Aerodynamics and Autonomy of the DelFly

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1 Introduction

One of the major challenges in robotics is to develop fly-sized robots that can autonomously fly around in unknown environments. The challenge derives from the fact that flying locomotion requires the robot to continuously react to its environment in real time, while the light weight of the robot significantly limits the energy, sensors, and processing onboard.

Essentially, there are two main approaches to creating fly-like robots: bottom-up and top-down. In the bottom-up approach[1,2,3], one starts by creating all the tiny parts that are deemed important to a fly-sized ornithopter. The most remarkable example of this approach is the 60 mg robotic insect developed at Harvard University, which can produce sufficient thrust to take off vertically[3]. This is achieved by using Smart Composite Microstructures (SCM). The robotic insect was still fixed to taut guide wires that restricted the robot to vertical motion and provided both energy and control. In future work, the group plans to allow all degrees of freedom and to incorporate onboard energy supply, sensors, and processing.

In the top-down approach, one starts with a fully functioning (relatively large-scale) ornithopter[4]. By studying this ornithopter, theoretical insights can be gained into the necessary properties for a smaller version. Research then progresses by creating and analyzing ever smaller systems, while always maintaining a fully functioning flying robot. One advantage of this approach is that it allows interplay between theory and practice. Especially in the field of artificial intelligence, having a physical and fully functioning robot is of great value[5,6,7]: real-world tests force the experimenters to take into account all aspects of the robotic system. In addition, they reveal physical properties of the system that can be exploited by the algorithms.

In this extended abstract, we discuss the current state of our research on aerodynamics and autonomy of the DelFly, a flapping wing MAV inspired by the dragonfly. The DelFly is part of our top-down approach in which we integrate the insights of flight experiments in the areas of aerodynamics and autonomous flight. In Section 2 we explain the main aerodynamical findings that led to the current design of the DelFly. In Section 3, we discuss our approach to achieving autonomous flight on the DelFly, focusing on the particular challenges posed by a flapping-wing MAVs. In Section 4, we conclude by explaining how both types of experimental findings influence our view on the creation of autonomous fly-sized robots.

2 Aerodynamics

The design of the DelFly is inspired by insect flight. Flapping wings simultaneously generate lift and thrust, and entail a favorable maneuverability and large flight envelope[8,9]. Indeed, the flight envelope of the DelFly II ranges from forward flight at 7 m/s to hover flight and even backward flight at 1 m/s. The most striking characteristic of DelFly's design are its two pairs of wings placed above each other. The main reason for having two wings flapping in anti-phase is to create a stable camera platform. However, the wing

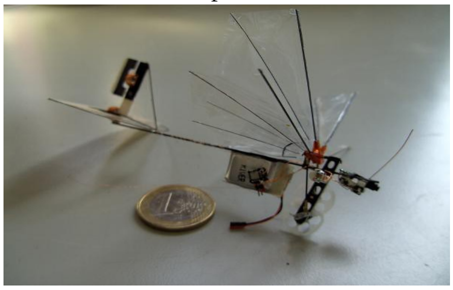

Figure 1: The DelFly Micro, 3.07g with a 10 cm wing span..

configuration also largely determines the aerodynamics and is crucial for the flight performance. A better understanding of the aerodynamic characteristics will allow us to further decrease the overall size of DelFly, while preserving its excellent flight performance. In this section, we discuss the main findings that have led to the current design. Most of this work has focused on hover flight, which is essential to autonomy experiments.

Most early design choices have been made on the basis of empirical research, measuring the generated lift and thrust-over-power ratios for different parameter choices. For example, the optimal flap angle and frequency for hovering have been determined experimentally for the DelFly II[10]. A dihedral angle of 30° to 36° was found to maximize the thrust for minimal power consumption. Some of the experiments have shown that seemingly minor design decisions may have a large impact on the aerodynamic properties. The best example in this respect is that the shape of the rod that forms the wing's leading edge has an enormous impact on the produced lift forces, determining whether or not the DelFly is able to perform the hover flight mode. A "D"-shape with the round side facing forward was found to lead to the best performance, providing more stiffness in the flapping direction than in the wing direction.

Recent research[11,12] with high-speed cameras and Particle Image Velocimetry (PIV) measurements has shed more light on the dynamic air flow around the wings during different parts of the flapping cycle, resulting in the following four main findings.

First, the D-shape of the rod results in a heaving and plunging movement that accompanies the flapping. While an insect does this actively, for the DelFly it occurs in a passive way. Due to aerodynamic, elastic and inertial forces acting on the wings, the leading edges travel in a "horizontal figure of eight" during one cycle, contributing to the lift generation.

Second, the PIV measurements show that during the translation phase of the flapping stroke, there is a leading-edge vortex (LEV) present, which is accompanied with maxima in the lift generation. The LEV does not appear to be as stable as in insect flight, since some vertex shedding is observed. For the new wing type, this is shown in the right part of Figure 2.

Third, since the biplane wings touch each other in the neutral position, the DelFly benefits from a 'clap-and-peel'

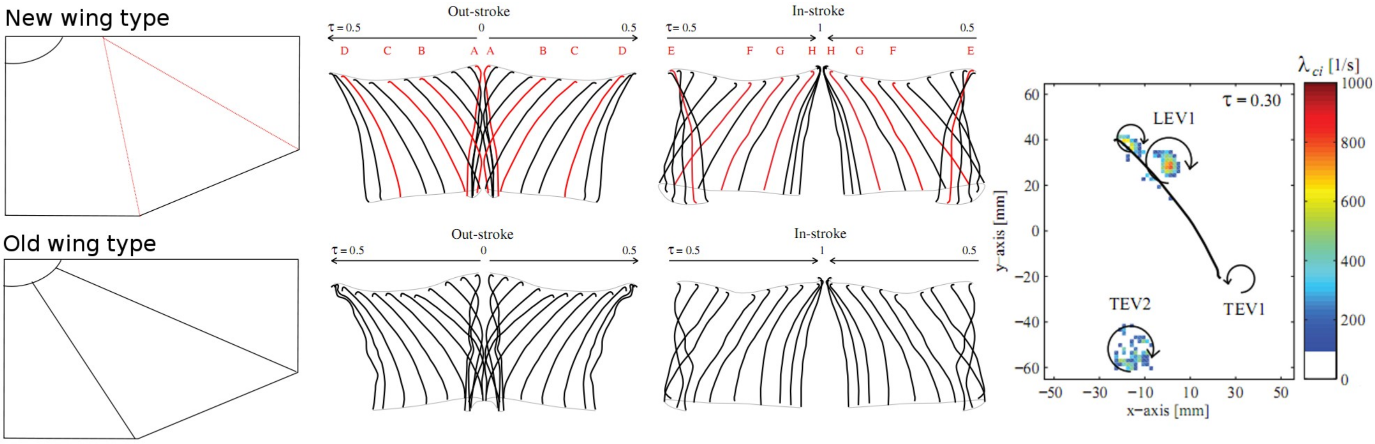

Figure 2: *Left* – placement of the stiffeners on the new wing type (top) and the old wing type (bottom). *Middle* – shape of a wing section during different phases of the flapping cycle for the new wing type (top) and the old wing type (bottom). *Right* – partial shedding of the leading-edge vortex during the peel movement.

mechanism. Due to the wing flexibility, this takes place in a gradual way, where the wings first touch at the leading edges, and with the contact point subsequently moving towards the trailing edges (see Fig. 2 center). The separation of the trailing edges occurs only halfway the outstroke. As the wings peel apart air is sucked in, which enhances the lift generation. This may be explained by a more gradual build-up of the circulation, which postpones the creation of the starting vortex and which can prevent an unstable LEV from shedding into the wake.

Fourth, both the placement and the type of the stiffeners can have a significant impact on the produced thrust and consumed power. Structured changes to both these factors lead to a new wing layout that results in a 10% higher thrust-to-power ratio. Figure 2 shows a comparison of the new wing type (top left) with the old wing type (bottom left). The new wing type features stiffeners that converge on the leading edge with smaller angles to the fuselage. The high-speed cameras have shown that this leads to a higher rigidity during the flap cycle.

For DelFly's improved wing design, the double wing configuration gives 6% more thrust than a theoretical doubling of the single wing thrust. This is much lower than the gain that insects get from this aerodynamic mechanism, which is generally assessed to be around 25% on average. A study on a 10 cm MAV of 2.3g showed an increase in thrust due to clap-and-fling which is strongly related to relative wind speed[13]. The higher the relative wind speed, the greater the clap-and-fling benefit. This can explain the difference, because the tests in this study are done for hover condition. The advantages of clap-and-peel have been exploited in the design of the DelFly Micro, which weighs 3.07 grams and has a wing span of 10 cm. DelFly Micro's wings were designed to also touch at the maximal flapping angle, creating an additional clap-and-peel movement in the middle of the flapping cycle. For the DelFly II, the improved design implies that it can operate autonomously for a longer duration.

3 Autonomous Flight

For a few decades it is now a well-accepted view that a robot's physical properties are important for the algorithms necessary to attain autonomous behavior[5,6,7]. Properties of the body, environment, and task can be exploited to devise seemingly simple sensing and control algorithms for achieving a complex task. In the DelFly project, we have mainly focused on the use of camera images for achieving basic survival skills. Our studies focus on how to extract the right information from the images fast enough for avoiding crashes with objects in indoor environments (the floor, the ceiling, and other obstacles). Advantageous properties are DelFly's passively stable flight characteristics, light weight, and slow hover mode. They allow the use of algorithms for obstacle avoidance and height control that run on frequencies in the order of ~10 Hz.

However, the particular physical realization of a robot can also pose particular challenges. Currently, a small camera onboard the DelFly is used that transmits its images analogically to a ground control station. Consequently, the images contain various types of noise. Besides thermal and other measurement noise, the images also undergo noise from interfering transmission sources such as WiFi networks. However, the most difficult properties of the images derive from the flapping-wing movements. Despite the biplane wing configuration, there is a residual motion up and down that interacts with the line-by-line-recording of the camera images, leading to heavy image distortions. Example images are shown in Figure 3. As a consequence of these image properties, well-known approaches using visual Simultaneous Localization And Mapping (SLAM) or biologically inspired optic flow methods do not give good results for indoor flight. In addition, both these methods deal quite badly with indoor environments that have little texture.

Figure 3: Two subsequent DelFly II images with image distortion.

Neuromorphic sensing with a higher time resolution[14] or future small-sized global shutter cameras may solve the image distortion problem. However, since nature often also finds solutions to difficult control problems on the basis of noisy and distorted sensor readings, we have explored novel ways to deal with the particularly challenging camera images.

The main idea behind our approach to autonomous flight is to complement optic flow information with the extraction of appearance features. Flies are known to stay away from small flying objects (possible predators) and fly towards tall

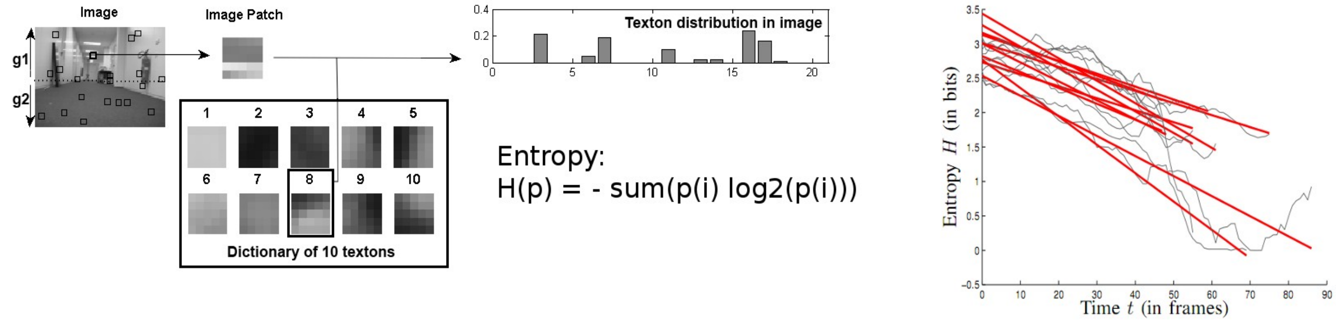

Figure 4: *From left to right*: a small number of image samples is taken from an image. The samples are compared with a texton dictionary, resulting in an estimate of the texton probability distribution in the image. The entropy of this distribution can serve as a measure of the appearance variation, which is used as a visual cue for obstacle proximity.

objects (possible feeding places)[15]. They do so by recognizing the appearance of these obstacles, since optic flow information was not present at the measured distances. We have used appearance features both for indoor height control [16] and outdoor obstacle avoidance[17]. Here, we shortly discuss our experiments on indoor obstacle avoidance[18].

Our approach to obstacle avoidance makes use of a novel appearance cue, based on the following principle. When approaching an object, its colors and detailed texture become more and more visible, while other objects move out of sight. We hypothesize that the color and detailed texture of one object typically vary less than the colors and textures of many different objects. The left part of Figure 4 shows how we estimate an image's appearance variation in a computationally efficient way by taking a small number of random image samples. Each sample is interpreted as being closest to a certain type of texture / color, resulting in a probability distribution of different colors and textures. The appearance variation can then be measured as the entropy of this distribution. The right part of Figure 4 shows the changes in entropy when the DelFly approaches different indoor obstacles. On this data set with only 10 videos, the entropy always decreases. Tests on more elaborate data sets showed a 90% entropy decrease for indoor environments and a 70% entropy decrease for outdoor environments. The entropy measurements can be performed reliably at ~30 Hz (camera frame rate) in an offboard processing setup, which is fast enough for real-time control. The combination of optic flow and the appearance variation cue resulted in better obstacle detection and more robust obstacle avoidance performance. A video of the technique can be found at http://www.delfly.nl/.

4 Conclusion

The DelFly is still a long way from a fly-sized autonomously flying robot. Still, the experimental findings discussed in this article show that the top-down approach leads to the identification of some of the key properties necessary for such a flapping wing robot. The influence of the different design parameters on the thrust-over-power ratio of the DelFly II are likely to still play a role on a smaller scale, as was already experienced with the DelFly Micro. In the area of design, a resonant flapping-wing mechanism would be a very interesting research direction, since it would further improve the energy efficiency. In addition, an active heaving and plunging mechanism would be worth investigating. In the area of autonomy, the investigation of neuromorphic computation could form a significant step forward. Moreover, enhanced insight into the processing of appearance cues by biological entities could contribute to more robust autonomous flight. Attaining a fly-sized autonomously flying robot is essentially a multi-disciplinary effort, and will eventually benefit from both the bottom-up and top-down approach.

References

1 Steltz, E., Avadhanula, S., and Fearing, R.S., "High Lift Force with 275 Hz Wing Beat in MFI", IEEE International Conference on Intelligent Robots and Systems, San Diego, October, 2007.

2 Steltz, E., Avadhanula, S., and Fearing, R.S., "High Lift Force with 275 Hz Wing Beat in MFI", IEEE International Conference on Intelligent Robots and Systems, San Diego, October, 2007.

3 Wood, R.J. "The first takeoff of a biologically-inspired at-scale robotic insect", IEEE Tranactions on Robotics, Vol. 24, No. 2, pp. 341-347, April, 2008.

4 G.C.H.E. de Croon, K.M.E. de Clercq, R. Ruijsink, B. Remes, and C. de Wagter, "Design, aerodynamics, and vision-based control of the DelFly", International Journal of Micro Air Vehicles, volume 1, number 2, 2010.

5 Brooks, R. A., "Elephants don't play chess.", Robotics and Autonomous Systems, Volume 6, Numbers 1–2, pp. 3–15, 1990.

6 Pfeifer, R. and Scheier, C. "Understanding Intelligence." MIT Press, Cambridge, MA, 1999.

7 Nolfi, S. and Floreano, D. "Evolutionary Robotics: The Biology, Intelligence, and Technology of Self-Organizing Machines.", MIT Press / Bradford Books, Cambridge, MA, 2000.

8 Ellington, C.P., Berg, C. van den, Willmott, A.P., and Thomas, A.L.R. "Leading-edge vortices in insect flight" Nature Vol. 384, Issue 19/26, pp. 626-630, 1996.

9 Dickinson, M.H., Lehmann F.-O., and Sane, S.P., "Wing Rotation and the Aerodynamic Basis of Insect Flight", Science, Vol. 284. no. 5422, pp. 1954 – 1960, 1999.

10 Bradshaw, N.L., and Lentink, D. "Aerodynamic and structural dynamic identification of a flapping wing micro air vehicle", American Institute of Aeronautics and Astronautics, 26th AIAA Applied Aerodynamics Conference, 2008.

11 K.M.E. De Clercq, R. de Kat, B. Remes, B.W. Van Oudheusden, and H. Bijl, "Aerodynamics experiments on DelFly II: unsteady lift enhancement", International Journal of Micro Air Vehicles, volume 1, number 4, 2010.

12 M. Groen, B. Bruggeman, B. Remes, R. Ruijsink, B.W. Van Oudheusden, and H. Bijl, "Improving flight performance of the flapping wing MAV DelFly II", IMAV 2010, Braunschweig, Germany, 2010.

13 Y. Kawamura, S. Souda, S. Nishimoto, C.P. Ellington, "Clapping-wing Micro Air Vehicle of Insect Size", Biomedical and life sciences, part 3, pp. 319-330, 2008.

14 N. Franceschini, S. Viollet, F. Ruffier, and J. Serres "Neuromimetic Robots Inspired by Insect Vision", Journal Advances in Science and Technology (Volume 58), Pages 127-136, 2008

15 G. Maimon, A.D. Straw and M.H. Dickinson, "A Simple Vision-Based Algorithm for Decision Making in Flying Drosophila", Current Biology, Volume 18, Issue 6, 2008, pages 464-470.

16 G.C.H.E. de Croon, E. de Weerdt, C. De Wagter, B. Remes, and R. Ruijsink, "Random sampling for indoor flight", IMAV 2010, Braunschweig, Germany, 2010.

17 G.C.H.E. de Croon, C. De Wagter, B. Remes, and R. Ruijsink, "Obstacle avoidance for MAVs by recognizing the sky", submitted.

18 G.C.H.E. de Croon, E. de Weerdt, C. De Wagter, B. Remes, "The appearance variation cue for obstacle avoidance", IEEE ROBIO 2010.