Wind Sensor and Robotic Model Wasp Development

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Abstract

Flying insects sense the speed and direction of the wind to provide directional information used in chemical plume tracking. To model this plume tracking using a mobile robot, an appropriate wind sensor is required. This paper initially describes the design of a wind sensor for this purpose. The sensor utilises three wind speed measurement devices, thermal anemometers, to determine wind speed and direction. These flow properties are obtained by examining and comparing the signals from the three sensors positioned around an obstacle. A number of different obstacles were produced and tested before the final enclosed design was chosen. The sensor prototype was then integrated with a small mobile robot. This robot was used in two series of tests. The first series examined a simple wind seeking process. The second series examined the production of cross-wind casting behaviour by the robot as observed in flying insects.

1 Introduction

Insects utilise chemical sensing for a number of tasks vital to their survival, including foraging for food and searching for a mate or a host for their young [Godfray, 1994]. In fact, odours are thought to be the major signals used by parasitoid insects in the process of host location [Kaiser *et al.*, 1994]. Many flying insects sense the wind speed and direction and use this information to assist them in these chemical sensing tasks [Jones, 1986]. Biological hypotheses to explain this plume tracking behaviours are postulated, but are often not tested in realistic physical simulations. The use of a robotic model enables the testing of these hypotheses under conditions similar to those facing the organism to be modelled. The construction of robotic models for this purpose can provide benefits both for robotics engineers and biologists [Beer *et al.*, 1998]. It can help engineers determine structures, sensors, actuators or behavioural patterns that allow robots to survive and thrive in the target animals' environment as well as providing biologists with evidence supporting or contradicting proposed hypotheses [Webb, 1995]. To use mobile robots as a simulation tool, there is a need for sensors that emulate those of the organism to be studied [Beer *et al.*, 1998]. In the case of flying insects, sensors are required that can accurately sense the wind speed and direction under conditions in which the insect functions and allow the robot to react as an insect would in the same situation.

This paper initially outlines the design of a differential wind sensor which allows a mobile robot to mimic the wind sensing capabilities of a flying insect, with low computational effort and power consumption. The range of wind sensors currently available has been reviewed, and the capabilities of the insect sensing system (and consequently the requirements of the sensor for the robot) are outlined. The possible designs that meet these requirements are investigated and a final sensor is chosen for construction. This design was then mounted on a mobile robot. This robot was tested using a simple wind seeking algorithm to examine its wind sensing ability. Further tests were undertaken to examine the ability of the robot model to accurately reflect the behaviour of the wasp.

2 Literature Review

A wide range of wind sensors have been developed to measure direction and velocity. However, most of these methods have been designed for outdoor use and cannot measure low airflows [Russell and Kennedy, 2000]. However several wind sensing options are appropriate for low flow measurement. These include the DC motor wind sensor [Russell and Kennedy, 2000] and thermal anemometers, including hot-wire anemometers [Lomas, 1986], pulsed wire anemometers [Bruun, 1995], RF thermocouples and the Shibaura thermal anemometer [Shibaura, 2002], used in a number of previous wind sensing mobile robots [Hayes *et al.*, 2002; Ishida *et al.*, 1994]. Other options include wind vanes and rotating anemometers, a biologically inspired sensor [Chapman *et al.*, 2000] and an ultrasonic sensor [Gouveia and Baskett, 1997].

A number of researchers have previously combined wind sensors with mobile robots to produce a robot capable of measuring the speed and direction of the wind. Russel *et al.* [2000] developed a novel wind sensor that can sense low flow. This sensor worked by measuring the effect of the wind on the rotational velocity of a paddle that is rotated at a constant speed [Russell and Kennedy, 2000]. Other groups have used thermistor based anemometer sensors that measure the change in temperature of a heated element when exposed to the wind [Hayes *et al.*, 2002; Ishida *et al.*, 1994]. Ishida *et al.* [1994] placed four of these sensors around an obstacle and used the output pattern of the sensor voltages to determine the wind speed and direction. Belanger *et al.* [2001] used two pressure transducers positioned 120° apart to determine the wind velocity. Other researchers have taken direct inspiration from the organs insects themselves use to sense wind flow. Chapman *et al.* [2000] created a wind sensor based upon the filiform hair cells of the cricket. These sensors consisted of a spring positioned between four signal pins. Depending upon the wind (and robot motion) the spring contacts with one of the signal pins indicating a wind direction. An array of these sensors allowed the robot to sense the wind direction [Chapman *et al.*, 2000]. These sensors all used currently available components, however there is no simple "off the shelf" solution for mobile robot based wind sensing at low velocities.

A number of projects were identified that attempted to reproduce the chemical plume tracking behaviour of various flying insects using robotics [Belanger *et al.*, 2001; Ishida *et al.*, 1994; Ishida *et al.*, 1996; Ishida *et al.*, 2001; Kuwana *et al.*, 1997; Kuwana and Shimoyama, 1998; Kuwana *et al.*, 1999]. These groups generally used information from two spatially separated chemical sensors to determine the chemical gradient. Groups who used a single chemical sensor did not combine this configuration with algorithms appropriate to the information received by the insect [Belanger *et al.*, 2001; Hayes *et al.*, 2001; Ishida *et al.*, 1994; Russell, 2001]. No research was identified that utilised an appropriate insect inspired plume tracking algorithm with a single chemical sensor and in particular no research was identified that investigated the chemical plume tracking behaviour of wasps.

3 Wind Sensor Development

To develop an appropriate wind sensor for this project, design specifications were set and a number of different design options were investigated. These steps are outlined in the following sections.

3.1 Specifications

In order to appropriately model the insect to be studied, a wind sensor must be designed that reflects the capabilities of the insect sensing system. The insect to be modelled in this project is the parasitoid wasp *Cotesia rubecula*. Experimental results by researchers observing this insect have shown that it displays a range of behaviours during the process of host finding, including purely cross wind movement, direct upwind flight and zig-zagging upwind flight [Kaiser *et al.*, 1994]. Furthermore Keller [1990] found that this wasp prefers to fly only in wind speeds of less than 1m/s, but not in still conditions. The wind sensing capabilities of the insects are such that even in alignment to the wind, there is some degree of error, as is reflected in the acceptable accuracy range set for the sensor. This sector of ambiguity has been proved in walking insects and proposed as a problem facing flying insects [Kennedy, 1986]. According to these experimental results, observations and project requirements a number of specifications have been set for the wind sensor and mobile robot system, shown in Table 1.

Table 1: Wind sensor specifications

Property	Specification
Wind range	0.3 to 1m/s
Speed accuracy	Within 0.1m/s
Directional accuracy	Within 15°

Flying insects have been found to use visual sensing mechanisms to keep track of their position [Srinivasan *et al.*, 1999]. It has also been observed that many insects track plumes at a relatively constant height, around the altitude of the plume [Baker and Haynes, 1996] and maintain a relatively constant ground speed during plume tracking [Kaiser *et al.*, 1994]. These observations indicate that a two-dimensional model, such as a wheeled mobile robot, is appropriate to represent a flying insect capable of three-dimensional motion for the investigation of wasp plume tracking. This will also allow comparison of the results from this study with other projects that have made a similar simplification.

3.2 Design Options

Several designs have been produced using thermal anemometers. These sensors generally measure the wind velocity on only one axis, unless the sensor is rotating. A two axis measurement cannot be obtained with a stationary single sensor. In order to produce a suitable output for this project a more complicated sensing strategy, using multiple sensors, was examined.

The first multiple thermal anemometer design used two orthogonal, unidirectional sensors. This option has the problem that most obstacles do not entirely restrict the flow that affects the sensor to a single direction, leading to errors in the overall wind direction and speed calculated. The second method involved the comparison of the signals from two sensors arranged around an obstacle (Figure 1). This set-up is analogous to the paired antennae of a flying insect. A simple wind seeking algorithm using this sensor configuration consists of the robot turning right when Sensor R measures a higher velocity than Sensor L and left when Sensor L measures a higher velocity than Sensor R. When the velocity readings from the two sensors are within a defined value of each other, the robot will be facing approximately into or away from the wind. The ambiguity can be resolved through the addition of a third sensor placed in front of and below the obstacle. This sensor position is analogous to the wind sensing hair beds found on the front of flying insects [Chapman, 1971]. Once the robot is facing into the wind, it can use this orientation as a reference and then turn a set angle to end up at this angle to the wind.

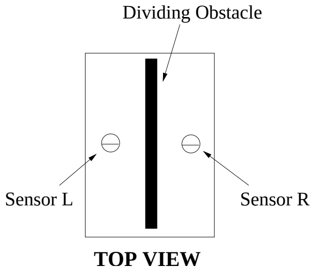

Figure 1: Multiple thermal anemometer obstacle layout for comparison method

3.3 Wind Sensing Element Selection

Most wind direction and magnitude sensors are designed for use on large fixed structures and to measure high winds. However there were a number of sensors identified in the literature review that would be appropriate for use in this project. These include the novel rotating paddle sensors, cooling effect sensors, rotating vane anemometers, biologically inspired sensors and ultrasound. Considering the constraints of this project, including size, cost and complexity, it was decided that a thermal anemometer was the appropriate option, to measure both the speed and direction of the wind simultaneously. A thermistor based sensor (F6201-1, Shibaura Electronics Co., Japan) was chosen, as it is internally temperature compensated and is supplied with conditioning circuitry. Its stability, combined with its robust nature when compared to traditional hot-wires, makes it an appropriate choice. This sensor outputs a voltage that is dependent upon the speed of wind flow to which it is exposed. It was also decided that the second design option presented, the comparison of two sensor signals from either side of an obstacle, was appropriate as it was a simple design that would provide the sensing information required for this project.

4 Experiments

Several experiments were undertaken to help determine an appropriate design for the composite wind speed and direction sensor. Further experiments were undertaken to test the implementation of this sensor on a mobile robot using a simple wind seeking algorithm and an insect casting algorithm. These experiments are described below.

4.1 Obstacle Experiments

A series of experiments was carried out to determine the appropriate height and shape of the central obstacle and its position in relation to the sensors. Obstacles tested included a simple plate, porous, cylindrical and enclosed obstacles. These experiments found that the appropriate selection was the enclosed obstacle. Using the enclosed obstacle, the sensor further from the wind source registered a higher velocity than the sensor closer to the source (Figure 2). This was opposite to the assumed situation, but this was overcome by reversing the cases in the sensor algorithm.

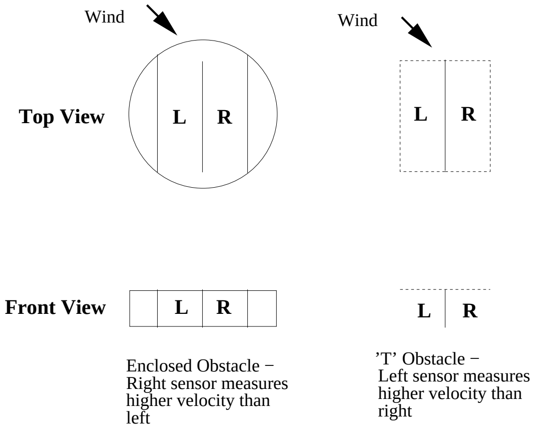

Figure 2: Comparison between the enclosed and simple plate obstacles

4.2 Differential Sensor Prototype

Based upon the results of the obstacle experiments, a wind sensor design was constructed. It is shown mounted on top of the micromouse mobile robot in Figure 3. Several tests were performed using this sensor in a wind tunnel with speeds varying from 0.33m/s to 1.26m/s. The differences between the right and left sensor outputs for each of these tests are shown in Figure 4. These results demonstrated that an ambiguity exists when the robot alignment is perpendicular to the wind direction, where the difference between the two sensor outputs is low. This situation is exacerbated at low velocities. The output from these tests also indicate the difficulty of determining whether the robot is facing directly into or away from the wind. However this problem was overcome through the addition of the third sensor, which measured higher velocity facing into than away from the wind. This prototype could be further developed to reduce these ambiguities, but for this application these modifications have not been considered.

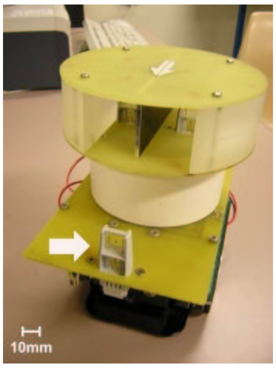

Figure 3: Final wind sensor design on top of the micromouse mobile robot (the third sensor is indicated by the lowest arrow)

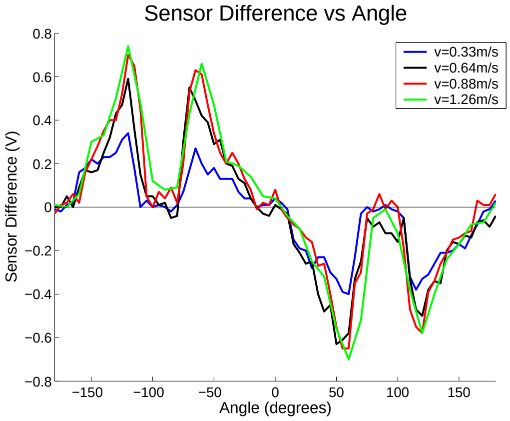

Figure 4: Differential output from the two sensors contained in the final differential obstacle for a range of wind speeds

4.3 Simple Wind Seeking Algorithm

The three sensor signals were processed using an Atmel micro-controller before being transmitted to the micromouse robot. A simple wind seeking algorithm was then implemented on the robot. The micro-controller program initially calculated an unweighted average of the last four measured values of each of the sensor signals. These averages were compared to determine whether the robot was facing into or away from the wind or if it should turn left or right to face into the wind. The controller then output these results to two binary inputs of the micromouse robot, which was programmed to respond accordingly. The protocol for this communication can be seen in Table 2. After each step the robot paused while it took another wind reading. This algorithm could in future be extended to measure the wind speed by measuring the front sensor output when the robot is facing into the wind. This value could then be compared to a look-up-table (obtained through wind tunnel calibration) to determine the speed of the wind.

Table 2: Sensor to micromouse communication protocol

Wind Direction	Action	Pin 0	Pin 1
Facing wind	Go forward	0	0
Wind to left	Turn left 5°	1	0
Wind to right	Turn right 5°	0	1
Away from wind	Turn 180°	1	1

The simple wind seeking algorithm was examined in a number of tests. These tests were undertaken on a flat surface with a desk fan as a wind source. A velocity profile for the centre line of the test area is shown in Figure 5. The surface was marked with 50mm squares to aid in post processing (Figure 6). The origin of the reference frame used for the experiment is also shown. These experiments were undertaken with the robot released at the point (250,100) with a direction -90° , 90° , 180° and 135° to the wind, with 0° defined as facing the fan and anticlockwise rotation defined as positive. Digital video was used to record each experiment, then post processed to produce a still photograph every 0.5 seconds. These photographs were then analysed to determine the position of the robot centre and its orientation. A graph of processed result for a typical test is shown in Figure 7, with a circle indicating the position of the centre of the robot and an arrow indicating its orientation for every second.

During this test the robot initially turned toward the source and moved at a bearing of around 80° to the wind. The robot then turned approximately into the wind and moved toward the fan. Along the way, the robot occasionally made small adjustments. In all tests, the robot progressed upwind. The longest the robot took to cover the 1400mm was 40 seconds, with an average time of 25.5 seconds.

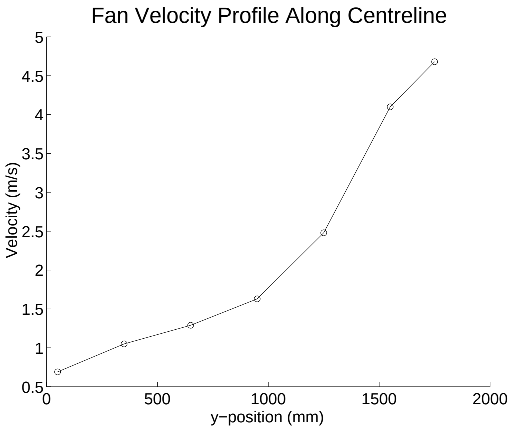

Figure 5: Fan velocity profile

Figure 6: Simple wind seeking algorithm test area

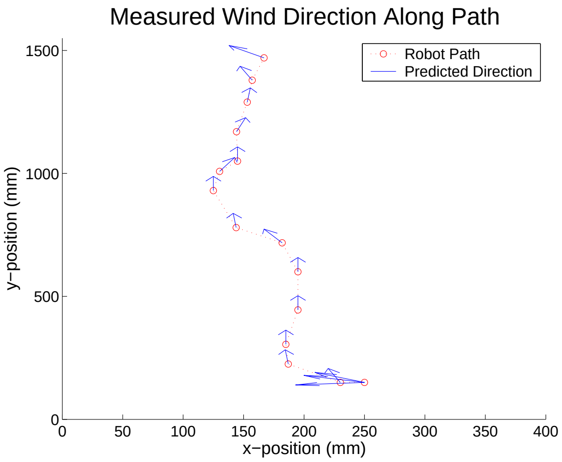

Figure 7: Processed results from a simple wind seeking algorithm test

4.4 Wasp Inspired Casting Algorithm

To enable the wind seeking robot behaviour to be extended for use as a model of a wasp in behavioural tests, it has to allow the robot to perform the various wind sensing related tasks of this insect. A flow chart outlining a simple anemotaxis algorithm can be seen in Figure 8. To implement this algorithm the robot has to effectively perform the task of casting. This process consists of moving directly across wind, back and forth for ever increasing distances until a chemical plume is detected. To determine if the current set-up allowed this behaviour, a series of tests were undertaken.

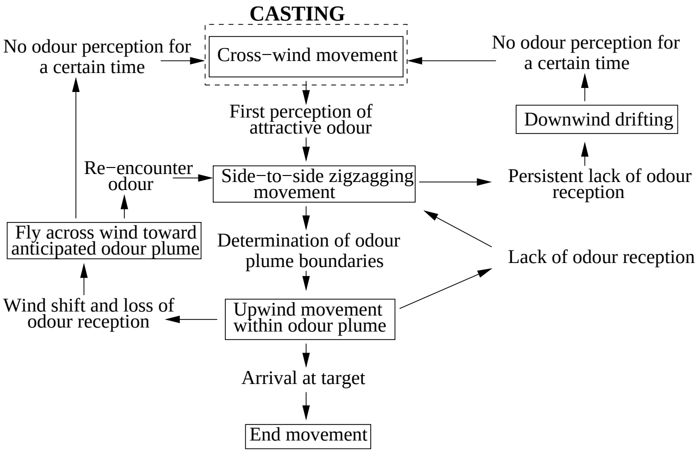

Figure 8: Flow chart for an anemotactic plume tracking algorithm

The casting tests were undertaken using a similar experimental set-up as was used in the simple wind seeking algorithm tests described in Section 4.3. The same experimental area was used, but the fan was placed such that the air flow was perpendicular to the longest side of the rectangular test area. The robot was then released in the centre of the test area at 90° to the wind. These experiments were recorded and post processed as for previous experiments. A typical set of results is shown in Figure 9, which again displays a circle marking the centre position of the robot and an arrow indicating its orientation for each half-second.

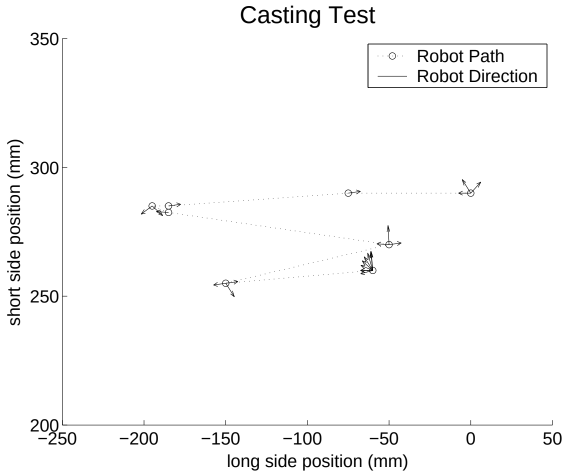

Figure 9: Processed results from a wasp inspired casting test

5 Discussion

The experiments outlined in this paper describe the design, construction and implementation of a wind sensor for a mobile robot. Initial experiments were performed to test the application of the design in a wind tunnel. These tests showed that the prototype wind sensor was able to determine the direction which the robot would need to turn to face into the wind, but ambiguities existed when the sensor was at ±90° to the wind or was facing directly into or away from it. The addition of a third sensor removed the "into the wind" ambiguity, as it registered a higher velocity when it was upwind of the other sensors than when it was downwind. It was considered that the ±90° ambiguity was unlikely to persist for long during an experiment, as any movement of the robot once it assumes it is facing into the wind is likely to take it out of the limited range of ambiguity around these angles, indicating a correct direction to the wind. Even allowing for this ambiguity these experiments show that this sensor design is capable of providing the information required to produce a robotic model wasp.

The second series of tests undertaken examined the response of a robot utilising a simple wind seeking algorithm. The results of these tests showed that in each case the robot was capable of traversing the length of the test area successfully within 40 seconds. During the course of these tests, the ±90° ambiguity arose infrequently and the robot rapidly corrected it when it did. This indicates the position taken during prototype testing of the sensor was adequate. In each of the tests, as the robot moved toward the fan, it made numerous small alterations to its path. These adjustments could have been due to the turbulence in the flow, the non-unidirectional nature of flow produced by the fan, local turbulence caused by imperfections in the obstacle and the motion of the robot. However as the specifications outlined for the sensor only require it to be within ±15° of the correct wind direction at any time, the performance of this sensor was adequate. The combination of the wind sensor, processing and a mobile robot base produced a robot capable of rapidly determining the wind speed and direction.

The final series of tests examined the implementation of an algorithm, to produce casting behaviour observed in the wasp *Cotesia rubecula* during chemical plume tracking. The initial turn to the wind was within 10° and subsequent turns performed by the robot, not referenced to the wind direction, were within 10° of the 180° required. The results of these tests showed that the robot model was capable of reproducing this aspect of insect behaviour using the sensor constructed. These tests indicate that this robotic model is an appropriate option for further use in the investigation of wasp chemical plume tracking behaviour.

6 Conclusion

To meet the overall needs of this project, a wind sensor had to be designed for a mobile robot, allowing it to imitate the wind sensing capabilities of the parasitoid wasp *Cotesia rubecula*. Wind sensors have predominantly been designed for use in outdoor conditions at fixed points with high winds. This project requires a wind sensor that is small, mobile and able to measure wind speed and direction at low velocities. A number of researchers have investigated this problem and produced appropriate wind sensors for use with mobile robots [Belanger *et al.*, 2001; Chapman *et al.*, 2000; Hayes *et al.*, 2002; Ishida *et al.*, 1994; Russell and Kennedy, 2000]. In the course of this project a sensor was designed and constructed using three thermal anemometers, arranged in and around an enclosed obstacle. This sensor was integrated with the mobile robot to produce a wind sensing robot. This robot has performed appropriately in a simple wind seeking test. It has also performed adequately in a series of tests that display insect casting behaviour. The current sensor design therefore appears to be acceptable for further use as a part of the robotic model wasp. The extension of the current robotic model to keep track of its position and allow chemical sensing will enable the detailed investigation of wasp chemical plume tracking.

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