Learning from the Moth: A Comparative Study of Robot-Based Odor Source Localization Strategies

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Abstract The odor search strategies of the moth have been researched since many decades. Many behavioral studies have described the behavior under well controlled conditions, making predictions on what the underlying mechanisms might be. However, it is almost impossible to asses these mechanisms directly since sensory and behavioral data on a freely behaving moth are very hard to obtain. Therefore, we propose a comparative study were the behavior of a robot is analyzed when controlled by a number of odor source localization models. Our results show that a system making use of stereo odor information outperforms some well-established chemical search models.

Keywords: Source localization, chemotaxis, autonomous robot, biologically based model

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INTRODUCTION

The problem of odor localization in insects has an enormous complexity. The best studied case of insect chemical localization is the moth. Female moths release sex attractant pheromones that are transmitted downwind. Male moths display a particular sensitivity to pheromone compounds released by the females and are capable to track pheromone plumes to its source [1]. This highly specific behavior is supported by specialized structures in the moth nervous system, the, so called, Macro Glomerular Complex of the primary olfactory center, the antennal lobe, which is dedicated to the detection of pheromone signals [2, 3].

So far, it has been very difficult to assess the details of moth chemotaxis directly because of the difficulty of visualizing a chemical plume without interfering with the flight behavior of the moth. Hence, it is still not quantitatively established whether the moth responds to a chemical gradient, filament contact or follows a more elaborated behavioral strategy. Experiments have been performed where a male moth was equipped with a third antenna with a wireless transmission system to approximate what it would sense [4, 5]. However, this is insufficient for a proper characterization of the relationship between chemical stimuli and behavior of the moth. It is known that there is a dependency of moth behavior on the structure of the pheromone plume [4-8]. In these experiments it was shown that a pulsed pheromone signal improves localization and induces faster flight.

In this study we propose to reverse engineer the problem by analyzing the behavior of a number of models under specific and controlled chemical localization conditions. We present a detailed evaluation of different models with detailed quantifications of performance.

METHODS

A custom circular robot with a diameter of 20 cm (FIGURE 1, left panel) was used in this study. It uses two active wheels placed on the axis of the robot, allowing in place rotation driven by geared motors (Parallax, Rocklin, USA). The wind direction was measured with a custom build sensor consisting of a wind vane that was fitted to a magnetic encoder (the angular position of the shaft was measured using a 2-axial magnetometer) that was placed near to the chemo sensor. The motor commands and sensory data are exchanged using a Bluetooth module (Bluetooth™ Class I, LinTech, Germany). The robot is controlled by the neural simulator program iqr [9] via a wireless link with a linux ground station. The olfactory board consists of a 6 grid array thin film metal oxide chemo-sensor (Alpha MOS SA, France) [10] that provides a broad spectrum of sensitivity to a wide range of volatile organic compounds while having relatively low power consumption (approx. 270 mW) and a high degree of miniaturization. The robot uses LI-PO rechargeable batteries (KOK 3270, Kokam, Korea) that provide up to 8 hours of running time [11, 12].

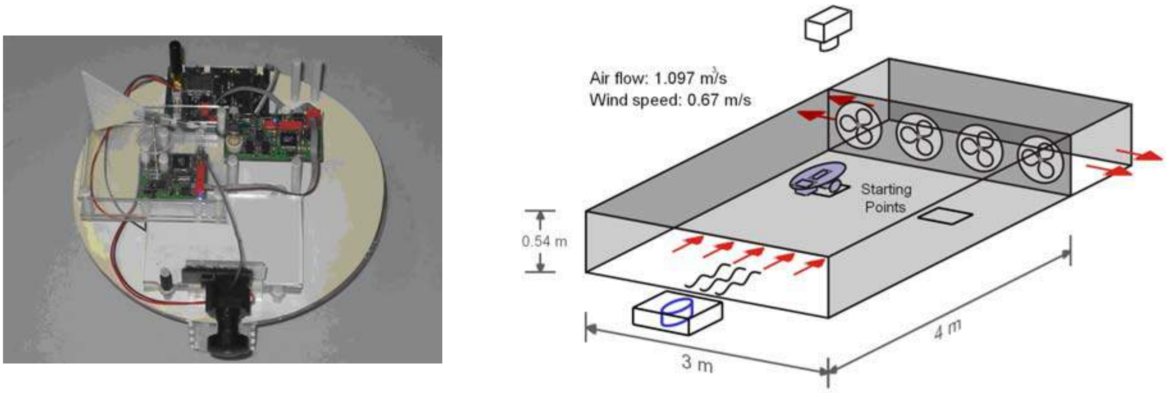

FIGURE 1. Experimental setup. Left panel: Mobile chemosensory vehicle. Visible are, from top to bottom, the control board with Bluetooth communication module, the chemo-sensor board and the wind direction sensor. Right panel: Structure of the wind tunnel. The wind tunnel is 4 m long, 3 m wide and 0.54 m high. 4 ventilators create negative pressure and suck the air into an exhaust tunnel. A custom made tracking system (see text for detailed description) tracks the robot within the wind tunnel. The odor source (blue) was placed in the middle of the entrance of the wind tunnel. The two squares indicate the two starting position for the experiments. Modified from Pyk et al. [10].

All of the mobile robot experiments were performed in a low-cost wind tunnel that was constructed from wood and transparent plastic sheets measuring 3 x 4 x 0.54 m (FIGURE 1, right panel). Four axial fans were installed at the wind tunnel exit in order to adjust for a uniform and symmetric velocity profile. A solution of fixed concentration of ethanol and distilled water (20% ethanol) was delivered using an ultrasonic release system (Mist of Dreams, XrLight, Zhongshong City, China) delivering about 0.8 ml/min of ethanol with an average air speed of 0.67 m/s.

The behavioral data was acquired in real-time with a custom-built general purpose video tracking system called AnTS. The AnTS tracking system receives its input from a CCD camera with a wide-angle lens fixed on the ceiling at about 3 m above the wind tunnel. To obtain an undistorted planar view of the arena, correction algorithms for perspective and wide-angle lens distortions were built into the AnTS tracking software. A 640 x 480 pixel image resolution was used to track the robot; this resulted in a spatial resolution of about 1 cm for the 3 x 4m wind tunnel at an update frequency of 15 Hz.

We used three different behavioral models: a Behavioral, a Braitenberg and aNeuronal based model.

- **Behavioral.** This model is solely based on two behavioral modes observed in the moth [13, 14]. Male moths tend to show a regular zigzagging behavior called casting when trying to intercept a filament of the pheromone plume. Once the plume is intercepted, moths make an upwind displacement in response to the pheromone contact, known as surge mode. Then, if the pheromone filament is lost, moths come back to the casting mode. Our particular implementation of this strategy is based on the one by Balkovsky et al. [15], where casting is characterized by an increase of the crosswind flight displacement over time if no chemical signal is detected.
- **Braitenberg Vehicle**. A Braitenberg like vehicle was considered as the simplest model that could make use of stereo information for odor localization [16]. In this case we implemented a classic Braitenberg vehicle, where the difference between the readings of two sensors with a spatial separation along a particular axis is transformed into motor commands that orient the robot towards the odor source.
- **Neuronal Model**. This model aims at exploiting known principles of the moth's behavior and its underlying neuronal substrate based on 3 components:

Odor modulated upwind progress. This is based on the neural substrate found in the Macro Glomerular Complex (MGC) of the Antennal Lobe (AL) of the moth, a glomerulus exclusively dedicated to the encoding of pheromone signals [2, 17]. The majority of the neurons in the MGC neurons (approx. 85%), most likely Projection Neurons (PN), are able to resolve odor pulses up to several Hz [17, 18]. Based on these neurons and behavioral studies [4-8], we designed a model that has a preference for pulsed signals as opposed to continuous stimulation. Therefore, the robot displays a short upwind surge when a contact with a pheromone patch occurs; and an inhibition of the upwind displacement when the moth is under continuous pheromone stimulation.

*Use of stereo information to modulate turning angle***.** Some Descending Neurons (DN) having dendritic arborizations in the Lateral Accessory Lobe (LAL) show a high/low firing rate state that switches depending on the difference of pheromone concentration in the insect antennae [19]. These neurons (flip/flop neurons) are synchronized with the change of orientation during the zigzag behavior in the

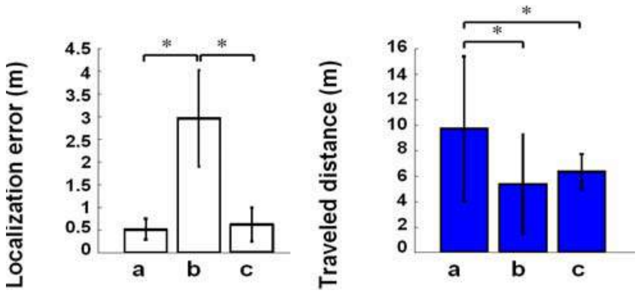

FIGURE 2. Comparison of the performance of the three proposed models (a – phenomenological, b – Braitenberg and c – neuronal). Left panel: Bar plots of the localization accuracy of the model. Right panel: Bar plots of the traveled distance (equivalent to energy consumption). Error bars indicate SD. See text for further explanation.

odor localization task [20]. Our model includes these flip/flop neurons to control the change in heading direction of the robot proportional to the difference of the sensed chemical concentration if above a certain threshold.

Self-steered counterturning. As suggested in previous studies [21], it seems that an internal oscillator could be used to control the timing of the zigzag turns observed in moths. Therefore, all the changes in heading direction generated by our model are performed synchronous with this internal oscillator.

RESULTS

In previous studies, the validity of the setup and sensor technology for chemical search was already demonstrated [10, 11]. The starting position of the robot in these experiments was at a distance of 3 m from the odor source and at 0.75 m from the walls, equally distributed at the left and right starting points of the wind tunnel (FIGURE 1, right panel).

The behavioral model (see methods) was tested for a total of 20 robot runs with a ratio of correct localization of 90%. Subsequently, the classic Braitenberg vehicle (see methods) was used for a total of 20 experiments. This model displayed a success rate of 10%. Although the robot was able to successfully detect the plume, it was incapable to follow it up to the source, and most of the runs do not pass the midline of the wind tunnel. Based on Kanzaki et al. [22], we added a looping behavior to the Braitenberg vehicle to ease the reacquisition of the odor plume when it is lost. Ten more robot experiments were performed with this modification. The addition of this reacquisition strategy increased the success rate from 10% (classic Braitenberg) to 40%. These experiments indicate that stereo odor information could be used in combination with higher level strategies to improve performance. Our neuronal model (see methods) shows a similar ratio of success to the behavioral one (85%).

If we consider the energy consumption (traveled distance) as a key factor for a successful behavioral strategy, we find that the least efficient behavior is displayed by the behavioral model, and that the Braitenberg vehicle is the most efficient. On this measure, the three models are statistically different ($p < 0.05$, 2-Sample t-test) (FIGURE 2, right panel). Since the robot moves at a constant speed, there is a correlation between time and distance traveled, consistent with the idea of a moth flying at a constant ground speed [1]. Nevertheless, the Braitenberg based model, which was the most optimal in distance terms, is very ineffective in the localization task and displays an error rate that is about five times larger than the one displayed by the other models (FIGURE 2, left panel). The lowest error is obtained by the phenomenological and neuronal models ($p < 0.05$, 2-Sample t-test), with no significant difference between them. From these results we conclude that our stereo-sensing neuronal model offers an optimal compromise between energy consumption, run time and localization error.

CONCLUSION AND DISCUSSION

We have presented a robot study of some well-established models of male moth chemical localization and introduced a novel neuronal model. We analyzed the performance of the models in robot experiments under controlled odor stimulation to study the effect and benefits of stereo odor information in the task.

The behavioral model displays a successful strategy with a low error rate but is not energy efficient (active search). This model has been shown in theoretical studies to be close to optimal when the search agent is inside the high probability plume area, but not when outside [15]. Some previous studies already investigated chemo-sensing Braitenberg vehicles with a passive delivery source, in a non-controlled air flow and show search times up to hours [23]. Our results suggest that the Braitenberg model is under-constraint, displaying the lowest success rate. However, when successful, this model presents the shortest trajectories in time and distance. Moreover, we demonstrated that a Braitenberg vehicle can be easily improved by combining it with a higher level strategy, i.e. plume reacquisition.

The neuronal model proposed in this study combines stereo sensing with behavioral and neural constraints derived from the moth. The localization error is indistinguishable from the phenomenological model, although it outperforms it in search time/traveled distance, i.e. efficiency. We will in future experiments evaluate its performance in outdoor robot chemical localization tasks.

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