Abstract
This paper presents the design details and flight tests validation of printed circuit board fabricated micro gliders. The purpose of the micro glider is to be launched from a super pressure balloon at high altitude, glide to the target position to collect data and upload data to the staying balloon. The mission demand requires the micro glider to finish precise landing with small size and low fabrication cost. To complete this concept, we designed a PCB fabricated aircraft with limited sensors including GPS and IMU. The first part of the article describes the aerodynamic design methods. The second part introduced the control and guidance system design by controlling the roll angle and flight path angle to complete the precise landing. In the simulation results presented in the third part, launch with no wind condition shows desirable precise landing ability. As a contrast, wind direction and magnitude have significant effects on the guidance ability and accuracy. In the last part, two real flight tests conducted in Inner Mongolia of China are described to compare the flight performance with the current aerodynamics and control system design. Returned data indicated the micro gliders could successfully fly at high altitude. The control algorithm can compute the command roll angle only with GPS and IMU, but some design details still need to be improved to achieve precise landing ability.

Keywords
Micro glider, flat-plate airfoil, panel method, PID control, high altitude launch test

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These flight campaigns showed the feasibility for the small or medium aircraft to be launched by small-sized balloons to fly at high altitudes. As for micro-sized aircraft, although it has developed for over 20 years and a significant number of famous designs with various possible applications, such as surveillance and data collection, have been deeply studied, the flight tests of micro air vehicles at high altitude are not well investigated. Present MAVs are designed for near-ground flight due to the short endurance and distance caused by limited energy storage. The latest MAV high altitude launch and flight were conducted by a Poland team to study the MAV flight performance in the stratosphere for the possible application in data measurement. In 2012, NRL firstly proposed a new concept application for MAVs, which was called close-in covert autonomous disposable aircraft (CICADA). In their design, the propulsion system was removed to save energy for the mission sensor. The prototype of the CICADA with the integrated sensors had been launched from a mother glider Tempest at 9000 m for stabilizing the initial attitude. The purpose of the test was to validate the aircraft design and the feasibility of the control and navigation algorithm. The continuous experiments for CICADA conducted by balloon, fixed-wing model aircraft and Blackhawk helicopter were over 200 times. On the other hand, progress of high altitude aircraft drop tests may be attributed to the development in balloon technology. In recent years, Google X lab proposed famous Loon project by applying super-pressure balloon to provide a wireless network to remote areas. The balloons fly at quasi-zero wind layer at 20 km altitude and can control the trajectory depending on the inner balloonet and accurate wind field prediction. The last continuous flight record of Project Loon is more than 180 days. The ingenious initiative for the balloon application promotes the new development of balloon technology and also, from our opinion, it provides a new potential aircraft launching platform.

For expanding the potential application of MAVs, our group proposed a new application mode by taking the advantages of the gliding micro air vehicle proposed by NRL and the controllable super-pressure balloon platform proposed by Google as a long-endurance, long-distance launching and data collecting system. In our concept design, except the basic energy cycle and flight control system, the balloon system should also include a gondola for carrying a great number of micro gliders and a small-sized communication base for transferring data received from micro gliders to satellites. Energy supply for the balloon and micro gliders in flight is supported by the solar panels carried by gondola. After the balloon flying to the nearby region around the target waypoint, the gliders will be launched from the balloon and autonomously glide to the target position. Then the balloon will be controlled by the balloonet to stay within a specific range above the target waypoint to receive and transfer data. The application concept of the balloon and micro gliders system is shown in Figure 1. The innovative application of the balloon system and micro air vehicles proposed by our group provides a possibility for the MAV to execute long-endurance long-distance scientific or military missions. On the demand of missions, the micro glider requires precise landing, data collecting and transmitting ability with low cost. Present successful flights in the stratosphere are achieved by small and medium-sized aircrafts. The launch altitude of micro-sized CICADA is not high enough compared with the stratosphere. For high altitude launched from 20 km, MAVs may show a different performance caused by the low Reynolds...
number effects and worse wind resistance ability due to lightweight and small size. Further, long-distance guidance flight and precise landing with limited sensors are other challenges for MAVs. In our study, because the print circuit board wing will result in poor aerodynamic performance, the primary purpose is to validate the feasibility of transition from initial launch to equilibrium flight at high altitude. The second purpose is to validate wind resistance performance with the current design at strong wind zone around 10 km altitude. The last purpose is to verify the effectiveness of the control and guidance algorithm depending on limited sensors for further developments.

**Micro glider design and fabrication**

The conceptual design of the micro glider requires the structure must be simple and compact enough so that it could be carried in large quantities by a balloon gondola. Further, the cost of each micro glider should be as low as possible for the demand of mass manufacturing. Enlightened by the project of CICADA, we selected printed circuit board (PCB) as the glider wing material due to low-cost easy-fabricated characteristics. Further, flying wing configuration is adopted to design our micro glider as the advantage of decreasing wing load for small and compact aircraft. Maximum wing load criteria is limited lower than 50 N/m², which follows the general criteria given by the present good performance fixed-wing micro air vehicles. Based on mission demands, the micro glider should provide a large flight distance with compact structure. In aerodynamic design of the micro glider, we consider maximum flight range as one of the critical indicators to evaluate flight performance, which is estimated by the general translation motion equation without considering rotation motion around the point of mass.

**Aircraft design**

**Wing planform design.** Since PCB cross-section is a flat-plate airfoil, wind tunnel results for the various

![Figure 2](image-url). Aerodynamic performance computed by panel results. (a) Lift coefficient. (b) Drag coefficient. (c) Lift-to-drag ratio. (d) Pitch moment coefficient.
planforms of the flat-plate airfoil in low Reynolds numbers are referred as the research foundation for the wing planform design and numerical calculation. As can be concluded from wind tunnel results, inverse Zimmerman planform shows the best \( L/D \) ratio with the same aspect ratio. Therefore, inverse Zimmerman planform is adopted as the planform of our micro glider main wing. Moreover, three aspect ratios \( AR = 1, 2 \) and 4 under the constant wing area \( S = 0.04 \) m\(^2\) (wingspan length \( s = 24, 32 \) and 46 cm respectively) and one larger wing area with \( AR = 2 \) (\( S = 0.062 \) m\(^2\), \( s = 40 \) cm) are computed by the panel method. As can be seen in Figure 2, lift and drag coefficients agree well with experimental data at small \( \alpha \), which validates the feasibility by applying the panel method. For the constant \( S = 0.04 \) m\(^2\), \( AR = 4 \) shows the highest \( L/D \) ratio of 10, which is 25% and 66% higher than \( AR = 2 \) and \( AR = 1 \), respectively. However, \( AR = 4 \) may not be suitable to match the compact structure demand. On the other hand, the general flight range of \( AR = 2 \) is only 25% lower compared to the flight range with \( AR = 4 \), which is acceptable compared to the advantage of compact structure. For the longer wingspan of \( s = 40 \) cm (\( S = 0.062 \) m\(^2\)) at \( AR = 2 \), the \( C_L \) and \( C_D \) show the same performance compared with \( s = 32 \) cm. The weight of the wing of \( s = 40 \) cm increases to 95 g but the wing load decreases to a better value of 34 N/m\(^2\). The calculation shows that the maximum flight range of the enlarged wing has the same performance of 160 km compared with small wing areas. It validates the conclusion that the flight range is only decided by \( L/D \) ratio. As concluded, although larger aspect ratio or larger wing area shows better \( L/D \) ratio or wing load performance, the flight range still fails to perform a more significant enhancement than the more compact and smaller size of \( S = 0.04 \) m\(^2\) (\( AR = 2 \)).

**Elevons dimension design.** Control of the micro glider flight is achieved by a pair of elevons. To maintain an acceptable \( L/D \) ratio while elevons deflect and further, to satisfy the full servo stroke demands while elevons deflect to limited angle, empirically the maximum elevon deflection angle should be smaller than 20°. On the other hand, for trimming pitch movement \( C_m \) of the flat-plate airfoil, the elevons need to maintain an up-deflection angle in flight, which expressed as \( \delta_{c_{\text{trimmed}}} \). To determine the optimum \( \delta_{c_{\text{trimmed}}} \), various elevon dimension including lengths, widths and positions are tested by panel method. Figure 2(c) presents the elevons width effect for determining the trim condition with the constant length and fixed

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**Figure 3.** Elevons calculations in panel method. (a) 10% local chord length with \( \delta_{\alpha} = -8^\circ \). (b) 10% local chord length with \( \delta_{\alpha} = -20^\circ \). (c) 20% local chord length with \( \delta_{\alpha} = -8^\circ \). (d) 20% local chord length with \( \delta_{\alpha} = -20^\circ \).
position at the 70% of semi-span length. As can be seen, trimmed angle of attack of the larger elevon area (20% local chord length) at the maximum \( \delta_c = -20^\circ \) is larger than 30\(^\circ\), which exceeds the stall \( \alpha = 12^\circ \). Apparently, it is over sensitive for the elevon deflection. Small elevons area (10% local chord length) with the static margin \( x_{acw} = 5\% \) also exceeds the stall \( \alpha \). It indicates that placing the center of gravity (CG) at 5\% static margin is too closer to the aerodynamic center and thus a counterweight is necessary to trim the CG for a better control ability. As a contrast, putting the CG at \( x_{acw} = 11\% \) shows a better performance that at the maximum \( \delta_c = -20^\circ \), the trimmed \( \alpha \) is still smaller than the \( \alpha_{stall} \).

Moreover, \( \delta_c = -8^\circ \) can trim the angle of attack at \( \alpha = 5.3^\circ \), which is just the \( \alpha \) corresponded to the maximum \( L/D \) ratio, shown in Figure 2(c) and (d). It also presents that the decrease of the maximum \( L/D \) ratio with \( \delta_c = -8^\circ \) is lower than 5\%. Figure 3 shows the dimension of elevon with 10\% and 20\% local chord length width at \( \delta_c = -8^\circ \) and 20\(^\circ\). In conclusion, to maintain a maximum glide range, elevon width of 10\% local chord length with the static margin \( x_{acw} = 11\% \) is preferable. Meanwhile, it also means the extra weight is necessary to trim CG with the current planform and elevons design due to the disadvantage by applying PCB as the inverse-Zimmerman planform wing material that the high-weight of the wing material is difficult to be trimmed only by the weight of the fuselage and batteries.

**Aerodynamic coefficients.** As described in “Elevons dimension design” section, a counterweight is needed to trim the CG and thus the wing leading edge is modified by adding a small area for mounting the counterweight. Further, to calculate the aerodynamic coefficients of the full glider body, including fuselage and elevons, we adopted CFD method to achieve more
precise results. Turbulence model of $k-\omega$ SST with low Reynolds number correction is used for closure RANS as it has been widely used for predicting micro air vehicles separation flow.\textsuperscript{18} The grids number of the numerical model is $1 \times 10^7$. As presented in Figure 4, there are mainly two characteristics different from the results given by the panel method. Firstly, the pitch moment shows an evident nonlinear performance after $\alpha = 6^\circ$, which is mainly due to the pressure center moving caused the flow started to separate after $\alpha = 6^\circ$. This nonlinear performance must be considered in the aerodynamic model. Secondly, the rolling coefficient $C_{l_b}$ performs a positive gradient at $\alpha = 0^\circ$, which may result in instability in rolling movement. For higher $\alpha$, the $C_{l_b}$ gradient recovers to the negative values. Figure 5 shows the pressure contour of the flow condition $\alpha = 0^\circ$ and $\alpha = 5^\circ$ at $\beta = 16^\circ$. As can be viewed, the tail and fuselage at $\alpha = 0^\circ$ block the flow passing to the trailing edge and thus a high pressure zone appears at the wing upper surface to generate a positive rolling movement. With the increasing of $\alpha$, the higher pressure zone at the wing upper surface reduced and the high pressure zone at wing lower surface dominates the rolling movement. It explains the reason that the $C_{l_b}$ recovers to static stability at positive $\alpha$. The value of $C_{l_b}$ could be considered as negative in micro glider aerodynamic model because the flight is in positive $\alpha$ condition. Table 1 shows the aerodynamic coefficients calculated by CFD method.

**Circuit and structure design**

Due to the simple and low cost demand of the structure, all the electronic components must be easy to obtain. Main sensors of the micro glider used in control system composed of a U-blox GPS, a 9-axis IMU and a STM32 SCM (CPU). The radio system is removed from a weather sonde to transmit data (downlink including the position and control outputs) to the ground station. The effective range of the radio is about 100 km. Two micro servos actuated by PWM

**Table 1.** Aerodynamic coefficients and inertia parameters for the micro glider.

|                | Longitudinal | Lateral-directional | Inertia parameters |
|----------------|--------------|---------------------|--------------------|
| $C_{l_a}$      | -0.051       | $C_{r_y} = 0$       | $J_k = 422.9$ kg/mm$^2$ |
| $C_{l_b}$      | 2.817        | $C_{r_x} = -0.33$  | $J_y = 798.2$ kg/mm$^2$ |
| $C_{l_x}$      | 0.9          | $C_{r_z} = 0$      | $J_z = 112.3$ kg/mm$^2$ |
| $C_{l_y}$      | 0.63         | $C_{r_z} = 0$      | $J_{xz} = 24.7$ kg/mm$^2$ |
| $C_{l_z}$      | 0.03         | $C_{r_z} = 0$      | $m = 200$ g         |
| $C_{b_d}$      | 0.086        | $C_{n_b} = 0.076$  |                    |
| $C_{b_l}$      | 0            | $C_{n_b} = -0.004$ |                    |
| $C_{b_x}$      | $0.009$      | $C_{n_b} = -0.002$ |                    |
| $C_{b_q}$      | $0.0036$     | $C_{n_b} = 0.007$  |                    |
| $C_{b_u}$      | $-0.21$      | $C_{n_b} = 0$      |                    |
| $C_{b_m}$      | $-0.266$     | $C_{n_b} = -0.01$  |                    |
| $C_{b_n}$      | $-0.365$     | $C_{n_b} = 0.006$  |                    |
| $C_{l_v}$      | 0.08         | $C_{n_b} = 0.08$   |                    |
| $C_{l_k}$      | 0.16         | $C_{n_b} = 0.16$   |                    |

**Figure 5.** Pressure with sideslip stream angle $\beta = 16^\circ$ with different $\alpha$. (a) $\alpha = 0^\circ$ upper surface. (b) $\alpha = 0^\circ$ lower surface. (c) $\alpha = 5^\circ$ upper surface. (d) $\alpha = 5^\circ$ lower surface.
siginal are used to control elevons. One main 3.7 V 2000 mAh lithium battery powers the electronic system and one ancillary 3.7 V 600 mAh lithium battery for powering the heating film to warming the main battery at high altitude. The main battery could power the electronic system for about 3 h. All components are placed along the central line region. Because the batteries are heavier (about 30 g) than other components, they are placed at the front for adjusting the position of CG. The structure and circuit layout design are shown in Figure 6.

The wing planform shown in Figure 7(a) was fabricated by a laser cutting machine. We selected 1 mm thickness PCB as the wing material due to the strength demand. Thickness lower than 1 mm will result in wing deformation in high dynamic pressure. Lightening hole was all distributed at the rear region and was sealed by sellotape to maintain the origin planform, as shown in Figure 7(b). The elevons and the servo actuators are connected by two aluminium-made push-pull rods. The geometrical relationship between the stroke of the servo motor and the elevon deflection angle is about $4^\circ$/mm. Figure 7(c) shows the soldered sensors. Fuselage shown in Figure 7(d) is fabricated by 3D print, providing the space for the batteries and radio component.

**Flight control design and simulation**

**Dynamic model linearization**

Nominal flight conditions are also determined by solving translation motion equation (2) based on trimmed condition $\delta_{e0} = -8^\circ$. Table 2 summarized nominal parameters at different altitudes. General flight dynamic equations are linearized by applying the theory of small perturbation based on the nominal flight parameters. The longitudinal and lateral decoupled linear models are written as follows

$$
\begin{bmatrix}
\Delta \dot{u} \\
\Delta \dot{z} \\
\Delta \dot{q} \\
\Delta \dot{\theta}
\end{bmatrix} =
\begin{bmatrix}
X_u & X_v & X_q + w_0 & -g \cos \theta_0 \\
Z_u & Z_v & Z_q + w_0 & -g \sin \theta_0 \\
M_{u} & M_{v} & M_{q} & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
\Delta u \\
\Delta \alpha \\
\Delta \psi \\
\Delta \theta
\end{bmatrix}
+ \begin{bmatrix}
X_{\delta_e} \\
Z_{\delta_e} \\
M_{\delta_e}
\end{bmatrix} \Delta \delta_e
$$

(1)

$$
\begin{bmatrix}
\Delta \dot{\beta} \\
\Delta \dot{\rho} \\
\Delta \dot{r} \\
\Delta \dot{\phi}
\end{bmatrix} =
\begin{bmatrix}
\dot{Y}_v & \dot{Y}_p + w_0 & \dot{Y}_r - w_0 & \frac{g \cos \theta_0}{V_{a0}} \\
\dot{L}_v & \dot{L}_p & \dot{L}_r & 0 \\
\dot{N}_v & \dot{N}_p & \dot{N}_r & 0 \\
0 & 1 & \tan \theta_0 & 0
\end{bmatrix}
\begin{bmatrix}
\Delta \beta \\
\Delta \rho \\
\Delta r \\
\Delta \phi
\end{bmatrix}
+ \begin{bmatrix}
\dot{Y}_{\delta_r} \\
\dot{L}_{\delta_r} \\
\dot{N}_{\delta_r}
\end{bmatrix} \Delta \delta_r
$$

(2)
where \( \Delta x_{1}, \Delta x_{2}, \Delta x_{4}, \Delta x_{5}, \Delta z_{1}, \Delta z_{2}, \Delta z_{4}, \Delta z_{5}, \Delta M_{1}, \Delta M_{2}, \Delta M_{q}, \Delta M_{d}, \Delta N_{1}, \Delta N_{2}, \Delta N_{q}, \Delta N_{d} \) are dimensional stability derivatives of longitudinal and lateral direction.

Figure 8 presents the longitudinal and lateral-directional response by solving equations (1) and (2). For longitude channel zero-input response, the response of \( z \) takes 15 s to recover. Compared to \( z \), gliding path angle \( \gamma \), pitch angle \( \theta \), and velocity response are relatively slow, which take about 60 s to recover to stability. However, considering the self-stable ability of the micro glider, the pitch control in longitude may not be indispensable. For lateral-channel zero-input response, all parameters show a quick response to recover to stability, which validates the effectiveness of the elevon design for controlling the roll motion. In conclusion, the phugoid mode, the roll mode and the Dutch-roll mode are stable.

### Control law design

General control method of the flying wing configuration is implemented by dividing the elevons motion into an elevator motion and an aileron motion under the
small deflection angle condition. The turning of the micro glider is achieved by changing the bank angle (bank to turn, BTT), which means an incremental aileron deflection angle \( \Delta \delta_a \) is needed to add to \( \delta_{a0} \) to change the roll angle \( \phi \). Pitch control is also achieved by adding an incremental elevator deflection angle \( \Delta \delta_e \) to the nominal elevator deflection angle \( \delta_{e0} \) to change the pitch angle \( \theta \). Thus, the right and left elevons deflection angle controlled by two single servos could be written as below

\[
\begin{aligned}
\delta_a &= \delta_{a0} + \Delta \delta_a \\
\delta_e &= \delta_{e0} + \Delta \delta_e \\
\delta_L &= -\delta_a + \delta_e
\end{aligned}
\]  

(3)

**Lateral-directional channel.** Based on the sensor ability, roll rate \( p \) and roll angle \( \phi \) are obtained from a micro 9-axis IMU. PID control method is adopted for roll control and thus the command rolling angle \( \phi_{cmd} \) is needed for turning flight. Figure 9 shows the roll control loop.

For simplifying roll control design, firstly equation (2) needs to be re-written as follows

\[
\begin{aligned}
\Delta p - L_p \Delta p &= L \Delta \delta_a + (L \bar{v} a_0 \Delta \beta + L \Delta r) \\
\Delta \phi &= \Delta p
\end{aligned}
\]  

(4)

Based on equation (4), the simplified transfer function could be expressed in equation (5)

\[
\begin{aligned}
G(s) &= \frac{K}{s(s+a)} = \frac{L \delta_a}{s(s-L_p)} \\
\Delta \phi(s) &= G \cdot \Delta \delta_a(s) + \frac{d(s)}{s(s-L_p)} \\
&= L \bar{v} a_0 \Delta \beta + L \Delta r
\end{aligned}
\]  

(5)

where \( K \) and \( a \) are determined by the complete transfer function. \( d \) is considered a disturbance on the system. For example, at altitude of 6 km, \( K = 945.23 \), \( a = 5.49 \). Note that the complete transfer function \( G_{\Delta \delta_a}(s) \) in Figure 9 could be substituted by \( K/(s+a) \) after simplification. The design of the lateral-directional controller is based on equation (5). In controller design, in case of over large \( \phi_{cmd} \) which may result in an unstable attitude and response, here we define the maximum error between command roll angle and real roll angle is no larger than 10°, expressed as \( e_{max} = 10^\circ \) and aileron deflection angle compared to nominal value is no larger than 5°, expressed as \( \Delta \delta_a^{limit} = 5^\circ \). Hence, we can determine the uniform proportional coefficient \( K_p = \Delta \delta_a^{limit}/e_{\phi}^{max} = 0.5 \). The derivative coefficient is determined as \( K_D = 0.0264 \) by solving the simplified roll angle transfer function. The integration coefficient \( K_I \) is determined by root-locus method. For specific, the root-locus equation is expressed in equation (6)

\[ 1 + K_I G_1 = 0 \]  

(6)

where \( G_1 = K/s^3 + (a+Kp)s^2 + KKp s \) is the open-loop transfer function. \( K_1 \) is tuned to 0.37 for maintaining a short settling response.

**Longitudinal channel.** Longitudinal channel control is dependent on the simplified transfer function formulated as below

\[
G_0(s) = \frac{K_0(s+a)}{s^2+ps+q}
\]  

(7)

where \( K_0 = -K_{p1}/p_{11}p_{12}, \ a = -z_2, \ p = -(p_{21}+p_{22}), \ q = p_{21}p_{22}, \ z_1 \) and \( p_{ij} \) are zeros and poles. For decreasing the error of steady-state response, PID control is still applied in the pitch control, where the control loop is shown in Figure 10. Pitch angle \( \theta \) is obtained from IMU. Derivative coefficients are determined by root-locus method. Based on the analysis, two design principles could be concluded. Firstly, two conjugate root-locus of the complex poles of \( G_0(s) \) affects the oscillation performance of the close loop response. Secondly, the close loop response speed is determined by the root-l azimuth around the original point. To the reason of trading off the overshoot and setting...
response speed, the final PID coefficients for pitch control are tuned to $K_P = -1.344$, $K_I = -0.765$, $K_D = -1$.

**Guidance law design**

Based on the overall analysis and control design in the sections ‘Aircraft design’ and ‘Control law design’, firstly the micro glider after launching will fall without control for a certain distance to recover to the equilibrium glide state and then the guidance law will be activated. The micro glider maintains steady flight in the longitudinal plane and only operates guidance law in the horizontal plane. As abovementioned, turning is implemented by changing the bank angle. As can be seen from the lateral guidance loop shown in Figure 11, the guidance law includes three parameters, which are course angle $\chi$, course angle rate $\dot{\chi}$ and roll angle $\phi$. Figure 11 could be simplified to an integration calculation by neglecting the dynamic response of the control loop (the dash box in Figure 11), as shown in Figure 12. Through the simplification, the guidance law design could convert to an equivalent control loop design. Note that the bandwidth of the roll angle control loop as the inner loop needs to be tuned far greater than the outer guidance loop.

In guidance law design, for no wind and no side slip angle condition, BTT control could be expressed as the coordinated turn, as shown in equation (8). The turning radius could be computed by equation (9)

$$\dot{\chi} = \frac{g}{V_g} \tan \phi = \dot{\psi} = \frac{g}{V_a} \tan \phi$$  \hspace{1cm} (8)

$$R = \frac{V_g^2}{g \tan \phi}$$  \hspace{1cm} (9)

By generating the desired course angle rate $\dot{\chi}_{\text{des}}$, the reference input $\phi_{\text{des}}$ and $\phi_{\text{cmd}}$ could be calculated as below

$$\left\{ \begin{array}{l} \phi_{\text{des}} = \arctan \left( \frac{V_g \dot{\chi}_{\text{des}}}{g} \right) \\ \phi_{\text{cmd}} = \min \left( \phi_{\text{des}}, \phi_{\text{permit}} \right) \end{array} \right.$$  \hspace{1cm} (10)

where $\phi_{\text{permit}}$ is the maximum roll angle limitation.

**Straight line mode guidance law.** In straight-line mode guidance law, it demands that the velocity vector of the micro glider always directs to the guidance way-point. In other words, the command course angle $\chi_{\text{cmd}}$ is always equal to the line of sight angle $\chi_{\text{los}}$, expressed as $\chi_{\text{cmd}} \equiv \chi_{\text{los}}$. From the straight-line mode guidance loop shown in Figure 13, it can be seen that the function of the guidance controller tracks a constant value in the straight flight process. P control or PI control are both optional. To eliminate the steady-state error in $\chi_{\text{los}}$ tracking process, we prefer PI control due to more accurate results. PI control for the straight-line mode guidance is expressed in equation (11). The corresponding close loop transfer function is expressed in equation (12)

$$\dot{\chi}_{\text{des}} = K_P \dot{e} + K_1 \int e dt$$  \hspace{1cm} (11)

$$H(s) = \frac{K_P s + K_1}{s^2 + K_P s + K_1}$$  \hspace{1cm} (12)
For maintaining the stability of the control loop, the damping ratio is defined larger than 1 for achieving an overdamped system. It allows a smooth flight path variation for the micro glider. Based on the simulation results, $K_p$ and $K_I$ are tuned to 2 and 0.5. The control loop of the straight-line mode guidance is shown in Figure 13.

Spiral descent mode guidance law. In this mode, the micro glider enters a spiral orbit around the target waypoint as the line of sight distance is close enough. In this stage, shown in Figure 14, depending on the error of course angle $\chi$ and the line of sight angle $\chi_{los}$, guidance law computes which side of the circle the micro glider enters. The relationship between the target waypoint course angle $\chi_0$ and line of sight angle $\chi_{los}$ could be expressed as $\chi_{los} = \chi_0 + \pi/2$ or $\chi_{los} = \chi_0 - \pi/2$. Moreover, for guiding the micro glider entering the circle orbit, $\chi_0$ need to be pre-corrected. Here the pre-correction line of sight angle $\Delta\chi$ as entering the orbit expresses as $\Delta\chi = \chi_{los} - \chi_0$. Meanwhile, $\Delta\chi$ varies linearly with the line of sight distance. By considering the target waypoint course angle $\chi_0$ and the pre-corrected line of sight angle $\Delta\chi$, the command line of sight angle at the two enter orbits could be expressed as below

$$\chi_{cmd} = \chi_{los} + \text{sign}(\chi_{los} - \chi) \cdot \left( -\frac{\pi}{2} + \frac{\Delta\chi}{\pi} \left( \frac{D - R}{R} \right) \right)$$

where initial $\Delta\chi$ is tuned to 30$^\circ$.

By analogy to the straight-line mode, the command line of sight angle $\chi_{cmd}$ in the spiral descent mode is still equal to a constant value. P control or PI control are also both optional for guidance law. In the spiral descent stage, we add a guidance feed-forward amount to enhance the response speed for the spiral flight. Therefore, the P control expressed in equation (14) is enough for tracking the feedback.

$$\dot{\chi}_{des} = K_p \cdot e + \dot{\chi}_s$$

The control loop for spiral descent mode is shown in Figure 15. According to the control loop, the close loop transfer function is expressed as below

$$H(s) = \frac{K_p}{s + K_p}$$

where $K_p$ is tuned to 2 based on the simulation results.

Mode switch. As described above, guidance law for the micro glider only operates in the horizontal plane, which means the minimum turning radius is the index parameter for circle flight guidance. As shown in Figure 16, at the condition of the line of sight distance larger than $N_1R$, straight-line mode is activated. At the condition of the line of sight distance less than $N_2R$, spiral descent mode is activated. Besides, at the interval of $[N_2R, N_1R]$, magnetic hysteresis is adopted for the guidance mode switch. The values of $N_1$ and $N_2$ are tuned to 5 and 3 based on simulations, which could produce a smooth circle orbit.

During the guidance process, the micro glider roll amplitude is limited by multiplying a scaled-down coefficient $\eta$ before the maximum roll angle in case of an excessive overload. The scaled-down minimum turning radius is expressed in equation (17)

$$\dot{\chi}_s = \text{sign}(\chi_{los} - \chi) \cdot \frac{V_g}{\max(D, R)}$$

where $K_p$ is tuned to 2 based on the simulation results.
\[ R = \frac{V_a^2}{g \tan(\eta \phi_{\text{perm}})} \]  

As the principle of constant dynamic pressure during flight, the velocity of the micro glider varies with the altitude and hence the minimum turning radius needs to be updated synchronously to judge the guidance logic. \( \eta \) is tuned to 0.8 depending on simulation results.

Both straight mode guidance and spiral mode guidance consist of two parts. Firstly it computes the command course angle \( \chi_{\text{cmd}} \). Then it computes the desired course angle rate \( \dot{\chi}_{\text{des}} \). Note that the error \( e \) between \( \chi_{\text{cmd}} \) and \( \chi \) is limited in the interval of \((-\pi, \pi] \). The expressions of error \( e \) are shown in equation (18)

\[
e = \text{Judgement}(\chi_{\text{cmd}} - \chi) = \begin{cases} 
\text{e, } |e| < \pi \\
\text{e}-2\pi, \text{e}>\pi \\
\text{e}+2\pi, \text{e} \leq -\pi 
\end{cases} \quad (18)
\]

Simulation results

For validating the control and guidance law design and comparing the flight path with and without wind effects, two initial heading angles \( \psi_0 = 45^\circ \) and \( \psi_0 = -135^\circ \) towards the waypoint are tested at the launching altitude 20 km. Wind velocities defined in simulations are dependent on the atmospheric vertical wind profile, where the maximum wind velocity appears at 10 km altitude and decreases linearly to a minimum amount lower than 3 m/s at 20 km and 0 km, respectively. The airline distance from the launching position to the target waypoint in simulation is 42 km. The control system is activated at 18 km for the reason that the micro glider can enter an equilibrium orbit at this altitude, where the elevons can generate enough moments for the controller. This also means the micro glider needs to self-stabilize only by the aerodynamic configuration at the initial glide stage. Simulation results of path and attitude at no wind condition are shown in Figures 17 and 18. As can been seen, the launch condition of \( \psi_0 = 45^\circ \) leads to an opposite flight to the waypoint at the uncontrolled stage. After the controller is activated, it outputs a command roll angle \( \phi_{\text{cmd}} = -10^\circ \) to control the micro glider to turn and then output \( \phi_{\text{cmd}} = 10^\circ \) to control the micro glider to enter to the straight orbit from turning. At the turning stage, the heading angle \( \psi \) varies from \( 45^\circ \) to \(-135^\circ \) only within about 3 min. As the micro glider is close to the waypoint, the command roll angle outputs a maximum angle of \( \phi_{\text{cmd}} = 20^\circ \) to switch the mode from the straight descent to the spiral descent. It could also be shown by fluctuations of the heading angle. Deflection angles of the left and right elevon keep flapping at the final landing stage to stabilize the micro glider heading angle, which also results in a small fluctuation of roll angle. The error between the final landing position and the waypoint is less than 150 m. The final landing velocity is about 20 m/s. Flight time is about 40 min. As a contrast, the initial heading angle of \( \psi_0 = -135^\circ \) performs a more desirable condition that the flight path is right to the waypoint. The guidance mode switches to spiral descent earlier at a higher altitude of 8800 m. \( \phi_{\text{cmd}} \) outputs mainly appear at the landing stage. Compared to launch with \( \psi_0 = 45^\circ \), apparently launch right to the waypoint shows a more effective flight distance. During the balloon flight, the gondola will always keep a low-speed spin speed, thus the initial launch heading angle \( \psi_0 \) and the launch time should be selected carefully to achieve a better flight range.

In wind effect simulations, flight performances at two maximum wind velocities of \( V_{w_{\text{max}}} = 10 \) and

![Figure 17. 3D (left) and planar (right) path with no wind condition.](image-url)
20 m/s at 10 km altitude are studied. \( V_{w}^{\min} \) at 0 km and 20 km altitude are 3.5 and 0 m/s respectively. Wind direction points to the waypoint. Flight results in the wind fields are shown in Figures 19 and 20. As can be seen, tailwind results show a significant reduction to the flight range. For specific, with initial \( \psi_{0} = 45^\circ \), even though the micro glider is in headwind condition in the initial flight stage, the wind effect can also be
neglected due to quasi-zero wind layer at 18–20 km altitude, which means the controller will guide the micro glider to turn to face to the waypoint with a mild wind condition. Further, the controller also shows the wind resistance ability to keep the path in a straight line at strong wind zones at the altitude of 10 km. On the other hand, micro glider launched with $\psi_0 = 45^\circ$ at simulated wind field fails to land near the waypoint due to a flight range reduction caused by flight in tailwind direction. With $V_{w,\text{max}} = 20$ m/s wind field, it shows a worse flight range of 22 km, which is 34% lower than $V_{w,\text{max}} = 10$ m/s. As a contrast, with simulated wind fields, launching with the heading angle of $\psi_0 = -135^\circ$ can complete the waypoint landing process. It can be viewed that with $V_{w,\text{max}} = 10$ m/s condition, the path enters to spiral orbit as it is close to the waypoint, but the orbit is difficult to be kept as a stable circle by the controller. Moreover, variations of the heading angle $\psi$ relative to wind direction in spiral mode result in fluctuations to pitch angle $\theta$ and descent velocity $w$. As concluded, controller performance in wind fields shows an ability to resist the medium wind effects. Wind directions and velocities will determine the flight range and the landing accuracy. For strong wind larger than tested $V_{w,\text{max}}$, the control codes may show unsatisfactory results in simulations. In real flight, wind fields including strong wind, gust, wind shear and turbulence are more complex than simulated wind fields. Adding a micro-sized heading sensor to the control system might be a choice to enhance the wind resistance ability for the next version micro glider design.

The last part simulated the abovementioned maximum roll angle $\phi_{\text{lim}}$ selection and spiral circle radius effects in the guidance performance. $\phi_{\text{lim}}$ simulation is carried out at $\psi_0 = 45^\circ$ with a constant wind of $V_{w,\text{max}} = 10$ m/s. As can be viewed in Figure 21(a) and (b), increase $\phi_{\text{lim}}$ can lead to a smaller radius to complete the turning stage. On the other hand, $\phi_{\text{cmd}}$ recovers to 0° faster with smaller $\phi_{\text{lim}}$. Thus, the tradeoff for selecting $\phi_{\text{lim}}$ decides the turning effectiveness. Spiral descent radius analysis is carried out with no wind condition. As shown in Figure 21(c) and (d), smaller interval of $[N_2 = 1R, N_1 = 2R]$ results in a shifted circle orbit. $\phi_{\text{cmd}}$ shows fluctuations during spiral descent, which is less stable compared to the selected interval of $[N_2 = 3R, N_1 = 5R]$. This result validates the rationality of $N_1$ and $N_2$ selection used in control codes.

Flight test

The flight tests of two micro gliders as a sub-payload of a 3000 m$^3$ super pressure balloon were conducted in Inner Mongolia, China, as shown in Figure 22. The two micro gliders were launched at the altitudes of 10,000 m and 20,000 m. It takes the balloon about 40 and 82 min to ascend to the launch altitudes, respectively. Attitude control for both lateral and longitude
direction is activated after the initial launches. The landing waypoint is the same as the balloon lifting-off position, where the longitude = 108.382070° and latitude = 41.696889°. $\phi_{\text{lim}}$ is set to $\pm 10^\circ$ for the reason to maintain a small roll angle to stabilize the attitude at turning.

Figure 23 shows the high altitude micro gliders launching process captured by the camera on the balloon gondola. As shown in Figure 23(a), we can see the first glider rolled over after separated from the slide rail. One possible explanation for this initial roll motion is that the strong wind zone at 10,000 m attitude produced an in-balanced roll moment on both sides of the wing. As suddenly separated from the slide rail, the micro glider lost the constraint and was driven by the moment to roll. The initial roll speed resulted in a tail spin at the initial stage and also resulted in the loss of the radio link. The re-receiving of the radio signal from the micro glider was at about 8000 m altitude, which is shown by 3D and planar path by Figure 24(a) and (b). After 8000 m, the glider had already recovered from tail spin and turned into a stable flight attitude. However, the path of the first glider still showed a strange self-induced spiral descent. Apparently, it was not dominated by the flight control program. We prefer to explain it by fabrication error, such as the deflection angle errors between the right and left elevons or the center of mass deviation. In previous low altitude uncontrolled launched tests, the spin tail correction and spiral flight were both observed. Because most of the time the micro glider was in self-induced spiral flight, the airline distance from the launching position to the landing position was only 3.3 km. The total flight time was 19 min.
Figure 23. Screenshot of the launch at the two altitudes. (a) Launch at 10,000 m. (b) Launch at 20,000 m.

Figure 24. Flight paths of the launch tests. (a) Balloon (yellow) and micro glider (purple) 3D path. (b) 1st micro glider 3D and planar paths. (c) 2nd micro glider 3D and planar paths.
The second micro glider launched at 20,000 m kept a stable initial attitude after separating from the slide rail, as shown in Figure 23(b). It may attribute to the mild wind field of the quasi-zero wind layer at 20 km altitude. The loss of radio link also happened during the flight. The glide path for the second micro glider was relatively straight, as shown in Figure 24(a) and (c)). However, it still failed to turn to the waypoint. The airline distance was about 15.8 km, which glided for about 26 min.

From the aircraft design point of view, the successful launch and flight tests verified the feasibility of designing a PCB fabricated micro glider to fly at high altitudes. The gliding process from launch to equilibrium flight indicates the trim condition calculated by panel method and CFD method is acceptable. However, the real flight duration of 26 min was lower than the ideal duration of 36 min obtained by simulation at no wind condition. It is mainly because the real micro glider shape is more complex compared to the ideal numerical model, which causes more parasitic drag in flight. Furthermore, the real atmosphere wind field including gust and adverse wind direction will also decrease the flight range. Thirdly, the tail spin or stall at the initial launch also shortens the effective altitude.

Figure 25(a) and (b) presents the flight data from the sensors on the two micro gliders. The north and east GPS velocities of the first micro glider show strong fluctuations caused by the spiral path. The true pitch angle of first micro glider also shows fluctuations from $-10^\circ$ to $15^\circ$, which is because the course angle in spiral flight is continuously changing with respect to the real wind field. This variation caused $Va$, fluctuations, and thus resulted in $\theta$ continuous fluctuations. To adjust the $\theta$ to the nominal condition of $-8^\circ$, it can be seen that the controller computed command $\delta_c$ matches the frequency of the $\theta$ fluctuation. For the second micro glider, because the path and $\theta$ are relatively stable, command $\delta_c$ outputted a limited value of $5^\circ$ to adjust $\theta$ to nominal condition. Roll angle showed it tracked the command roll angle actuation frequency, but did not track the amplitude of command $\phi_{\text{lim}} = \pm 10^\circ$ properly. Three possible reasons may explain the paths in true flights. Firstly, the ideal initial state of the right and left elevon deflection angle should be equal at the initial launch. However, with the consideration of manufacturing errors, the initial deflection angle of the two elevons maybe not equal. Because the weight of the micro glider is light, the turning flight is sensitive to the two elevons error even though the error is small, thus the error may cause the controller to fail to correct the paths. Secondly, the true pitch and roll angles of in controller are both estimated by angular acceleration obtained from IMU. The airspeed was estimated from GPS velocity. Thus, the accuracy of the attitude and the airspeed is mainly dependent on the accuracy of sensors. In our previous ground tests, the roll and pitch angle is accurate, but in high altitude with wind disturbance, the accuracy of sensors needs to be verified carefully. Thirdly, the low temperature of $-50^\circ$C at the stratosphere may cause angular speed shifting in the measurements of IMU, which resulted in wrong angular speed outputs. To verify the assumption of the negative effect of the manufacturing error on the guidance flight, flight paths with different deflection angles between the right and left elevons are simulated, which is equivalent to $\delta_{a0} > 0$. As shown in Figure 26, as $\delta_{a0}$ exceeds the limited aileron value of $\delta_a^{\text{limit}} = 2^\circ$, the path shows shifted spiral orbits at constant wind field. Further, for $\delta_{a0} = \delta_a^{\text{limit}}$, the path can be kept as straight but still fails to enter spiral descent mode when close to the waypoint. The controller can output a correct command course angle $\gamma_{\text{cmd}}$ ($\gamma_{\text{cmd}} = -135^\circ$ at launching point) which always points to the waypoint, but the larger error of $\delta_{a0}$ caused the right and left elevon cannot recover to equality, as shown in Figure 27. The elevons can only recover to equality at $\delta_{a0} < \delta_a^{\text{limit}}$, and thus $\delta_{a0} = 2^\circ$ shows a successful guidance flight even with initial elevons error. The shifted spiral orbits caused by the initial error of $\delta_{a0} > \delta_a^{\text{limit}}$ and straight path caused by $\delta_{a0} = \delta_a^{\text{limit}}$ can be corresponded to the real paths of the first and second micro gliders, which may match the possibility of the assumption of manufacturing errors. In the fabrication of the micro gliders, the relationships between the servo electrical signals and the elevons deflection angles were measured manually by using a protractor. It might be possible to lose accuracy in the process of manual measurement, which may be the source of the error of $\delta_{a0}$.

Based on the high altitude launch test results, both the aerodynamic design and control algorithm need to be improved. Potential improvements are concluded in four parts. Firstly, the roll and pitch coefficients in the aerodynamic model are referred to as a linear non-coupled model. However, for a flying wing aircraft, particular for the flat-plate wing that the trim condition is maintained by the elevons deflection, nonlinear aerodynamic coefficients at large elevon deflection angle resulted in couple effects between roll and pitch angle, which may cause errors by using linear elevon control model of $\delta_a$ and $\delta_c$. The precise calculation method and new aerodynamic model need to be developed. The elevons separated the aerodynamic model may be more accurate for flat-plate flying wing MAVs. Secondly, the accuracy of fabrication needs to be enhanced. Effectiveness for the increase of $\delta_a^{\text{limited}}$ will be validated in the further launch tests. At last, the current circuit design does not include the heading sensor. In the further micro glider design, a
Figure 25. Controller outputs for the launch tests. (a) 1st micro glider. (b) 2nd micro glider.

Figure 26. 3D (left) and planar (right) path with the consideration of initial elevon errors.
micro heading sensor or a wind estimated algorithm would be necessary to be included in the control system to provide a more precise heading angle.

**Conclusion**

This article presents the design details of the aerodynamics and control system for a print circuit board fabricated micro glider launched from high altitude with only limited sensors. Control algorithm at no wind condition with the specified aerodynamic design showed a possibility to control micro glider to land precisely around the target waypoint within a distance error less than 200 m. Simulations with the ideal wind model indicated that the controller performance is mainly determined by the wind velocities and directions. For flight with a headwind of $V_{w}^{\text{max}} = 20 \text{ m/s}$, flight range is lower than flight in no wind condition. Additionally, large wind magnitude and adverse wind direction also resulted in a difficult calculation for the control program. Flight tests of two micro gliders showed successful flights, which validated the feasibility by using PCB as wing material to flight at high altitude. The two micro gliders flew for about 19 and 26 min with launch altitude of 10,000 m and 20,000 m, respectively. The command roll angle for the two micro gliders showed saturated outputs, which means the control systems were working during flight. However, on the other hand, the real roll angle failed to track the command roll angle with proper amplitude. This was caused by the possible reasons including unequal initial elevons deflection angles, inaccurate true roll angle computation or IMU drift under low temperature. As a result, the path failed to show an ideal turning and spiral flight towards the target waypoint compared to the successful turning and landing path in simulation results. In conclusion, the feasibility of the aerodynamic design and control algorithm is validated by the simulation results. However, due to the harsher environment in the stratosphere including varied wind field, low air density and low temperature, the parameters preprogrammed in the control system for resisting the wind and the insulation may need to be redesign to achieve guidance flight and precise landing in real flight.

**Data availability**

The data used to support the findings of this study are available from the corresponding author upon request.

**Declaration of conflicting interests**

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