Modeling and control of multi-airfoils system of exploration robot

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Abstract. Most polar exploration robots use batteries or fuel engines to provide power, which greatly limits the robot's range of motion, and may cause pollution problems, affecting the fragile external environment of Antarctica. In view of this situation, the detection robot studied in this paper adopts three sail system driven by wind directly. Firstly, referring to the wing structure, the lift and drag forces generated by the multi wing sail system are analyzed, and the coupling relationship among the thrust, roll force and lift resistance of the robot is obtained, and the lift drag coefficient function is fitted. Then the control system of the robot is designed and manufactured. Finally, the experiment of anti sideslip ability, anti overturning ability and starting wind speed of the probe robot prototype is carried out, and the experimental data are analyzed to prove the correctness and rationality of the theoretical analysis.

1. Introduction
The polar regions contain huge amounts of natural and scientific resources. On the one hand, the polar ice and snow overed areas are the largest cold source of the earth system, and changes in environmental elements play a key role in global climate change [1]; on the other hand, the development and utilization of polar resources is irrelevant in terms of politics and economy. The strategic significance of comparison [2-3]. Therefore, at present, major countries in the world are greatly increasing their investment in polar surveys and research. The application of Antarctic robots is relatively active, but most of them use batteries or fuel engines to provide power. Limited by the number of batteries or fuels carried by the robots, the range of activities of these detection robots is still very limited, and it is not yet possible to achieve long-term and large-scale activities. The range (a radius of hundreds of kilometers) endurance, so it still cannot meet the requirements of long-term and space-time endurance required for Antarctic scientific research.

The high winds in Antarctica (which often exceed the applicable working wind speed range of existing wind power generation) and the low conversion efficiency of wind power generation restrict the application of wind power technology in detection robots. Based on the current research status at home and abroad, there are few research results on robotic multi-wing sail systems. Therefore, the development of a wind-driven detection robot multi-wing sail system is of great significance for realizing long-term long-range detection in polar regions.
2. Structural design of the detection robot
The detection robot is driven by the shearing flow of three wing sails, and the thrust and roll force of the robot are changed by controlling the angle of attack of the multi-wing sail system, so that the robot has low wind speed start, smooth autonomous cruise and anti-overturning performance. The angle of attack of the multi-wing sail system can be adjusted by the multi-sail rotation mechanism and the revolution mechanism. The multi-wing sail system is installed on a mobile platform with a wheeled structure. The structure diagram of the detection robot is shown in Figure 1.

2.1. Wing sail structure design
The wing sail is optimized from the airfoil NACA0018 in cross section. Therefore, the wing sail structure is designed according to the load-bearing and function of typical components of the wing. For vertically installed wing sails, the center of gravity of the wing sail is located on the mast axis and no additional bending moment is generated. Therefore, the structural design of the wing sail mainly meets the requirements of bearing bending moment, torque and maintaining aerodynamic shape.

2.2. Multi-sail rotation transmission structure design
The detection robot uses a multi-sail rotation transmission mechanism based on a parallelogram linkage. Compared with gear transmission, chain transmission and other transmission methods, connecting rod transmission has the advantages of accurate transmission ratio, high efficiency, and realization of multi-axis large wheelbase synchronous transmission.

Through the optimization design of multi-sail spacing, the triangle formed by connecting A, D, and G is an equilateral triangle, and the length of its side is calculated as the diameter of the circumscribed circle. According to the structural requirements, the length of the driving and slave cranks is designed as follows: the length parameters of the rods in the multi-sail rotation transmission mechanism are OC, OF, OI, AB, DE, HG are 505.2mm, OA, OD, OG, BC, EF, IH is 80mm, as shown in Figure 2.
2.3. Multi-sail revolution transmission structure design
The revolution movement of the multi-sail relative to the mobile platform is controlled by the revolution motor, and the rotation movement of the multi-sail around the respective mast axis is controlled by the rotation motor. From the perspective of structure and design space, the rotation motor is installed on the revolution plate, and its output shaft is directly connected to the rotation disk, and the revolution motor is installed on the back side of the central axis, and the synchronous belt transmission is used to control the multi-sail revolution, as shown in Figure 3.

The revolving shaft is designed as a hollow shaft, and the diameter of the inner hole is slightly larger than the outer diameter of the rotation motor, so as to ensure that the multi-sail revolution does not interfere with the rotation of the three wing sails. The multi-sail revolution is driven by the revolution motor to drive the small pulley, and the power is transmitted to the large pulley via the timing belt. The number of teeth of the large and small pulleys are respectively the sum, the transmission ratio, and the center distance of the synchronous belt wheels, and an idler pulley is designed to tension the synchronous belt outside.

![Figure 3 multi-sail revolution transmission structure](image)

| 1  | revolving motor |
| 2  | synchronous belt |
| 3  | chassis plate |
| 4  | rotating motor |
| 5  | rotating disk |
| 6  | revolving disk |
| 7  | Rotation bearing seat |
| 8  | Rotation motor support |
| 9  | Revolution shaft |
| 10 | Large pulley |
| 11 | Small pulley |
| 12 | Idler |

2.4. Mobile platform design
The mobile platform of the detection robot must meet the installation requirements of the multi-wing sail system, as well as the mobility and stability requirements. Since the multi-wing sail system is installed on the mobile platform, the mobile platform will not interfere with the multi-wing sail system within the range of 360° in diameter, which meets the installation requirements of the multi-wing sail system. The detection robot can move in wheel or sled type. Because the sliding friction force when sled moves is much greater than the rolling friction of wheel, the mobile platform adopts wheel type.

Stability includes static stability and dynamic stability. Static stability refers to the reliable connection of parts of the mobile platform, and its structural strength and rigidity are within the allowable value range. Dynamic stability means that the detection robot can withstand the maximum roll force generated by the multi-wing sail system without overturning under the direct drive of the wind, and the navigation direction can be controlled during the cruise detection process.

3. Dynamic analysis of the detection robot
3.1. Lift and drag analysis
The incoming current acts on the multi-wing sail system to generate lift and drag, which are coupled into thrust and roll force along the robot's heading and perpendicular to the heading direction. Suppose the real wind speed is, the real wind direction angle is the robot speed, the apparent wind
speed acting on the multi-wing sail system is, the sail direction angle is, and the robot is pushed forward, so that the robot has a tendency to sideways sliding and a rolling moment to cause the robot to overturn trend, and can be expressed as

$$\begin{bmatrix} F_{hu} \\ F_{r} \end{bmatrix} = (\rho_{air} A_{in} v^2 / 2) \begin{bmatrix} \cos \theta & \sin \theta \\ \sin \theta & -\cos \theta \end{bmatrix} \begin{bmatrix} C_L \\ C_D \end{bmatrix}$$

(1)

3.2. System dynamics analysis and modeling
When the robot is turning, the forward speed at the center of mass of the robot is very large compared with the lateral speed. When the wind speed and direction are constant, it can be approximated as a constant, so its steering dynamics model is:

$$m \cdot \dot{u} \cdot (\beta + \omega) = Q_f \cdot \sin \delta + F_y \cdot \cos \delta + F_{yl} + F_{yr}$$

(2)

$$J \dot{\omega} = (Q_f \cdot \sin \delta + F_y \cdot \cos \delta) L$$

(3)

The side force of the tire has an approximately linear relationship with the slip angle\(^4\), namely:

$$F_y = k \cdot \beta$$

(4)

k——The cornering stiffness of the tire.
The slip angle can be expressed approximately linearly as\(^3\):

$$\beta_f = \left( \frac{v + L \omega}{u} \right) - \delta = \left( \beta + \frac{L \omega}{u} \right) - \delta$$

(5)

$$\beta_{fl} = \beta_{ru} = \frac{v}{u} = \beta$$

(6)

When the robot is moving forward, the wheel rotation angle is generally very small, which also makes the yaw angle of the center of mass of the robot very small. Therefore, \(\delta\) can be approximately zero. Then the steering dynamics equation of the robot is:

$$\dot{\beta} = \frac{3k}{mu} \beta + \frac{k \cdot L - mu^2}{mu^2} \omega - \frac{k}{mu} \delta$$

(7)

$$\dot{\omega} = \frac{k \cdot L^2}{Ju} \beta + \frac{k \cdot L}{J} \beta - \frac{k \cdot L}{J} \delta$$

(8)

$$\begin{bmatrix} \dot{\beta} \\ \dot{\omega} \end{bmatrix} = \begin{bmatrix} \frac{3k}{mu} & \frac{k \cdot L - mu^2}{mu^2} \\ \frac{k \cdot L}{J} & \frac{k \cdot L^2}{Ju} \end{bmatrix} \begin{bmatrix} \beta \\ \omega \end{bmatrix} + \begin{bmatrix} -\frac{k}{mu} \\ -\frac{k \cdot L}{J} \end{bmatrix} \delta$$

(9)

4. Design of control system of detection robot

4.1. Robot hardware control system design
The detection robot uses wind speed, wind direction, and heading angle (the angle between the direction of the incoming wind and the longitudinal direction of the hull) as the system input variables. After calculation, the rotation angle or revolution angle of the sail position is used as the system
output to control the travel speed of the polar robot; the azimuth of the front wheel is used as the system output to control the direction of travel of the polar robot. In order to achieve the above functions, the hardware system design of the sail robot is shown in the Figure 4:

In order to meet the control requirements of the polar robot while ensuring that the system power consumption is reduced as much as possible, the controller adopts a double-layer system control board design. Among them, the lower control board is used as the driving board and data conversion board, using low-end ARM, STM32F103 series main control chip, and cooperating with CAN, RS485, RS232, and PWM interface module chips to ensure the reliability and stability of the underlying system. The upper control board adopts the TQ2440 main control unit of the ARM9 series, which further reduces power consumption while meeting the control performance requirements. And through the Linux system platform, complete data collection, calculation processing, state storage, file transfer and other functions.

![Figure 4 hardware control system block diagram of detection robot](image)

4.2. Sail control method based on optimal sailing curve
At present, the control basis for sails in sailing and sailing aid systems is mainly based on the best sailing angle curve of the sails. Through the previous force analysis of the sail, it can be seen that there is a coupling relationship between the thrust coefficient, the lift coefficient and the drag coefficient. From formula (10), we can get:

\[ F_T = \left( \rho_{air} A_{sm} V^2 / 2 \right) C_T = \left( \rho_{air} A_{sm} V^2 / 2 \right) \left( C_L \cdot \sin \theta - C_D \cdot \cos \theta \right) \]  \hspace{1cm} (10)

\[ C_T = C_L \cdot \sin \theta - C_D \cdot \cos \theta = L(\alpha) \cdot \sin \theta - D(\alpha) \cdot \cos \theta \]  \hspace{1cm} (11)

\( \alpha \) —— Angle of attack
\( \theta \) —— Apparent wind angle

Since the sail model has been determined, the thrust produced is mainly affected by the angle of attack. Therefore, at a certain windward angle \( \theta \), by changing the size of the angle of attack \( \alpha \), the relationship curve between the thrust coefficient and the angle of attack \( \alpha \) can be obtained. And at a certain angle of attack \( \alpha_0 \), the obtained thrust coefficient reaches the maximum value, namely \( C_{T_{\text{max}}} \), and the angle of attack at this time is the best angle of attack, namely

\[ C_{T_{\text{max}}} = L(\alpha_0) \cdot \sin \theta_1 - D(\alpha_0) \cdot \cos \theta_1 \]  \hspace{1cm} (12)

The best angle of attack can be obtained by the derivative method and the curve method. The derivation method is to derive the equation (12), set the derivative to zero, and solve the equation to
obtain the best angle of attack when the thrust coefficient is the largest at a certain windward angle \( \theta_i \), namely

\[
\frac{\partial L(\alpha)}{\partial \alpha} \sin \theta_i - \frac{\partial D(\alpha)}{\partial \alpha} \cos \theta_i = 0
\] 

(13)

The other is the C\(_L\)-C\(_D\) curve method. After the sail model is determined, the C\(_L\)-\( \alpha \) and C\(_D\)-\( \alpha \) curves of the sail can be obtained through theoretical calculations or through wind tunnel tests. If the C\(_L\)-\( \alpha \) and C\(_D\)-\( \alpha \) curves are combined, the C\(_L\)-C\(_D\) curve can be obtained, as shown in Figure 5. Each point in the figure represents the lift coefficient C\(_L\) and drag coefficient C\(_D\) corresponding to a certain angle of attack \( \alpha \).

Then the apparent wind direction is parallel to the x-axis of the horizontal axis of the coordinate system where the curve is located, and the vertical heading is used as the tangent to the curve. The angle of attack \( \alpha \) corresponding to the tangent point obtained at this time is the best attack angle corresponding to the windward angle \( \theta_i \). Angle \( \alpha_0 \), the vertical distance from the tangent point to the heading is the corresponding thrust coefficient C\(_T\) of C\(_L\) and C\(_D\) coupling, and the thrust coefficient C\(_T\) is the maximum thrust coefficient C\(_T\)\(_{\text{max}}\) corresponding to the windward angle \( \theta_i \), as shown in Figure 6.

After obtaining the best angle of attack \( \alpha_0 \), correspondingly, according to the relationship between the windward angle \( \theta \), the angle of attack \( \alpha \) and the sail angle \( \gamma \), the best sail angle \( \gamma_0 \) can be obtained, namely
\[
\gamma_0 = \theta_1 - \alpha_0
\]

\[
\gamma = \gamma_1 + \gamma_2
\]  

If the maximum thrust is obtained through the rotation of the sail at this time, it must
\[
\gamma_1 = \gamma_0 \quad \gamma_2 = 0
\]

If you get the maximum thrust through the sail revolution at this time, you must
\[
\gamma_1 = 0 \quad \gamma_2 = \gamma_0
\]

After obtaining the best angle of attack when the thrust coefficient is the largest, change the windward angle \( \theta_i \), so that the corresponding maximum thrust coefficient, best angle of attack, and best sail angle at different windward angles can be obtained, so as to plot the best maneuverability. Sail angle curve, see Figure 8.

In practical applications, the sailing curve is usually stored in the computer in the form of a table. When the windward angle is determined, the best sail position angle and the thrust coefficient at this time can be determined by interpolation method to control the actuator to complete the driving of the sail.

Although the optimal sail angle curve of a sail can accurately determine the sail position angle at a certain moment, this method requires large storage space, slow calculation speed, and poor real-time responsiveness. For the robot system, this greatly increases the hardware requirements and the adjustment of sail action is delayed. Therefore, when designing the sail control system, the query range should be set according to the actual application to minimize the time occupied by the query.
It can be seen from the graph of the best sailing angle that the thrust generated by the sail is the component of the force of the resistance and lift in the forward direction. When the robot is driving downwind, the resistance generated by the sail is expressed as the thrust of the robot, so when adjusting the sail At the same time, it is necessary to make the sail produce greater lift at the medium angle of attack, but also make the sail produce greater resistance at the higher angle of attack [11]. At the same time, when the heading of the robot is (330°, 30°) (-30°, +30°) and (+160°, -160°) (160°, 200°) in the direction of the coming wind, the robot's The speed is relatively small, so when the sail-driven robot travels in these two areas, it should be controlled to make a "Z" movement, as shown in Figure 9, to obtain a greater speed by changing the direction of the incoming wind. That is, the sailing car must not run in the above two special areas.

![Figure 9 "Z" shape walking route of probe robot](image)

4.3. Robot software control system design

Software is the core part of the sail robot system. The normal operation of the entire system requires the collaborative work of data acquisition, data processing, and data monitoring modules to orderly realize the functions of each part of the system.

Data collection process: Collect data from various sensors of the robot, including collecting real-time data of wind direction and wind speed, calculating real-time speed and wind direction, GPS position data for drawing the robot's trajectory, self-posture data, and analyzing and evaluating the current pose of the robot.

Data processing process: format conversion, unit adjustment, and noise filtering of the collected data.

Algorithm control process: Perform calculations on the collected sensor data and send the calculation results to the control output process of sail position and steering angle, thereby indirectly controlling the traveling speed and heading angle of the robot.

Control output process: Convert the angle data sent by the sail position and heading angle control process into control commands, and send them to the driver to control the angle output of the steering gear and servo motor.

Data monitoring process: Real-time status information of the robot. Such as speed, acceleration, etc, are transmitted to the wireless module, and finally sent to the ground monitoring system software.

5. Probing robot prototype experiment

5.1. Probing robot prototype parameters

The front and rear wheels of the detection robot are made of solid-core high-elastic rubber wheels. Its use temperature range is that it has excellent impact resistance and rotation flexibility, waterproof and abrasion resistance, and has high elasticity, which can buffer and absorb vibration to make the robot Cruise on uneven ground to maintain its stability. Considering the total weight and motion performance of the robot, a 6-inch rubber wheel with a diameter of 150mm and a width of 50mm is adopted. The important parameters of the probe robot prototype are shown in Table 1.
Table 1 important parameters of probe robot prototype

| Parameter                                             | Value          |
|-------------------------------------------------------|----------------|
| Front wheel spacing $L_x$                              | 425.7 mm       |
| Rear wheel spacing $L_y$                               | 1860 mm        |
| The height of the center of gravity from the ground $H_1$ | 274.15 mm      |
| The height of the aerodynamic center from the center of gravity $H_2$ | 656.85 mm |
| Distance of front wheel from center of gravity along course $L_1$ | 1108 mm      |
| Distance from the center of gravity along the course of the rear wheel $L_2$ | 1130 mm |
| Total mass of robot $M$                                | 46.47 kg       |
| Multi-sail effective area $A_m$                        | 0.753 m$^2$    |
| Coefficient of sliding friction between wheel and ground $\mu_s$ | 0.1            |
| Rolling friction coefficient between wheel and ground $\mu_r$ | 0.039          |
| Rolling static friction coefficient between wheel and ground $\mu_g$ | 0.039          |

5.2. Anti-Slip Ability Prototype Experiment

As shown in Figure 10, the detection robot is under the action of the wind force of a specific apparent wind direction on a flat ground, no matter whether it adjusts the angle of attack of the multi-wing sail system through multi-sail revolution or rotation, the apparent wind speed that it can withstand without side slip is compared with the simulation results, and with the increase of the motor output angle, the smaller the deviation, which may be due to the resistance of the mobile platform of the prototype in the air flow field. The existence of the mobile platform causes the inconsistent distribution of the upper and lower flow fields of the multi-wing sail system and the blower. The output wind is caused by divergence and other reasons, but the overall change rule is still consistent with the simulation curve.

The analysis of Figure 10 (a) and Figure 10 (b) found that the experiment was carried out under the same apparent wind angle, the apparent wind speed deviation that can be withstood by the multi-sail rotation adjustment multi-wing sail system without side slip is greater than the multi-sail revolution adjusts the angle of attack of the multi-wing sail system. The reason may be that when the multi-sail revolves, the relative position of the multiple wing sails does not change, but when the multi-sail rotates, the relative position of the multiple wing sails is the changes make the changes in the external environment and the flow field generated by the robot structure have a greater impact on the rotation of the multi-sail.
5.3. Start the wind speed prototype experiment

According to the start-up wind speed simulation results of the probe robot prototype, the robot should use the multi-sail revolution to adjust the multi-wing sail system to start when the apparent wind direction angle is 90°. Therefore, this article will verify the output angle of the revolution motor when the apparent wind direction angle is 90°. It is the starting wind speed value corresponding to 70°, 74°, 78°, 82°, 86° and 88°. The experimental platform is shown in the Figure 11.

The comparison with the simulation results is shown in Table 2.

| Angle (°) | Simulation Experiment Value | Prototype |
|----------|----------------------------|-----------|
| 70       | 5.50                       | 7.6       |
| 74       | 5.8                        | 7.8       |
| 78       | 6.45                       | 8.3       |
| 82       | 7.81                       | 9.6       |
| 86       | 11.63                      | 13.2      |
| 88       | 19.53                      |           |
experimental value

| Deviation | 2.10 | 2.0 | 1.85 | 1.79 | 1.57 |

It can be seen from Table 2 that there is a deviation between the experimental value of the start-up wind speed and the simulation result. The possible reason is the same as that of the prototype anti-skid ability experiment, but the overall change rule is still consistent with the simulation curve, which proves the correctness of the simulation analysis result. This provides a good foundation for the autonomous movement of robots in the Antarctic environment.

6. Conclusion
In this paper, a multi-wing sail wind-driven direct-driven exploration robot roams the Antarctic continent for data collection and analysis. The multi-wing sail system overcomes and utilizes the natural environment of Antarctica to realize polar cruise detection. The detection robot with the multi-wing sail system can use the sufficient wind energy in the Antarctic region to drive its own motion, and realize the long-term and long-distance polar scientific research work of the robot.

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References
[1] Chen, L. Q. (2002) Study on the role of the Arctic and Antarctic regions in global change. Earth Sci. Front. 9(2): 245-253.
[2] Chen, D. H. (2004) Accelerate and advance the scientific investigation in the South Pole, change from the scientific research and develop to resources and scientific research simultaneously. Ocean development and management. 21(3):37-40.
[3] Zhang, L. (2008) The Antarctic Treaty System and the maintenance of maritime rights and interests in my country's Antarctic region. Ocean Development and Management. 25(2):65-74.
[4] Jia, X. Y., Xu, C. S., Bai, X. (2008) The invention and way of thinking on least squares. Journal of Northwest University: Natural Science Edition, 36(3):507-511.
[5] Xie S, Feng K, Peng Y, et al. (2014) Design and analysis of an autonomous controlled four wheeled land yacht[C]/Information and Automation (ICIA), 2014 IEEE International Conference on. IEEE, 2014: 773-778.
[6] Nuno A Cruz, Jos’e Carlos Alves. (2010) Auto-Heading Controller for an Autonomous Sailboat, OCEANS 2010 IEEE - Syney,1-6.
[7] Jos’e Carlos Alves, Nuno A. Cruz. (2009) An FPGA-based Embedded System for a Sailing Robot, 2009 12th Euromicro Conference on Digital System Design / Architectures, Methods and Tools, 2009: 830-837.
[8] Nuno A. Cruz, Jos’e Carlos Alves. (2008) Autonomous sailboats: an emerging technology for ocean sampling and surveillance, OCEANS 2008:1-6
[9] P. F. Rynne and K. D von Ellenrieder. (2008) ,A Wind and Solar-Powered Autonomous Surface Vehicle for Sea Surface Measurements, 978-1-4244-2620-1/08, 2008 IEEE.
[10] Mirzaei P A, Rad M. (2013) Toward design and fabrication of wind-driven vehicles: Procedure to optimize the threshold of driving forces[J]. Applied Mathematical Modelling, 37(1): 50-61.