The “Smellicopter,” a bio-hybrid odor localizing nano air vehicle

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***Abstract*— Robotic airborne chemical source localization has critical applications ranging from search and rescue to hazard detection to pollution assessment. Previous demonstrations on flying robots have required search times in excess of ten minutes, or required computation-intensive signal processing, largely because of the slow response of semiconductor gas sensors. To mitigate these limitations, we developed a hybrid biological/synthetic chemical sensing platform consisting of a moth antenna on an aerial robot. We demonstrate that our robot, a 9 centimeter nano drone, can repeatedly detect and reach the source of a volatile organic chemical plume in less than a minute. We also introduce wind vanes to passively aim the robot upwind, greatly simplifying control. To our knowledge this is the first odor-finding robot to use this approach, and it allows for localization using feedback only from sensors carried on-board rather than GPS, allowing indoor operation. The chemical sensor consists of a hybrid biological/synthetic integrated chemical sensor (electroantennogram) using an excised antenna of the hawkmoth *Manduca sexta* and associated miniaturized electrophysiology conditioning circuitry. Our robot performs an insect-inspired cast-and-surge search algorithm inspired by the odor-tracking behavior observed in *Manduca sexta*. These results represent a significant step toward robots that have the speed and sensitivity of biological systems.**

I. INTRODUCTION

Chemical gas sensors are used in many situations where human safety is at risk, either to help locate trapped persons in natural disasters, or to detect the presence of dangerous chemicals in the environment. For example, chemical sensors could be used in earthquake zones for locating survivors, in industrial facilities to monitor the concentration of toxic chemicals or to detect hazardous leaks, or urban conflict areas to detect explosives or chemical warfare agents. In situations such as these there is a need for autonomous systems or robots with chemical sensing capabilities, either to supplement limited human resources in search and rescue efforts, or for operating in environments that are too toxic or dangerous for people to enter.

Fig. 1. The Smellicopter is a modified commercial Crazyflie drone with custom electroantennogram circuit and vanes for passive upwind orientation.

Chemosensing robots require three distinguishing elements: a robotic platform with maneuvering and navigation capability, a sensor that can detect a particular volatile chemical, and an olfactory search strategy. In order for a chemosensing robot to be effective, the robot must be designed with the characteristics of its operating environment in mind. Also, its sensor must be selective for a chemical that is relevant to its task. In many cases, the operating environment of the robot will include confined spaces and unpredictable terrain which impede terrestrial robots.

Unmanned aerial vehicles (UAVs) are attractive platforms for building chemosensing robots because they can navigate in complex 3D environments without the challenges of difficult terrains. Recently there have been demonstrations of multirotor UAVs performing olfactory searches with differing search strategies and using metal oxide gas sensors. Neumann *et al.* presented an outdoor olfactory search on a 1 m diameter quadrotor using both a bio-inspired strategy, and a particle filter strategy [7]. Additionally, Luo *et al.* [5] demonstrated an indoor olfactory search using a UAV slightly larger than the commercial Crazyflie drone that could infer the direction of a gas source in the robot’s inertial frame calculated using data from three metal oxide sensors.

A limitation of metal oxide sensors is that they have slow response times and large refractory periods in the presence of high gas concentrations [6], which requires long pauses of about 20 seconds at each location for the sensor reading to stabilize. Luo’s method avoided these long

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pauses by performing many thousands of calculations each second using an off-board computer with a powerful desktop GPU [5]. Such solutions may challenge small UAVs that are suitable for operation in confined spaces because they are powered by small batteries and can carry only limited payloads. Slow olfactory searches may be impractical, and complex computations require specialized hardware which comes at a cost to both power and weight. Building an autonomous UAV with olfactory search capability in real world conditions remains an ongoing challenge.

In contrast to synthetic systems, many living organisms have evolved highly effective and efficient chemical sensing capability and olfactory search behaviors which are vital to tasks such as locating mates and food [11]. For example, male moths can track females over great distances and detect female pheromones at concentrations far less than parts per trillion [2]. Biological odor detectors, such as moth antennae in electroantennogram preparations, offer a faster response and more sensitive discrimination than is possible with current engineered chemical sensors. To be used in specialized applications, *Manduca sexta* and many other insect species have the potential to be genetically edited by using CRISPR to engineer the sensitivity to specific odors.

This work presents an autonomous hybrid bio-synthetic UAV that uses living tissue to detect chemical gas and performs an olfactory search that mimics the behavior of flying insects. The system detects the presence of particular chemicals using an electroantennogram on an excised moth antenna. This approach provides highly sensitive, selective, fast responding sensing capability at low weight and low power. The olfactory search is performed using a reactive strategy called cast-and-surge that guides the UAV upwind to the gas source. Upwind flying is achieved passively using aerodynamic wind vanes and reduced yaw control authority. This wind-driven passive orientation results in a system which reacts quickly to chemical signals with minimal computational requirements and using all onboard sensing. To the best of our knowledge, this system is the smallest and lowest power chemosensing robot ever demonstrated.

II. SYSTEM COMPONENTS

A. *Electroantennogram (EAG)*

An electroantennogram is an analog circuit that measures the response of a living biological antenna to chemical or mechanical stimulus. These antennae serve as critical sensory organs for insects and other arthropods. In addition to their capacity to sense wind and vibrations, antennae most notably provide olfactory information to the insect to find food and mates [13]. Chemical sensing follows from a complex cascade of molecular interactions. Volatile compounds diffuse into the interior of the antenna where they then bind to odor binding proteins. Those complexes then bind to, and activate, G-protein receptor molecules on the membranes of chemosensory neurons populating the interior of the antenna. Once activated, G-protein mediated pathways provide a whole cell response that greatly amplifies the influence of a single odorant. That amplified response yields an action potential that propagates down the antenna to the brain of the insect. An electroantennogram measures the aggregate electrical activity of the olfactory neurons in an antenna by measuring the voltage drop across the antenna.

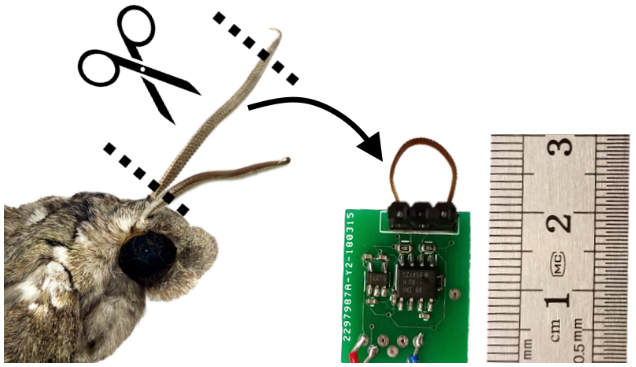

Fig. 2. The electroantennogram (EAG) is comprised of a single excised antenna from a *Manduca sexta* hawkmoth and our custom signal conditioning circuitry. Our EAG circuit board has a footprint of less than 3 cm^2.

One method for producing an electroantennogram is to remove the antenna from the moth and insert wires into both the base and the tip of the antenna. We have observed that antennae from the *Manduca sexta* hawkmoth in this preparation will continue to produce a signal for up to four hours, but the signal strength will continuously decline over this period. This decline has been recorded in the excised antenna of *Agrotis ipsilon* [3]. Antennal signals can also be captured by probing the brain of the insect and the tip of a single antenna to measure individual neuronal responses [3]; however, this requires additional processing of the spike rate rather than the simple thresholding of a local field potential that we can apply for our electroantennogram.

The electroantennogram (EAG) requires an analog device that amplifies the voltage across an antenna preparation and filters the signal so that it can be measured by an analog to digital converter (ADC). EAGs have been shown to respond faster than metal oxide sensors [6], and are suitable for detecting the presence of chemical gas at a rate of up to 10 Hz [6]. Our EAG design outputs a signal between zero and three V so that signal can be measured by the ADC of many common microcontrollers. The basic elements of the EAG are 1) a high gain preamplifier 2) an active bandpass filter and 3) an output amplifier, which are shown in Fig. 3. The EAG weighs just 1.5 g and consumes only 2.7 mW of electrical power. *Manduca sexta* moths are cold anesthetized prior to removing antennae by being placed on ice for at least 15 minutes. For the antenna preparation, we use an excised antenna from a *Manduca sexta* moth which we connect to the EAG by inserting a segment of 75 μm diameter stainless steel wire into each end of the antenna.

Rather than use a generic amplifier, our EAG circuit is tuned to the characteristics of antenna from *Manduca sexta* to provide a low noise and high amplitude output signal. We found our antenna preparation will produce a voltage signal between 10 μV and 1 mV in response to chemical stimuli, so

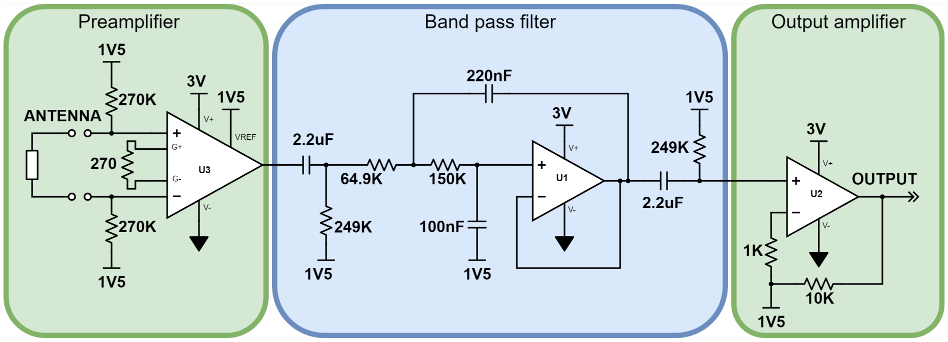

Fig. 3. Electroantennogram Analog Schematic. Premplifier U3 part number is INA118, and the part number of op amps U1 and U2 are TLV2333.

we fixed the gain of the EAG to 1000. The antenna signal also contains an undesirable offset voltage that drifts over time in a manner unrelated to the chemical stimulus, causing a previously noted baseline drift [6]. Lastly, we found that the resistance of our antenna preparations ranges from 500 to 750 kΩ. The large resistance of the antenna preparation causes 60Hz noise from the environment to appear at the input. To attenuate this 60Hz noise, and remove the effect of baseline drift on the EAG output, our design includes a 4th order bandpass filter. The magnitude response of the EAG model is shown in Fig. 4.

Due to the large gain of the circuit, we observed that the total input offset voltage of the preamplifier can cause the output signal to saturate, and thereby corrupt the chemical signal. To reduce the total input offset voltage error, we used INA118 from Texas Instruments for our preamplifier because it features 1 nanoamp input offset current and 20 mV input offset voltage. As a result, our EAG design rejects baseline drift at the output, can tolerate 10 mV of offset voltage without affecting the output signal, and attenuates high frequency noise to provide a high signal to noise ratio.

We validated the EAG design by stimulating the antenna excised from a cold anesthetized moth with a floral mixture of compounds present in the flower *Datura wrightii* [10] which the *Manduca sexta* moth feeds from. This mixture is an attractant for both female and male *Manduca sexta* and is effective in producing EAG responses. The composition of this mixture is shown in Table I.

TABLE I

CHEMICAL COMPOSITION OF FLORAL SCENT.

Compound	Concentration (mL)
Benzaldehyde	0.02
Benzyl Alcohol	0.5
Geraniol	2.0
Linalool	0.05
Mineral Oil (dilutant)	2.5

We despositied 5 μL of the scent mixture on the inside of a disposble pipette and allowed it to dry. This way, when the pipette is squeezed it expels a puff of floral scented air. The EAG was placed inside of an OMEGA mini wind tunnel with airspeed at 2.5m/s. The pipette is placed perpendicular to the air flow at the intake of the wind tunnel to ensure that the antennal response recorded is due to chemical stimulus and not to mechanical stimulus from the puffed air. The pipette is puffed by hand at various frequencies. Each stimulus results in an obvious spike in the output signal that decays in a fraction of a second.

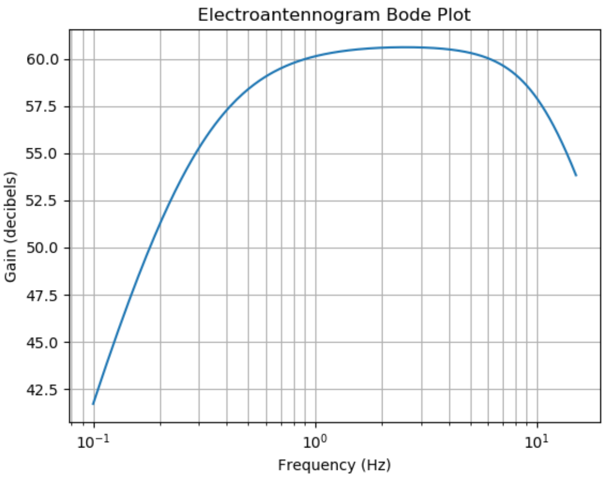

Fig. 4. EAG Model Magnitude Response

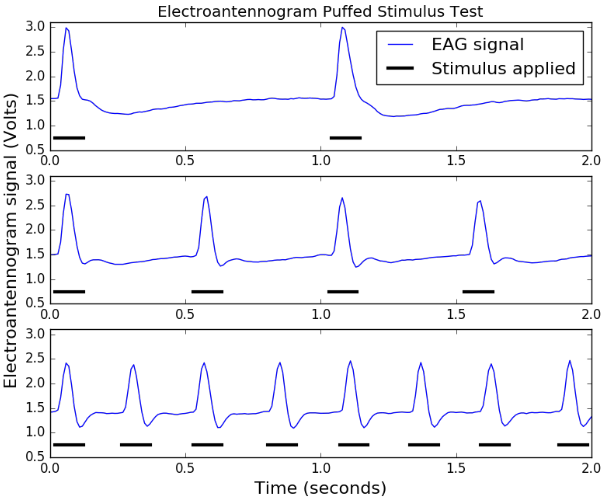

Fig. 5. The EAG response to a hand puffed stimulus. Floral scent is hand puffed using a disposable pipette perpendicular to the intake of a mini wind tunnel containing the EAG.

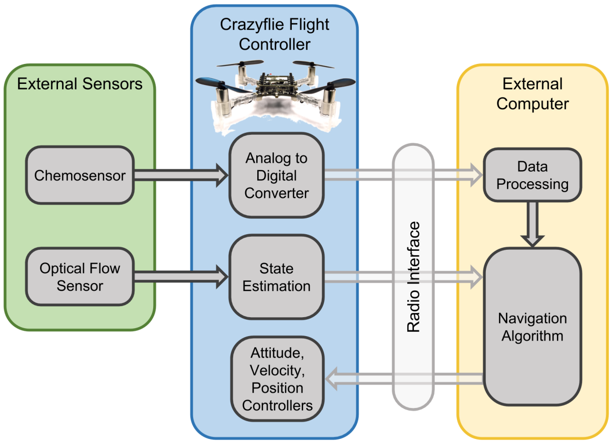

Fig. 6. System Architecture Diagram

Fig. 5 shows the signal recorded from the EAG when stimulated with scented air. In the plots, the stimulus was delivered by hand at approximately 1, 2, and 4 Hz with the aid of a metronome. The black bars in each subplot are approximations which represent the onset of the stimulus. In contrast to metal oxide sensors, the response and recovery times of antennal EAGs are quite rapid, under a quarter of a second.

B. Nanodrone System Architecture

The EAG sensor interfaces with an autonomous nanodrone. For this, we used a commercially available nanodrone called Crazyflie 2.0 that features open source software and extensible open hardware. The Crazyflie occupies just 85cm^2 and weighs only 23 g, placing Crazyflie among the smallest autonomous nanodrones on the market. In addition to the stock Crazyflie, we have added to it an external sensor that is designed by the manufacturer. This sensor uses an optical flow camera and infrared laser range finder to provide the Crazyflie with velocity measurements, which allows the Crazyflie to hover without drifting and without a GPS system. When carrying this payload, the Crazyflie can fly for up to seven minutes from a single cell lithium-polymer battery with 250 mAh of capacity. The Crazyflie also includes a Bluetooth radio transceiver, and the manufacturer sells a USB radio dongle for which a python driver library is available so that users can access vehicle telemetry and controls from an external computer.

Using the radio dongle, our implementation retrieves the EAG data and state information from the Crazyflie and inputs the data into a navigation program. This program then uses the radio dongle to send velocity commands back to the Crazyflie. Similarly to [5], we used an external computer run the navigation program; however, our navigation program consists only of simple thresholding of the EAG signal and transmitting velocity commands. The Crazyflie is fully capable of running the program with no additional hardware. We only used an external computer for its ease of use in programming and debugging. An overview of the architecture of the entire system is presented in Fig. 6.

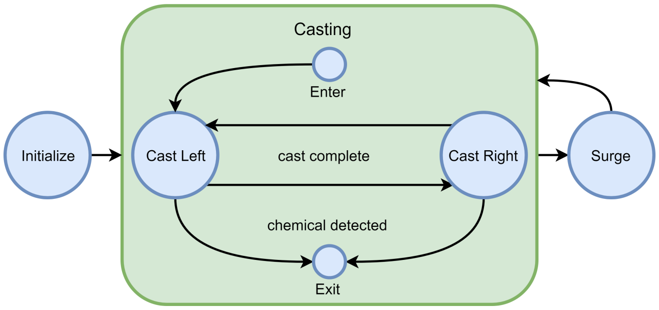

Fig. 7. Cast and Surge State Machine

C. Navigation Program

To demonstrate an olfactory search using the smellicopter, we implemented a navigation program similar to one used in [7] that is inspired by the insect foraging in a single horizontal plane. Flying odor tracking insects will often fly in a crosswind casting pattern and encountering an odor will cause the insect to steer into the wind [13]. This crosswind casting can be in the form of spiraling [6], [3], zigzagging [3], [4], or simple crosswind back-and-forth movement with no upwind component [4]. Although insects perform a three-dimentional tracking while following an odor plume, 3D algorithms have not been tested on flying platforms yet. Luo et. al. [5] does locate a source in 3D but uses a multi-stage approach which consists of a separate vertical search algorithm to find the altitude of a turbulent plume and then switches to a horizontal only search algorithm to locate the source. Our implementation, illustrated in Fig. 7, uses a zigzagging strategy, and it requires that the smellicopter is in an environment with a relatively consistent wind or airflow. We chose to focus on testing an existing strategy that has been extensively tested in literature, the 2D cast-and-surge algorithm, to show our bio-hybrid platform's odor localization capability. Future work will test other localization strategies including casting in a vertical direction in addition to crosswind casting.

For our 2D cast-and-surge tests, the vehicle takes off to a height of 40 cm and then hovers for ten seconds to allow it time to orient upwind. The smellicopter starts casting left and right crosswind. When a volatile chemical is detected, the smellicopter will surge 25 cm upwind, and then resume casting. Volatile chemicals are detected by simple thresholding of the EAG signal. As long as the wind direction is fairly consistent, this strategy will bring the insect or robot increasingly closer to a singular source with each surge. Moreover, the casting allows the insect or robot to regain the plume even if there is a slight shift in the wind direction or movement of the source; however, the algorithm requires that the smellicopter is facing upwind most of the time.

D. Upwind Flying

Knowing the wind direction is an important capability for performing an olfactory search because it allows the robot to narrow the set of search directions. Past efforts to perform olfactory search using autonomous UAVs have used

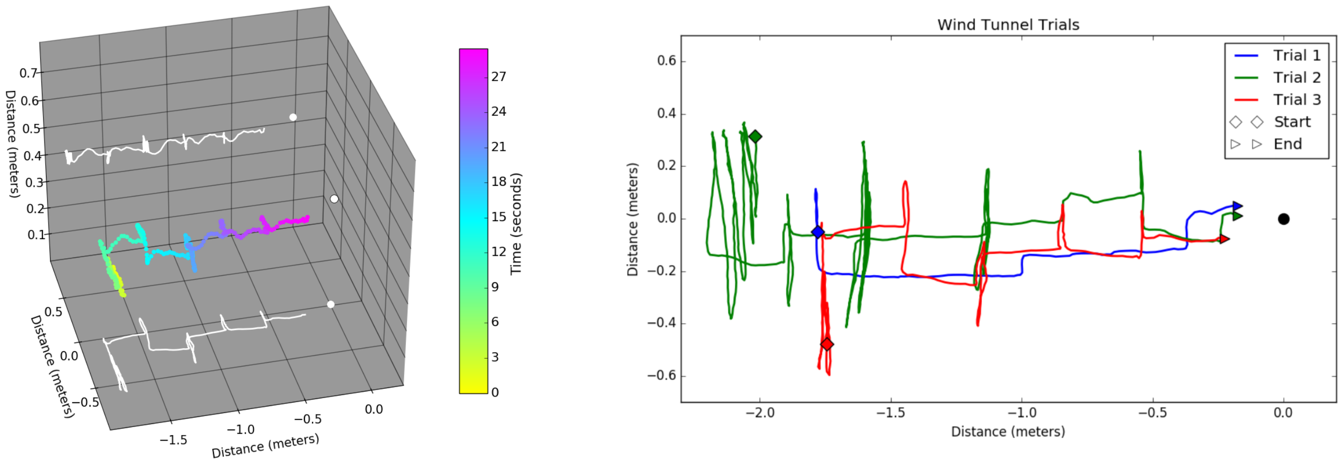

Fig. 8. Tests of the Smellicopter performing an olfactory search in a wind tunnel, where the wind direction is from right to left. On the left is a single test colored to show time duration and with vertical and horizontal projections of the flight path. A top-down projection of the same test and two additional trials with varied starting positions are shown in the right plot. The position of the source is marked with a circle in each plot.

numerical methods to estimate the wind vector. Neumann *et al.* used the law of cosines to compute the wind vector from the wind triangle [7], but that required an airspeed reference function that was derived from wind tunnel characterization of the drone. Luo *et al.* estimated the direction of the wind by filtering the UAV attitude [5], but this method requires that the wind speed imparts an attitude bias that exceeds the uncertainty of the attitude state estimate.

In contrast, we have used a passive control scheme to force the Smellicopter to constantly face upwind by adding thin plastic wind vanes to the back motor mounts and modifying its yaw controller. The internal yaw PID controller of the Smellicopter is disabled, and the gains of the yaw rate controller are reduced. The wind vanes are oriented such that if the Smellicopter is not facing upwind, the force of the air flow on the vanes imparts a large yaw torque, causing the Smellicopter to rotate until it is facing upwind. This process works much like a weather vane, where the wind force on the tail of the vane rotates until the weather vane is facing upwind. The smellicopter holds its position using optic flow while allowing the wind force on the wind vanes attached to the back to rotate the whole vehicle until it is facing upwind.

III. DEMONSTRATION

To demonstrate the ability of the Smellicopter to localize a chemical source, we designed a simple olfactory search task. We placed a filter paper disk with floral scent deposited on it at intake of a wind tunnel that is 2 m long with a 1 m square cross-section. We set the wind speed at approximately 1 to 1.5 m/s. We started the Smellicopter at varied positions near the output of the wind tunnel and had it perform the cast and surge algorithm illustrated in Fig.7.

The source is a 2 cm diameter circle of filter paper with approximately 5 mL of floral scent defined in section IIA above deposited on it immediately before beginning the trial. When using a newly excised antenna from a cold anesthetized moth, the Smellicopter was first hovered both in the presence of odor and in the absence of odor to manually tune the threshold value of the electroantennogram so that any electrical or mechanical noise is rejected and only signals resulting from odor response pass the threshold. Chemical sources used in odor localization experiments with electroantennograms commonly use higher concentrations than are naturally occurring to ensure activation of the antenna within the plume. We chose this amount and concentration of floral scent to show that our platform can successfully follow a chemical plume to its source. Future experiments will test varying odor concentrations.

The left plot in Fig. 8 shows the Smellicopter navigating to the source of the odor plume. Multi colored line shows the 3D trajectory of the Smellicopter as estimated from its optic flow-based position estimator. White lines show the vertical and horizontal projections of the 3D trajectory and white circles show the location of the source relative to each path. The colorbar indicates the time progression of the trial, which was approximately 30 seconds. The wind tunnel is as described in the Experimental Setup above with the wind direction from right to left. The Smellicopter's position is estimated from the optical flow data and verified using video.

This test and two additional tests are shown in the right plot of Fig 8 in a top-down view. The Smellicopter starts on the ground downwind of the source in varied locations. The Smellicopter takes off and hovers at a height of 40 cm above the platform and hovers in place for 10 seconds while the yaw control is lowered to allow passive upwind orientation as was described in section IID. If the Smellicopter detects an odor, it surges upwind. While the Smellicopter does not detect an odor, it casts crosswind with increasing casting width. The tests are automatically terminated once it is approximately 10 cm downwind of the source to avoid the Smellicopter colliding with the intake screen of the wind tunnel.

Our tests show that the Smellicopter rapidly approaches the source, and in each test the Smellicopter ends its search algorithm within 3 cm of the source in the y axis. Each trial ends approximately 10 cm from the source in the x axis to avoid collision with the intake grate of the wind tunnel. The navigation program we demonstrated does not yet have the capability of identifying the source. With the current search strategy if the trial was not terminated and the intake grate did not impede the motion of the Smellicopter, the final surge would move the Smellicopter past the source. At this point, it would be upwind of the source and stay in the casting state. In this situation it would continue to cast until a chemical signature from a new source is acquired, or until the wind direction shifts so that the Smellicopter is downwind of the source once again.

IV. CONCLUSION

A biological chemical gas sensor was developed and integrated on a nanodrone where a biologically inspired cast and surge algorithm was used to successfully localize a chemical gas source in a hardware demonstration. To the authors' knowledge, the work reported here represents the first time a biological odor detector has flown on an aerial robot and a passive method has been used to determine wind direction; furthermore, this work is the first to demonstrate such an aircraft operating with sensor autonomy, that is, relying on no external position information while still improving vehicle speed and processing requirements over prior work.

A. Future Work

The Smellicopter is a unique platform that has great potential to be used to test biological hypothesis for insect flight or as a tool to help save lives by finding survivors in disaster areas and detecting hazardous chemical leaks.

Recent advances in genetic engineering and the development of the gene editing tool CRISPR allow for the electroantennogram to be sensitive to additional chemicals other than the molecules that the antennae are naturally sensitive to. In particular, the genome of the *Manduca sexta* moth has been fully sequenced which will allow our current electroantennogram circuitry to detect signals from an antenna with genetically edited odor binding proteins. With this capability, the Smellicopter can use multiple antenna to detect and discriminate between odors that the moth is naturally attracted to as well as detect chemicals such as explosives and people for search and rescue.

The Smellicopter has potential for more realistic physical demonstrations of various odor localization approaches than what is possible in models. Chemical plumes and dynamic wind conditions are challenging to model, especially when combined with vehicle dynamics and control. The Smellicopter is a robust, affordable platform which would allow rapid testing of olfactory search strategies in hardware and under realistic conditions. Additionally, because the Smellicopter is similar in size to insects such as the *Manduca sexta*, and the electroantennogram does not have the latency of commercial sensors, it is an ideal platform for comparing bio-inspired odor localization strategies. One such example is to investigate whether insects search behaviors are purely reactive or whether they maintain an internal model of the plume to optimize their search trajectory [8], [12]. Due to the power and weight constraints of drone platforms, determining the optimal search strategy given a unique task, such as locating trapped persons or a hazardous chemical leak, is vital to the timely success of the completing the task. Using the Smellicopter as a platform to test these strategies and optimize them will bring us one step closer to making life-saving drones reality.

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