**Supplementary Note 1: Analytic Model for 3D Rotational Falling Fliers**

The aerodynamic behavior of a flier of the sort considered in this paper represents a complex structure-fluid interaction problem. As a simplification, we consider the system in a stable flying state, i.e., with a constant terminal velocity and a constant rotating speed . These two key parameters that describe the falling behavior of fliers depend strongly on both the properties of the air (e.g., air density , dynamic viscosity , etc.) and the geometry of flier (e.g., 3D configuration, tilted angle of blades, area, etc.):

**, (S1.1)**

Herein, we use a representative simplified model to parametrically characterize the geometry of the flier, which has several blades (number of ) evenly located at a radius from the center point (Fig. 2a). Each blade is tilted by an angle , and has a chord length , in-plane width and thickness . The density of the flier material is . We assume that the blade width is small comparing to the radius ().

Focusing on the side view of a single blade (Fig. 2a, bottom enlarged subplot), the air flow is of velocity , which can be decomposed into a vertical component and a horizontal component . This problem now corresponds to a 2D airfoil (side cross-section of blade) with a coming air flow of velocity and attack angle , where

**, (S1.2)**

**. (S1.3)**

The drag force along the direction of airflow and lift force perpendicular to the direction of airflow can be expressed as

, **(S1.4)**

, **(S1.5)**

where and are the drag coefficient and lift coefficient of the airfoil, respectively, which can be obtained by 2D CFD simulations of airfoils (Fig. S3). Decomposing the drag force and the lift force into the rotational and vertical directional forces ( and ) yields

, **(S1.6)**

. **(S1.7)**

The force equilibrium condition is given by

,  **(S1.8)**

,  **(S1.9)**

under the assumption , where is the weight of flier.

**1. Rotating speed**

With the horizontal equilibrium condition , Eq. (S1.6) yields

,  **(S1.10)**

where is the lift-to-drag coefficient of the airfoil, which depends on the airfoil geometry, Reynolds’ number (Re) and the attack angle () of the coming air flow (see Supplementary Figure S5b). For a given airfoil geometry under a certain Reynolds’ number, Eq. (S1.10) yields

.  **(S1.11)**

The value of can be solved by this implicit equation (S1.11) for a given tilt angle . Moreover, this suggests the scaling law

,  **(S1.12)**

that the rotating speed of flier is proportional to its terminal falling velocity over radius.

**2. Terminal velocity**

Equation (S1.7) yields

.  **(S1.13)**

Rewriting Eq. (S1.13) with the drag coefficient of flier yields

,  **(S1.14)**

where , and is the total membrane area of flier. The drag coefficient of the flier is affected by both the drag coefficient and lift-to-drag ratio of its blade.

**3. Considering the effect of Reynolds’ number on drag coefficient**

The drag coefficient of blade () saturates at high Re, but at small Re it is nearly proportional to . The simulation results of drag coefficient of a flat airfoil versus Reynolds’ number are presented in Fig. S7a. The CFD simulation results can be fitted by the function

**, (S1.15)**

where for and for . Substitution of Eq. (S1.15) into Eq. (S1.13) gives

.  **(S1.16)**

We define as the area fill factor of flier, according to

**. (S1.17)**

With Eq. (S1.17), the Eq. (S1.16) can be rewritten as

.  **(S1.18)**

when . Recall that , Eq. (S1.18) yields

  **(S1.19)**

for large Re, where . Likewisely, for small Re, Eq. (S1.18) yields

,  **(S1.20)**

where . Again, Eqs. (S1.19) and (S1.20) requires the assumption that .

**4. Modification of theory by the extension of fill factor**

The above analysis is based on the assumption that the fill factor is small (. To extend the model to practical cases where the fill factor can be larger (e.g., close to 1 in the range of [0,1]), we simulated the simplified flier model with various fill factors (Fig. S13). It was shown that the linear relation between and is true only for . For larger the theory must be amended by changing the fitting law to . Therefore, the amended model is given by

. **(S1.21)**

*5. Effect of self-weight and load on terminal falling velocity*

The weight of flier consists of two parts, i.e., self-weight () and load (), as given by

.  **(S1.22)**

Substitution of Eqs. (S1.9) and (S1.22) into (S1.21) yields

. **(S1.23)**

For macrofliers, the terminal velocity is given by

. **(S1.24)**

For microfliers, the terminal falling velocity is

. **(S1.25)**

**Supplementary Note 2: Effect of Porosity on Terminal Velocity**

The idea of utilizing porosity to reduce the terminal falling velocity arises from structures in nature (Fig. S8a). For example, feathers consist of micro-fibers, between which there are void spaces. The aerodynamic properties of feathers are still very good even with these void spaces. The benefits of the void spaces are in significant reductions in the overall weight. Another example is dandelion seeds, with similar micro-fiber structures but even more void spaces, with capabilities for exceptionally low terminal velocities. Thus, we explored the possibility of adding porosity into the fliers (Fig. S8b&c) to reduce these velocities. The porosity (i.e., ) is defined by

**, (S2.1)**

where is the area of voids and is the area of a void-free flier. The area with voids present is

 **, (S2.2)**

We consider a representative 2D flat airfoil, for which the CFD simulations reveal that the porosity leads to an increase in the drag coefficient by increasing and , recall Eq. (S1.2), as shown in Fig. Sd&e, and can be fitted analytically by

**, (S2.3)**

**. (S2.4)**

Eqs. (S2.3) and (S2.4) indicate that increases faster than with porosity. This behavior can be explained by the flow fields near the porous airfoil, as shown in Fig. S9. At low Re, the boundary layer surrounding the airfoil, which can be seen as a virtual airfoil, is not affected by the porosity on the flat airfoil. The drag force acting on the airfoil, is therefore not significantly decreased. However, at large Re, the thickness of boundary layer is comparable to the size of void, such that the drag force decreases similarly to the area as porosity increases.

Therefore, per Eqs. (2) and (3), the knock-down factor of porosity on for a microflier is given by

**, (S2.5)**

and for a macroflier, the terminal velocity knock-down factor is

**, (S2.6)**

**as validated by the falling tests as shown in Fig. S10.**

**Supplementary Note 3: Effect of Attack Angle on the Drag Coefficient of 2D Flat Airfoil**

The tilt angle affects the terminal velocity through the attack angle (). A larger indicates a smaller and (Fig. S7) due to its smaller attack angle (, for the point on the flier at radius ), and therefore leads to a larger . For a large flier, the lift-to-drag ratio () of the blade can also increase significantly with small attack angle. Therefore, a small tilt angle can increase the flier drag coefficient through , per Eq. (1.13), that . However, the lift-to-drag coefficient for a microflier is very small such that only the drag coefficient of blade plays an important role. Therefore, optimizing the tilt angle is not helpful for microscale fliers.

The 2D (two-dimensional) airfoil is the cross section of a blade for a 3D flier. Figure S7a shows the CFD simulated (see details in Methods and Fig. S3b) drag coefficient of a 2D flat airfoil (i.e., ) versus Reynolds number, where the subscript ‘(b)’ denotes the ‘blade’. The drag coefficient of the airfoil, as defined by

**, (S3.1)**

where A is the area of the airfoil (per unit depth). can be empirically given by

**, (S3.2)**

**where and are the fitting parameters. Notably, Eq. (S1.2) indicates that is dominated by at high Re, but is dominated by at low Re. In other words, and stand for the viscous and inertia effects of the flow, respectively (Fig. S7b). To investigate the effect of attack angle () on , we first study the effect on and , as presented in Fig. S7c&d, which can be analytically fitted by**

**, (S3.3)**

 **. (S3.4)**

**Substitution of Eqs. (S1.3) and (S1.4) into Eq. (S1.2) gives the drag coefficient as a function of**

**. (S3.5)**

**Supplementary Note 4: Stability analysis of rotating-falling fliers (spinners)**

The stability of the rotating-falling state of the flier is analyzed by simplifying the flier as a rigid body and considering the influence of air flow. Generally, the rotational movement for a rigid body can be described as

, **(S4.1)**

where is the rotating velocity of the rigid body, , and are the three-dimensional unit vectors of the rotating coordinate along with the rigid body, and , and are the rotating speed components. Euler’s rotation equations take the general form:

, **(S4.2)**

where , and are assumed to be the principal moments of inertia, and is the torque on the body. Consider the flier as a rigid body free falling in the air (air density , dynamic viscosity ) at a terminal velocity , and rotating with an angular speed along the z direction, where the rotational movement is given as

. **(S4.3)**

If a perturbation is applied on the flier and causes a slight tilt angle on 1 and 2 directions (Fig. 2f) as and , respectively, then the angular velocity becomes

, **(S4.4)**

where and are both assumed to be small. Euler’s equations (S4.2) take the form

. **(S4.5)**

Consider the torque of the air flow on the flier body as

. **(S4.6)**

For small perturbations off the balanced state as

. **(S4.7)**

The dependence of torque on angle perturbation is given by

, **(S4.8)**

where is the distance between the center of pressure and center of gravity. The dependence of torque on angular speed perturbation is

, **(S4.9)**

in which is the unit area of the flier locates at radius , and is the drag force per unit area acting on the flier as given by

, **(S4.10)**

The velocity perturbation is

. **(S4.11)**

Substitution of Eq. (S4.10) and (S4.11) into equation (S4.9) gives

. **(S4.12)**

Under the assumption that the area distribution of microflier is uniform at radius , Eq. (S4.12) yields

, **(S4.13)**

Substitution of equations (S4.8) and (S4.13) into (S4.5) and (S4.7), yields the control equations

, **(S4.14)**

, **(S4.15)**

Rewriting them in matrix form and normalized as

, **(S4.16)**

where , , , and . For the extreme case that the flier is highly symmetric and , Eq. (S4.16) becomes

, **(S4.17)**

where . Equation (S3.17) can by diagonalized by the transformation

, **(S4.18)**

that

. **(S4.19)**

This is a decoupled oscillation equation with damping, of which the 4 eigenvalues are

, **(S4.20)**

, **(S4.21)**

which can be normalized as

, **(S4.22)**

 **(S4.23)**

The stability of the solution (i.e., when ) requires that all real part of the eigenvalues are negative. Define as the stability factor as

. **(S4.24)**

The stability condition requires .

The solution of Eq. (S4.17) is expressed as

. **(S4.25)**

**The amplitude of oscillation () decays with time as**

, **(S4.26)**

where is the amplitude of the initial perturbation. Therefore, a larger means the amplitude decays faster that the flier can recover to its balanced stable state faster.