The optimized and predicted results that FWMAV can achieve hovering and low-speed forward flight with minimal energy consumption
FWMAV 能够实现悬飞和低速前飞时能量消耗最小的优化结果和预测结果

FWMAV (mg)	前飞速度(m/s)	航程 (m)	巡航时间 (minutes)	升重比 (*L*/*D*)	悬飞消耗的时均能量密度 (W/kg)	拍打频率 (*f*, Hz)	展弦比 (*AR*)	雷诺数 (*Re*)
80	0.5189	1355.1	43.5	1	9.5728	15.7975	3.2871	661.6246
200	0.6665	681.6856	17.05	1	24.4425	16.9128	3.4953	981.0652
4000	1.1571	1372.1	19.8	1	21.0829	12.8772	2.9375	7420.8
115	1.4399	451.3105	5.22	1.3985	79.7620	100	4.3353	1072.7
380	1.7135	363.7485	3.54	1.7321	117.7652	70	4.3353	2170.1
657	1.7135	628.9020	6.12	1.0018	68.1138	70	4.3353	2170.1
4000	1.0236	629.6622	10.25	1.0078	40.6423	12	2.9000	6677.9

这里的数据是在前进比(即前飞速度与翼尖速度的比值)为 0.25 时，电池占飞行器总重量的一半的情况下 FWMAV 能够实现悬飞和低速前飞时能量消耗最小的优化结果和预测结果 。

Variables to be optimized

x=[f, phi_m, K, eta_m, C_eta, Phi_eta, R_wingeff, C_avereff, xr, C_maxy];

(1) While m_FWMAV=80*10^{-6}mg, the Combination optimization results

x =[15.7975,1.2896,0.5016,1.0875,4.7362,-1.562,15.5081,7.7486,9.9626,0.0151];

(2) While m_FWMAV=200*10^{-6}mg, the Combination optimization results

x =[16.9128,1.242,0.1083,0.8213,4.7407,-1.4121,19.0364,9.0774,12.6923,0.0047];

(3) While m_FWMAV=4000*10^{-6}mg, the Combination optimization results

x =[12.8772,1.0664,0.0353,1.3488,0.3911,-1.5705,69.7031,28.6843,14.5563,0.1250];

(4) While m_FWMAV=115*10^{-6}mg, the Combination optimization results

x =[100,0.9599,0.0001,0.7854, 2.375,-1.5708,11.95,3.46,3.05,0.356737];

(5) While m_FWMAV=380*10^{-6}mg, the Combination optimization results

x =[70,0.9599,0.0001,0.7854, 2.375,-1.5708,20.3150,5.8820,5.1850,0.356737];

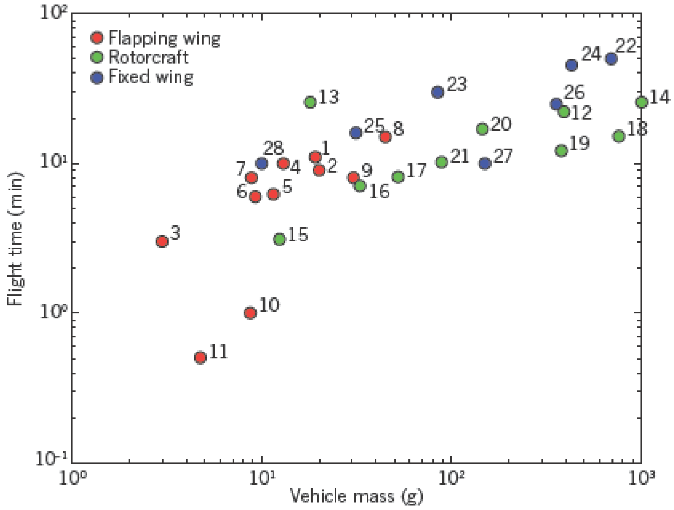
(6) While m_FWMAV=657*10^{-6}mg, the Combination optimization results

x =[70,0.9599,0.0001,0.7854, 2.375,-1.5708,20.3150,5.8820,5.1850,0.356737];

(7) While m_FWMAV=4000*10^{-6}mg, the Combination optimization results

x =[12,0.9599,0.0001,0.7854, 2.375,-1.5708,70,29.31,15,0.356737];

Flight time against mass of small (less than 1 kg) drones reported by literatures



1. Nano Hummingbird
2. DelFly Explorer
3. DelFly Micro
4. H2Bird
5. MicroBat
6. Bionic Bird
7. Avitron V2.0
8. 36cm Ornithopter
9. 28cm Ornithopter
10. 15cm Ornithopter
11. 10cm Ornithopter
12. Parrot Bebop drone
13. PD-100 Black Hornet PRS
14. DJI Phantom 2
15. Seiko-Epson uFR-II
16. Ladybird V2
17. Mini X6
18. 350.QX2
19. AR.Drone 2.0
20. QR Y100
21. QR W100S
22. eBee
23. Black Widow
24. Wasp III
25. Univ. Florida MAV
26. H301S
27. Diamond 600 EP
28. EPFL MC2

Figure 1 | Flight time against mass of small (less than 1 kg) drones. Examples include each of the drone types shown in Fig. 1 (fixed wing, rotary and flapping wing). Regardless of the type, there is a clear trend in how flight time scales with mass. Smaller drones have significantly reduced flight times (tens of seconds compared with tens of minutes for larger drones). This is due to actuation limitations and the physics of flight at small scales, as discussed in this Review, and brings about challenges for all levels of autonomy described in Box 1.

BOX 1 **Control autonomy**

According to the definition by the International Organization for Standardization, robot autonomy is the ability to perform intended tasks based on current state and sensing, without human intervention[98]. This definition encompasses a wide range of situations, which demand different levels of autonomy depending on the type of robot and the intended use. For example, although autonomy in tethered robots does not concern energy management, mobile robots with long-range travel may require the capability to decide when to abort the current mission and locate a recharging station. In the case of the small drones discussed here, we can identify three levels of increasing autonomy (Table 1).

●●**Sensory-motor autonomy:** translate high-level human commands (such as to reach a given altitude, perform circular trajectory, move to global positioning system (GPS) coordinates or maintain position) into combinations of platform-dependent control signals (such as pitch, roll, yaw angles or speed); follow pre-programmed trajectory using GPS waypoints.

●●**Reactive autonomy (requires sensory-motor autonomy)**: maintain current position or trajectory in the presence of external perturbations, such as wind or electro-mechanical failure; avoid obstacles; maintain a safe or predefined distance from ground; coordinate with moving objects, including other drones; take off and land.

●●**Cognitive autonomy (requires reactive autonomy)**: perform simultaneous localization and mapping; resolve conflicting information; plan (for battery recharge for example); recognize objects or persons; learn.

Table 1 | Levels of autonomy: requirements, availability and readiness for market

	Exteroceptive sensors	Computational load	Supervision required	Readiness level	Validated on drone type
Sensory-motor autonomy	None or few	Little	Yes	Deployed	All types
Reactive autonomy	Few and sparse	Medium	Little	Partly deployed	Fixed wing, rotorcraft and flapping wing
Cognitive autonomy	Several and high density	High	None	Not yet deployed	Mostly rotorcraft