What's the best design for a flying Mars robot?

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A concept for an airplane on Mars. Credit: MIT

Building a flying vehicle for Mars would have significant advantages for exploration of the surface. However, to date, all of our surface exploring vehicles and robotic units on Mars have been terrestrial rovers. The problem with flying on Mars is that the Red Planet doesn't have much atmosphere to speak of. It is only 1.6% of Earth air density at sea level, give or take. This means conventional aircraft would have to fly very quickly on Mars to stay aloft. Your average Cessna would be in trouble.

But nature may provide an alternative way of looking at this problem.

The fluid regime of any flying (or swimming) animal, machine, etc. can be summarized by something called the Reynolds Number (Re). The Re is equal to the characteristic length x velocity x fluid density, divided by the dynamic viscosity. It is a measure of the ratio of inertial forces to viscous ones. Your average airplane flies at a high Re: lots of inertia relative to air stickiness. Because the Mars air density is low, the only way to get that inertia is to go really fast. However, not all flyers operate at high Re: most flying animals fly at much lower Re. Insects, in particular, operate at quite small Reynolds numbers (relatively speaking). In fact, some insects are so small that they swim through the air, rather than fly. So, if we scale up a bug-like critter or small bird just a bit, we might get something that can move in the Martian atmosphere without having to go insanely fast.

We need a system of equations to constrain our little bot. Turns out that's not too tough. As a rough approximation, we can use Colin Pennycuick's average flapping frequency equation. Based on the flapping frequency expectations from Pennycuick (2008), flapping frequency varies roughly as body mass to the 3/8 power, gravitational acceleration to the 1/2 power, span to the -23/24 power, wing area to the -1/3 power, and fluid density to the -3/8 power. That's handy, because we can adjust to match Martian gravity and air density. But we need to know if we are shedding vortices from the wings in a reasonable way. Thankfully, there is a known relationship, there, as well: the Strouhal number. Str (in this case) is flapping amplitude x flapping frequency divided by velocity. In cruising flight, it turns out to be pretty constrained.

A potential design of an ‘Entomopter’ from Georgia Tech Research Institute

Our bot should, therefore, end up with a Str between 0.2 and 0.4, while matching the Pennycuick equation. And then, finally, we need to get a Reynolds number in the range for a large living flying insect (tiny insects fly in a strange regime where much of propulsion is drag-based, so we will ignore them for now). Hawkmoths are well studied, so we have their Re range for a variety of speeds. Depending on speed, it ranges from about 3,500 to about 15,000. So somewhere in that ballpark will do.

There are a few ways of solving the system. The elegant way is to generate the curves and look for the intersection points, but a fast and easy method is to punch it into a matrix program and solve iteratively. I won't give all the possible options, but here's one that worked out pretty well to give an idea:

Mass: 500 grams
Span: 1 meter
Wing Aspect Ratio: 8.0

This gives an Str of 0.31 (right on the money) and Re of 13,900 (decent) at a lift coefficient of 0.5 (which is reasonable for cruising). To give an idea, this bot would have roughly bird-like proportions (similar to a duck), albeit a bit on the light side (not tough with good synthetic materials). It would, however, flap through a greater arc at higher frequency than a bird here on Earth, so it would look a bit like a giant moth at distance to our Earth-trained eyes. As an added bonus, because this bot is flying in a moth-ish Reynolds Regime, it is plausible that it might be able to jump to the very high lift coefficients of insects for brief periods using unsteady dynamics. At a CL of 4.0 (which has been measured for small bats and flycatchers, as well as some large bees), the stall speed is only 19.24 m/s. Max CL is most useful for landing and launching. So: can we launch our bot at 19.24 m/s?

For fun, let's assume our bird/bug bot also launches like an animal. Animals don't take off like airplanes; they use a ballistic initiation by pushing from the substrate. Now, insects and birds use walking limbs for this, but bats (and probably pterosaurs) use the wings to double as pushing systems. If we made our bots wings push-worthy, then we can use the same motor to launch as to fly, and it turns out that not much push is required. Thanks to the low Mars gravity, even a little leap goes a long way, and the wings can already beat near 19.24 m/s as it is. So just a little hop will do it. If we're feeling fancy, we can put a bit more punch on it, and that'll get out of craters, etc. Either way, our bot only needs to be about 4% as efficient a leaper as good biological jumpers to make it up to speed.

These numbers, of course, are just a rough illustration. There are many reasons that space programs have not yet launched robots of this type. Problems with deployment, power supply, and maintenance would make these systems very challenging to use effectively, but it may not be altogether impossible. Perhaps someday our rovers will deploy duck-sized moth bots for better reconnaissance on other worlds.

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