is necessary to bind the end of Dyneema rope which has been unreeled and set well firmly in time.

The continuous work flow is shown in Figure 8.
5. Conclusions
By utilizing the multi-motor UAV to conduct continuous unreeling and setting of leading string, the destruction rate of young crops and the compensation at the early stage can be reduced; in addition, it can reduce the operation at height, enhance efficiency, and shorten construction period. There are good economic and social benefits in case of utilizing small-sized UAV to conduct unreeling and setting of leading string, and this will be the development direction of construction where there are numerous crossed objects and construction in the forest zone. This method can not only simplify the construction steps, but reduce the dangerousness of construction, guarantee the safety and stability of power transmission line construction, with relatively large research and development prospect.

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