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Biomimetic visual navigation in a corridor: to centre or not to centre?*

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KEYWORDS

AFCS (Automatic Flight Control System), MAV (Micro-Air Vehicle), Urban canyon navigation, Optic Flow (OF), Hovercraft, Biomimetics, Bionics, Biorobotics.

ABSTRACT

As a first step toward an Automatic Flight Control System (AFCS) for Micro-Air Vehicle (MAV) obstacle avoidance, we introduce a vision based autopilot (LORA: Lateral Optic flow Regulation Autopilot), which is able to make a hovercraft automatically follow a wall or centre between the two walls of a corridor. A hovercraft is endowed with natural stabilization in pitch and roll while keeping two translational degrees of freedom (X and Y) and one rotational degree of freedom (yaw Ψ). We show the feasibility of an *OF regulator* that maintains the lateral Optic Flow (OF) on one wall equal to an OF set-point. The OF sensors used are Elementary Motion Detectors (EMDs), whose working was directly inspired by the housefly motion detecting neurons. The properties of these neurons were previously analysed at our laboratory by performing electrophysiological recordings while applying optical microstimuli to single photoreceptor cells of the compound eye.

The simulation results show that depending on the OF set-point, the hovercraft either centres along the midline of the corridor or follows one of the two walls, even with local lack of optical texture on one wall, such as caused, for instance, by an open door or a T-junction. All these navigational tasks are performed with one and the same feedback loop, which consists of a lateral *OF regulation loop* that permits relatively high-speed navigation (1m/s, i.e 3 body-lengths per second). The passive visual sensors and the simple processing system are suitable for use with MAVs with an avionic payload of only a few grams. The goal is to achieve MAV automatic guidance or to relieve a remote operator from guiding it in challenging environments such as urban canyons or indoor environments.

ABBREVIATIONS

OF	Optic Flow
EMD	Elementary Motion Detector
AFCS	Automatic Flight Control System
LORA	Lateral Optic flow Regulation Autopilot
MAV	Micro-Air Vehicle

I. INTRODUCTION

Winged insects are able to navigate swiftly in unknown environments by rapidly extracting visual information from their egomotion. One of these visual cues is the Optic Flow (OF), which is the apparent motion of the image of the constrasting features projected

onto the retina. It is used in particular for navigational tasks such as obstacle avoidance (Kirchner and Srinivasan 1989), terrain following and landing (Srinivasan et al. 1996).

Roboticians often equip mobile robots with active sensors based on, for instance, sonar or laser to sense the world. Most of these robots use the acquired information to create metric maps for planning a path through the environment. Similarly, robots using passive visual inputs have been programmed to create a 2D or 3D model of the environment, or to compute the OF with a complex processing system.

The biorobotic approach developed at our laboratory over the past 20 years has led to reconstructing artificial agents based on OF sensing (Franceschini et al. 1992; Mura and Franceschini 1996; Viollet and Franceschini 1999; Ruffier and Franceschini 2003; Franceschini 2004; Ruffier and Franceschini 2005). The OF sensor used was an angular velocity sensor originally designed in 1986 (Blanes 1986; Franceschini et al. 1986). The principle of this electro-optical velocity sensor was based on findings obtained at our laboratory on the fly Elementary Motion Detectors (EMDs) by performing electrophysiological recordings on single neurons while concomitantly applying optical microstimuli to two single photoreceptor cells within a single ommatidium (Franceschini et al. 1989).

Here we ask whether two lateral OF sensors incorporated into a feedback loop that builds an *OF regulator* (Ruffier and Franceschini 2003) could make an agent automatically navigate in a corridor. From careful observations of honeybees flying through a narrow tunnel and maintaining equidistance between the two walls, Srinivasan et al. proposed a balance strategy that consisted in equalizing the OFs perceived on either sides (Kirchner and Srinivasan 1989). Over the past 15 years, several research scientists took up this biological idea to design visually-guided terrestrial vehicles (Combs and Roberts 1992; Duchon and Warren 1994; Santos-Victor et al. 1995; Weber et al. 1997; Kröse and Dev 1997; Carelli et al. 2002; Argyros et al. 2004), or simulate flying agents (Neumann and Bühlhoff 2001; Muratet et al. 2005) that would centre along the midline of a corridor or a canyon. This behaviour which makes an agent navigate in the midline of a corridor is called the «*centring response*». However, attempting to balance the two

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lateral OFs would make these visually-guided agents rush into an opening in a wall, since an opening offers zero OF. To solve this problem, Weber et al. proposed to switch to a « wall-following behaviour » whenever the average of the two lateral OFs becomes larger than a given threshold (Weber et al. 1997). Santos-Victor et al. proposed to switch to a « wall-following behaviour » whenever one of the lateral OFs is zero (Santos-victor et al. 1995). Here, we propose a seamless control that requires no explicit switching between different behavioural modes.

As a first step toward an Automatic Flight Control System (AFCS) for a Micro-Air Vehicle (MAV), we decided to equip a hovercraft with an autopilot based on a lateral *OF regulation loop*, called LORA (Lateral Optic flow Regulation Autopilot). We chose this platform because a hovercraft is an « aircraft » with inbuilt roll and pitch stabilisation, which keeps three degrees of freedom (X,Y, Ψ) when navigating in the plane. A hovercraft moving on a flat ground experiences negligible friction. Its motion is holonomic in the plane and can be disturbed in X, Y, and Ψ , for instance by headwind, sidewind or turbulences, in much the same way as an aircraft in level flight.

In section 2, we describe the insect based visual guidance principle adopted. Section 3 focuses on the simulation set-up used to test the lateral *OF regulation loop* on a hovercraft. Section 4 shows simulation runs of a hovercraft equipped with the LORA autopilot and able to navigate in a corridor at a relatively high-speed (1m/s) without having to switch between control laws for automatic wall-following, automatic centring, and automatic reaction to an aperture along a wall. We show that depending on the OF set-point, the hovercraft will either centre in a corridor or follow one of its two walls without being dramatically disturbed by the local absence of contrast on one wall.

II. VISUAL GUIDANCE STRATEGY

Optic flow under pure translation – Consider a hovercraft moving along the ground speed vector \vec{V} in an unknown straight corridor with randomly contrasted walls. The two diametrically opposite eyes detect a right and left OF, ω_R and ω_L , respectively (Fig.1). The two translational OFs are defined as follows:

$$\omega_R = \frac{V_x}{D_R} \quad (1)$$

$$\omega_L = \frac{V_x}{D_L} \quad (2)$$

where V_x is the ground speed of the hovercraft projected onto the X-axis, D_R and D_L are the distances between the right wall and the left wall, respectively. For the purpose of cancelling the rotational component of the OF due to the yaw rotation Ψ of the hovercraft, the eyes counter-rotate so as to remain aligned with Y-axis. This gaze stabilization could be achieved on the basis of a micro rate-gyro that would measure the (relatively low) yaw

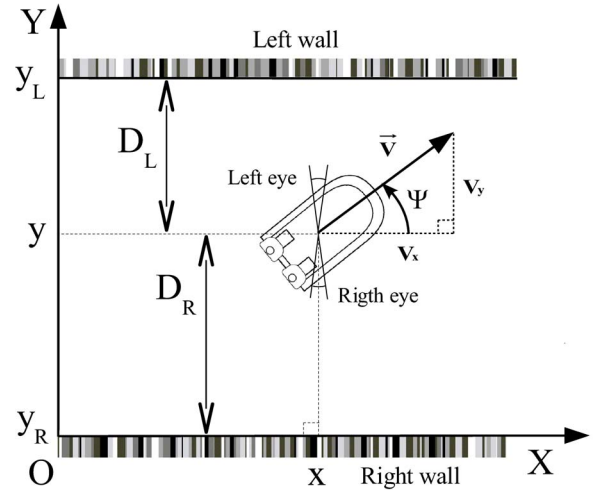


Figure 1. Hovercraft moving at ground speed \vec{V} through an unknown textured corridor. The two symmetric eyes detect the right OF ω_R and left OF ω_L , as described by Eq.1 and Eq.2. The pair of lateral eyes is mounted on the hovercraft with one degree of freedom in yaw allowing their gazes to be oriented steadily along the Y-axis. The autopilot controls only one degree of freedom of the hovercraft (its yaw velocity Ψ).

velocities affecting the miniature hovercraft (Coombs and Roberts 1992; Lewis 1997). As a consequence, the eyes move in a pure translation and hence detect a purely translational OF.

Bio-inspired LORA principle – The visual guidance principle proposed here is inspired by observations made on the flight behaviour of honeybees (Kirchner and Srinivasan 1989). These authors showed that honeybees flying along a straight corridor tend to centre their trajectory as if they were balancing the right and left OFs. Upon analyzing the flight of a tethered fruitfly, Götz noted that the yaw torque (that determines the yaw velocity) results from the differential thrust of the two wings, while the forward thrust (that determines the ground speed) results from the total thrust of the two wings (Götz 1968). Yaw velocity and ground speed are also key parameters in the LORA autopilot that guides our hovercraft.

LORA feedback loop – The LORA autopilot regulates the lateral OF (Fig.2) using two non-emitting sensors (EMDs). The sign function automatically selects the wall that will be followed, namely the wall that generates the maximal OF. This strategy differs from other strategies used in terrestrial or aerial robotic research (e.g., with distance servoing based on a sonar or a laser ranging sensor, or ground speed servoing based on a wheel tachometer or a Doppler-radar sensor). The key point of the LORA autopilot is that it estimates neither the distance (D_R or D_L) to the walls nor the vehicle's ground speed V but only the lateral OF, which is the ratio between ground speed (projected onto the X-axis) and distance (Eq.1,2).

The hovercraft then reacts to variations in the lateral OF by acting upon its yaw velocity. Any increase in the

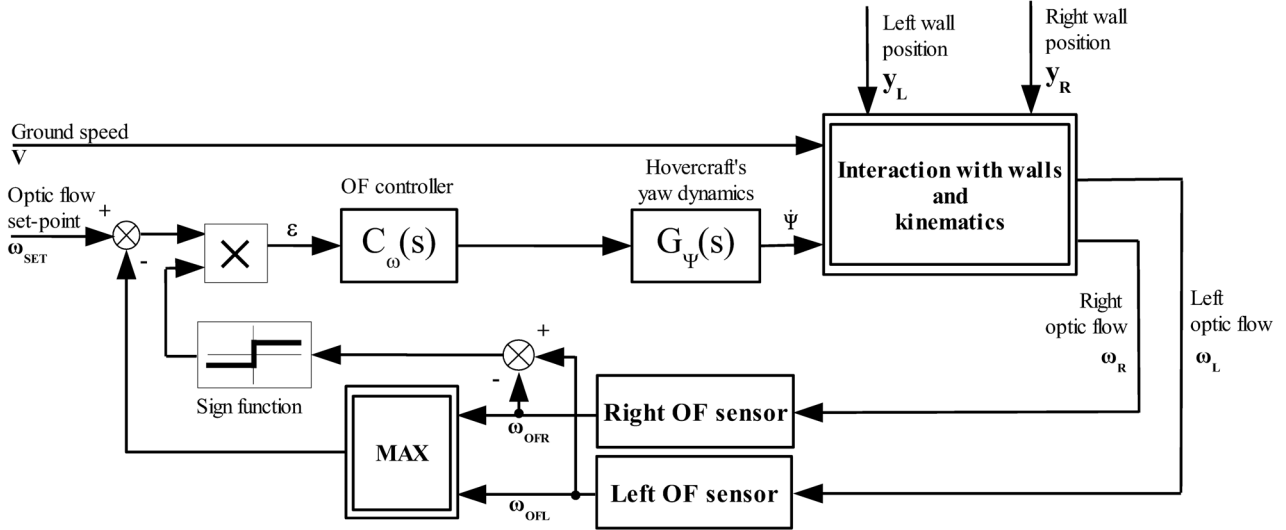


Figure 2. The LORA autopilot has two inputs (the ground speed V and the yaw velocity $\dot{\psi}$). The Optic Flow (OF) controller $C_\omega(s)$ (Eq.4) that is incorporated into the loop regulates the lateral OF, which is measured by OF sensors (i.e., angular motion detectors). $C_\omega(s)$ commands the yaw velocity $\dot{\psi}$ of the hovercraft. The maximum value between the right and left lateral OF (ω_{OFR} or ω_{OFL}) is compared with an OF set-point ω_{SET} , and the direction of obstacle avoidance is given by the sign of the difference between the right and left lateral OFs. The block « Interaction with walls and kinematics » is detailed in figure 3.

lateral OF is interpreted as a decrease in the distance to the wall. The maximum criterium (Fig.2) selects the nearest wall, i.e., the one that generates the higher OF on the eyes, and it is this OF that is compared with the OF set-point ω_{SET} . The direction of avoidance is given by the sign of the difference between the right and left lateral OFs. In the steady state, the higher OF from the two walls becomes equal to the set-point ω_{SET} . The error ε (Eq.3) that feeds the OF controller is computed as follows :

$$\varepsilon = \text{sign}(\omega_{OFL} - \omega_{OFR}) \times (\omega_{SET} - \max(\omega_{OFR}, \omega_{OFL})) \quad (3)$$

In the rare case where the two measured OFs happen to be balanced, the error ε is null.

A lead controller $C_\omega(s)$ (Eq.4) was introduced into the feedback loop to increase the damping, thus improving the stability and decreasing the response overshoot.

$$C_\omega(s) = 4 \times \frac{2.5s+1}{0.2s+1} \quad (4)$$

There are two main parameters in the LORA autopilot :

1. the robot's ground speed V ,
2. the OF set-point ω_{SET} , which defines the ratio between the ground speed V and the distance to the nearer wall.

III. SIMULATION SET-UP

All experiments were carried out as computer simulations on a standard PC equipped with MATLAB™/SIMULINK.

Hovercraft dynamic model

Yaw dynamics - The dynamic model $G_\psi(s)$ of our hovercraft, which describes the relation between yaw velocity and the output of the OF controller is a first-

order low-pass filter with a time constant of 0.5s (Eq.5).

$$G_\psi(s) = \frac{0.1}{0.5s+1} \quad (5)$$

Speed dynamics - For the simulation, the ground speed V is maintained constant at 1m/s. Figure 3 shows the connections between the inputs (ground speed and yaw velocity) and outputs (ground speed vector components $[V_x, V_y]$). Although the hovercraft is basically a holonomic platform, the way we control it with two rear thrusters (Fig.1) does not provide for an independent control of each ground speed vector component.

Eyes and optic flow sensors - Each lateral eye consists of only two photoreceptors (hence two pixels) whose visual axes are separated by an interreceptor angle $\Delta\phi = 4^\circ$. The angular sensitivity of each photoreceptor is a bell-shaped function whose acceptance angle (angular width at half height) is also $\Delta\rho = 4^\circ$. The principle of the EMD circuit that serves as an OF sensor was described earlier (Blanes 1986; Franceschini et al. 1986; Viollet and Franceschini 1999; Ruffier et al. 2003). It is a nonlinear circuit whose inputs are the two photoreceptors and whose output is a monotonic function of the angular velocity within a 10-fold range (from 40 to 400°/s) (Ruffier and Franceschini 2005). In case it does not detect any new contrast, the OF sensor holds the last measured value during 0.5s.

Simulated visual environment - The straight corridor is 12-meter long and 1-meter wide. Its right and left walls (Fig.4) are lined up with a random pattern with a large spatial frequency range (from 0.069 $c/^\circ$ to 0.87 $c/^\circ$ as seen from the midline: $Y=0.5m$), and a large contrast range (from 3.2% to 18.6%).

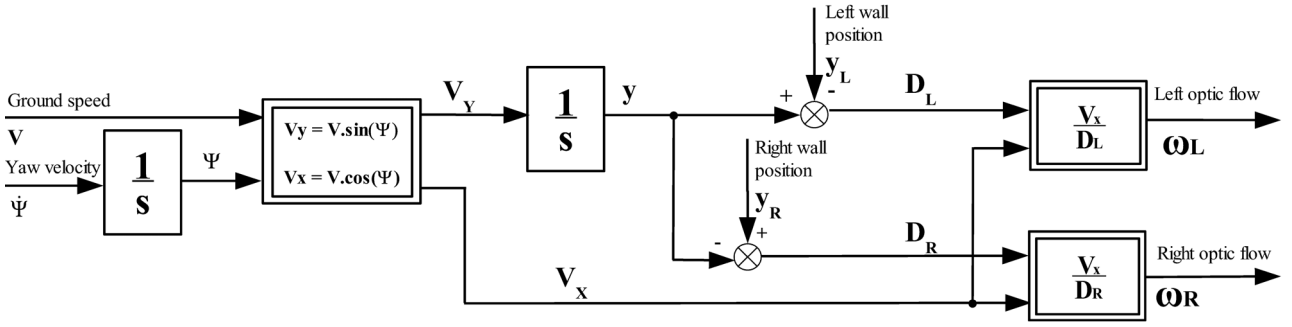


Figure 3. This scheme describes the block entitled « Interaction with walls and kinematics » in figure 2. It shows the connections between the two OF outputs (ω_R and ω_L), the two inputs (ground speed V and yaw velocity $\dot{\Psi}$). The wall located at right (Right wall position y_R) and the wall located at left (Left wall position y_L) (Fig.1) are to be considered as disturbances for the visual feedback loop (Fig.2).

Visual interactions with the walls - The control architecture of the hovercraft includes multiple processing steps and is depicted in figure 2 and 3. Each OF sensor is composed of one lens/two photoreceptors assembly that drives an EMD circuit. The output signal of each photoreceptor is computed at each time step by summing all grey levels patterns within its field of view (which extends over about $3 \Delta\rho$, i.e., 12°) and by weighing it by a bell-shaped angular sensitivity function. Visual interactions between the hovercraft and the two walls are the main issue of this work, which extends to the horizontal plane previous simulations of a rotorcraft flying *above* a textured ground (Ruffier 2004).

IV. SIMULATION RESULTS

Automatic wall following - Figure 4 shows the robot's trajectories that result from our control scheme based on a lateral *OF regulator*. This scheme automatically generates clearance from one wall. The greater the OF set-point ω_{SET} , the smaller the distance to the wall because the latter is an inverse function of the

OF set-point (Eq.1,2). It is noteworthy that the LORA autopilot enables the hovercraft to control its distance to the wall, even though it has no way to measure its ground speed or distance to the wall. In these trajectories where the two measured OFs are smaller than the OF set-point, the hovercraft is seen to regulate its distance with respect to one wall (here the right one). Trajectory 1 shows that in the particular case where the two measured OFs is equal to the OF set-point, the hovercraft automatically follows the midline thus producing the behaviour known as the « *centring response* ».

Automatic centring behaviour - Figure 5 shows that when the measured OFs are larger than the OF set-point, the hovercraft attempts to centre between the right and left walls, with oscillations about the midline. The magnitude of these oscillations is a function of the error ε (Eq.3), which cannot be cancelled by the visuomotor control loop considering the width of the corridor. The OF is minimum along the midline of the corridor where the error ε is also minimum. Trajectory 3 again shows the particular case where the two measured OFs are equal to the OF set-point (as in Fig.4, curve 1). In this case, the

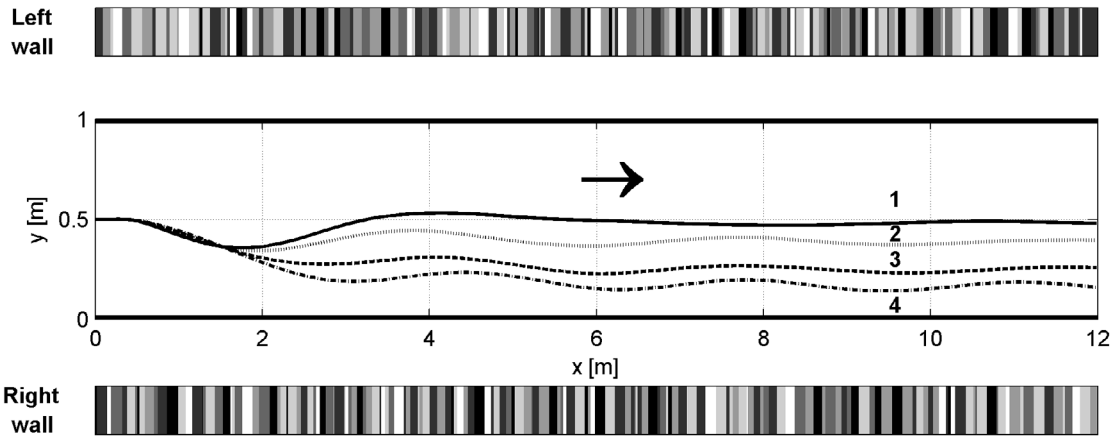


Figure 4. Four simulated trajectories of the hovercraft moving to the right (arrow) in a one-meter large corridor at the same ground speed (1m/s) but with different OF set-points ω_{SET} (1: $\omega_{SET} = 120^\circ/s$; 2: $\omega_{SET} = 150^\circ/s$; 3: $\omega_{SET} = 170^\circ/s$; 4: $\omega_{SET} = 230^\circ/s$). The two walls are lined up with a printed pattern with a large spatial frequency range, and a large contrast range. In these trajectories where the OF set-point is larger than either one of the two measured OFs, the hovercraft regulates its distance with respect to the right wall. Trajectory 1 shows the particular case where the two measured OFs are equal to the OF set-point. In this case, the hovercraft centres along the midline.

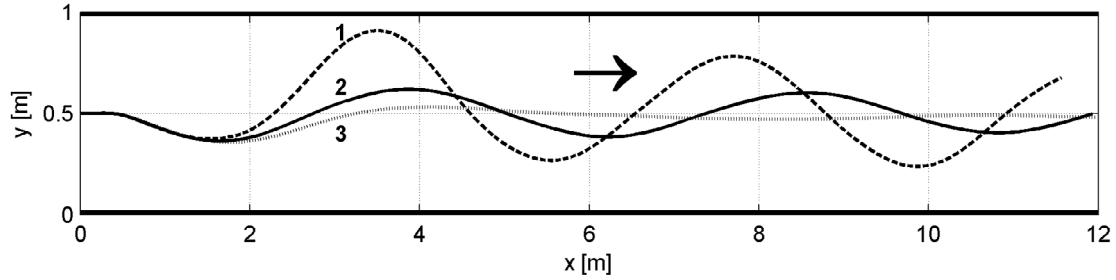


Figure 5. Three simulated trajectories at the same ground speed (1m/s) with different OF set-points ω_{SET} (1: $\omega_{SET} = 80^\circ/s$; 2: $\omega_{SET} = 100^\circ/s$; ; 3: $\omega_{SET} = 120^\circ/s$). The textured environment is the same as in figure 4. In these trajectories where the OF set-point is smaller than the two measured OFs, the hovercraft is seen to centre between the two walls, with more or less oscillations about the midline.

hovercraft follows the midline without oscillations because the visuomotor closed loop just cancels the error ε .

Automatic reaction to an opening - Figure 6 shows the effect of a local absence of contrast on one wall. This « no contrast zone » simulates an open door, or a T-junction. Though unable to measure any OF along the 4m wide aperture on its right hand side, the hovercraft is seen not to be dramatically affected and to follow automatically the opposite textured wall. In trajectory 1 (Fig.6), the hovercraft initially displayed a centring behaviour. Along the right aperture, the hovercraft followed the left wall and the LORA autopilot generated a safe distance about 0.5m (for $\omega_{SET}=120^\circ/s$ and $V=1m/s$) with respect to the left wall. By contrast, trajectory 2 shows the effect of the « no contrast zone » when the measured OFs are smaller than the OF set-point. The hovercraft at first followed the right wall and the LORA autopilot generated a safe distance of about 0.35m (for $\omega_{SET}=170^\circ/s$ and $V=1m/s$) with respect to the right wall. The hovercraft then encountered the opening at $X = 4m$. Trajectory 2 shows that from $X = 4m$ to $X = 4.5m$ the hovercraft is not affected by the opening because the right OF sensor holds the right measured OF for another

0.5s. After this delay, the hovercraft becoming « blind » to the right wall automatically follows the left wall, due to the change of sign of the error ε (Eq.3).

V. DISCUSSION AND CONCLUSION

Our results show that the LORA autopilot, based on a lateral OF regulation loop, is efficient at making a miniature hovercraft automatically follow a wall, or automatically centre along the midline of a corridor, while appropriately reacting to a local absence of contrast on one wall. All these navigational tasks are performed at a relatively high-speed (1m/s), with a minimalist visual system (two pairs of pixels).

In this study, we described the LORA autopilot, which allows a hovercraft to navigate in a straight corridor with randomly patterned walls. It is based on a visuomotor control loop that acts as a lateral OF regulator. This principle contrasts with the formerly proposed strategy that consists in equalizing the two lateral OFs (Kirchner and Srinivasan 1989). The LORA autopilot assumes that the ground speed is commanded in open loop, whereas Srinivasan et al. proposed that honeybees control their flight speed by regulating the image speed (Srinivasan et al. 1996). Visual control of

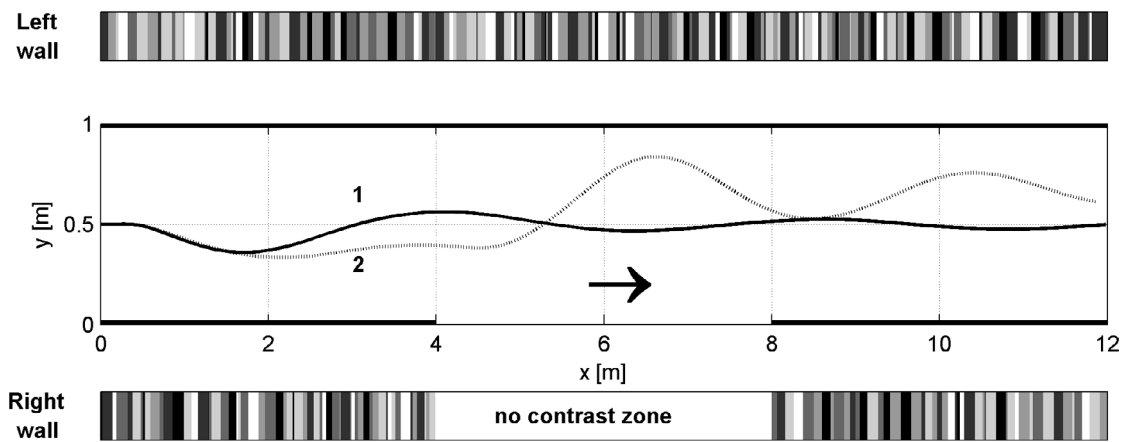


Figure 6. Effect of a « no contrast zone » on two simulated trajectories with the same ground speed (1m/s). In trajectory 1 ($\omega_{SET}=120^\circ/s$), the robot is centred and hardly affected by the 4-meter long « no contrast zone » along the right wall because it follows the left wall when the right OF is zero. In trajectory 2 ($\omega_{SET}=170^\circ/s$), the hovercraft starts following the right wall because it is the nearest. When the hovercraft encounters the right aperture (« no contrast zone »), it automatically turns to the opposite wall (left) that now becomes the nearest wall.

ground speed based on a lateral OF regulation scheme should also be investigated with the aim to reduce the magnitude of the oscillations observed when the hovercraft tries to centre between the two walls (Fig.5). This improvement will require independent control of each ground speed vector component.

The hovercraft navigates at about the same speed as the bee in a corridor, and like bees it can be disturbed by wind as in a real flight. Implementation of the LORA autopilot on a miniature hovercraft (e.g., Seguchi and Ohtsuka 2003) is under way.

The LORA autopilot we have described here for the visual guidance of a terrestrial or aerial vehicle was inspired by the insect world. Biologically inspired vision systems can provide solutions based on a much smaller number of pixels than those used by present-day computer-vision systems destined for mobile robots. Our study has shown that a robot can navigate in a corridor even with a minimalist number of pixels. The LORA autopilot is a first step towards visually guided navigation (e.g., MAV) in unknown indoor or outdoor environments. The same control scheme can also account for some insect behaviours. Passive visual sensors with a simple processing system will be particularly suitable for use with micro-aircraft, which suffer from stringent constraints on avionic payload and onboard energy resources.

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