**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\*10-6mg, 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\*10-6mg, 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\*10-6mg, 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\*10-6mg, 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\*10-6mg, 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\*10-6mg, 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\*10-6mg, 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**



**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 intervention98. 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).

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.
2. **●●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.
3. **●●Cognitive autonomy (requires reactive autonomy)**: perform simultaneous localization and mapping; resolve conflicting information; plan (for battery recharge for example); recognize objects or persons; learn.

