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From Bees' surface following to Lunar landing

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To better grasp the visuomotor control system underlying insects' height and speed control (Srinivasan et al. 1996, Portelli et al. 2010a), we attempted to interfere with this system by producing a major perturbation on the free flying insect and observing the effect of this perturbation. Honeybees were trained to fly along a high-roofed tunnel, part of which was equipped with a moving floor. The bees followed the *stationary* part of the floor at a given height. On encountering the *moving* part of the floor, which moved in the same direction as their flight, honeybees descended and flew at a lower height (See Fig. 1 E-F). In so doing, bees gradually restored their ventral optic flow (OF) to a similar optic flow value to that they had perceived when flying over the stationary part of the floor. OF restoration therefore relied on lowering the groundheight rather than increasing the groundspeed (Portelli, Ruffier, Franceschini 2010b).

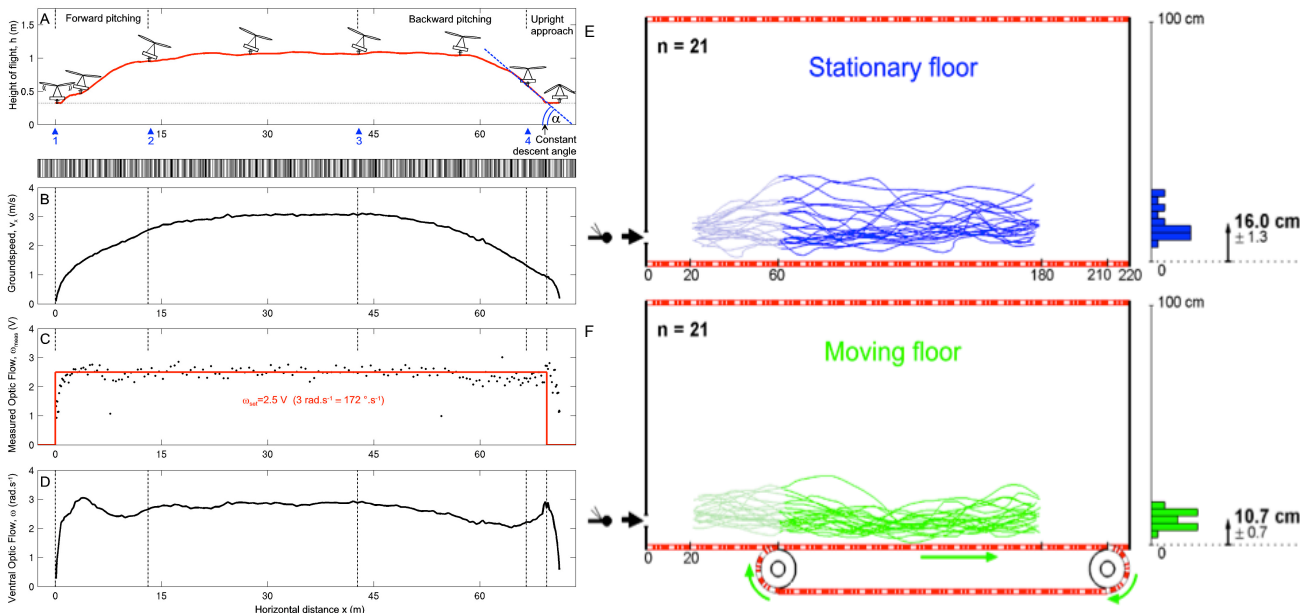


Figure 1: Honeybees altitude control accounting for the ventral optic flow regulator demonstrated here on a robotic Micro-Helicopter (MH) (A-D) Flight Parameters Monitored during a 70 m Flight performed by the robotic micro-helicopter equipped with an Optic-Flow Regulator. The complete journey (over the randomly textured pattern shown in [A]) includes take-off, level flight, and automatic landing. (A) Vertical trajectory in the longitudinal plane. On the left, the operator simply pitched the MH forward rampwise by an angle of 10° (between arrowheads 1 and 2). The ensuing increase in groundspeed (up to 3 m/s; see [B]) automatically triggered a proportional increase in groundheight: the MH climbed and flew level at a groundheight of approximately 1 m, as dictated by the OF set-point ($\omega_{set} = 3 \text{ rad/s}$, i.e., $172^\circ/\text{s}$, i.e., 2.5V as shown in [C]). After flying 42 m, the MH was simply pitched backward rampwise by an opposite angle of -10° (between arrowheads 3 and 4), and the ensuing deceleration (see [B]) automatically initiated a proportional decrease in groundheight until landing occurred. During the final approach, which started when the MH had regained its completely upright position (arrowhead 4), the robot can be seen to have flown at a constant descent angle, as also observed in bees' landing performances (Srinivasan et al. 2000). Because the landing gear maintains the robot's eye 0.3 m above ground (dotted horizontal line), touchdown occurs shortly before the groundspeed v_x has reached zero, and the MH ends its journey with a short ground run. (B) Groundspeed v_x was monitored throughout the journey. (C) Output ω_{meas} of the OF sensor was monitored throughout the journey and shows the relatively small deviation from the OF set-point ω_{set} (in red); even during the transient initial and final stages where the groundspeed varies considerably, see [B]. (D) Ventral optic flow generated ω (calculated as v_x/h), output of the feedback loop. This ventral OF resulting from the MH flight pattern was held relatively - but not perfectly - constant throughout the journey. Although a single trajectory is shown in (A), all the take-offs, level flights, and terrain-following and landing maneuvers analyzed were found to be extremely reliable and never led to any crashes. (E-F) Side view of the trajectories of 21 individual honeybees flying freely along a high-roof tunnel under two conditions: over a stationary or a partially moving part of the floor. The horizontal visual field of the camera ($20 \text{ cm} < x < 180 \text{ cm}$) covered the transition between the stationary and moving parts. The blue trajectories were recorded over the stationary floor, and the green trajectories, over the part of the floor set in motion. All error bars are \pm SEM. (E) When the floor was stationary, the honeybees flew at a height of $16 \pm 1.3 \text{ cm}$ above the floor. (F) When the floor was set in motion (at a speed of $V_{Floor} = 0.5 \text{ m/s}$) in the same direction as the honeybees' flight, the insects descended and flew at a height of only $10.9 \pm 0.7 \text{ cm}$ above the floor, restoring the initial ventral optic flow.

Adapted from Franceschini, Ruffier, Serres 2007 and from Portelli, Ruffier, Franceschini 2010b

This result can be accounted for by a control system called an *optic flow regulator*, that is, a feedback control system based on an OF sensor, which strives to maintain the ventrally perceived OF at a constant set point by adjusting the vertical lift (See Fig. 1 A-D) (Ruffier, Franceschini 2005; Franceschini, Ruffier, Serres 2007). This visuo-motor control scheme may not only explain how honeybees land at a constant descent angle (Srinivasan et al. 2000) but also how they navigate safely along surfaces on the sole basis of OF measurements, without any need to measure either their speed or their distance from the ground, the ceiling or the surrounding walls (Serres et al. 2008, Portelli et al. 2010a), that is, without relying on any of the conventional avionic sensors such as velocimeters or rangefinders.

Results obtained in neurophysiological, behavioural, and biorobotic studies on insect flight control were used to safely land a spacecraft on the Moon in a simulated environment. The *optic flow regulator* for automatic landing was tested in a realistic simulated Lunar environment (Valette et al. 2010). Visual information was provided using the ESA's PANGU software program and used to regulate the optic flow sensed during the descent of a 2-DOF spacecraft. The results of the simulation showed that a single 2-pixel optic flow sensor coupled to an optic flow regulator was able to robustly control the autonomous descent of the simulated lunar lander (See Fig. 2). "Low gate" located approximately 10 m above the ground was reached with reduced vertical and horizontal speeds of 4m/s and 5m/s, respectively. It was also established that optic flow sensing methods can be used successfully to cope with temporary sensor blinding and poor lighting conditions (Valette et al. 2010), as typically occurs at the Moon south pole that the 2018 Next ESA mission is planning to explore.

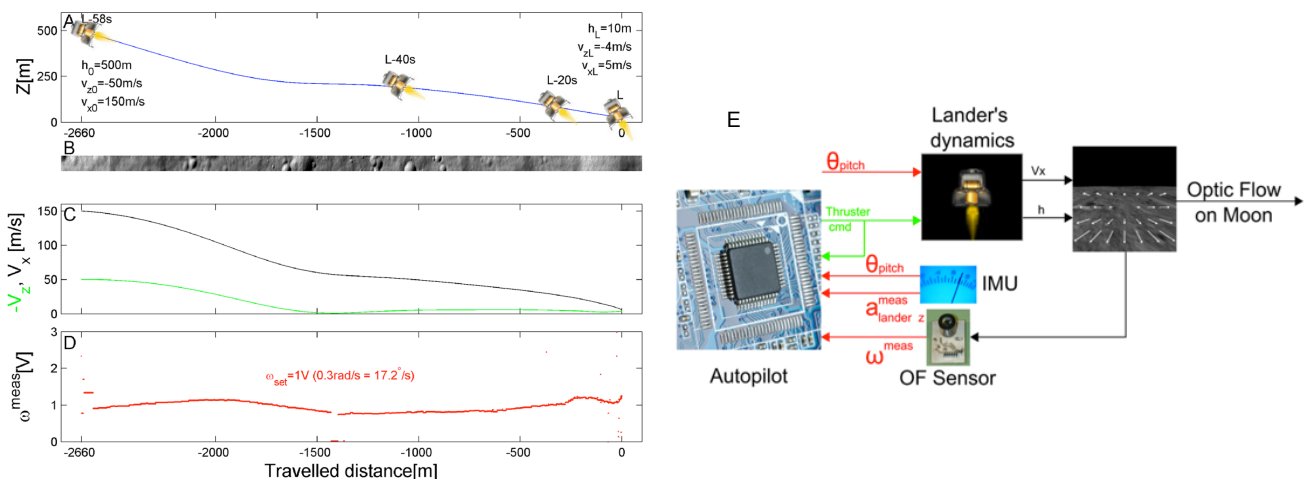


Figure 2: Automatic landing based on a biomimetic OF sensor combined with a bio-inspired control scheme. The automatic approach lasted 58.4s, starting from an initial height of 500m, with an initial ground speed of 150m/s and an initial vertical speed of 50m/s.

(A) Vertical trajectory in the longitudinal plane. At t_i -58.4s (58.4s before reaching "low gate" at time t_l), the lander's pitch angle θ_{pitch} was equal to -60° and decreased exponentially to -30° at t_l -10s. The ensuing decrease in the ground speed (150m/s to less than 10m/s at t_l -10s) led to an automatic decrease in the ground height and the vertical speed, which kept the measured OF near the set-point.

(B) Lunar surface as presented to the simulated lander during the entire landing phase.

(C) Ground speed v_x (black) and Vertical speed v_z (green) monitored throughout the landing phase.

(D) Output ω^{meas} of the OF sensor was also monitored during the landing phase and the data recorded show that the OF remained fairly constant during the landing phase, $\omega_{set} = 1V$ ($0.3rad/s = 17.2^\circ/s$).

(E) Sketch of the OF-based lunar landing autopilot. The digital autopilot received the following inputs: the pitch angle θ_{pitch} (given by an IMU), the measured OF ω^{meas} (given by an EMD) and the vertical acceleration (given by an accelerometer). In addition, the controller imposed the thrust level and the lander's pitch.

Adapted from Valette et al. 2010

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