Identifying Challenges for Aerial Robots Operating in Near-Earth Environments

Keith W. Sevcik, William E. Green and Paul Y. Oh*
Drexel University, Philadelphia, PA
kws23@drexel.edu, weg22@drexel.edu, paul.yu.oh@drexel.edu

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 technologies 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), 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.

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-
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 5 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/m³ at standard temperature and pressure. The blimp holds roughly .17 m³ 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:

\[ M \dot{V} = F_d + F_g + F_p \]

\[ V = [V_x \ V_y \ V_z \ \omega_x \ \omega_y \ \omega_z]^T \] (Velocities along and angular rates about the axes)

\[ M = \text{6x6 mass and inertia matrix} \]

\[ F_d = \text{Dynamic force vectors (coriolis and centrifugal terms)} \]

\[ F_g = \text{Gravity and buoyancy vectors} \]

\[ F_p = \text{Propulsive force vectors} \]

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:
The gravity and buoyancy vector $F_g$ is given by:

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

The gravity and buoyancy vector $F_g$ is given by:

$$
\begin{bmatrix}
k_x(mg - B) \\
k_x(mg - B) \\
k_z(mg - B) \\
ak_xk_yB \\
(-a_xk_x + a_xk_z)B \\
-k_ya_xB \\
\end{bmatrix}
$$

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:

$$
\begin{bmatrix}
T_p\cos\mu \\
T_t \\
-T_p\sin\mu \\
T_t d_{tz} \\
T_p(d_z\cos\mu - d_x\sin\mu) \\
T_t d_{tx} \\
\end{bmatrix}
$$

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.

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-
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. Signal from microcontroller to transmitter. Conventionally, 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 Technologies’ 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
A wireless camera is coupled with a computer vision algorithm to achieve line following. 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). Realistically, 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 Aerial Robot Competition

In investigating different sensing methodologies, several questions arose about the use of aerial robots in near-Earth environments. Problems such as the use of distributed versus local computing, the affect of environmental obscurants, and the range, resolution and robustness of sensors were common across different sensing technologies and aerial platforms. An annual indoor aerial robot competition was conceived to help identify these issues and encourage innovative solutions. The challenges addressed would increase in

---

2 http://www.rctoys.com/eyecam.php
3 http://www.hauppauge.com
4 http://www.xbow.com
complexity, with the goal of achieving full autonomy by the year 2015.

In May 2005, Drexel University organized the first indoor aerial robot competition. The inaugural competition, featuring undergraduate teams from Drexel University and Swarthmore College (advised by Professor Bruce Maxwell), focused on both autonomous navigation and target identification in urban-like areas.

4.1 Autonomous Collision Avoidance

One of the major challenges of autonomous flight in near-Earth environments is the limited availability of GPS. This was mimicked by hosting the competition indoors. The autonomous collision avoidance section utilized a 90 x 20 foot space populated with obstacles such as telephone poles and wire, urban structures, trees, etc (see Figure 8). While these obstacles were symbolic of an outdoor setting, hosting the competition indoors prevents the use of GPS for future competitions. The obstacles were overlaid on a white cloth, and a black line ran through the course to denote a collision-free path. Teams had to implement a line following algorithm in real-time that was invariant to changing lighting conditions (i.e. a glass roof enable sun to light up portions of the course) and noise from indoor video transmission. Towards the end of the course, robots were met with a low-speed fan to simulate wind disturbances. Points were awarded based on how far through the course robots were able to travel.

4.2 Teleoperated Target Identification

The other section of the competition consisted of several mock victims spaced out in a 90 x 50 foot area. These victims were positioned in a non-conscious manner, perhaps as a result of a chemical or biological agent released through the ventilation system of an office building (see Figure 9). Using a wireless camera mounted on the blimp’s gondola, teams utilized teleoperated control to identify survivors and deploy markers (symbolic of radio beacons) pinpointing their locations before hazmat teams can arrive. Blimp operators were only permitted to view video images transmitted wirelessly from the blimp’s camera and could not directly view the search area. Points in this section were awarded based on the marker proximity to survivors.

---

72 Thanks to Professors Hong Zhang and Rungun Nathan from Rowan and Villanova Universities, respectively, for judging the competition.
4.3 Results

The difficulty of the line following section was evident after practice runs for each team. To compensate for this, each team was allotted two restarts (i.e. the blimp can be placed back in the position it last lost the line). With the incorporation of this rule, both teams were able to follow the line until reaching the fan area, a distance of 75 feet. Once confronted with low speed wind currents, each team’s blimp was immediately blown off course, unable to demonstrate gust stabilization. The target identification task also proved to be difficult. Teams were only able to locate and mark 1 to 4 victims out of a possible 8. In addition to the scores accumulated in the collision avoidance and target identification sections, each team was also judged on the design of both the flight system and the marker deployment mechanism. The overall winner of the 2005 competition was Drexel University.

The key challenges identified in the inaugural competition were found mostly in the line following section. For example, sunlight shined sporadically on the course resulting in large gradients which affected the efficiency of the computer vision algorithms. Also, wireless video transmission indoors is diminished, but still usable at short distances (i.e. < 100 feet). Furthermore, stabilizing an aerial robot in the presence of wind gusts is still a prevalent challenge.

In the teleoperated portion of the competition, teams found it difficult to interpret the raw video transmitted from the blimp’s wireless camera. A bird’s eye view is oftentimes unfamiliar to the operator and may require some image processing (e.g. object recognition) techniques to identify victims, tables, chairs, etc. During the teleoperated portion of the course, one of the teams lost control of their blimp when it was flown over a portion of the course that had been heated by sunlight. This observation identified thermals as a major concern for aerial robots operating in near-Earth environments.

5 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 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.

References


