Biomimetic Visual Sensing and Flight Control

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Abstract:

There is increased interest in new classes of mini- and micro-UAVs with sizes ranging from one meter to ten centimeters. Many envisioned applications of such UAVs require them to be able to fly close to the ground in complex environments. The difficulties associated with flying in such environments coupled with the reduced payload capacity of such airframes means that new methods of sensing and control need to be considered. Good models for such methods are found in the world of flying insects. This paper discusses several research efforts aimed at developing new sensing and control algorithms inspired by insect vision and flight behaviors. These efforts are part of DARPA's Controlled Biological and Biomimetic Systems (CBBS) program. In these (and related) efforts, many elegant control stratagems have been discovered which suggest that simple reflexive schemes combined with the measurement of optic flow may be sufficient to provide many aspects of autonomous navigation in complex environments. Furthermore, these efforts are implementing these behaviors in real flying UAV platforms by using novel hardware and software to measure optic flow, and inserting optic flow measurements into a control loop using a combination of "best engineering approaches" with inspiration taken from biology. This has resulted in fixed- and rotary-wing mini-UAVs that are able to hold an altitude and perform terrain following.

Author Biographies:

Dr. Geoffrey Barrows is the founder of Centeye, Inc., a microelectronics start-up specializing in the development of visual motion or "optic flow" sensors for use in UAV, surveillance, and toy applications. Under support from DARPA, he is developing optic flow sensors weighing just grams, and implementing biologically inspired algorithms for providing autonomous small-scale navigation to mini- and micro-class fixed-wing UAVs. Prior to founding Centeye, he was a research scientist at the Naval Research Laboratory (NRL), where he participated in NRL's micro air vehicle (MAV) effort.

Dr. Javaan Chahl is a research scientist at the Australian Defence Science and Technology Organisation and a visiting fellow at the Centre for Visual Sciences at the Australian National University in Canberra. He is currently implementing biologically derived sensors and flight control algorithms for fixed-wing and rotary-wing aircraft to demonstrate hover and terrain following.

Prof. Mandyam Srinivasan is the director of the Centre for Visual Sciences at the Australian National University in Canberra. He is well known for his research on small-scale navigation and learning in the honeybee. This work led to an increased understanding of how honeybees use visual cues such as optic flow to perform take-off, landing, obstacle avoidance, and odometry. Under support from DARPA and ONR, he is currently studying the effects of neurotoxins on honeybee learning, and is implementing biologically derived flight control algorithms onto rotary-wing and fixed-wing aircraft. Prof. Srinivasan is a fellow of the Royal Academy of Sciences and the Australian Academy of Sciences.

1. Introduction

Mini- and Micro-air vehicles (MAVs), new classes of UAVs with small wingspans[1], can benefit from research on the sensory systems and flight behaviors of flying insects. Many proposed MAV applications include flying low over the ground and between obstacles, which require navigation based on sensing other than GPS for altitude control and collision avoidance. To provide such capability in a package that is light enough to fit on a MAV requires significant size reductions in traditional avionics sensors, or entirely new sensory modalities. A natural source for inspiration is the world of insects, which have evolved light yet robust sensor and control systems.

This paper discusses work funded by DARPA's CBBS (Controlled Biological and Biomimetic Systems) program whose purpose is to develop new biomimetic, or biologically inspired, sensing and control capabilities for MAVs. This includes a description of the past and present research efforts of several prominent groups that are aimed at understanding the stratagems used by flying insects, and the applications of these insights to new sensing and control algorithms for MAVs. This includes work on the flight patterns and behavior of honey bees, drosophilae (fruit flies), dragonflies, and work on understanding different visual sensing modes within flying insects, and efforts aimed at turning these insights into hardware and software controllers that are flown on actual UAVs. These efforts are currently funded by the CBBS program, a DARPA program within the Defense Sciences Office (DSO) and managed by Dr. Alan Rudolph. A list of these efforts include:

<u>Australian National University (ANU)</u>: *Profs. Mandyam Srinivasan, Javaan Chahl, and Gert Stange* – Exploration of learning and navigation in honeybees, implementation of vision-based sensors in hardware and software, and integration of these sensors into autopilots for rotary- and fixed-wing aircraft.

<u>University of California at Berkeley</u>: *Profs. Michael Dickinson and Ron Fearing* – Exploration of optomotor reflexes, flight behaviors, and aerodynamics in Drosophila (fruit fly), implementation of biological navigation strategies in a flight gantry, and development of a 2cm "Micro Flying Insect" (MFI).

<u>California Institute of Technology and Massachusetts Institute of Technology</u>: *Profs. Christof Koch and Rahul Sarpeshkar (respectively)* – Analog VLSI vision systems and fusion of optic flow and inertial sensing.

<u>Centeye, Inc.</u>: *Dr. Geoffrey Barrows* – Development of optic flow microsensors and integration of these sensors onto mini UAVs.

The purpose of this paper is not merely to summarize the efforts of the above-mentioned researchers. This paper seeks to communicate that insights obtained by studying biology are enabling the development of new sensors, control rules, and even aerial platforms. Furthermore, these sensors and control rules are ***already*** enabling new types of flight behavior in which airplanes autonomously fly close to the ground in complex environments. We use the adjective "biomimetic" when referring to these approaches, implying that many of the advances resulted from mimicking methods of sensing, signal processing, and control as found in biology.

This paper is organized as follows: Section 2 gives a brief overview of "conventional" UAV systems and some of their weaknesses when compared to biological systems. Section 3 overviews insect-based vision with an emphasis on optic flow. This includes a discussion on how insects are believed to make use of optic flow cues to navigate through a complex environment. Section 4 discusses physical implementations of these sensing methods. Sections 5 and 6 describe initial efforts at integrating such sensors and control algorithms into hardware control loops and into UAV test platforms. Section 7 briefly describes the Berkeley Micro Flying Insect (MFI). Section 8 summarizes potential applications of UAVs carrying these technologies.

2. Conventional UAV systems

Sensing and flight control for conventional aircraft is an established art. Aerodynamics and flight control algorithms for relatively high Reynolds number aircraft are well known, and have been successfully implemented in a variety of platforms of varying sizes. Typical sensors for navigation include standard inertial measurement units (IMUs), pressure sensors for measuring altitude, and the global positioning system (GPS) for absolute positioning. More advanced UAVs include active sensors such as radar and laser range finding.

The above sensors are appropriate for larger aircraft that generally fly far above the ground. When scaling down to smaller mini sized UAVs, advances in electronics allows (or almost certainly will allow) most of the sensors and autopilots to be appropriately miniaturized. The problem is more difficult for micro size UAVs (nominally 15 centimeters across), but

[1] For purposes of discussion, we shall define a "mini air vehicle" as an aircraft with a wingspan on the order of one or two meters, and a "micro air vehicle" as an aircraft with a wingspan on the order of 15 centimeters or smaller.

further advances in RF integrated circuit technology and ultra-wideband (UWB) radars will ultimately provide both the GPS and altitude-measurement capabilities needed for higher altitude flight. Likewise recent micromechanical (MEMS) rate gyros have been developed that have performance specifications sufficient for stabilizing such micro air vehicles.

These sensing methods have their weaknesses, however. Electronic warfare (EW) is an art as old and developed as radar and wireless communications. GPS signals are weak and subject to jamming by the proverbial jammer made from “a hundred dollars/euros of electronic parts”. The construction of such a jammer is well within reach of a technically sophisticated terrorist organization.

Another significant weakness of GPS is that it is less useful for flying close to the Earth’s surface. For example, consider scenarios in which an MAV needs to autonomously fly several meters high over uneven terrain, inside an “urban canyon”, or underneath a forest canopy. GPS will certainly fail in these cases because the vertical resolution of GPS is not sufficient for flying this close to the ground and the update rate is too slow. Furthermore, even if these were not factors, the UAV would have to know the location of every building, tree, or obstacle. This is clearly not reasonable, especially in an ever-changing battle space. A means for detecting obstacles relative to the MAV, instead of relative to an absolute coordinate system, is thus necessary. Radar (or perhaps sonar) techniques would work for simpler environments, but would begin to fall apart in more complex environments with multiple obstacles. Therefore alternative techniques need to be sought.

An important idea put forth in this paper is that flying insects can serve as a model for MAVs that will fly in complex environments. First, insects have relatively small brains, which means that any image processing and control systems are limited in complexity. Second, flying insects spend much of their adult life flying through complex environments filled with a variety of obstacles, some of which they land on and take off from. The ways that insects have evolved to operate in this environment therefore serve as models for alternative methods of operating in a complex environment. Next we shall consider how insects do this.

3. Vision-based sensing and flight control in insects

Insects, like most animals, make heavy use of visual cues for navigation. Here we discuss two sets of cues- perception of depth from optic flow, and perception of the horizon from the tiny ocelli optical sensing organs. We also discuss how insects use optic flow to navigate through a complex environment.

3.1 Optic Flow

Visual motion or “optic flow” provides many important visual cues [1]. Optic flow refers to the apparent movement of texture in the visual field resulting from the insect’s motion. Information from optic flow can be used to perceive depth, including the presence of any obstacles with which the insect is on a collision course. Refer to Figure 1 for a depiction of optic flow as experienced by an insect flying horizontally above the ground. The insect can estimate its flight altitude from the observed optic flow in the downward direction. Faster optic flow indicates a low flight altitude. An insect can also detect obstacles in the forward direction by detecting expansion, or divergence, in the forward visual field. More rapid expansions imply a closer proximity to the obstacle. The “focus of expansion” (FOE) from which the optic flow originates indicates the direction of heading. If the FOE is located inside a rapidly expanding region, then a collision is imminent. If the FOE is located outside a rapidly expanding region, then the insect may fly near an obstacle, but will miss it. By looking for other optic flow patterns, the insect can also detect self-rotation.

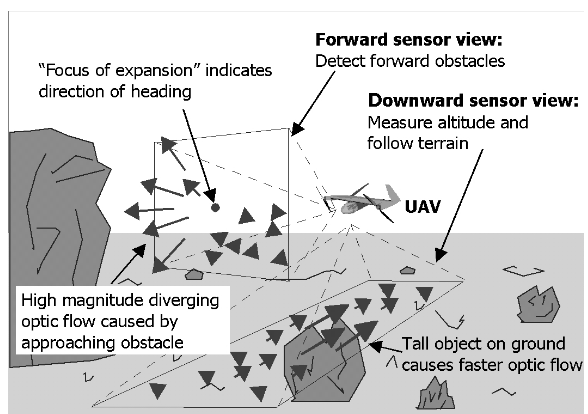

Figure 1: Optic flow as experience by a UAV

A rigorous discussion of optic flow is beyond the scope of this paper, but a simple quantified discussion is presented here. Figure 2 depicts a top-level view of a UAV traveling to the right, and undergoing yaw rotation at rate ω. (Clearly if the rotation rate were not zero, then the flight path would be curved. Here we consider only the instantaneous velocity of the aircraft.) Suppose there is an object at a distance d from the UAV, and at an angle θ off the instantaneous velocity vector. The optic flow (OF) experienced by the aircraft in the direction of the obstacle is:

$$OF = -\omega + (v/d)\cos\theta. \quad \textit{(Equation 1)}$$

The left term is due to self-rotation and the right term is due to translation relative to the obstacle. To effectively use optic flow to detect the obstacle, the self-rotation, ω must first be known, so that this component of optic flow can be subtracted out. The value ω can be obtained by standard angular rate gyros. The reader should note that a similar figure can be drafted in which the view of the UAV is from the side, ω represents the pitch rate, and the obstacle is a point on the ground.

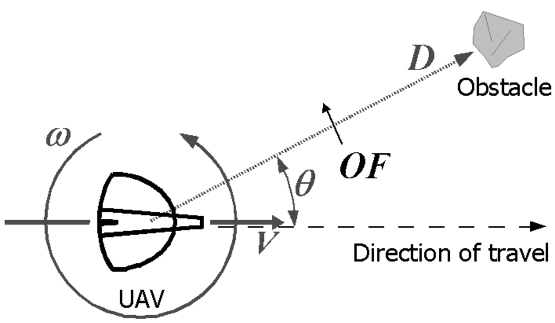

Figure 2: Top-level view of UAV traveling a velocity v past an obstacle

Two cases for the right-hand term should be considered. The first is when $\theta = 90°$. This is equivalent to flying parallel to the ground, and looking directly at the ground. Because $\cos(\theta)$ is maximum here, the optic flow is "strongest", and most easily detected. The other special case is when the obstacle is in the direction of flight, or $\theta = 0°$. In this case, the optic flow due to the obstacle is zero. Essentially, optic flow cannot be used to detect obstacles in the direction of motion. However, the optic flow in the direction of motion is due entirely to self-rotation, so this presents an easy way to measure pitch rate or yaw rate using optic flow. Roll rate can also be measured with appropriately placed sensors.

For other angles of θ, the optic flow component due to translation of the obstacle is weaker and measurable if θ is not too small. This presents a trade-off for using optic flow for, say, terrain following or altitude control. The further one looks forward, the further in advance one is able to detect a bump or obstacle that threatens the UAV. However, looking forward reduces the magnitude of the optic flow measurement due to the obstacle. This requires a higher-precision optic flow measuring algorithm and angular rate gyros for the weak translation component to be detected.

Alternatively, if the aircraft's velocity v is zero, it can measure its rotation ω from the optic flow. If the aircraft's velocity is nonzero, the rotation ω can still be estimated. In other words, optic flow can be used to obtain the information normally provided by a rate gyro. One possible method is by averaging the optic flow seen in all directions, perhaps ignoring those regions with high optic flow that are obviously due to nearby objects. The measurement will not be exact, but accurate enough for some applications.

From this discussion, a flight control engineer should already begin to see uses of optic flow for tasks such as landing, take-off, altitude control, and terrain following. The above relationships are straightforward. The immediate challenges are: 1) obtaining a robust measurement of optic flow using a sensor system that can fit onto a UAV, and 2) integrating the obtained depth perception information with a UAV's control system. The latter is not a stretch for flight control engineers for applications such as altitude control, terrain following, and take-off/landing. However more advanced strategies are required for tasks such as obstacle avoidance, especially in complex environments with dense obstacle fields.

3.2 Experimental setups for studying how insects use optic flow

In order to study how insects use optic flow to perform navigation, insect biologists have constructed a number of apparatuses to expose insects to controlled optic flow, and to measure the insect's response to different stimuli. A few of the setups used by CBBS program participants are described here. What the reader should take from this discussion is not a list of experimental apparatuses, but an intuitive notion of the different techniques used to understand insect flight behavior.

A recent example is a "virtual reality chamber" built by Prof. Michael Dickinson of U. C. Berkeley for studying optomotor reflexes in the drosophila, or fruit fly, in a control loop [2,3]. This chamber essentially comprises a cylindrical virtual reality chamber lined with thousands of LEDs aimed to face inwards. These LEDs are turned on and off in sequence to create moving patterns, which are perceived as optic flow by an insect inside the chamber. A drosophila is mounted inside the chamber on a wire. A laser beam is aimed at a small mirror attached to the wire. An array of photosensors across the laboratory room picks up the reflected laser "spot", and determines its position, which thus determines the torque generated by the insect as it tries to turn left or right. The loop is closed in that the insect's response (turn left, turn right, etc.) is provided to the computer that controls the LEDs, so that the optic flow can be appropriately modified. If the fly attempts to turn right, then the visual texture will be made to appear to rotate towards the left. With this setup, the optomotor reflexes of the fly can be observed and measured in a controlled fashion. For example, if a fly is exposed to optic flow turning one direction, it will attempt to turn the opposite direction. This signal is fed back to the simulator, which slows the generated optic flow. Eventually the fly is able to bring the optic flow to a stop. The simulator enables the study of how fast or how well the fly is able to stabilize the optic flow.

A more recent setup in Dickinson's lab is a virtual reality chamber that exposes the fly to physical rotation as well as visual rotation. When undergoing physical rotation, the whole assembly, including the fly on its mount, is rotated. Using this apparatus, the fly's reflexes that respond to optic flow can be separated from the reflexes that respond to inertial rotation.

Another chamber in Dickinson's laboratory is a "flight gantry chamber", essentially a circular chamber of diameter slightly less than one meter in which fruit flies are allowed to fly freely [4]. Different texture can be placed on the walls, as well as different obstacles placed in the interior of the chamber. Two video cameras capture the three-dimensional flight paths of the flies. This chamber allows the flight paths made by the flies traveling in space, near the walls, or near obstacles to be recorded and studied.

Prof. Srinivasan's laboratory at the Australian National University has also constructed a number of experimental setups to test how insects use optic flow for navigation [5]. One item is a long tunnel, about 20 centimeters in width and several meters in length, through which honeybees are directed to fly. The honeybees are typically trained either to fly a certain distance (enticed with a reward of sugar water) or are trained to fly all the way through. Texture can be mounted on the walls, providing a stimulus for optic flow. Additionally, one of the walls can be shifted at a constant rate, which controllably distorts the optic flow experienced by a honeybee.

Srinivasan's laboratory has also constructed numerous other chambers and experimental setups designed to explore how honey bees take off, land, and navigate through mazes. These apparatuses are similar to Dickinson's free flight arena in that multiple cameras and image processing software are used to capture the three-dimensional flight trajectory the bee makes while executing different maneuvers.

3.3 How insects use optic flow

Let us now turn to a discussion on how insects may use optic flow. Insects have evolved a number of simple but effective "stratagems", or heuristics, for using optic flow to perform tasks. These stratagems have a simplicity that makes them intuitive and (presumably) easy to implement. Many of them can be thought of as reflexes that would make them appropriate for implementation in lower-level control loops in a biomimetic autopilot. Let us consider a few stratagems originating from research in insect behavior:

Centering Response: *"To fly a collision-free path between two obstacles, equalize the optic flow on the left and right sides."*

This stratagem was observed being performed by honeybees in Srinivasan's group in the early 1990's [5,6]. Honeybees were directed to fly down the above-described tunnel apparatus, with one wall shifting at a constant rate. The bees shifted their flight paths such that the observed optic flows were approximately equal – if the right wall was moving backwards, the bees flew on the left side of the tunnel. Clearly, this simple heuristic would keep the bee towards the center of a real-world tunnel even as the tunnel changes width or turns. This stratagem also enables a bee to fly between two objects. One can see from Equation 1 and Figure 2, and from applying symmetry, that if an insect is flying down a tunnel with little or no yaw rotation, keeping the optic flow equal on both sides ensures that the insect is at the center of the tunnel.

Landing Strategy: *"To come to a landing, follow these rules: a) keep the optic flow on the landing surface constant, b) keep the forward speed proportional to the vertical speed."*

Srinivasan's group also observed this behavior by studying the three-dimensional paths made by landing bees [7]. The reason this stratagem works is simple: As the bee is approaching the landing surface, she must decrease her forward motion proportional to her height in order to keep the optic flow constant. As the height approaches zero, so does the flight speed. Using this simple stratagem, an agile flier is guaranteed to execute a perfect landing. Variations of this stratagem can be conceived for fixed-wing aircraft, which generally do not fly at zero velocity.

Saccade response: *"Avoid collisions with obstacles by turning away from regions of high image velocity."*

Dickinson observed this behavior in drosophilae that were allowed to fly freely in the circular "free flight arena" [4]. The flies tended to fly straight lines until they approached a wall. When they got too close to the wall, the flies would execute a sharp turn away from the wall and resume flying straight. Extensive analysis of the flight paths and velocities, aided with cameras and machine vision software, revealed that saccades were performed when the optic flow on one side was essentially too high for too long. This stratagem clearly can be useful for avoiding collisions with large obstacles such as trees and buildings.

Hovering Strategy: "To achieve hover, zero the image velocity everywhere"

When the fly has zero velocity relative to the objects in its environment, the optic flow is zero everywhere. This stratagem has applications beyond stable hovering: it is useful for docking and for flying in formation. In these cases, the fly need only hold the optic flow zero at all parts of the visual field containing the relevant objects to track.

Clutter response: *"Regulate flight speed at a safe level by maintaining the average global image velocity constant."*

Srinivasan's group observed that when flying through a tunnel of varying width, the flight speed tended to be proportional to the width of the tunnel [6]. From Equation 1 above, it should be clear to the reader that simply keeping the optic flow in the direction of the walls constant can perform such a behavior. Such a behavior could be very useful when flying through an environment dense with obstacles: If the obstacles are closer together, then a slower flight speed is appropriate for maneuvering around these obstacles.

Forward focus of expansion strategy: *"Maintain a straight-ahead course by holding the image velocity in front at zero."*

Srinivasan's group observed that honeybees tend to prefer a flight path in which the optic flow in the forward direction is zero. Essentially, the FOE is kept in the desired direction of travel. This behavior is useful for maintaining a flight path in a "straight ahead" direction even if there is a wind that causes sideslip. Clearly, for this stratagem to work, the yaw rate must be held at zero.

Fixation strategy: *"Maintain a straight-ahead course by fixating objects in the forward direction, and minimizing lateral optic flow in the ventral (downward) field."*

This stratagem is similar to the previous one. Dickinson's lab observed that drosophila tend to fly paths toward objects that stand out from the background [2]. If the side slip is zero, which is the case when the optic flow in the downward direction is strictly forward to backward, and if the fly is not rotating, then the flight path is guaranteed to be in a straight line. This stratagem is intuitively similar to classic "dead reckoning" techniques used in orienteering.

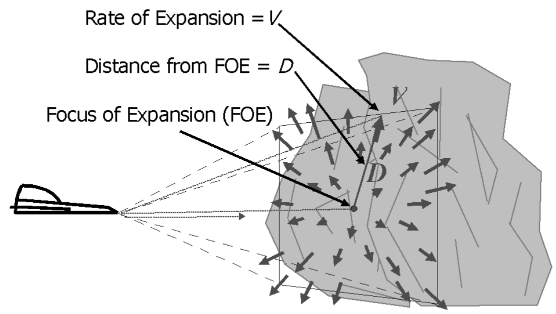

Figure 3: Detecting collision from divergence in optic flow

Forward collision response: *"Detect imminent head-on collisions by measuring relative rate of expansion."*

A classic cue in optic flow that can be used to detect an imminent collision is that the divergence in the optic flow, or the rate of expansion, is large and increasing. Refer to Figure 3, which depicts an insect flying towards an obstacle. If one considers V, the optic flow at a point on the obstacle, and D, the distance from that point to the FOE, then the ratio D/V is a first order approximation of how soon the insect will collide with the object. Similarly, if one divides the image diameter of an obstacle (as seen from a flying insect) by the rate at which that image is increasing, one obtains the same approximation. It has been observed in many insects that when the optic flow divergence becomes "high enough", the insect will execute an appropriate behavior such as turning around or preparing to land.

Strategy to decide between saccade response and forward collision response:

In some circumstances, an insect may experience optic flow patterns that could warrant either a turn, as in a saccade response, or executing a more drastic maneuver (such as a 180° turn) to avoid a collision. In other words, if an insect is detecting an upcoming obstacle from high magnitude optic flow, can the obstacle be avoided by simply steering away or is it necessary to turn around or prepare for a collision? An observation made in Dickinson's laboratory provides a hint [2]: If the optic flow is unbalanced, so that the region of high optic flow is on one side of the focus of expansion, then flies tend to saccade away from the region of high optic flow. Likewise, if the FOE is to the side, then the flies saccade away from the FOE. Both of these cases are hints that the obstacle is to the side; hence a saccade is enough to avoid collision. On the other hand, if the region of high optic flow divergence is on both sides of the FOE, and the FOE is forward, then the flies will tend to land. In this latter case, the obstacle is clearly in front of the fly so that a simple saccade is not sufficient to avoid a collision.

3.4 Ocelli

When one thinks of insect vision, one generally thinks of the large compound eyes that are visible to the unaided human eye. These eyes perform almost all of the optic flow and "target recognition" that an insect needs to perform. However there are additional visual organs, the ocelli that some insects use extensively for achieving stable flight. The Ocelli are essentially small "simple eyes" (lens and a retina, rather than compound eyes) found on the top of the insect's head, in between the larger compound eyes. Unlike the compound eyes, these organs usually require a magnifier for the human eye to see.

Ocelli tend to have a very low resolution, equivalently just a few pixels. Stange at ANU has observed that the optical characteristics of the ocelli are that they tend to blur the image in the horizontal direction, a fact that leads us to speculate that ocelli primarily respond to the horizon for flight stabilization. By picking out differences in light intensity and spectra in the vertical direction, the boundary between the region below and above the horizon can be detected, which allows the insect to determine it's pitch and roll angle. In this current age where imagers are considered "better" if they have higher resolution, the elegance of the ocelli is easily overlooked. They present a simple, direct system by which the horizon can be detected. Simplicity is required with a flying insect's mass constraint.

3.5 Measuring self-rotation using inertial sensing and optic flow

Insects do have inertial sensing. Above it was discussed that insects respond to global optic flow patterns that indicate ego-motion, including rotation. Additionally, some flying insects sense rotation using "halteres", which are small structures protruding from the thorax that vibrate out of phase with the wings. Tiny hairs near the halteres pick up perturbations resulting from rotation, thereby providing the insect with an effective gyroscope. Experiments in Dickinson's lab provide evidence that flies sense their rotation from both the halteres and global optic flow. These two methods are believed to be complementary: Optic flow seems most useful for detecting rotations that are too slow for the halteres to detect, while the halteres seem most useful for detecting rotations too fast for the fly's eyes to measure [8].

4. Implementations of biomimetic vision algorithms and sensors

The measurement of optic flow is known to be a computationally intensive problem. The literature on optic flow computation is vast and goes back thirty years. It is only recently that "mainstream" processors (e.g. the Pentium series from Intel) have become fast enough, and optic flow computation algorithms efficient enough, so that optic flow can be adequately measured for UAV flight control.

4.1 Srinivasan and Chahl

The best example of such an optic flow measurement system comes from efforts by Srinivasan and Chahl. In the early 1990's, Srinivasan invented an elegant and efficient least-squares-based optic flow algorithm, the "Image Interpolation Algorithm" [9]. This algorithm was used in experiments with ground robots during the late 1990's. In 2000, Chahl's group implemented an enhanced version of this algorithm on a 450MHz Pentium III computer. By making use of the MMX instruction set, a single processor is fast enough that optic flow can be computed at rates of several radians per second with a standard frame rate. An autopilot constructed by Chahl's group fuses the optic flow measurement with the inertial rotation information obtained from a 3-axis off-the-shelf gyroscope to detect the optic flow due to translation, and thus nearby objects.

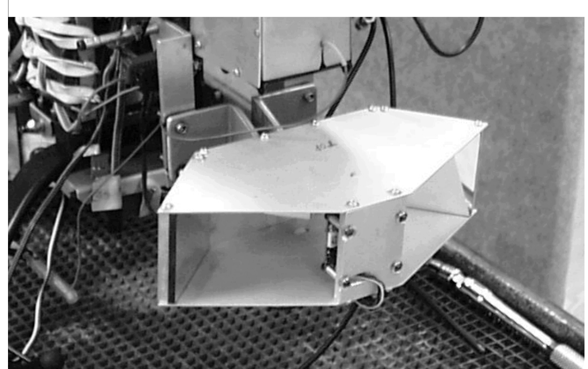

Figure 4: Front-end attachment to camera enabling stereo imaging

Institution: Australian National University
Device: Optic flow sensor and depth perception sensor (2001)
Hardware:
- 450MHz Pentium III processor using MMX instruction set
- Stereo vision attachment

Algorithm:
- Image interpolation algorithm
- Adaptation to process stereo imagery

Frame Rate: 60 frames per second interlaced
Resolution/quality:
- Two-dimensional optic flow over entire image
- Stereo depth perception over entire image

In another version of their sensor, Chahl's group constructed a stereo imager using a set of mirrors that split the visual field, with each half viewing the scene from a different vantage point. This device mounts onto the camera as an attachment, and is essentially no different from similar devices that have been fabricated this past century for stereo photography (Figure 4). A variation of the interpolation algorithm is used to measure the parallax in the image, and hence the depth. The result is that two methods of perceiving depth are used in one imager, and using similar software, which results in a more robust measurement of depth.

4.2 Optic flow microsensors weighing several grams

Ultimately these sensing capabilities will need to be extended to tinier aircraft having a 15-20cm wingspan and a payload capacity of less than ten grams. A significant challenge is that of fabricating an optic flow sensor that fits such a weight budget. Dr. Geoffrey Barrows, of Centeye, Inc., has developed a class of optic flow sensors that are able to measure optic flow sufficiently well for altitude control, and can fit in a package weighing several grams (Figure 5) [10]. These sensors make use of a "vision chip", which is essentially an integrated circuit with both image acquisition and image processing on the same die. The output of the vision chip is a version of the image sufficiently processed so that optic flow can be measured with a microcontroller.

Current versions of these sensors using a vision chip and a microcontroller can integrate more than one hundred elementary motion detectors (EMDs) per sensor. An EMD is the most basic architectural unit (implemented in hardware and/or software) that senses visual motion. Sensors under development will contain thousands of EMDs.

Versions of these sensors have been implemented in which the entire sensor is implemented onto a single chip [11]. These sensors have yet to be flown.

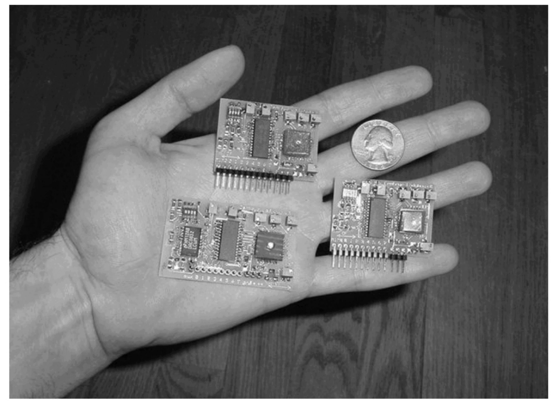

Figure 5: Optic flow microsensors

Institution: Centeye, Inc.
Device: Optic flow microsensor (summer 2001)
Mass: 5 – 20 grams
Processor:
- PIC 18c252 microcontroller at 10MHz
- Proprietary Centeye vision chip

Algorithm:
- Competitive Feature Tracker (CFT) algorithm

Frame rate:
- 100 – 5000 frames per second depending on application and resolution

Resolution/Quality:
- Linear array of 18 or 36 photoreceptors, producing optic flow measurements in four different directions, arranged 1x4 across the visual field.

Yet smaller optic flow sensors are being developed. Self-sufficient vision chips that compute optic flow (albeit at a low resolution) have been the subject of academic research for over ten years. Several of these designs have been shown robust enough to measure optic flow in real world environments, although such chips have yet to be incorporated onto an aircraft. One such design was fabricated by Prof. Reid Harrison, formerly of Prof. Christof Koch's laboratory at the California Institute of Technology and now of the University of Utah. This chip contains an array of biologically inspired Hassenstein-Reichardt visual motion detector circuits to implement a vision-chip inspired from the neural circuits in insect visual systems [12]. This vision chip responds to real-world textures. Another promising vision chip design was fabricated by Prof. Rahul Sarpeshkar of the Massachusetts Institute of Technology, while a graduate student at Cal Tech [13]. This sensor has circuits that generate a pulse whenever the intensity at a pixel in the vision chip rapidly increases. Visual motion is detected by looking for sequences of pulses coming from adjacent pixels in the image. This sensor is also able to measure visual motion coming from real-world textures.

<u>Institution</u>: California Institute of Technology
<u>Device</u>: Optic flow sensor chips
<u>Processor</u>: Proprietary analog vision chip
<u>Algorithm</u>:
- A) Hassenstein-Reichardt motion sensing algorithm
- B) Facilitate and Sample motion sensing algorithm

<u>Frame Rate</u>: Operates in continuous time, but equivalent to about 1000 frames per second

4.3 Artificial Ocelli for horizon detection

Chahl and Stange's effort at ANU is developing an artificial ocelli system based on the ocelli of the dragonfly [14]. Lenses focus light onto an array of photodiodes, arranged to form a low-resolution imager. Optical filters are arranged over the photodiodes to make them sensitive to specific colors of light. The obtained image is processed to identify the horizon. The location of the horizon is then provided to the autopilot, which adjusts the aircraft pitch or roll angle as appropriate.

It should be noted that there already exist "horizon detectors" using similar principles, including ones that work in the infrared regime instead of the visible light regime. The ocelli being produced by Chahl and Stange are different in that the type of light spectra being detected, as well as the processing occurring within the ocelli, are inspired from those of actual biological ocelli. They believe that this combination will produce an ocellar system that is robust, performs under a variety of environments, and does not get degraded by the sun.

4.4 Omnidirectional imagers

Finally, it should be noted that one major difference between biological visual systems and artificial ones is that the latter tend to have a restricted field of view, while the former have a near global view of the environment, in many cases 360 degrees around the insect's body. In order to provide a similar capability to machine vision systems, many researchers have explored the use of curved mirrors to provide an omnidirectional field of view to a camera. Chahl and Srinivasan [15,16] have pursued this as well, with the intention of using such an "omni cam" to enable the measurement of optic flow over 360 degrees. This will allow a future UAV to perceive depth in all directions, and provide additional visual feedback on its state.

5. Demonstration of biomimetic visual systems in a model or simulated control loop

A next logical step after creating an optic flow algorithm or sensor is to explore its use in a model control loop. This can be a simulated control loop, in which both the sensor and "robot" exist within a computer or a hardware loop in which a physical sensor moves about in a real-world environment. There is an extensive literature on robotic navigation using optic flow. Here we will focus on work of CBBS program participants.

The image interpolation algorithm for optic flow developed by Srinivasan is an appropriate algorithm for implementation, given that it requires no novel processor or sensor hardware. Srinivasan and Chahl have inserted this algorithm onto several wheeled robots during the 1990's. A primary example is a tunnel following robot that has cameras looking to the left and right [17]. The purpose was to demonstrate that the above-described "centering response" observed in honey bees can be inserted onto a land robot. Two cameras provided input to a processor running Srinivasan's interpolation algorithm, along with additional code for steering the robot. When released at the entrance of a twisty tunnel not much larger than the robot, the robot was able to find its way to the end using depth perception entirely from optic flow and by using the strategy of keeping at the center of the tunnel.

More complex behaviors have also been explored in a gantry system in which a camera was mechanically moved through a complex environment [18]. The environment was a paper maché terrain designed to mimic a canyon with high walls and varying slopes. The camera was an omnidirectional camera, mounted on a gantry that allowed three degrees of freedom movement in space and one degree of freedom of rotation. By using an appropriate combination of the above-described "centering response" and "saccading response", the gantry was able to maneuver the camera down the canyon.

Other work by Srinivasan and Chahl's group explored autonomous flight control of UAVs with optic flow, in fully simulated environments. In an effort to develop an autopilot for a rotary wing aircraft that makes extensive use of optic flow, a complete control loop was simulated in software. Kinematic models of the aircraft generated 6 DOF motions from provided control signals. Ray tracing image-rendering software created frame-by-frame the imagery seen by a video camera mounted on the aircraft. Optic flow was measured from the synthetic imagery using the image interpolation algorithm. Control signals were generated from the optic flow information, and simulated inertial rate gyros, by using standard rotary wing control algorithms, modulated accordingly to generate appropriate responses to the visual information. Using this setup, this group was able to demonstrate behaviors such as take-off, landing, altitude control, and hover all using optic flow as a means of perceiving the environment. The act of implementing this control loop on a simulated helicopter is certainly more difficult than using a simpler aircraft, but the result of the work is more applicable to insertion on a real aircraft.

The above set of experiments, along with related work in the literature, support the hypothesis that optic flow can be used to provide visually based navigation to an aircraft, without knowledge of absolute position (e.g. as provided by GPS).

Early support for the notion that vision-chip based optic flow sensors could provide autonomous navigation capability was performed by Barrows during 1999 and while an employee at the Naval Research Laboratory [10]. In this work, prototype versions of the optic flow sensors were placed onto a toy glider. Simple "saccading" algorithms were implemented to demonstrate a simple wall-avoidance algorithm: A single optic flow sensor was mounted on the glider and aimed towards the left direction. The glider was tossed towards a wall on the left side, at a shallow angle. The sensor sensed the imminent collision by detecting the increased optic flow from the approaching wall, and triggered a rudder to steer the aircraft away from the wall. Although a simple experiment, this showed that optic flow sensors small enough for micro air vehicles were becoming robust enough for insertion into real-world control loops.

6. Demonstration of biomimetic vision on flying aircraft

It is one thing to fabricate sensors that operate in laboratory environments or in simulation. It is another to actually fly them on a powered aircraft and in a control loop. Currently several demonstrations have been performed in which flying platforms used the above sensors to fly through an environment and avoid collisions.

6.1 UAV platforms at the Australian National University

The group at ANU, led by Chahl, has been flying their sensors on helicopters and fixed-wing aircraft since late 2000. The first platform of note is a gas-powered RC-type helicopter (Figure 6) outfitted with the setup described above in Section 4.1 (optic flow computed using the image interpolation algorithm and 3-axis rate gyros). The camera was aimed diagonally downward and forward. Using this setup, the helicopter was able to fly forward at 60 km/h and hold an altitude of about 10 meters above the ground. The image processing was performed using a 450 MHz Pentium III computer. To reduce the risk associated with the demonstration (helicopter crashes are expensive, even for "RC-model" sized versions), and to enable real-time control system tuning, the actual image processing was performed on ground, with the video imagery and control signals respectively downlinked from and uplinked to the helicopter. If it were not for safety and convenience factors, the required machine vision system could have been mounted on the helicopter.

Figure 6: ANU Helicopter

<u>Institution</u>: Australian National University
<u>Platform</u>: Gas-powered helicopter, about 1.5m blade-span
<u>Sensors</u>:
Optic Flow: 450 MHz Pentium III with the image interpolation algorithm
Inertial: 6 axis IMU
<u>Behaviors demonstrated</u>:
Altitude control using optic flow: 50km/h at 10 meters altitude
Vision-based hover in 30-km/h winds

In other experiments, vision-based hovering was demonstrated by having the aircraft hover at a fixed position above the ground using optic flow for containment of drift velocities and stereo for measurement of height. Successful hovering was performed even in turbulent wind speeds gusting up to 40 km/h. This was a demonstration of the "hovering response" stratagem described above.

In yet a third experiment, a 2 meter wingspan fixed-wing aircraft outfitted with an optic flow vision system and artificial ocelli was flown in a set of experiments to perform altitude control and terrain following. The aircraft was able to follow terrain at flight speeds of 60 km/h.

Institution: Australian National University
Platform: Gas-powered fixed-wing aircraft, about 2 meters
Sensors:
 Optic Flow: 450 MHz Pentium III with image interpolation algorithm and stereo vision sensor
 Ocelli: four-direction electronic dragonfly ocelli
Behaviors Demonstrated:
 Altitude control and terrain following.

6.2 UAV platforms at Centeye, Inc.

The group at Centeye, led by Barrows, has been integrating optic flow visual microsensors onto aircraft since 2000 [19]. To date, these optic flow sensors have been used to provide RC aircraft with altitude control (at altitudes of just meters) and terrain following over shallow (±10°) terrain. For these demonstrations, an on-board sensor controlled the aircraft elevator to provide altitude control while a human pilot steered the aircraft with the rudder.

Collision detection and collision avoidance are currently being explored. The current sensors are able to detect an imminent collision with an obstacle such as a tree, but without enough accuracy to be reliable. In one experiment, a pair of sensors (Figure 7) was placed in the yaw control loop using a variant of the saccade response described above: if the optic flow on one side exceeded a threshold, the sensor turned the rudder to steer the aircraft away. This simplified setup worked in a couple of trials, but only when the aircraft was flown towards the obstacle at a shallow angle, and then only occasionally. The effect is currently weak, but encouraging.

Figure 7: Optic flow sensors mounted on aircraft

Institution: Centeye, Inc.
Platform: RC-type fixed-wing aircraft with electric propulsion, about 1 meter
Sensor:
 Optic Flow: Centeye vision-chip based optic flow sensor (10-20 grams)
Behaviors Demonstrated:
 Reliably:
 Altitude control using optic flow: Altitudes ranging from 2-3 meters to 10 meters
 Terrain following over 10 degree terrain
 Intermittently:
 Obstacle detection and avoidance when approaching a large obstacle (i.e. tree) from the side and at a shallow angle.

7. Micro Flying Insect (MFI)

Insights from biology are also inspiring new flying platforms. A joint effort by University of California at Berkeley professors Michael Dickinson and Ron Fearing is studying the flight control rules and behaviors of the drosophila (fruit fly), and developing a 2-centimeter wingspan "micromechanical flying insect" (MFI) [20]. Prof. Dickinson is studying the wing-flapping motions and the optomotor reflexes made by the drosophila under different flight environments and while executing different flight maneuvers. Video cameras and machine vision software capture the physical motion of the moving wings. These experiments have yielded information on both the mechanical trajectories of the wings and the fly's body orientation while hovering, flying straight, and executing rapid saccade turns.

A device dubbed "Robofly", essentially a scaled-up mechanical model of moving insect wings that is immersed in a bath of mineral spirits, imitates the captured motion dynamics. The observed flow patterns model the air currents generated by the insect's wings, while strain gauges on the wings estimate the resulting lift. These results have led to an understanding of how the drosophila generates thrust and torque for flying. Qualitatively, it can be said that the drosophila "swims" through the air rather than "flies" through it.

Fearing's group is fabricating the actual MFI robot. Figure 8 shows an artist rendering of the MFI. This robot is modeled after the calliphora or blowfly. Each of the two wings will each be driven by two piezo-actuators. A wing's two actuators drive it through a novel mechanical differential that amplifies and transforms the actuators' linear motions into "stroke" and "rotate" motions required for each wing [21,22]. The wings are driven at mechanical resonance to maximize propulsion efficiency.

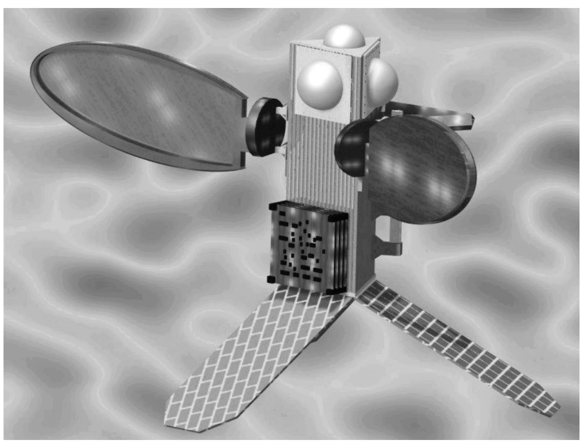

Figure 8: Artist rendering of the MFI

At the time of writing, all the novel physical and electrical components have been fabricated. The actuators and differential drive mechanisms have been fabricated and demonstrated on a test bench. The force generated by one wing is currently sufficient to move a rotating boom on which the wing is mounted. The MFI will be powered by electricity, initially from a tether and later from micro solar cells or micro lithium batteries. The solar cells are about one centimeter in length and have on-chip circuitry for producing switched potentials of over a hundred volts for driving the actuators.

Remaining tasks include system integration and the development of control rules for flight. The control rules will be developed using the findings from Dickinson's work on the drosophila. Fearing expects to demonstrate tethered flight in 2002 and free flight in 2003. The finished MFI will fly at about 2 meters/second using solar power.

8. Applications

Mini and Micro Air Vehicles provided with autonomous navigation are certain to be applied in a number of application areas once the full capabilities are realized. Early applications will clearly come from the military sectors, with later entry into the commercial markets once the appropriate business cases are made. The types of applications in which UAVs with collision avoidance would be useful would fit into these categories:

• Applications which require a sensor, imager, or other payload to be flown or transported in a complex environment, such as in an urban canyon, or close to the ground.

• Applications in which GPS is not available.

• Applications in which active means of sensing (radar, sonar, etc.) are not practical, or are subject to jamming.

Below is a list of applications, both military and commercial, for which MAVs provided with collision avoidance may find use. It is certain that those with an entrepreneurial mind can add to this list.

<u>Military Applications</u>:

- Over-the-hill imaging
- Transporting a sensor or imager underneath a forest canopy for close-up sensing
- Transporting a sensor or imager in urban canyons
- Communications transponder

<u>Civilian Applications</u>:

- Environmental monitoring
- Surveying
- Surveillance / Security
- Agriculture- rapidly survey a field of growing plants
- Mobile wireless transponder
- Exploration of dangerous areas (e.g. volcanoes)
- Geological exploration of other planets (e.g. Mars aircraft)
- Search and rescue

9. Discussion

The above exposition provides significant evidence that biologically inspired sensing and control techniques are appropriate for providing autonomous navigation capabilities to small UAVs. The measurement of optic flow, a technique inspired by biology, provides information that is useful for providing depth perception to aircraft. Furthermore, techniques are becoming available to measure optic flow reliably, whether in the form of an image processing algorithm operating on video data, or a visual microsensor weighing a few grams. The efforts of insect biologists have revealed a number of different strategies that insects use to navigate in the environment. These advances have led some researchers to insert such algorithms and sensors onto robots, including real aircraft platforms, to demonstrate that some desirable autonomous flight capabilities are being demonstrated.

The above successes are clearly early and not yet hardened enough for insertion into "mainstream" UAV systems. Work needs to be performed in improving the performance and reliability of these sensors and algorithms. This would include developing ways to measure the performance of control algorithms according to metrics such as probability of failure, energy consumed, and so forth. Furthermore (and perhaps more importantly), more complex navigation behaviors need to be implemented, enabling future UAVs to fly through a complex environment and avoid collisions with various obstacles.

Below is a list of "autonomous navigation capabilities" that the author believes can be demonstrated using biologically inspired sensing and control. These capabilities are listed in estimated qualitative level of difficulty. Along with these capabilities is a statement on the state of the art of implementations of such behaviors. The author believes that the first five capabilities are demonstrable in the near future.

<u>Capability 1: Altitude Control</u>

Autonomously fly a set altitude above the ground (or water), or within a set range of altitudes above ground.
<u>Status</u>: Demonstrated in rotary- and fixed-wing aircraft over ground but not water.

<u>Capability 2: Terrain Following</u>

Follow the shape of land terrain, climbing over hills and dipping into valleys. The relative altitude above the ground need not be exact, but the aircraft should avoid collisions with the ground.
<u>Status</u>: Demonstrated in fixed-wing aircraft.

<u>Capability 3: Take-off and landing</u>

Autonomously take off and land, without the use of GPS.
<u>Status</u>: Takeoff demonstrated on rotary wing aircraft. Landing simulated for rotary wing.

<u>Capability 4: Avoid sparse obstacles</u>

Detect and avoid collisions with sparse obstacles such as buildings, trees, and telephone poles. By "sparse", it is meant that the UAV need not negotiate more than one or two obstacles at a time.
<u>Status</u>: Demonstrated on wheeled vehicles and in simulation but not in the air. Initial attempts with aircraft are promising.

<u>Capability 5: Fly down a tunnel</u>

Fly down a tunnel, down a canyon, or in between two large objects, such as buildings (e.g. "urban canyon"). It is not necessary to stay exactly in the middle, but collisions on the side should be avoided. In performing this task, it is assumed that the aircraft has already entered or is entering such a tunnel.
<u>Status</u>: Demonstrated on wheeled vehicles and "hardware in the loop" but not flight tested.

<u>Capability 6: Avoid obstacles in dense obstacle field</u>

Detect and avoid collisions with obstacles in a dense obstacle field, such as underneath a forest canopy.
<u>Status</u>: Not demonstrated.

<u>Capability 7: Arbitrarily difficult</u>

This includes more complex behaviors such as flying in buildings, in caves, and so forth.
<u>Status</u>: Not demonstrated.

One important question is that of how to achieve all the above capabilities. In the authors' opinions, success will come with a combination of creative exploration of advanced capabilities with software models and wheeled robots, the insertion of well understood stratagems into existing UAV platforms using "best engineering approaches", and advancing the development of visual sensors and image processing algorithms. Good engineering practices aided by the continuing development of visual sensors and computational hardware (e.g. "Moore's Law") will make the demonstration of all seven of the above capabilities inevitable.

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