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Exploring Search-And-Rescue in Near-Earth Environments for Aerial Robots

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Abstract

Homeland security missions executed in near-Earth environments are often time consuming, labor intensive and possibly dangerous. Aerial robots performing tasks such as bomb detection, search-and-rescue and reconnaissance could be used to conserve resources and minimize risk to personnel. Flying in environments which are heavily populated with obstacles yields many challenges. Little data exists to guide the design of vehicles and sensor suites operating in these environments. This paper explores the challenges encountered implementing several different sensing technolgies in near-Earth environments. The results of applying these technologies to control a robotic blimp are presented to direct future work.

1 Introduction

Homeland security missions bring new and unfamiliar territories which must be patrolled and kept safe. Caves, forests and other near-Earth environments along with urban structures, such as buildings and tunnels, are difficult and time consuming to safeguard. Furthermore, search-and-rescue missions are most often dangerous and require large, diverse task forces [2]. Robots offer a means to offset this demand in resources and personnel. Much of the research effort has been in applying ground-based robots [8], however flying or hovering offers capabilities unachievable by ground based robots.

Small-scale aerial platforms, such as micro-air-vehicles (MAV's),[1] are capable of flying in environments heavily populated with obstacles and can assist in such missions. However, there are several constraints for MAV's and small unmanned-aerial-vehicles (UAV's) that conventional UAV's, such as the Predator, do not face. For example, equipping MAVs with larger-scale navigational sensor suites, such as inertial measurement units (IMU's), global positioning systems (GPS) and pressure sensors is not feasible due to payload limitations. Furthermore, GPS-based methods will not work in buildings, tunnels or caves because satellite signals are occluded. The net effect is that small, lightweight (i.e. less than 100 *g*) alternative sensor suites are required for aerial vehicles flying in near-Earth environments.

Figure 1: A 30 *inch* diameter blimp carrying a 14 *gram* mini wireless camera can provide surveillance images for use in disaster scenarios.

The assessment and evaluation of such sensor suites demands an aerial platform which is small and can fly safely and slowly in near-Earth environments. Commercial vehicles currently being developed by Honeywell, BAE Systems and Piasecki Aircraft are capable of maneuvering in areas rich with obstacles. However, they are not yet available as research platforms. Nonetheless, collision avoidance and autonomous navigation sensor suites will be needed and can be developed in parallel. A simple and safe platform, such as a blimp, can serve as a test bed for sensor suite evalua-

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[1] MAV's are defined as aerial vehicles capable of safe, controlled flight in near-Earth environments. For example, vehicles such as those used in [3], while small, move too fast to navigate areas densely populated with obstacles.

tion. Figure 1 shows a blimp, with a 30 *inch* diameter (allowing it to fit through standard doorways) and a payload capacity of around 60 g. This is enough to carry a miniature wireless camera or stereo pair, compact sensors and other small electronic packages.

Prior work has demonstrated the ability to control and navigate aerial vehicles utilizing a variety of sensing techniques. Vision based guidance and control has been demonstrated by [3]. Optic flow sensors studied in [1] have been used to perform autonomous tasks with MAV's. Localization and guidance using wireless motes has been achieved in [12]. However, the difficulties faced in near-Earth environments tend to segregate these sensing methods, making them effective for accomplishing only specific tasks. Little has been done to evaluate these technologies from a single, consistent platform.

This paper illustrates how these sensing techniques can be applied to a blimp. Section 2 discusses a blimp's platform characteristics and dynamics. Section 3 demonstrates the use of optic flow sensors, computer vision and wireless motes. Finally, section 4 concludes by summarizing and discussing future work.

2 Aerial Platform

Several aerial platforms have been experimented with and evaluated. Rotorcraft, such as helicopters or ducted fan units [7], can hover but are extremely difficult to control. Fixed-wing aircraft can be designed to fly at extremely slow speeds [9], but are limited by their payload capacities. Lighter-than-air vehicles, in contrast, are easy to fly, inexpensive, and capable of hovering.

2.1 Lighter-Than-Air Vehicles

Helium is the most common gas used in blimps today, with a lifting capacity of 1.02 kg/m^3 at standard temperature and pressure. The blimp holds roughly .17 m^3 of helium, giving it a theoretical lifting capacity of 174 g. Experimental results show an actual lifting capacity of 200 g. The total mass of the balloon, gondola, fins and mounting tape is 135.8 g. Therefore, the maximum payload that can be carried by the blimp is 64.2 g. This is substantially greater than typical near-Earth MAV's, making it an ideal platform for testing a variety of sensors.

The blimp has two electric motors with attached propellers positioned on the gondola which allow forward and backward movement. These two motors can also pivot via a radio-controlled (RC) servo to provide an upward or downward angle to the thrust vector, as depicted in Figure 2. This allows the blimp to increase or decrease its altitude respectively. Yaw (i.e. rotation about the vertical axis) is controlled by an electric motor and propeller placed in the blimp's rear fin.

The general approach for modeling a blimp followed by [13], [14] and [15] assumes that:

1. The airship can be modeled as a rigid body, thereby neglecting aeroelastic effects.
2. The volume and mass of the airship can be considered constant.

This model is often applied to much larger blimps that use control surfaces to direct the craft. Since the system under investigation is much smaller, the following assumptions can be made to simplify the model:

3. The blimp is symmetric about the XZ plane.
4. The blimp is moving slow enough and is designed in such a way that the aerodynamic forces are negligible.

Therefore, the dynamics for the blimp can then be written as:

$$M\dot{V} = F_d + F_g + F_p$$

$V =$ $[V_x \quad V_y \quad V_z \quad \omega_x \quad \omega_y \quad \omega_z]^T$ (Velocities along and angular rates about the axes)
$M =$ 6x6 mass and inertia matrix
$F_d =$ Dynamic force vectors (coriolis and centrifugal terms)
$F_g =$ Gravity and buoyancy vectors
$F_p =$ Propulsive force vectors

The remainder of the system definition closely follows the derivation presented in [13]. All equations of motion are defined about a reference frame fixed to the body of the blimp whose origin is located at the center of buoyancy, which is assumed to be coincident with the center of volume. The center of gravity of the airship is defined relative to the center of buoyancy. The mass matrix accounts for all masses and inertias present in the system, including virtual terms associated with the apparent added inertia of a blimp. The dynamic force vector F_d is defined as follows:

$$\begin{bmatrix} -m_zV_z\omega_y + m_yV_y\omega_z \\ -m_xV_x\omega_z + m_zV_z\omega_x \\ -m_yV_y\omega_x + m_xV_x\omega_y \\ -(J_z - J_y)\omega_z\omega_y + J_{xz}\omega_x\omega_y + (m_z - m_y)V_yV_z \\ -(J_x - J_z)\omega_x\omega_z + J_{xz}(\omega_z^2 - \omega_x^2) + (m_x - m_z)V_xV_z \\ -(J_y - J_x)\omega_y\omega_x - J_{xz}\omega_z\omega_y + (m_y - m_x)V_xV_y \end{bmatrix}$$

The gravity and buoyancy vector F_g is given by:

$$\begin{bmatrix} k_x(mg - B) \\ k_y(mg - B) \\ k_z(mg - B) \\ a_zk_yB \\ (-a_zk_x + a_xk_z)B \\ -k_ya_xB \end{bmatrix}$$

Where k_x, k_y and k_z are components of a unit vector in the direction of gravity. Finally, the propulsive forces vector F_p for this specific actuation scheme is given by:

$$\begin{bmatrix} T_pcos\mu \\ T_t \\ -T_psin\mu \\ T_td_{tz} \\ T_p(d_zcos\mu - d_xsin\mu) \\ T_td_{tx} \end{bmatrix}$$

$T_p =$ Force from thrust propellers
$T_t =$ Force from turning propeller
$\mu =$ Angle of inclination of thrust propellers
$d_x, d_z =$ x and z location of thrust propellers
$d_{tx}, d_{tz} =$ x and z location of turning propeller

Utilizing these equations of motion, it is possible to apply an input force to the thrust propellers and the turning propeller so the resulting linear and angular velocities can be observed. By tuning the various constants used to characterize the system, the model can be made to closely approximate the reactions of the real world system.

2.2 PC-to-RC

In order to allow the blimp to be autonomously controlled by a ground-based PC, a PC-to-RC circuit was constructed [10]. Figure 3 shows how the circuit is interfaced with the PC and a standard 4-channel RC transmitter. This setup allows digital commands sent from the PC to be converted into pulse width modulated (PWM) signals. PWM signals can then be sent wirelessly to the blimp's onboard receiver.

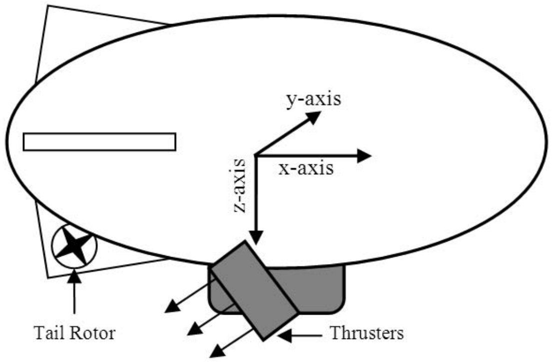

Figure 2: Blimp diagram

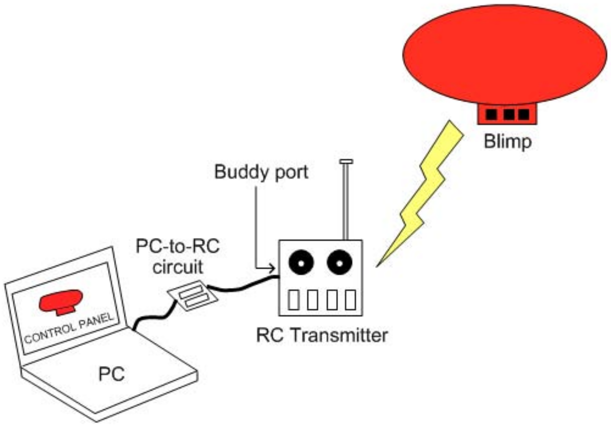

Figure 3: A PC-to-RC circuit converts digital commands to RC signals. Commands are then sent wirelessly to the blimp through a RC transmitter.

The control software running on the PC generates 8-bit numbers for each of the 4 channels on the transmitter. The numbers correspond to the length of the PWM signal. Pulse lengths vary from 1 to 2 ms, where 1.5 ms usually represents the neutral position of a RC servo. The microcontroller, integrated into the PC-to-RC circuit, receives the numbers and generates the pulse to be sent to the RC transmitter. The pulses are grouped into frames, with a frame containing one pulse for each channel. Figure 5 shows the signal that would be sent to a 4 channel transmitter.

The frames sent from the microcontroller are received through the buddy port on the transmitter. Tradi-

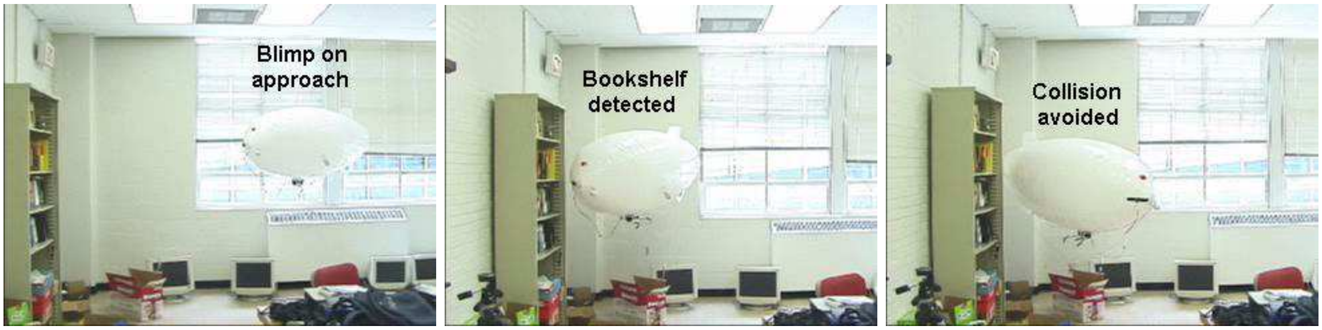

Figure 4: Optic flow is used to sense when an obstacle is within close proximity of the blimp. The blimp avoids the collision by giving full throttle to the yawing motor.

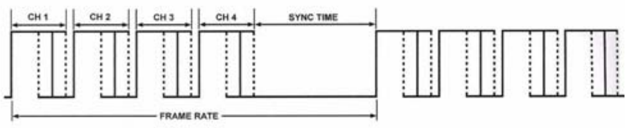

Figure 5: Signal from microcontroller to transmitter.

tionally, the buddy port is used to allow a trainer to take over the control of an amateur under their tutelage. This port can also be used to allow the computer to take control of the transmitter. Autonomous control can then be achieved based on information gathered about the surrounding environment.

3 Sensors

Intelligence obtained from sensors allows the robot's control system to make sophisticated decisions. In addition to traditional sensors such as sonar, infrared (IR) and vision, biomimetic sensors can be constructed as lightweight packages. Integrating such hardware can produce a robust sensor suite for near-Earth environments.

3.1 Biomimetic Sensing

Insects make heavy use of vision, especially optic flow, for perceiving the environment [4]. Optic flow refers to the apparent movement of texture in the visual field relative to the insect's velocity. Insects perform a variety of tasks in complex environments by using their natural optic flow sensing capabilities. While in flight, for example, objects which are in close proximity to the insect have higher optic flow magnitudes. Thus, flying insects, such as fruit flies [11] and dragon flies, avoid imminent collisions by saccading (or turning) away from regions of high optic flow.

Capturing such sensing techniques into a packaged sensor is a vast research area. Neuromorphic chips have been available for many years [6]. However, to achieve the desired weight of 1-2 grams, mixed-mode and mixed-signal VLSI techniques [5] are used to develop compact circuits that directly perform computations necessary to measure optic flow [1].

Centeye has developed the one-dimensional *Ladybug* optic flow microsensor based on such techniques. A lens focuses an image of the environment onto a focal plane chip which contains photoreceptors and other circuitry necessary to compute optic flow. Low level feature detectors respond to different spatial or temporal entities in the environment, such as edges, spots, or corners. The elementary motion detector (EMD) is the most basic circuit that senses visual motion, though its output may not be in a ready to use form. Fusion circuitry fuses information from the EMD's to reduce errors, increase robustness, and produces a meaningful representation of the optic flow for specific applications.

The resulting sensor, including optics, imaging, processing, and I/O weighs 4.8 grams. This sensor grabs frames up to 1.4 kHz, measures optic flow up to 20 rad/s (4 bit output), and functions even when texture contrast is just several percent. Integrating insect flight patterns with Centeye's hardware collision avoidance was demonstrated using the blimp (see Figure 4). Although Centeye's optic flow sensors are not yet available commercially, Agilent Technoligies' ADNS-2051 optical sensor can be utilized to achieve similar results.

3.2 Computer Vision

To perform more sophisticated vision techniques such as line following, a wireless image acquisition system

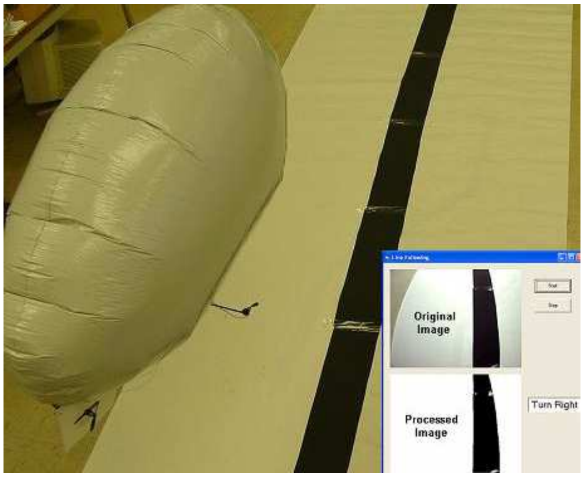

Figure 6: A wireless camera is coupled with a computer vision algorithm to achieve line following.

is required. RC Toys' *Eyecam* [2] provides a reliable wireless video feed when utilized indoors. It is about as small as a US quarter coin, weighs just 15 grams and transmits color video on 2.4 GHz frequency. The output from the receiver is composite video, which can be digitized with Hauppauge's USB-Live [3] in order to plug-and-play into a PC.

To demonstrate line following, the blimp was placed over a black line with a white background. A program was created to process the video feed. The video was then thresholded into a simple black and white image. Code was written to calculate the location of the centroid of the line within the image plane. PD control was then implemented to direct the blimp along the line (see Figure 6). Realisticaly, such ideal environments will not be encountered. However, the same path following techniques can be applied if the location of the blimp is known.

3.3 Wireless Mote Localization

Wireless motes provide a means for localizing the blimp. The term "motes" refers to a general class of technologies aimed at having small, robust and versatile sensors that are easily deployable over a wide area. Such sensor networks could be distributed in factories to monitor manufacturing conditions, spread over fields to log environmental conditions for agriculture, or mixed into concrete to actively measure building stresses and vibrations.

The smartdust series of motes manufactured by Crossbow Technologies[4] consists of small wireless transceivers which can be interfaced with any sensor. Crossbow offers two common packages, the MICA2 and the MICA2DOT. At the core of these motes is an ATmega128L AVR microprocessor. This microprocessor executes all of the code programmed into the mote.

Code is written for the TinyOS operating system. TinyOS is an event driven operating system that handles low level microprocessor and radio networking tasks. This intrinsic networking ability allows for quick development of networks of wireless motes. The motes decide the most efficient network arrangement, resulting in an adhoc network. The TinyOS architecture also supports multihopping, allowing two motes out of range of each other to pass their information between intermediate motes.

The radio module used by the MICA2 and MICA2DOT provides a measurement of the strength of received signals. The signal strength between a mobile mote attached to the blimp and wireless motes on the ground can be used to determine the relative position of the robot. If the location of the ground based motes is known, the robot can be localized. Such a strategy could be used to determine the absolute position of an aerial vehicle, the location of a vehicle relative to a target, or the position of an aerial vehicle relative to ground based robots carrying motes.

To demonstrate this capability, a program was written to cause one of the motes to act as a beacon. Ground based motes that detected this beacon were programmed to relay the strength of the received signal to a computer base station. These strengths were displayed using a visual basic GUI which indicated motes in proximity to the beacon (see Figure 7).

4 Conclusions

The design of a sensor suite for a MAV varies greatly from the sensor suites utilized on traditional UAVs. Flying below tree tops or in and around urban structures prevents the use of GPS. Furthermore, devices such as IMU's and gyros often strain the payload capacities of small, lightweight aircraft. Design then focuses on achieving fundamental autonomous tasks such as altitude control and obstacle avoidance using the smallest packages possible. However, even the most highly-developed control system will fail when

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[2] http://www.rctoys.com/eyecam.php

[3] http://www.hauppauge.com

[4] http://www.xbow.com

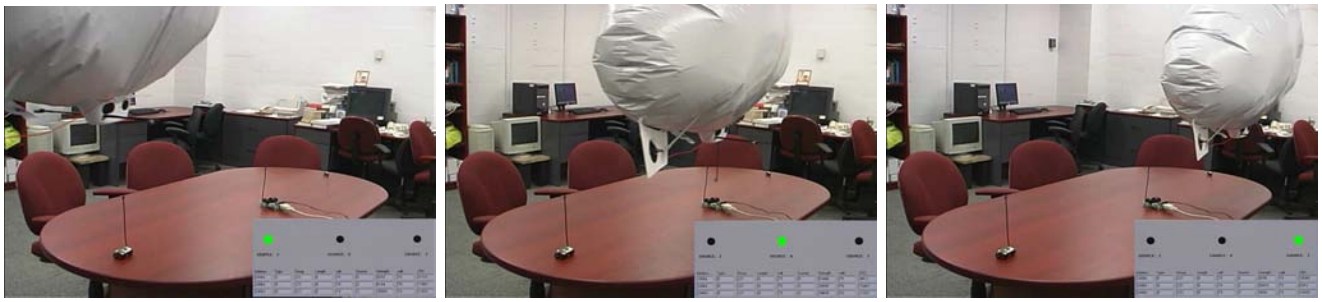

Figure 7: Signal strength is measured between a mobile node attached to the blimp and fixed nodes placed on a table. As the blimp passes by, the graphic corresponding to the nearest node is lit.

presented with unforeseen obstacles. Telephone wires, for example, are extremely thin, but could easily be fatal to a MAV. Such near-Earth environment impediments demand the use of varied sensing technologies to ensure robustness. Through fusion of optic flow sensing, vision based guidance and wireless network localization, aerial vehicles are provided with a diverse sensor suite capable of addressing the issues faced.

This paper demonstrates the porting of these techniques onto a robotic blimp, which provides a robust, versatile platform who's dynamics are well understood and documented. To begin to characterize these sensor suites, future work must be conducted to measure the reactions of these sensors to variables introduced in a controlled near-Earth environment. To facilitate controller design, experimental results must be duplicated in simulated models. With well understood models and corroborating physical data, design can then move towards making MAV's fully autonomous in near-Earth environments.

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