Moth-Inspired Plume Tracking Strategies In Three-dimensions

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Abstract—Two simple three-dimensional moth inspired odor-tracking algorithms, Counter-turner and Modified counter-turner, were tested on a robotic platform. The Counter-turner uses the plume edge to modify the timing of the crosswind movements, while the Modified counter-turner uses the plume centerline. Both algorithms shows some success in tracking the plume to its source. In addition, flight tracks show promise in mimicking the flight tracks observed in biological experiments with the moth *Manduca Sexta.*

Keywords- Biologically Inspired Systems, moth, plume tracking, Robot Sensing and Sensor Fusion, wind tunnel

I. INTRODUCTION

A mobile autonomous robot capable of tracking an odor plume to its source could be used to locate hazardous material spills or leaks. In theory, such a robot could locate anything emitting a particle provided the robot has an appropriate sensor to detect the particle. The idea of using robots for these tasks has been suggested by other authors [1]. Robots are well suited to these tasks and their use will decrease or eliminate human exposure to toxic or hazardous substances. There are three possible types of odor tracking robots: terrestrial, air-borne, and water-borne. This paper focuses on the study of plume tracking algorithms for air-borne robots.

One can imagine many possible strategies for tracking an odor plume to its source. These strategies could be based on some simple rules and further developed through trial and error. The problem is complex because the concentration of an odor plume does not uniformly decrease with increasing distance from the source. If this were the case, a plume-tracking robot would only need to follow the plume concentration gradient. In reality, an odor creates a time-averaged gradient, but at any instant in time, the odor is concentrated in packets that move downwind and disperse primarily by the effects of turbulence generated by the source itself [2][3][4][5].

Another approach for developing a plume tracking strategy is to study a biological system that has already solved the plume tracking problem. Most of our current knowledge of odor tracking in flying animals is based on the observed behavior of male moths tracking wind-borne plumes of female sex attractant pheromone. Several algorithms have already been developed based on this knowledge and tested in simulation [5][6].

The plume tracking behavior of the tobacco hornworm moth *Manduca sexta* (Figure 1.) has been extensively studied in a laboratory wind tunnel [7]. A piece of filter paper containing female sex-attractant pheromone is placed at the upwind end of the test section of the wind tunnel and a male moth is released at the downwind end. The behavior is recorded from above and from downwind. The position of the moth is then digitized from the video recordings to obtain a three-dimensional reconstruction of the flight path.

Figure 1. *Manduca sexta*, the tobacco hornworm moth

The overhead view of a male *M. sexta* tracking a pheromone plume is shown in Figure 2. The position of the moth was sampled at 30 Hz and is shown relative to the source at (0,0). The source was not in view of the overhead camera in this experiment. When initially introduced to a plume the moth immediately turns into the wind. With a stationary source, the odor plume can only travel downwind. The moth then tacks rhythmically back and forth across the wind. On average, the inter-turn duration of these tacks is about 500 ms, and is an inherent property of the system [8]. If the position of the moth had been recorded all the way to the source, one would see that the upwind progress becomes slower as the moth approaches the source. The source is still in view of the overhead camera in this experiment. Far from the source these tacks make upwind progress, while close to the source the tacks become perpendicular to the wind direction. This is due to the decrease in forward speed as the moth approaches the source. Another aspect of moth odor tracking behavior is searching or “casting” behavior. If the moth looses the plume, it will fly perpendicular to the wind and expand the lateral extent of its movements in order to reacquire the plume [8]. This casting behavior can be seen in Fig. 2 at about 0.8 meters from the source.

In this paper, we test three dimensional plume tracking algorithms on a robotic platform. The robot has little resemblance to a moth [13]. However, because the robot can translate in three dimensions in an air flow and the behavior of
the robot is based on the plume tracking behavior of a moth, 
the robot has been named Robo-Moth.

II. ROBO-MOTH

Robo-Moth is a wind tunnel with a linear Cartesian robotic 
gantry located at the downwind end of the test section (Figure 
4) The wind created in the wind tunnel carries a plume from a 
ionized air generator to the robot. The floor of the treadmill is 
the surface of a conveyor belt. In Robo-Moth, the plume source 
rests on the conveyor belt and moves downwind over time 
instead of the robot moving upwind toward the source. Robo-
Moth’s control system coordinates vertical and lateral motions 
of the gantry with forward motion of the conveyor belt for a 
total of three translational degrees of freedom. The gantry has 
a range of motion of about 400 mm and 320 mm in the 
horizontal and vertical directions respectively, and the plume 
generator is placed about 800 mm from the sensor head 
mounted on the gantry.

An ion plume is used instead of a chemical plume because 
ionized air molecules can be detected more easily. Ionized air 
plumes have been studied by others [9] and have been shown to 
disperse in air in a manner similar to pheromone molecules. 
The major drawback to using an ion plume is that the source of 
an ion plume appears larger than the pheromone source used in 
biological experiments. This is caused by the repulsive forces 
of the ions on each other. To make the source appear smaller, 
an aluminum foil ring was placed around the ion generator to 
ground out some of the ions. Figure 3 shows a time averaged 
representation of a typical ion plume produced in Robo-Moth’s 
wind tunnel.

Figure 3. Typical ion plume. Determined by taking ion concentration 
measurements at 45 equally spaced positions along the wind tunnel.

Figure 4. A wide angle view of Robo-Moth showing the test section (left 
side of image) and the diffusion section (right side of image).

Robo-Moth provides a complete testing environment for 
plume tracking. Before Robo-Moth, most plume tracking 
studies were limited to two-dimensional simulations or 
terrestrial robots.
III. ROBO-MOTH ODOR TRACKING ALGORITHM

Two three-dimensional plume tracking algorithms based on the behavior of *M. sexta* have been implemented on Robo-Moth. The algorithms are based on a previously developed two-dimensional algorithm [10].

The odor tracking algorithms employed by Robo-Moth use instantaneous plume concentration measurements and wind direction to control speed and flight angle. The algorithms exhibit two characteristic behaviors modeled after the behavior of moths tracking pheromone plumes: in plume behavior and out of plume behavior. The in plume behavior consists of movements across the wind with varying amounts of upwind progress depending on the plume concentration. The out of plume behavior consists of movements perpendicular to the wind direction in an attempt to reacquire the plume. The flight velocity (v) of Robo-Moth is determined by three parameters: speed (the magnitude of the velocity), heading (α), and pitch (β). Figure 6 shows how the heading and pitch angles are defined. The Cartesian coordinate system is aligned such that the positive x-direction is to the right when viewed from downwind, the y-direction is in the opposite direction of gravity, and the z-direction is opposite the direction of the wind. The heading angle is measured in the horizontal plane relative to the z-axis. The pitch angle is measured from the horizontal plane to the velocity vector.

![Figure 6. Illustration of the heading angle (α) and pitch angle (β)](image)

A timer is used to switch behaviors or flight directions. Studies suggest that moths have an internal timer that tells them when to turn[11]. The idea of an automated turn timer makes sense when one considers the size of the moth and the sparse distribution of odor molecules comprising the plume. The internal timer directs the moth to turn back and forth across the plume and does not allow the moth to fly too far from the plume, while looking for more plume information. Since it is not yet possible to record from the antennal nerves of the moths during flight, very little is known about how moths use plume concentration information in conjunction with this timer. Two similar algorithms were developed using different kinds of plume information to reset the inter-turn timer. The first algorithm, the Counter-turner, resets its turn timer based on the transition from no plume concentration to plume concentration. In affect, the plume edges are used to reset its inter-turn timer. The second algorithm, the Modified Counter-turner, resets its turn timer upon detecting the maximum concentration reading for each movement across the wind. It achieves this by resetting the inter-turn timer when the current plume concentration measurement exceeds the maximum previously measured concentration for a given crosswind movement. Unlike, the Counter-turner, which only resets its timer once for each crosswind movement, the modified version ideally, resets its timer multiple times as it approaches the maximum concentration of the plume, for a particular crosswind movement.

IV. SOFTWARE IMPLEMENTATION

The algorithms described in the previous section are implemented as finite state machines. There are three states used in both algorithms: tacking, reacquire, and turning. The tacking state represents the in plume behavior. The reacquire state represents the out of plume behavior. Once the inter-turn
timer expires, the turning state is executed, which transitions between the two previous states or changes the crosswind direction within those states.

Pitch and heading are controlled by separate finite state machines, each with their own inter-turn timer, each expiring after 500 ms. The phase relationship of these two flight angles determines the shape of the flight trajectory. Since most biological studies have only observed the moth plume tracking behavior from overhead, very little is known about how moths control pitch. The inter-turn timers for both algorithms are initially set to be 180 degrees out of phase, so that a large cross-sectional area of the wind tunnel can be traversed. This is achieved by forcing the value of one inter-turn timer to zero and the other to be half the inter-turn duration. Since the timers are reset more often when using the Modified Counter-turner, it maintains the 180 degrees phase separation, where the Counter-turner might not.

Figure 7. Flight angles (pitch and heading), and flight speed vs ion concentration.

Figure 7 shows the general relationship between the control variables and the plume concentration. For all control variables, the threshold and saturation concentrations are 0.9 mV and 15.5 mV respectively. The threshold concentration is just slightly larger than the background noise present in the environment. The saturation concentration is the concentration of the source. Experiments involving biological moths are often done with pheromone-laden filter paper, which does not look like a female moth. However, the moth still exhibits near source behavior. This implies that the moth expects a certain pheromone concentration near the source. The heading flight angles for threshold and saturation concentrations are 50 and 85 degrees respectively. These angles produce the behavior observed in moths, where their flight trajectories become more perpendicular to the wind as it approaches the source. The pitch flight angles for threshold and saturation concentration are 45 and 0 degrees respectively. This also produces observed behavior similar to that of moths where their flight trajectories in the vertical plane do not change as much when they approach the source.

V. TYPICAL FLIGHT TRAJECTORIES

Figure 8. Views of typical Robo-Moth flight trajectory (Counter-turner). The source in this case is located 800mm upwind from Robo-Moth’s starting point, 80mm above the center position of the gantry, and along the overhead centerline. Note: the source is not in the center of the gantry range.

Figure 8 shows a typical flight trajectory of Robo-Moth using the Counter-turner algorithm. From these trajectories, the characteristic crosswind tacking behaviors can be seen. In addition, the lack of altitude change near the source can also be seen.

VI. ALGORITHM PERFORMANCE

To compare the different algorithms, three trials were run at each of nine different starting points in the cross-section of the wind tunnel. A trial was considered successful if it came
within 40 mm of the source. Two types of failures were defined. A limit switch failure is one where Robo-Moth attempted to travel beyond the physical limits of the robotic gantry. These were considered failures so that the use of the limits of the robotic gantry would not influence the results. The other type of failure was a timeout failure. A timeout failure was a failure to reach the plume source within 45 seconds. Of all the trials run, only limit switch failures were encountered.

Table 1 Time required to reach the source using counter-turner and modified counter-turner algorithms. Starting positions are relative to the center line of the wind tunnel. *N/A represents a limit switch failure. Time in seconds

<table>
<thead>
<tr>
<th>RoboMoth 3D Success Stats</th>
<th>Trial Position (X,Y,Z) mm</th>
<th>Trial 1</th>
<th>Trial 2</th>
<th>Trial 3</th>
<th>Average Time</th>
<th>Success Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Counter turner</td>
<td>(100, 82, 0)</td>
<td>30.1</td>
<td>N/A</td>
<td>22.8</td>
<td>26.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(-100, 82, 0)</td>
<td>24</td>
<td>20.5</td>
<td>24.2</td>
<td>22.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(100, 0, 0)</td>
<td>23.2</td>
<td>28.8</td>
<td>N/A</td>
<td>26.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0, 82, 0)</td>
<td>19.2</td>
<td>19.1</td>
<td>20.7</td>
<td>19.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(-100, 0, 0)</td>
<td>N/A</td>
<td>24.3</td>
<td>21.3</td>
<td>22.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(100, -82, 0)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0, -82, 0)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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<tr>
<td></td>
<td>(-100, -82, 0)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
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</tr>
</tbody>
</table>

| Modified Counter turner    | (100, 82, 0)            | N/A    | 17.5   | N/A    | 17.9         |                   |
|                            | (0, 82, 0)              | 28.7   | N/A    | N/A    | 28.7         |                   |
|                            | (-100, 82, 0)           | N/A    | N/A    | N/A    | N/A          |                   |
|                            | (100, 0, 0)             | N/A    | N/A    | N/A    | N/A          |                   |
|                            | (0, 0, 0)               | 24     | 17.7   | N/A    | 20.9         |                   |
|                            | (-100, 0, 0)            | N/A    | N/A    | N/A    | N/A          |                   |
|                            | (100, -82, 0)           | N/A    | N/A    | N/A    | N/A          |                   |
|                            | (0, -82, 0)             | N/A    | N/A    | N/A    | N/A          |                   |
|                            | (-100, -82, 0)          | N/A    | N/A    | N/A    | N/A          |                   |

Table 1 shows that the counter turner algorithm successfully tracked the plume more often than the modified counter turner algorithm. In addition, all trials where the starting position was 82 mm below the centerline of the wind tunnel failed. To further investigate the differences between the two algorithms, plots of all the flight tracks, or superimposed scatter plots were created.

Figure 9 and Figure 10 show that both algorithms produce very similar flight tracks. Inspection of the side view flight superimposed scatter plots, show where the limit failures occur. For both algorithms, most failures go beyond the lower altitude limit less than 100 mm after starting. This implies that the starting position was too low to allow for successful odor tracking. In addition, upper altitude limit failures occur for the modified counter-turner beyond the upper at various downwind downwind positions. This difference between the two algorithms is due to larger flight widths of the Modified Counter-turner algorithm. The larger flight widths are due to the inter-turn timer resetting more often than the Counter-turner algorithm.

VII. CONCLUSIONS

The range-of-movement limitations inherent to Robo-Moth combined with the particular settings that we used in these
trials made comparisons of the two algorithms difficult. However, the superimposed scatter plots show that both algorithms effectively track the ion plume to its source. When the limit failures are ignored both algorithms have a high rate of success.

Both algorithms also exhibit behavior similar to the behavior of *M. sexta*. The altitudes of individual flight tracks level off as they approach the source. The crosswind distance significantly decreases as the flight tracks approach the source. Both of these flight behaviors are characteristics of moth flights.

In the future, the plume source could be lowered to the center line of the robotic gantry, or the robotic gantry could be expanded to fill the entire wind tunnel cross-section. In addition, statistical analysis of Robo-Moth’s flight trajectories could be done in order to compare to similar statistics of *M. sexta* flights.

**REFERENCES**


