Search of the Scent Source in Turbulent Flows

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March 25, 2014

Introduction

Certain animals are able to detect odor patches in turbulent flows, and through an innate search strategy, they are able to find the odor sources allowing them to find food, mates, or even to avoid danger. Such animals like the moth and certain species of sharks are able to determine the location of an odor source by using their sense of smell and their ability to determine wind direction. These kinds of olfactory search strategies can be useful to humans in order to find hazardous substances such as drugs, chemical leaks, or explosives (Balkoysky). They can even be implemented into robots in order to find these sources of odor in turbulent flows. This is of great interest, especially as it raises the questions of how these kinds of search strategies can be applied in urban settings, where there are buildings that disperse odor flumes differently than with moths in an open field. By studying and adapting the most efficient search algorithms for odor detection developed in other papers, our group will address this issue of odor searches in a turbulent urban setting.

Turbulent flows are irregular wind fluctuations; that is, there are constant changes in wind magnitude and direction and diffusion due to wind eddies (merrian-webster). These turbulent flows depend on a high ratio of inertial force and viscosity force, known as Reynolds number (MIT). Because of these irregularities in the wind, odor is not always present, and when it is, the local concentration gradient does not always point in the direction of the source. Additionally, when far from the source, the concentration of the odor decreases and the time between detections increases (Balkovsky). This creates the need of elaborate search strategies that we take our inspiration from.

The basis for our project is the moth's olfactory search strategy, which been studied by Eugene Balkovsky and Boris I. Shraiman in their paper "Olfactory Search at High Reynolds Number" (2002). This article investigates the statistical aspects of the dispersal of odor in turbulent flows, as well as proposed different search algorithms in order to find a time-efficient search method. Our project will be modeled with the main ideas of this article but applied to a more complex environment. Due to the constant changes in the wind velocity, the dispersal of odor is modelled in the following way: the odor will be stretched and diffused, and the probability of an odor patch to survive a certain time *t* is given by a decaying exponential expression.

In the case of the moth's odor search, the female moth releases pheromones to attract a male suitor. However, the female produces only a few amounts of odor molecules, and as a result, there is no gradient for the male moth to follow. The moth therefore has to use its sense of smell and its ability to determine wind direction to help it find the female moth. The search flight strategy is based on a counter-turning pattern that is made of casting and zigzagging. Casting is done in the absence of odor and consists of crosswind movement, and zigzagging when the odor is present, and results in the upwind progression. The same movements can be applied to an odor-sensitive robot to combat odor-related issues like bombs or drugs.

Modelling the Odor Plume

In order to come up with a simple model, the properties of order plumes must be examined. Odor patches arrive and are detected as bursts. While the small scale structure of the burst can give some information about distance from the source, it would require much processing. Instead the burst (patch) is treated as a single event. The mean velocity of the wind is defined as V and is set my atmospheric conditions which do not change on the time scale of odor movement. Odor molecules move according to local velocity with fluctuations around V. Ultimately their motion is a random walk being pushing downwind. The fluctuations have a correlation length defined as L, which can be estimated as the height about ground. The odor's motion at scales larger than L is Brownian. The diffusion coefficient is given by eddy diffusivity D, estimated as $Lv_{\text{rms.}}$ v_{rms} is the root-mea-square of velocity fluctuations. An odor patch stretches and diffuses as it moves which implies that odor patches have a finite lifespan. The probability of a patch to survive for time t in the flow is expected to behave as $e^{-\frac{tv_{rms}}{L}}$.

When considering that relatively long-live odor patches moving in a random walked biased downwind, a 2d model can be constructed. Patches start at the source which is at $(0,0)$. Moving downwind means that after every move the patch will have increased along the y axis and the random walk on the x axis means there is an even chance (1/3) between moving left, staying still, and moving right. These two rules represent odor dispersion at length scales larger than L. A 3D model is not essential as the random walk and distribution of patches will be unaffected. The following figure is a plume that was made by Balkovsky and Shraiman according to those rules. The distribution of patches has the form

$$p(r) = \frac{1}{\sqrt{4\pi Dy}} \exp\left[-\frac{x^2}{4Dy}\right] \quad [1]$$

Where $D = \frac{p_R + p_L}{2}$ is the eddy diffusivity, the boundary of the plume has the form $|x| \sim (Dy)^{\frac{1}{2}}$ and the probability of finding an odor patch when $x \gg (Dy)^{\frac{1}{2}}$ is extremely small. This is exemplified by Figures 1 and 2.

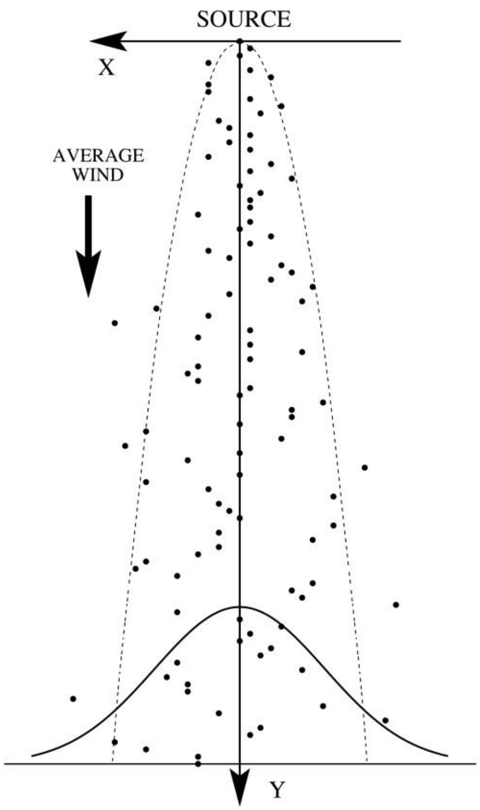

Fig. 1. The model odor field (dotted) and probability density function of patch distribution. (Balkovsky, Shraiman)

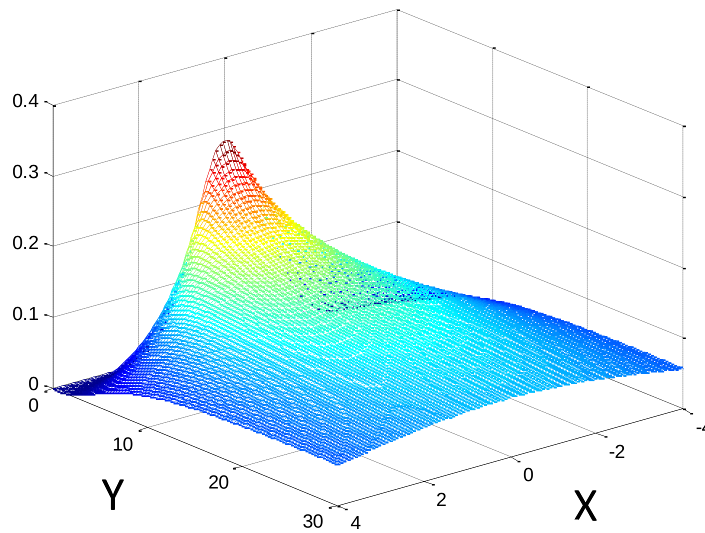

Fig. 2. The probability distribution function. Red indicates the most probable location of odor plume

Strategies

To ensure the odor-sensitive robot is designed to travel on the most time efficient path, and therefore the best possible search algorithm, in addition to modelling the behavior of the plume Balkovsky and Shraiman also developed a mathematical model and a series of strategies the robot might select. This search algorithm is relevant to any time-sensitive odor search such as sniffing for a bomb in in a crowded area. Before beginning the model, specific rules were established in order to maintain a structured and realistic model. Assuming the robot is not aware of the target prior to the first detection of odor, the robot does not begin searching until it gets the first whiff. To simplify modelling the robot's movement, each time step it is assumed to move one lattice step along the x or y axis, and only travels upwind towards the source.

The first strategy examined by Balkovsky and Shraiman is a passive strategy. In this approach, the robot simply waits at a site until it detects an odor patch, moves to the location of the last patch and remains stationary until detecting another patch, repeating the process until eventually locating the source.

The second strategy described by Balkovsky and Shraiman involved a more "active" process of locating the scent source. Once a scent source is detected, the robot moves a unit upwind towards the direction that the scent patch was detected. From there, the robot begins a conical zigzagging motion until the next scent patch is located, where the process is then repeated. The amplitude of each successive crosswind movement increases linearly as seen in the figures to right, ensuring that the robot covers every possible location of previous scent patches (see Figure 3)

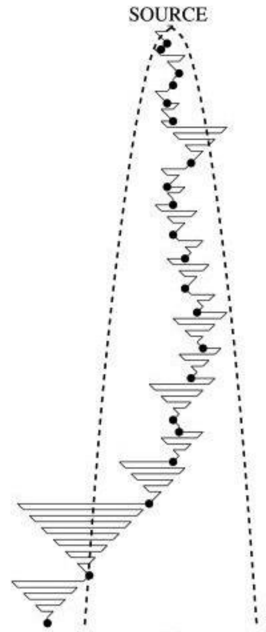

Fig. 3. Second Strategy

Finally, the third and most effect strategy that Balkovsky and Shraiman describe is a modification of the "active search" and of strategy 2. Instead of spending time searching the entire cone of possible odor locations, the robot focuses on areas in which the probabilities are highest to encounter the next scent patch. In this case, the amplitude of each successive crosswind movement increases proportionally to the square of the distance from which the previous scent patch was located as shown in the figures to the right. This results in a parabolic search pattern with a greater net upwind velocity then the previous strategy (See Figure 4)

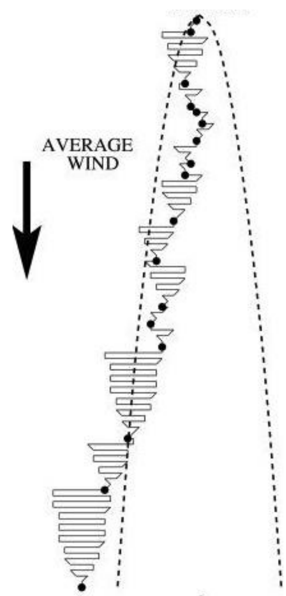

Fig. 4. Third Strategy

Results and Conclusions

The passive strategy is the least efficient of the strategies, but will always lead to the source. The probability distribution function for this method is analytically calculated to be

$$\rho(t) = \frac{1}{\sqrt{2\pi\Delta}} \exp\left\{-\frac{(t-t_s)^2}{2\Delta}\right\} \quad [2]$$

$$t_s \propto y_0^{\frac{3}{2}} \exp\left(\frac{x_0^2}{4Dy_0}\right), \Delta \propto y_0^2 \exp\left(\frac{x_0^2}{2Dy_0}\right)$$

where (x_0, y_0) is the robot's initial position, Δ is the probability distribution function variance and t_s is the typical search time. Further analysis of this probability distribution function shows that the search time will increase exponentially outside of the parabolic region, where $x_0 > 4Dy_0$ and where encountering an odor plume is least probable. This implies that the passive search is a poor strategy for robots located outside of the parabolic region and explains the distant robot's tendency to get trapped outside of the parabolic region. Though the robots have a significantly higher probability of finding the source once inside the parabola, even those inside the parabola have a larger search time following the passive method than a robot actively searching for the scent due to the low probability of an odor patch travelling to that specific location, especially far downwind of the source. Obviously, in a dangerous situation like a bomb threat, the inefficiency of this method is far from ideal, though it does demonstrate the significant improvement to the algorithm caused by actively searching.

The probability distribution function of both of the "active search" strategies is

$$\rho(t) = \frac{1}{4\sqrt{\pi \mathrm{bt}}} \exp\left(-\frac{(t-t_s)^2}{2bt}\right)\left(1+\frac{t_s}{t}\right) \quad [3]$$

though the where the typical search time is dependent on the strategy. The second, conincal active search strategy yields a typical search time of $t_s = ay_0^{\frac{5}{4}}$. The benefit of this strategy is that the typical search time is independent of the initial crosswind position of the robot. The downside, however, is the fact that this conical movement toward the scent source spends time searching where there are low probabilities of odor particles being detected.

The typical search time for the third decreases during the parabolic active search: $t_s = a_2 y_0^{\frac{7}{6}}$ since the robot saves time by neglecting the statistically unlikely areas to find the odor plume. This search time shows that the modified "active search" strategy is less dependent on the downwind initial position of the robot. The typical search time is also independent of the initial crosswind position of the robot. The major drawback of this strategy comes in the fact that there is now a small possibility of the scent plume being lost due to not searching every possible scent location as shown in the conical movement of the previous method.

To determine which strategy is the most effective, the probability distribution functions were used to determine their efficiencies based on typical search time. The modification of the "active" search strategy with the parabolic movement is shown to be the most efficient.

The histograms below (Figure 5 and 6) were obtained using Monte Carlo simulations of search time, where the broken line represents the "active" search method and the solid line represents the "passive" search method.

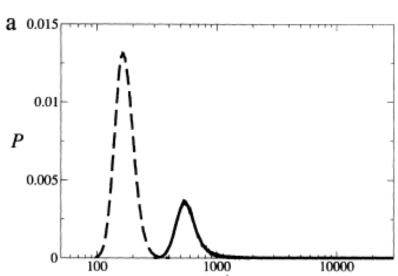

Fig. 5. Initial position (0,50)
Broken line represents active search.
Solid line represents passive search

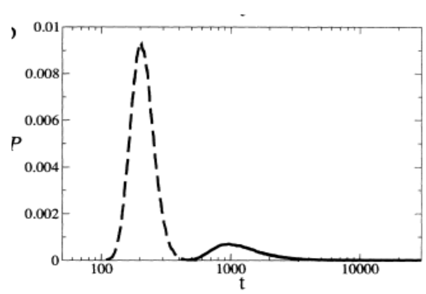

Fig. 6. Initial position (10,50)
Broken line represents active search.
Solid line represents passive search

The figure on the left shows a robot with an initial position of (0, 50), directly downwind of the scent source. The figure on the right shows initial position (10, 50). The mean search time of the "active" search was unaffected by the change in initial crosswind position. However, we notice a significant affect in the “passive” search strategy.

Future Work

In our adaptation of the olfactory search scenario, we consider how smell might disperse in a city grid. Given this environment and a known velocity vector for the wind, we intend on developing an analytical model for how the odor disperses through the city streets. Also, given a hypothetical “sniffer” robot, we will develop an effective search algorithm to find the source of the scent.

The city grid consists of equally spaced, tall, square buildings. Tall is defined as high enough from street level such that the more turbulent airflow above the buildings does not significantly affect the air flow at street level. The wind is presumed to flow in channels, such that on any given street, the wind flow can be approximated by the component of the wind vector that is parallel to that street. This assumption is sound given that the greater wind vector never runs parallel to one of the city streets. The wind must always come in at an angle. If the wind were parallel to one of the streets it would flow perpendicular to the faces of the buildings, this would result in eddies forming behind the structures, which would require an entirely separate analysis.

The scent source is regarded as a point in the center of one intersection. The source releases one odor “patch” for each time interval. The odor patch travels in the direction of the component wind vector that affects it. When an odor patch reaches an intersection, the probability that it will follow one wind flow or another is weighted by the velocity of that given wind flow.

Some preliminary calculations have already been made and Monte Carlo simulations were run. One such simulation is displayed below (Figure 7). In this specific simulation the wind vector points to the Northeast. It can be seen that the odor patches follow a parabolic distribution similar to the one presented in the butterfly scenario. This indicates that the assumptions made for the Monte Carlo simulation are possibly accurate. More Monte Carlo simulations will be run to test the analytical models that we will derived.

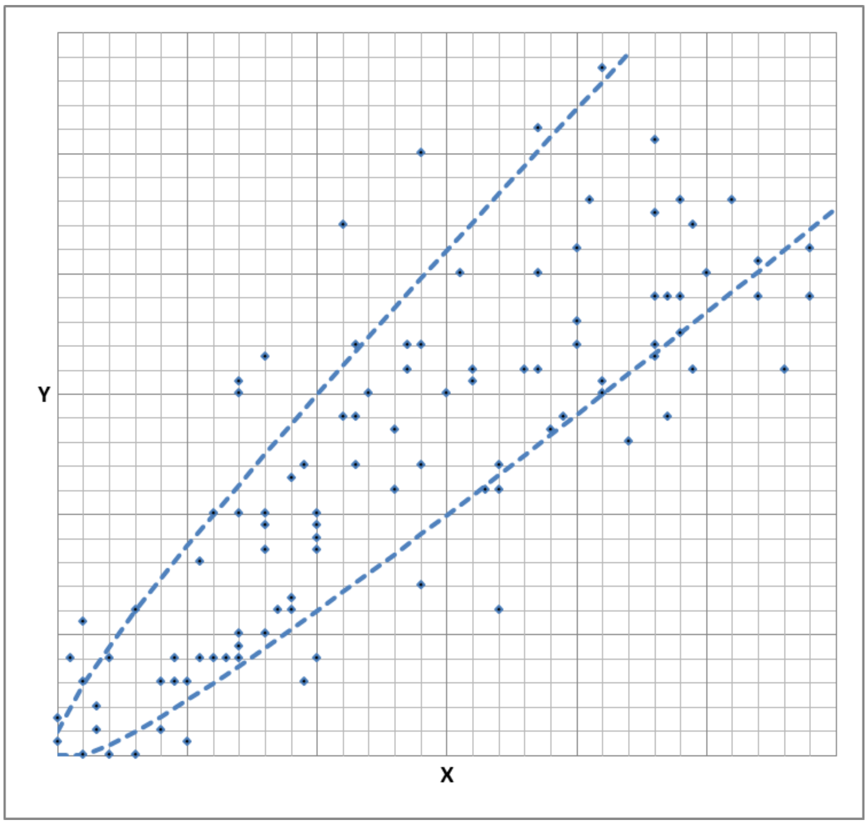

Fig. 7. Monte Carlo simulation with wind vector pointing from the Northeast

After an analytical model has been found for the dispersion of odor patches we will develop a search algorithm for a sniffer bot, possibly based off of the search method that the moth uses. The limited mobility that the city grid poses a unique challenge for the sniffer bot, and it will require some innovation on the current algorithm.

References

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