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Quad-thopter: Tailless flapping wing robot with four pairs of wings

Christophe De Wagter, Matěj Karásek and Guido de Croon

Abstract

We present a novel design of a tailless flapping wing micro air vehicle, which uses four independently driven pairs of flapping wings in order to fly and perform agile maneuvers. The wing pairs are arranged such that differential thrust generates the desired roll and pitch moments, similar to a quadrotor. Moreover, two pairs of wings are tilted clockwise and two pairs of wings anti-clockwise. This allows the micro air vehicle to generate a yaw moment. We have constructed the design and performed multiple flight tests with it, both indoors and outdoors. These tests have shown the vehicle to be capable of agile maneuvers and able to cope with wind gusts. The main advantage is that the proposed design is relatively simple to produce, and yet has the capabilities expected of tailless flapping wing micro air vehicles.

Keywords

Tailless, flapping wing, micro air vehicle, ornithopter, Unmanned Air Vehicle (UAV)

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Introduction

Flying animals remain unrivaled when it comes to their flying skills and flight characteristics. Hummingbirds can hover and maneuver in narrow spaces to feed and then subsequently fly hundreds of kilometers when migrating.[1] Besides the energy and sensory processing aspects, a great deal of the advantages of flying animals over current micro air vehicles (MAVs) is attributed to their way of propulsion. Flapping wings are predicted to achieve higher lift coefficients than conventional MAV designs, especially when scaled further down towards insect scales. In addition, they are expected to have a higher energy efficiency when flying at higher speeds, extending range and duration of the flight.[2]

Despite considerable efforts – and successes[3,4] – in the last few decades, the dominating MAV types are still rotorcraft, fixed wings or recently combinations of both.[5,6] An important reason for this is the difficulty of producing a flapping wing MAV that fulfills some of the promises of animal flight.

On the one hand, there is a large class of 'tailed' flapping wing MAVs, which goes back to rubber-band flapping wing vehicles designed in the 19th century.[7] Flapping wing MAVs, such as 'small bird',[8] 'big bird',[9] or the 'DelFly',[10] have a single degree of freedom (DOF) motor-driven flapping wings for generating thrust. The control moments are generated by actuated control surfaces on the tail. Since the tail is relatively large, it dampens the body dynamics sufficiently to make this type of MAV passively stable.

The tail actuation typically consists of a rudder and an elevator and can be used for changing the MAV's direction, height, or velocity. However, the aerodynamically stabilizing tail section also makes the vehicle particularly sensitive to external perturbations.[10] The forces and moments generated by the tail actuators are in general insufficient to compensate perturbations in 'gusty' environments, with even air-conditioning causing considerable problems to these light wing loading MAVs. Finally, elevator and rudder effectiveness vary dramatically based on the incoming airflow and can even reverse when descending in hover. This makes tuning autopilot control loops dependent on more

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sensors and creates uncontrollable areas in the flight envelope.

On the other hand, there is a growing class of 'tailless' flapping wing MAVs, which use the wings themselves for control. The idea is that the wings can generate much larger forces and moments in shorter times than tailed actuators. In combination with the absence of a tail and its damping effect, this leads to a higher maneuverability. The first successful design of this class was the 'Nano Hummingbird'.[3] It featured an ingenious but complex mechanism to generate all three moments required for full attitude control. Recently, other MAVs of similar size have been designed, which aim for simpler designs, but which have not yet shown the same maneuverability as the Nano Hummingbird and, at the same time, suffer from very limited flight endurance of several tens of seconds at best.[11–13] The smallest type of flapping wing MAV of this class is the well-known 'Robobee',[14] which for now requires the energy source to be off-board.

Although current tailless flapping wing MAVs are closing in on the ideal set by nature, none of them are yet both able to perform real flight missions and at the same time relatively easy to construct.

To broaden the field of application of flapping wing MAVs, a light and simple wing actuation mechanism would be needed that can quickly create large attitude control moments in all three axes. Based on this idea, we present in this paper a new tailless flapping wing MAV design, referred to as a 'quad-thopter'. The design is similar to a quadrotor, in the sense that it uses the thrust of four wing pairs to do thrust vectoring (Figure 1). It is also reminiscent of the very early 'Mentor' design,[15] which also had four wing pairs for flying. However, that design used a single main actuator driving the four wings at the same flapping frequency. The control relied upon control surfaces interacting with the wake of the flapping wings, which had rather low effectiveness, limiting the controllability of the system. Instead, the 'quad-thopter' can drive all wings independently from zero to maximal thrust, which can generate significant roll and pitch moments, and the flapping planes of diagonally opposing wing pairs are tilted with respect to each other for yaw controllability.

The quad-thopter design proposed in this paper represents a close-to-optimal choice in the design space consisting of the magnitude of the generated control moments, the control bandwidth, and the weight, size and energy requirements of the actuators. In addition, the quad-thopter is relatively easy to construct with widely available current-day technology and has a flight time of 9 min or more, depending on the flight regime. Hence, it is suitable for real-world missions.

In Section Tailless flapping wing, we discuss current flapping wing designs and actuators in more detail in order to get a better understanding of the difficulties involved in tailless flapping wing MAV design. Then, in Section The Quad-thopter, we present the new design. We study the body's vibrations in Section Residual Vibration and the less evident yaw moment generation in Section Yaw versus efficiency. We describe the flight characteristics in Section Flight Testing, showing pictures of the flapping wing MAV in flight and providing links to flight footage. Finally, we draw conclusions in Section Conclusions.

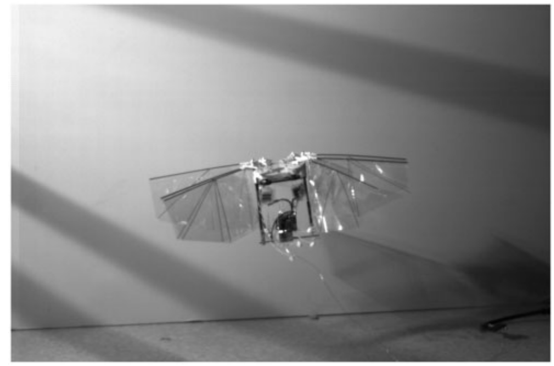

Figure 1. High-speed camera recording of a quad-thopter.

Tailless flapping wing

Moment generation

Most ornithopter designs use a tail, which provides passive aerodynamic stabilization and typically carries also conventional actuated control surfaces. When the tail is removed, active stabilization becomes necessary and some mechanism is required to create the three moments needed to orient and stabilize the platform.

Many solutions have been proposed. Some add propeller thrusters besides the flapping wing.[16] But the vast majority of researchers, inspired by biological fliers, search for new DOFs to incorporate in the main flapping wings to vary their aerodynamic force over the flapping cycle.[3,4,13,17] To use these DOFs in closed-loop control, they must be actuated with sufficient speed and force.

Hovering without tail

The minimal requirement for controllable hovering of an aircraft is thrust vectoring. Instead of controlling the 6DOFs (three-dimensional (3D) position and 3 attitude angles) of the free-flying body directly, two position variables are controlled indirectly through the attitude which in turn controls the thrust vector and hereby the longitudinal and lateral acceleration. This allows for 6DOFs hover with only four independent control variables. Most concepts use flapping power

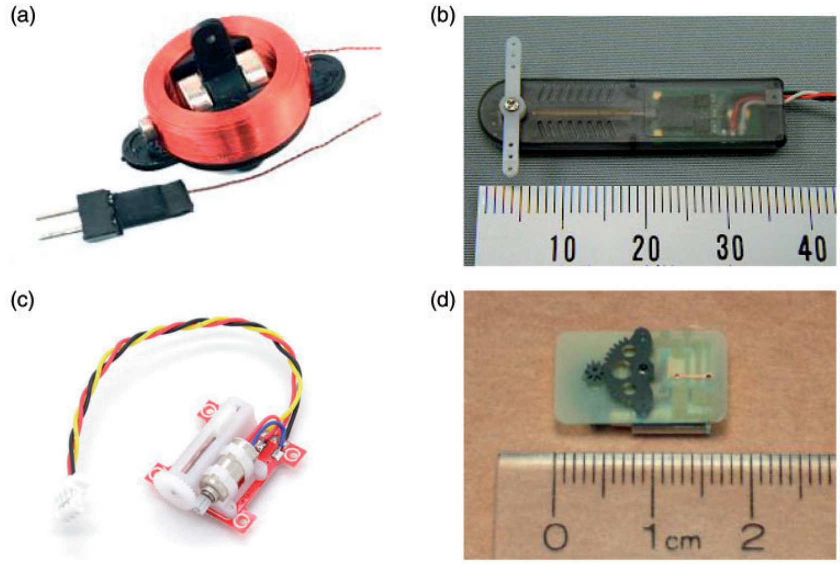

Figure 2. Overview of actuator types for lightweight flapping wing MAVs: (a) magnetic servos, (b) shape memory alloy servos, and (c, d) servos with brushed DCs (images from www.microflight.com,www.servoshop.co.uk, www.hobbyking.com, www.microflierradio.com).

control combined with three external actuators – for instance, to move the roots of trailing edges[18] or drive all the flapping DOFs.[17] Since actuators do not contribute to thrust generation but only add weight, these must be very light. Finding sufficiently light, fast, and strong actuators is an integral part of designing a flight-capable multi-DOF flapping mechanism.

Actuator review

The main driving motor must be sized to produce sufficient thrust. Sizing the control actuators is more complex. In practice, on small flapping wing vehicles in the presence of disturbance, actuators must be fast, strong, and light. This combined requirement is not trivial.

Coil actuators (Figure 2(a)) are fast but create very small moments, which makes them suitable only for actuation of conventional tail control surfaces. Shape memory alloys (Figure 2(b)) have shown high strength at minimal weight, but are slow, fragile, and create minimal deflections that need to be amplified.

Most servos consist of small brushed motors with a reduction gearbox and include a position feedback mechanism with a potentiometer (Figure 2(c)) or magnet and hall effect sensor (Figure 2(d)). The gear ratio can be altered to change the speed versus force, but to increase both, a larger and heavier motor is needed; its size can even come close to the one of the main flapping motor. In contrast with the main motor which runs all the time, actuator motors are used very inefficiently and only work part of the time.

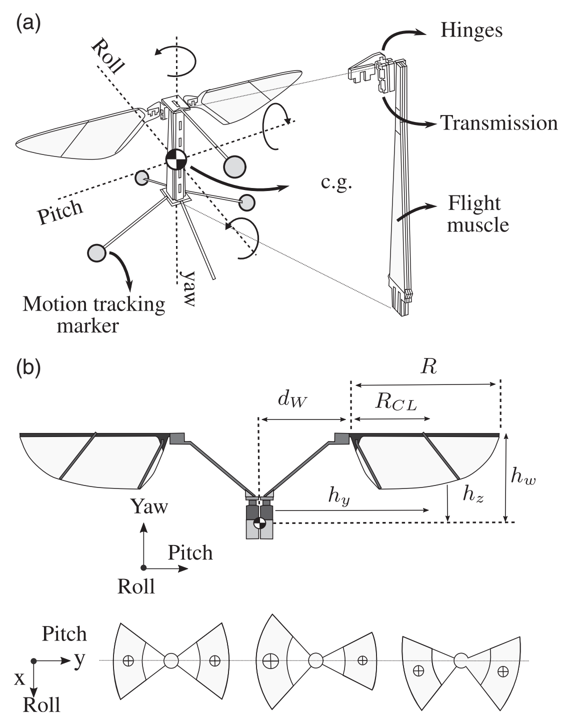

Figure 3. MAV designs that use their main actuators also for control: (a) piezo actuators[14] and (b) brushed DCs.[19]

Moment control using the flapping motor

To use most of the actuators in their efficient regime, the main flapping actuator(s) can be used to also generate the control moments. Such ideas are not novel. RoboBee[14] uses the two main flapping piezo-actuators driven with independent waveforms to generate the four independent controls (see Figure 3 (a)). The flapping amplitudes of the left and right wings can be driven independently, and a bias can be added (to both actuators) for pitch control. Finally, a speed difference in up- and downstroke can generate yaw moments, while the same flapping motion also provides the main thrust force.

The quest to achieve this same idea using traditional rotating electric motors has led some researchers to attach brushed motors directly to the wings[19] as illustrated in Figure 3(b). These motors are used outside their design operational regime with very low efficiency and high wear as they vibrate back and forth instead of turning in one direction at high speed. Nevertheless, their efficiency can be improved by using resonance mechanisms. All three required control moments can be generated by varying amplitude of the stroke and velocity profiles within the stroke in a differential way (left/right and upstroke/downstroke).

Still, electric motors are most efficient when turning at higher speed, in which case a crank mechanism is required. Unless a variable crank mechanism is used – which in turn is controlled by actuators – this makes it impossible to vary amplitude anymore while also the phase and frequency become coupled.

To generate different thrust on the left and right wings, they must be uncoupled and driven by separate motors. In this case, the motors are used efficiently, since their main task remains to be thrust generation, while variations anywhere between zero and full power

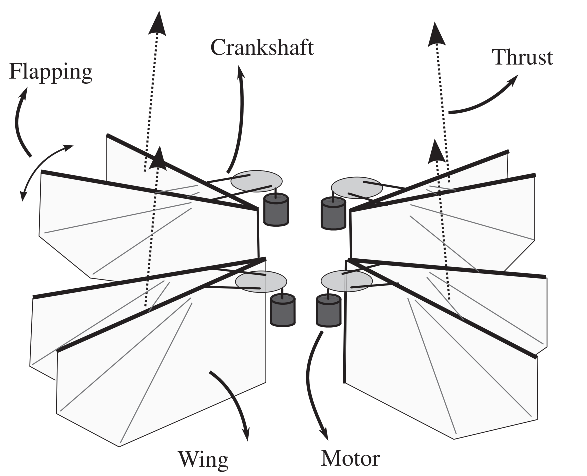

Figure 4. Quad-thopter. Four pairs of flapping wings are arranged in an X-configuration with a small angle between thrust vectors to allow control of the yaw axis.

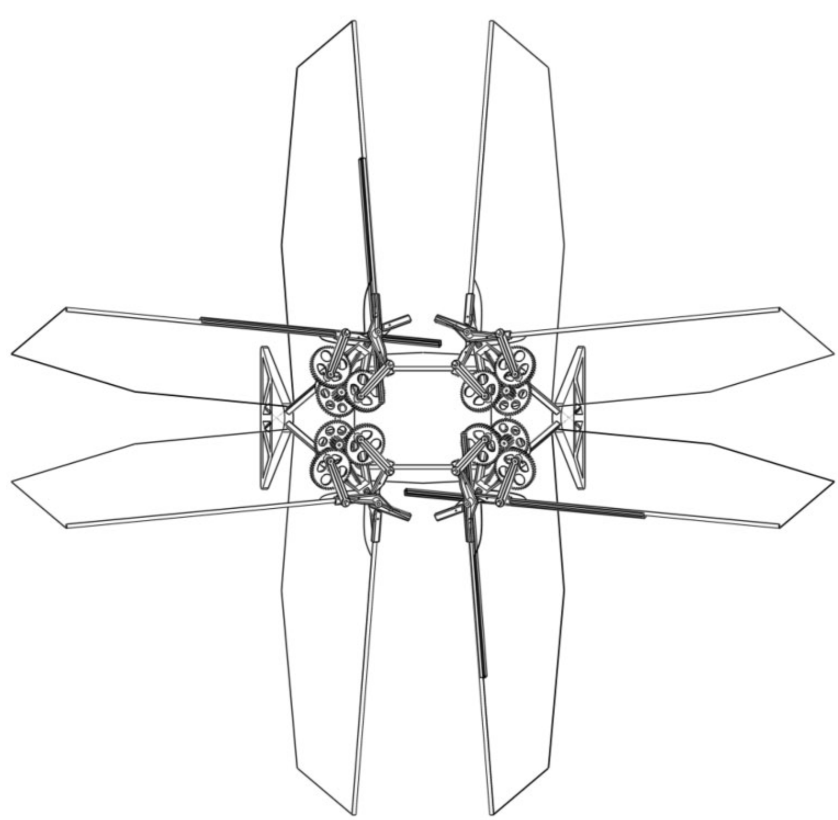

Figure 5. Quad-thopter final prototype – top view. When thrust vectors are non-parallel, two oping pairs of wings can create a yaw moment. The maximal dimension is 28 cm from tip to tip and the weight is 37.9 g with a 205 mAh battery.

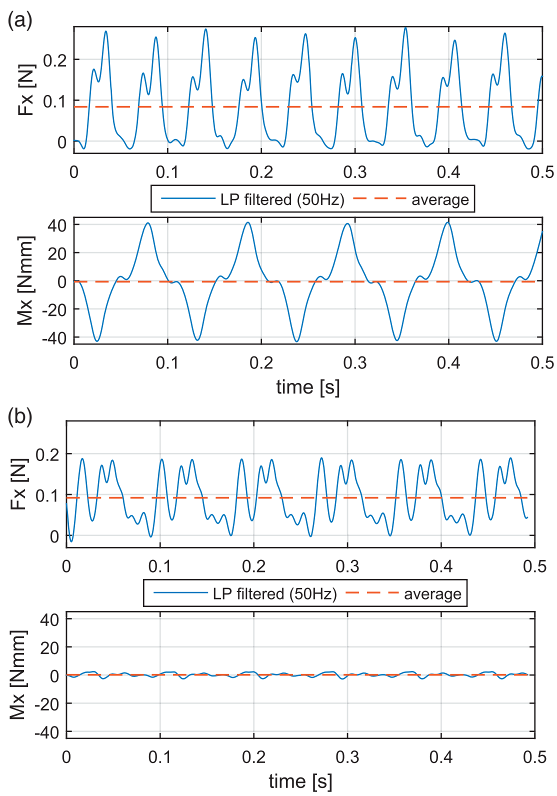

Figure 6. Thrust force and moment around principal body axis (data include also inertial effects): (a) single wing flapping with 90° amplitude and (b) double-wing flapping in antiphase with 40° amplitude. The reaction torque on the body is significantly reduced when using the double-wing setup while generating a similar amount of thrust as the single wing.

can yield very large moments with minimal response times. This, however, comes at a cost that it is impossible to keep both wings in phase.

The quad-thopter

In order to have full control authority in hover, which requires an independent generation of at the three body moments and the total thrust, one solution is to combine four sets of wings, each driven by a separate motor and a crankshaft as is shown in Figure 4. When the four thrust vectors can be controlled independently, this can generate moments for attitude control much like a quadrotor, allowing full 3D hover control.

But unlike in a quadrotor, where propellers have a non-zero average torque, an additional control is needed for the yaw. This can be obtained by tilting the thrust vectors with respect to the average thrust vector as per Figure 5.

This setup does still suffer from the effect described in Section *Tailless flapping wing* that wings can flap out of phase. This could potentially lead to very large yawing moments on the fuselage, resulting in fuselage rotation that will cause loss of flapping amplitude and loss of lift. To cope with this problem, instead of using single flapping wings, a phase locked pair of wings as found in, for instance, the DelFly II[10] is used instead. This means that whatever frequency each of the four motors is running, for every single wing moving one

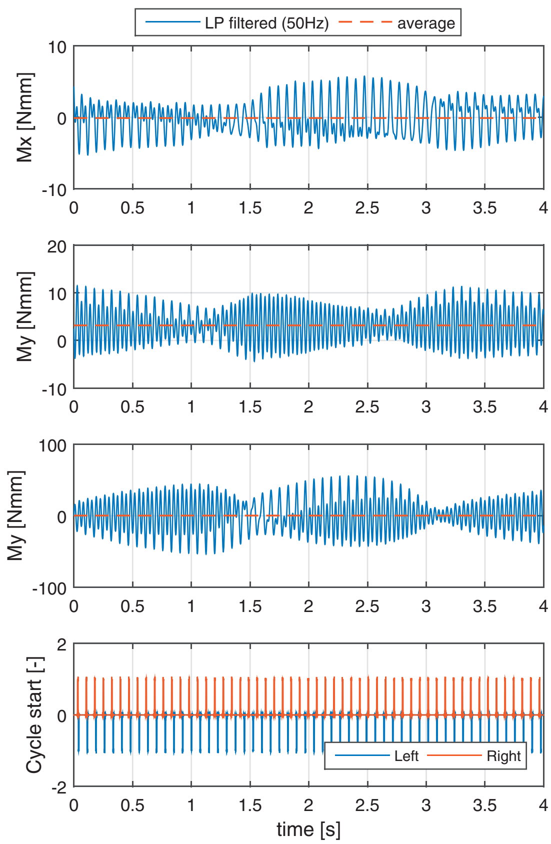

Figure 7. Two double-wing experiment: A beat phenomenon can be observed in the moment data when a difference in flapping frequencies of left and right double-wings is present. The cycle start is detected by a hall effect sensor and a magnet attached to the flapping mechanism. The residual vibration is especially strong around the roll (z) axis.

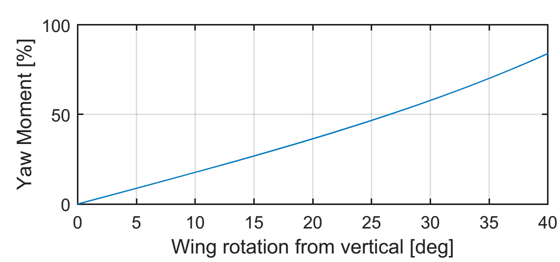

Figure 8. Yaw force in function of thrust rotation. Note that the yawing moment increases more than linearly with the wing rotation due to the average hover-lift increase caused by the efficiency loss.

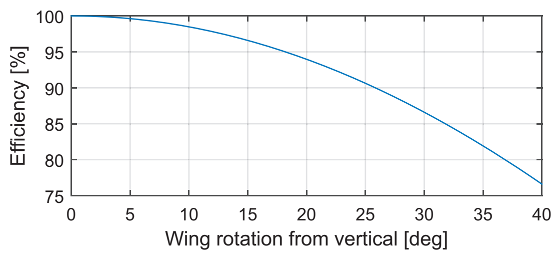

Figure 9. Efficiency in function of thrust rotation.

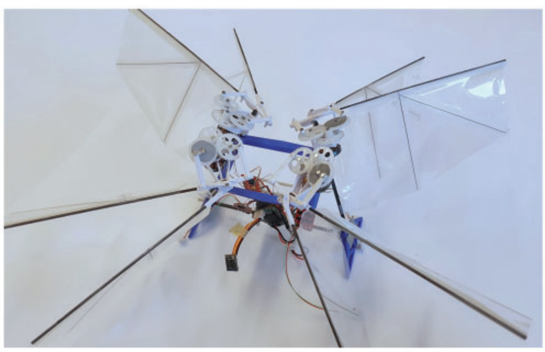

Figure 10. Photo of the final quad-thopter prototype.

Table 1. Weight breakdown of the final quad-thopter prototype.

Part	Mass
4 wing pairs with gears, motor and ESC	5.06 g × 4
3D printed frame parts	5.95 g
Frame carbon	2.2 g
3D printed battery holder	1.2 g
Wires	0.43 g
Lisa-MX-S autopilot	0.95 g
Deltang Rx31 receiver	0.23 g
205mAh 1 cell LiPo battery	6.7 g
Total	37.9 g

way there is a corresponding wing moving the other way, canceling each other out.

The resulting setup has fast and powerful attitude control while its complexity remains moderate. On the one hand, four gearboxes are needed, but on the other hand, a simple fixed gear crankshaft can be used. Fragile, underpowered, slow or expensive actuators are no longer needed. In terms of weight, all actuators are directly used to create thrust, which increases efficiency and the maximally available thrust.

The lack of tail section significantly reduces the sensitivity for perturbations, while active attitude control with full authority controls the attitude. This enables maneuvers that were not possible with the tail, like a fast vertical descend.

The platform is capable to transition to forward flight in the same way as its tailed counterpart. In forward flight, attitude must also be actively controlled. Similarly, as with hybrids like the Quadshot,[5] the vehicle pitches down almost 90° and the wings start to produce lift perpendicularly to the thrust direction.

Residual vibration

Although the moments of the flapping itself are canceled out during stationary hover as shown in Figure 6, the thrust generated by a wing pair is non-constant in time. The fact that all wings generate thrust and flapping torque with peaks at different times still results in vibrations on the main central fuselage.

The DelFly concept has been using a double pair of flapping wings to minimize fuselage rocking. For every wing performing an upstroke, there is exactly one wing doing a downstroke. The double pair of wings doing clap and fling has also shown to be able to achieve higher thrust density.[10]

This concept can be re-used in the tailless flapper with four wings and four motors. Replacing every wing with a pair of wings flapping in antiphase removed the largest residual vibration. The wing mass, in this case, does not cause large inertial vibrations anymore, because for any wing moving in one direction another wing moves in the opposing direction.

The result is a vehicle with four main driving motors and four pairs of flapping wings flapping at different rates. The main residual vibration now is when two opposing pairs flap with 90° phase shift, with the difference between the minimal thrust during a stroke and the maximum thrust during a stroke as the driving force for the vibration. Due to their different rates, the phase shift is not constant, but varies over time; a beat phenomenon (vibration of pulsating amplitude) will be present, see Figure 7. When using a wing design with small thrust variation during a stroke, this vibration can be reduced to acceptably small levels.

To keep fuselage motion to a minimum, fuselage inertia $I = m \cdot r^2$ can play an important role.

Yaw versus thrust efficiency

Pitch and roll are driven by differences in thrust generated by the left and right wings and fore and aft wings, respectively, but yaw is less evident. To achieve yaw, the lift vectors of two opposing wings are misaligned with respect to the vertical body axis. One diagonal is given a right-hand yawing alignment, while the other pair of wings is given a left-hand yawing moment.

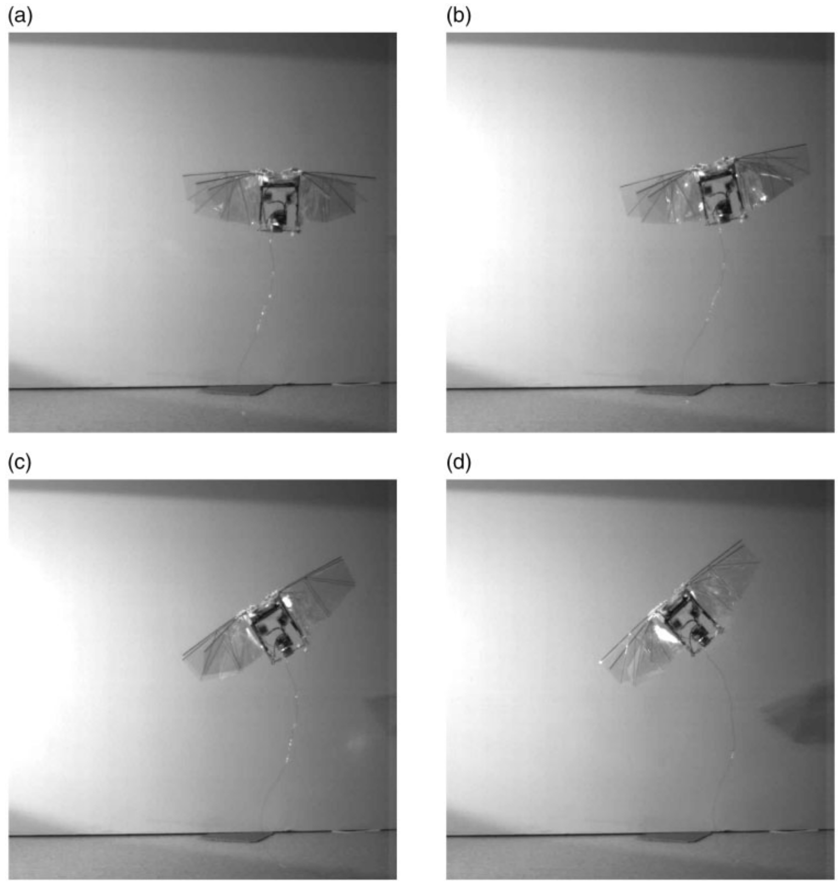

Figure 11. High-speed camera recordings at 66.6 ms interval show a step in attitude from hover to a steady 40° of roll being executed in less than 266 ms or less than four wing beats at 15 Hz.

The amount of misalignment can be used to increase the yaw control effectiveness (See Figure 8) at the cost of less efficient thrust generation as not all lift vectors now point perfectly upward.

Since thrust efficiency is lost to achieve yaw control (See Figure 9), the yaw channel could still benefit from using an actuator instead. Since the yaw is very well damped thanks to the wing area, a slower but more powerful actuator could still be considered to, for instance, deflect the trailing edges of the wing[18] to also deflect the thrust vector. In this case, only three sets of flapping wings would be required for full attitude control much like the tri-copter concept.

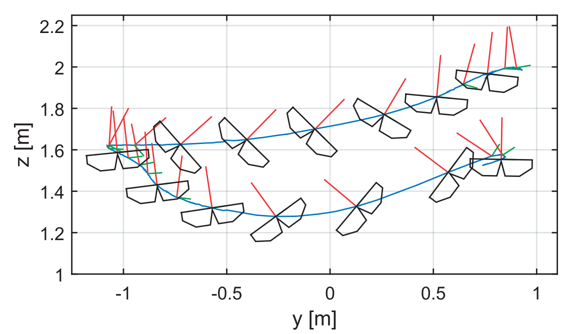

Figure 12. Indoor test flight recorded by Optitrack. The quad-thopter starts at the bottom right and makes a 2 m step to the left and then back to the right in under 3 s. Note that the vehicle does not need negative roll during the slow down.

Flight testing

A quad-thopter was built using DelFly II flapping mechanisms. Instead of a double pair of wings, only one side was mounted per flapping mechanism. DelFly II brushless motors were used and equipped with 3.5 Amp BLDC motor controllers.Brushless Direct Current Since the vehicle is not naturally stable, a paparazzi-UAV[20] Lisa-MX-S[21] autopilot was mounted. Standard rotorcraft stabilization was programmed and the quad-thopter was tuned during manual flight in attitude direct mode.

An initial prototype was used in the high-speed camera recordings and outdoor flights. A final prototype was used in the indoor lateral step tests. Figure 10 shows a photo of the final prototype. Table 1 gives the weight breakdown of the final prototype.

Figure 11 shows the response to a 40° step input in roll. Within less than four beats of the fastest flapping wings (15 Hz) the attitude change was fully obtained.

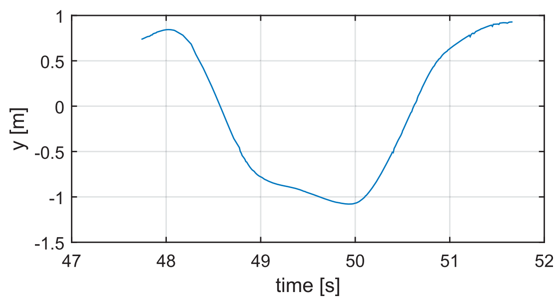

Figure 13. Lateral position change in function of time during the lateral step shown in Figure 12.

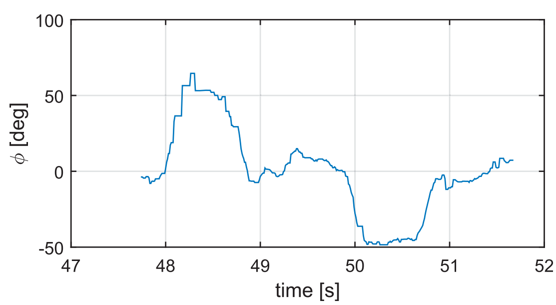

Figure 14. Roll angle during lateral step.

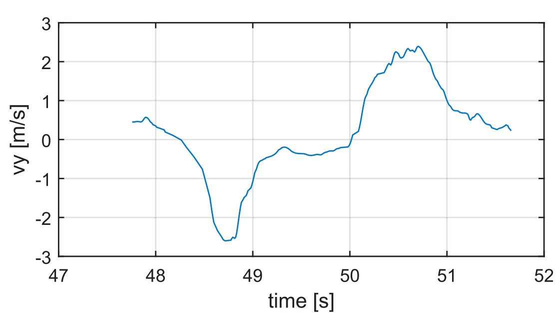

Figure 15. Speed during lateral step.

Position step responses were performed using the prototype shown in Figure 10 and measured using an Optitrack camera system. The quad-thopter was commanded in attitude mode to make a lateral step of about 2 m. A side view of the maneuver is shown in Figure 12. The quad-thopter will quickly reach the commanded left roll angle of 50° and start accelerating. About half a meter before the target, the attitude is commanded to zero. Because of the lateral area of the wings and relatively low wing loading, the quad-thopter stops by itself when commanded back to zero attitude. Then a right step is commanded. Everything combined is executed in under 3 s.

The corresponding timing of the motion is shown in Figure 13. As can be seen, the entire lateral acceleration from hover followed by 2-m motion and deceleration only takes about 1 s. Figure 14 shows the roll angle of the quad-thopter during the maneuver. It shows that roll angles of over 50° are achieved in about a quarter of a second.

Finally, the speed profile of the lateral step is shown in Figure 15. Note that during the lateral step the quad-thopter was only rolled 50° and did not nearly reach its maximum speed but instead was subjected to lateral drag.

Lateral steps at higher angles were performed but often resulted in lost tracking from the Optitrack. One sequence at 80° roll was successfully recorded during a 3-m lateral step as shown in Figure 16. As shown in Figure 17 the quad-thopter reaches speeds of 3.5 m/s and roll angles of 80° while stepping sideways 3 m in less than 1.5 s.

To illustrate the forward flight and disturbance handling capabilities, outdoor flights have been performed as shown in Figure 18. Very aggressive start and stops are possible. When compared to DelFly II with its aerodynamic tail, the sensitivity to turbulence is reduced an order of magnitude by the fast powerful moments created by opposing wing pairs and stabilized by electronic attitude control. The maximal flight speed, however, is very close to that of DelFly II and

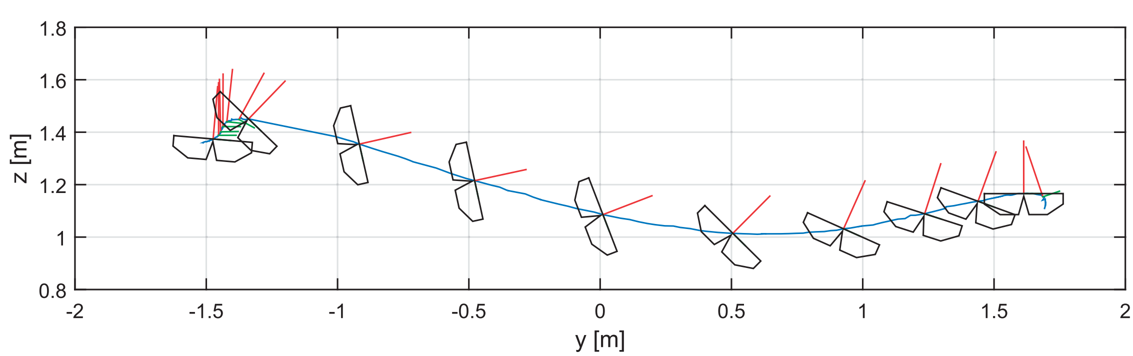

Figure 16. A 3-m lateral command where speeds of 3.5 m/s and angles of 80° roll are reached.

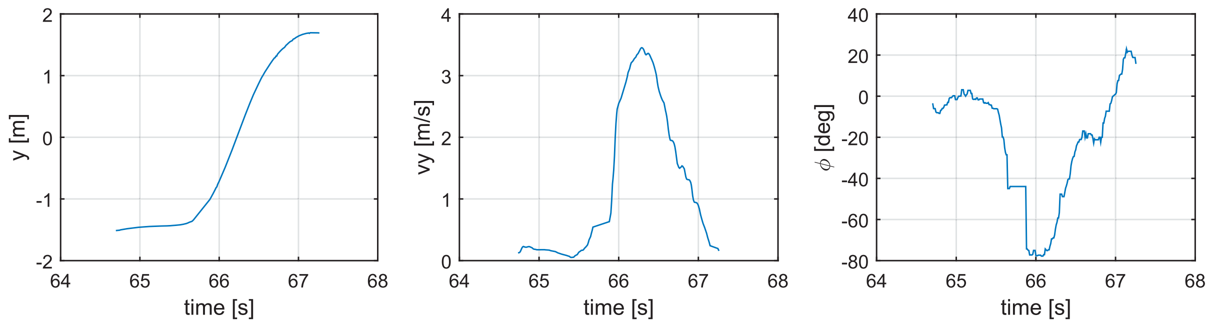

Figure 17. Position, speed, and attitude captured by an external optitrack motion tracking system during a 3-m lateral step command.

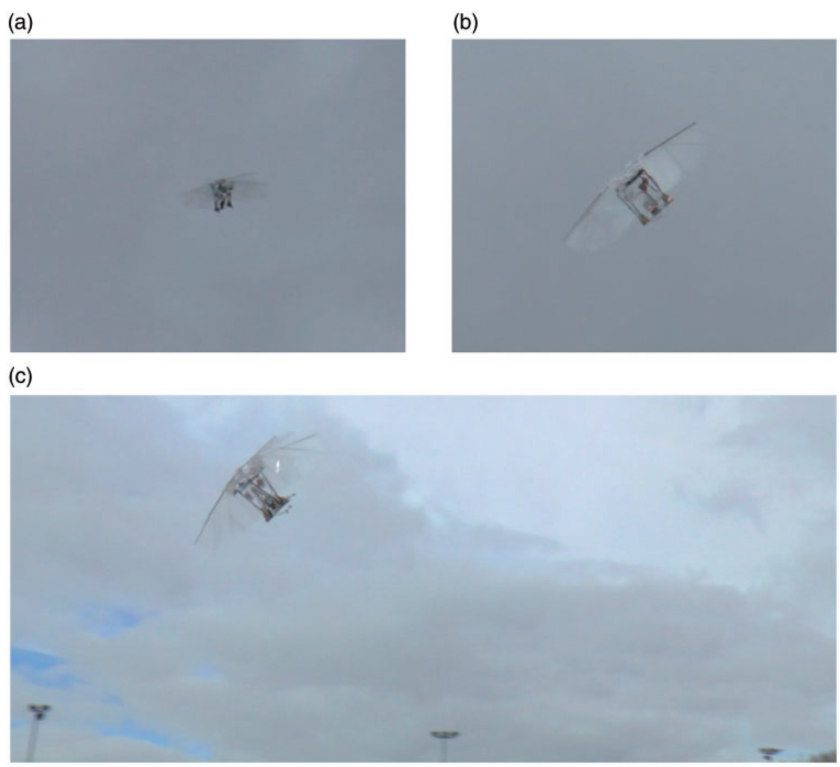

Figure 18. Quad-thopter in-flight outdoor in various phases of the flight: (a) hover, (b) semi-transitioned, (c) fast forward flight.

is limited by the maximal flapping frequency that can be obtained.

Video footage of quad-thopter flight was placed on YouTube (https://www.youtube.com/playlist?list=PL_KSX9GOn2P9HTG4SY59KbgH2fT9cxY06).

Conclusions

In this paper, we proposed a novel flapping wing design, a 'quad-thopter'. In the article, we have discussed the various design parameters relevant to a highly maneuverable, tailless flapping wing MAV. We conclude that the design represents a close-to-optimal choice in the design space consisting of the magnitude of the generated control moments, the control bandwidth, and the weight, size and energy requirements of the actuators. In addition, the quad-thopter is relatively easy to construct with widely available current-day technology. The implementation of the design built and tested in this work has a flight time of 9 min or more, depending on the flight regime. This makes it suitable for real-world missions.

Although the presented design does not correspond to any (known) biological counterpart, the quad-thopter has a number of characteristics featured by natural fliers. For instance, the proposed quad-thopter becomes more efficient in forward flight, much more than quadrotors, increasing the range and endurance. Furthermore, the wing surfaces induce drag, which can be used for braking. This means that in contrast to quadrotors, quad-thopters do not have to thrust in the backward direction to brake, which also gives them the ability to brake faster. Finally, the quad-thopter features an enhanced safety because of the absence of fast-rotating rotors, and hence it is more suitable for flying around humans.

We hope that the presented design will be apter than previous designs for widespread use in academia and industry, helping to break the hegemony of rotorcraft and fixed wings.

Declaration of conflicting interests

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