Optic flow to control small UAVs

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Abstract— **Autonomous flight in confined or cluttered environments such as houses or urban canyons requires high manoeuvrability, fast mapping from sensors to actuators and very limited overall system weight. Although flying animals are well capable of coping with such situations, roboticists still have difficulties at reproducing such capabilities. This paper describes how we took inspiration from flying insects to progress toward the goal of developing small UAVs able to dynamically fly in cluttered environments. This endeavour allowed us to demonstrate a 10-gram microflyer capable of fully autonomous operation in an office-sized room using fly-inspired vision, inertial and airspeed sensors. This encouraging result is now being ported to outdoor scenarios such as low-altitude flight in urban or mountainous environments. Important is that these autonomous capabilities are achieved without the help of GPS nor active range finders, which allows to develop very lightweight autopilots.**[1]

I. INTRODUCTION

Current UAVs tend to fly in open sky, far from any obstacles and rely on external beacons – mainly GPS – to localise themselves and navigate. This approach precludes them from evolving autonomously at low altitude, in cluttered or confined environments as insects do. At EPFL, we have been developing control strategies allowing for automating flight and collision avoidance without relying on external aids nor active distance sensors [8]. To achieve this, we took inspiration from flies and bees, studied their sensor suites and ways of processing information in order to extract principles that could then be applied to small artificial flyers. It turned out that insects are mainly relying on low-resolution, monocular vision [4], inertial [5] and airflow sensors [2] to control their flight. This is interesting because the corresponding sensors are now commercially available with small, light packaging, and extremely low power. Therefore, rather than opting for bulky active 3D range finders weighing a few kilograms [6], dynamic flight in the vicinity of obstacles can be achieved with far lower weight by using passive sensors such as vision, MEMS rate gyros and miniature anemometers.

II. AUTONOMOUS FLIGHT INDOORS

As a first step towards the realisation of completely autonomous flying systems, we decided to impose dramatic weight constraints by developing an indoor flying platform. Flying indoor requires slow motion and small size, which calls for ultra-light overall weight. Our current prototype, the *MC2*

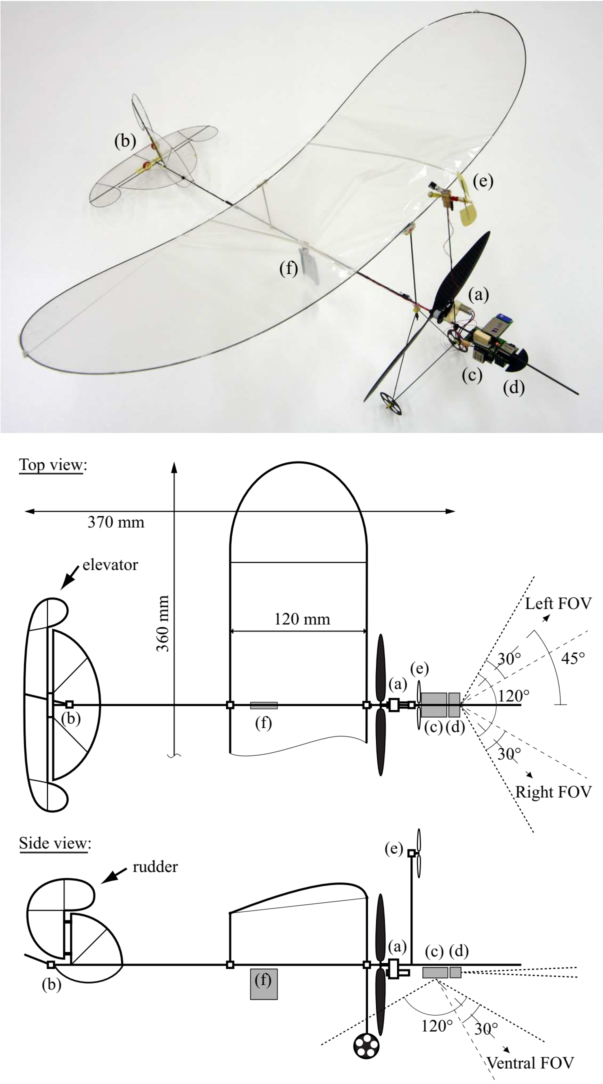

Fig. 1. The 10-gram *MC2* microflyer. The on-board electronics consists of (a) a 4 mm geared motor with a lightweight carbon fiber propeller, (b) two magnet-in-a-coil actuators controlling the rudder and the elevator, (c) a microcontroller board with a Bluetooth module and a ventral camera with its pitch rate gyro, (d) a front camera with its yaw rate gyro, (e) an anemometer, and (f) a 65 mAh lithium-polymer battery.

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(figure 1) is based on a remote-controlled 5.2-gram home flyer designed by Didel SA for the hobbyist market. This model consists mainly of carbon fiber rods and thin Mylar plastic films. The wing and the battery are connected to the frame by small magnets such that they can easily be taken apart. Propulsion is ensured by a 4-mm brushed DC motor, which transmits its torque to a lightweight carbon-fiber propeller via a 1:12 gearbox. The rudder and elevator are actuated by two magnet-in-a-coil actuators. The stock model airplane has been transformed into a robot by adding the required electronics and modifying the position of the propeller in order to free the field of view in the flight direction. When equipped with sensors and electronics, the total weight of the *MC2* reaches 10.3 g [10]. In its robotic configuration, the airplane is capable of flying in reasonably small spaces at low velocity (around 1.5 m/s). The average consumption is in the order of 1 W and the on-board 65 mAh lithium-polymer battery ensures an endurance of about 10 minutes.

Regarding the sensor suite, we implemented the same sensory modalities as in flies. Since omnidirectional vision is not yet feasible on such lightweight UAVs, we opted for two wide FOV, linear cameras. Only three segments of 20 pixels out of these two cameras have been selected for optic-flow extraction in three specific directions: left, right, and down. Additionally, two MEMS gyros have been mounted to sense pitching and yawing rates. Finally, a small custom-made anemometer ensures the functionality of airflow sensing. These sensors are connected to the onboard 8-bit microcontroller, which processes image sequences to estimate radial optic flow in the three viewing directions using an image interpolation algorithm [7], [9].

The rationale behind our control strategy is that optic flow estimates can be interpreted as proximity values if the following conditions are respected:

1) the rotational optic-flow component (i.e. the optic flow due to self-rotations) is removed in order to keep only the translational part of it, which alone carries information about depth; this process is often referred to as *derotation*;
2) the angle (also called eccentricity) between the flight direction and the viewing direction of an optic-flow detector must be large enough to get usable optic-flow values; this is because the translational optic-flow amplitude is proportional to the sine of this angle [3], [8];
3) the forward velocity of the airplane needs to be regulated in order to lower the effect of speed variations on optic flow.

In our case, the first condition is ensured by subtracting self-rotations as provided from the two rate gyros from the optic-flow measurements. This is possible because rotational optic flow is not sensitive to distances and we showed that its amplitude almost perfectly follows the rate gyro measurements when the airplane is undergoing pure rotational movements [9]. The second conditions is achieved by having an angle of 45° between the flight direction of the airplane (which is roughly parallel to the fuselage) and the viewing directions of the optic-flow detectors (OFD, see figure 2). The third condition is approximately met by means of a proportional controller linking the anemometer output to the torque applied to the main propeller. Optic-flow values can therefore be interpreted as proximity indicators, whose output can be mapped into actuator commands by means of simple weighted connections (figure 3). This way of directly connecting inputs to outputs is inspired from Braitenberg [1] and allows for very reactive flight while avoiding computationally expensive deliberative layers.

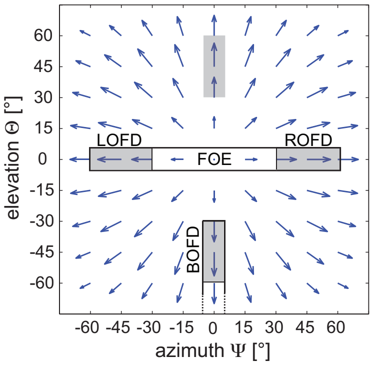

Fig. 2. Typical translational optic-flow pattern arising in the frontal field of view (here represented with an azimuth-elevation graph). The thick rectangles represent the zones covered by the two cameras mounted on the *MC2*. By carefully defining the sub-regions where optic-flow is extracted (gray zones within the rectangles), three radial optic-flow detectors (OFD) can be implemented at an equal eccentricity of 45° with respect to the flight direction. These are prefixed with L, B, and R for left, bottom and right, respectively.

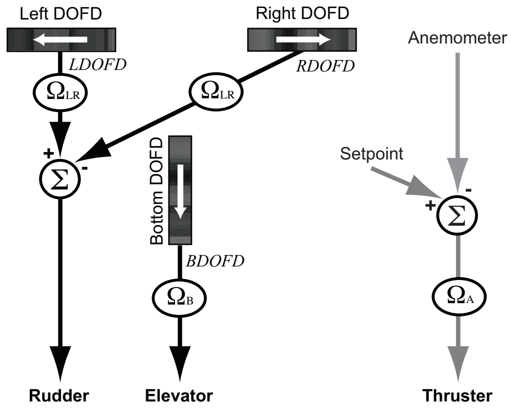

Fig. 3. The control scheme for completely autonomous navigation and 3D collision avoidance. The three OFDs are prefixed with D to indicate that they are derotated (see text for details). The signals produced by the left and right DOFDs, i.e. *LDOFD* and *RDOFD*, are basically subtracted to control the rudder, whereas the signal from the bottom DOFD, i.e. *BDOFD*, directly drives the elevator. The anemometer is compared to a given set-point to output a signal that is used to proportionally drive the thruster. The Ω ellipses indicate that a transfer function is used to tune the resulting behaviour. These can be simple gains or combinations of a threshold and a gain.

After some tuning of the parameters included in the Ω transfer functions (threshold and gains), the simulated *MC2* could efficiently circle the room while avoiding collisions with

Fig. 4. The 400-gram flying wing testbed that will be used for optic-flow-based navigation in cluttered outdoor environments.

the ground and the surrounding walls.[2] After being launched by hand in the test arena, the *MC2* would fly autonomously for a few minutes until caught by the experimenter.

III. CONCLUSION AND FUTURE WORK

Instead of flying straight and level between GPS waypoints, flying in cluttered environments requires continuous maneuvering and quick reactions to avoid collisions. The use of insect-inspired sensors and control strategies allowed us to demonstrate autonomous operation of a 10-gram airplane in a confined environment. This is the result of a search for a minimal way of automating an ultralight flying system that cannot rely on classical range finders, nor external aids. We believe that a generalized version of the proposed control strategy[3] can easily be ported to larger platforms, which would allow for a greater number of pixels and thus more optic-flow detectors while keeping its reactive nature. Covering a larger fraction of the field of view will improve the robustness in presence of poorly textured or geometrically complex obstacles. Preliminary experiments in simulation yielded good results with a model of our 400-gram flying wing (figure 4) in various kinds of cluttered environments such as cities or hilly regions. We are now in the process of transferring these results to the actual UAV.

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[2] The video corresponding to this experiment can bee downloaded from http://lis.epfl.ch/microflyers

[3] Patent pending: PCT/IB2008/051497