

Closed Quarter Aerial Robot Prototype to Fly In and Around Buildings

Paul Y. Oh, William E. Green and Geoffrey Barrows
Drexel University, Philadelphia PA and Centeye Inc., Washington DC
Email: paul@coe.drexel.edu, weg22@drexel.edu and geof@centeye.com

Abstract

Urban environments are time consuming, labor intensive and possibly dangerous to safe guard. Accomplishing tasks like bomb detection, search-and-rescue and reconnaissance with aerial robots could save resources. This paper describes a prototype called CQAR: Closed Quarter Aerial Robot, which is capable of flying in and around buildings. The prototype was analytically designed to fly safely and slowly. An optic flow microsensors for depth perception, which will allow autonomous takeoff and landing and collision avoidance, is also described.

1 Introduction

More often homeland security missions occur in closed quarters which are spacious but enclosed urban environments like stadiums, underground parking lots, subway tunnels and train stations. Common missions include bomb detection, reconnaissance and surveillance. For disaster mitigation or military operations, missions include search-and-rescue, and bomb damage assessment. All of these missions risk human life, are time consuming and often demand large allocations of resources. Employing robots for such missions has been attempted for decades with marginal success [7]. Recent experiences at the World Trade Center and in Afghanistan underscore that ground based robots often cannot overcome rock piles, climb stairs quickly or function effectively without a tether [2].

Aerial robots, capable of flying in closed quarters, may be an alternative to wheeled or tracked robots. Flying permits traveling down tunnels or halls quickly while not inhibited by stairs (see Figure 1). Milestones in aerial robotics have been achieved have been recently achieved using sensor suites that include GPS, inertial measurement units, laser altimeters, ultrasound and computer vision to perform missions like terrain-following, base station keeping and automated landing. These successes are however limited to outdoor flying. For example, GPS does not provide the re-



Figure 1: Closed quarters like this multi-floor atrium are enclosed but spacious for aerial robots.

quired precision for operation in closed quarters and GPS signals are easily jammed. Also vision-based methods that reference the horizon (Pipitone et al [9]) are also inappropriate indoors. Furthermore, closed quarters often demands being small and must fly slowly and safely in order to maneuver through halls and tunnels. Conventional fixed-wing micro aerial vehicles which typically have a 6-inch wing span but fly at 20 miles per hour [5]. Small rotorcraft, including quad-rotors [6], are even more difficult to fly than conventional model helicopters. These aircraft are inherently unstable and hence autonomy for indoor flying will remain challenging. Lighter-than-air vehicles, like blimps, fly slowly and can hover [12]. Buoyancy however is proportional to volume and hence blimps are often too large to fit through doors. Recently flapping has been investigated as a flight mode but results have been limited to lab demos while tethered to a table top power supply [3]. The net effect is the design methods for flying robots outdoors do not apply well in closed quarters.

Our vision is to design a flying robot we call CQAR: *Closed Quarter Aerial Robot* (pronounced “seeker”). Designing such a robot has become possible re-

cently due to advances with Lithium-polymer batteries, lightweight materials like carbon fiber rods, small but powerful embedded micros, low-power sensors and high-torque miniature motors. Recently, Nicoud and Zufferey at EPFL in Lausanne Switzerland debuted an indoor aerial robot prototype [8]. Their current version does not feature any sensors but does use Bluetooth to control the vehicle from user input to a laptop computer. This paper formulates a design prototype for a closed quarter aerial robot and documents our progress in autonomous take and landing using optic flow microsensors. Section 2 describe the multidisciplinary design optimization used to understand design tradeoffs in flight structure, aerodynamics, task performance and sensor selection. Section 3 reveals the resulting prototype along with some results in using carrying a wireless camera. Section 4 discusses the capabilities of using optic flow microsensors for flight control and autonomous takeoff and landing. Section 5 concludes and outlines near-future goals.

2 Optimal Design Matrix

A closed quarter aerial robot demands understanding how aerodynamics, sensor suite integration and task influence design. Towards this a multi-disciplinary design optimization (MDO) matrix (Grasmeyer, Keennon [5]) is very helpful. The MDO method originated in the automobile industry and has evolved into an invaluable discipline that supplies engineers with techniques to move engineering system design closer to optimal. Inputting some initial components into a design matrix will yield the most applicable platform and its corresponding equations of motion.

Each design variable used has a large impact on platform selection (see Figure 2). The parameters that make up the design matrix include initial variables X_I , velocity variables X_V , size variables X_S , payload variables X_P , and hover variables X_H . The initial variables determine the mission type and include parameters such as environment (closed quarter, outdoors or both), desired tasks (search and rescue or reconnaissance), expendability, vertical takeoff and landing requirements, and stealthy operation. The velocity parameters are used to establish speed range capabilities. The size variables represent the platforms maximum characteristic length as well as propeller diameter. This will conclude whether or not the vehicle can fit through small openings like doorways. Payload variables determine the weight and dimensions of the designed sensor suite. The hover parameters assess

X = Vector of input design variables

X	$=$	$\begin{bmatrix} X_I \\ X_V \\ X_S \\ X_P \\ X_H \end{bmatrix}$	$=$	$\begin{bmatrix} \text{Initial variables} \\ \text{Velocity variables} \\ \text{Size variables} \\ \text{Payload variables} \\ \text{Hover variables} \end{bmatrix}$
X_I	$=$	$\begin{bmatrix} A_{\text{DB}} \\ T_D \\ C_{\text{total}} \\ \text{VTOL} \\ O_{\text{stealth}} \end{bmatrix}$	$=$	$\begin{bmatrix} \text{Environment} \\ \text{Desired Tasks} \\ \text{Expendable} \\ \text{Vertical Takeoff and Laning Required} \\ \text{Stealthy Operation} \end{bmatrix}$
X_V	$=$	$\begin{bmatrix} V_{\text{cruise}} \\ V_{\text{max}} \\ V_{\text{min}} \end{bmatrix}$	$=$	$\begin{bmatrix} \text{Cruise Velocity}^{\circ} \\ \text{Maximum Velocity} \\ \text{Minimum Velocity} \end{bmatrix}$
X_S	$=$	$\begin{bmatrix} b_{\text{max}} \\ T_{\text{quick}} \end{bmatrix}$	$=$	$\begin{bmatrix} \text{Maximum Characteristic Length}^+ \\ \text{Propeller Diameter} \end{bmatrix}$
X_P	$=$	$\begin{bmatrix} W_p \\ l_p \\ w_p \\ h_p \end{bmatrix}$	$=$	$\begin{bmatrix} \text{Payload Weight} \\ \text{Payload Length} \\ \text{Payload Width} \\ \text{Payload Height} \end{bmatrix}$
X_H	$=$	$\begin{bmatrix} R_{\text{hover}} \\ L_{\text{hover}} \end{bmatrix}$	$=$	$\begin{bmatrix} \text{Hover Requirement} \\ \text{Maximum Hover Length} \end{bmatrix}$

* If indoors, will it need to withstand wind gusts

+ 3 foot (or less) to fit through standard doorways

c Used for calculations only - not platform selection

Figure 2: Design matrix input parameters

whether or not there is a requirement and also the endurance of the hover. Common input parameters such as flight endurance, range or propeller geometry were not selected in this design matrix because such parameters can be manipulated once the optimal platform is selected.

Based on the input parameters specified above, the program executes a series of commands to generate the most suitable aerial platform and its corresponding equations of motion. A graphical representation for the command sequence is shown in a flow chart (see Figure 3). The shaded boxes represent the input parameters of the user and described as follows. First, given the danger of closed quarter missions, the unit must be expendable. Second, although stealth vertical takeoff and landing are attractive features, they

are not necessary in closed quarters. Third, the unit's velocity should range from 5 to 10 MPH to safely fly and maneuver down halls and tunnels. Last, the unit should fit through doors. The result of these inputs suggest a fixed-wing design.

3 Fixed-Wing Aircraft

Fixed-wing aircraft design has a long history and governed by the principle that an aircraft's weight is proportional to its cruise velocity

$$W = \frac{1}{2}\rho V^2 SC_L \quad (1)$$

Therefore, the lighter the aircraft, the lower the velocity requirements to maintain steady and level flight. Lower velocity requirements also correspond to higher maneuverability, which is crucial for closed quarters. The four forces of flight on a fixed wing aircraft are lift L , drag D , thrust T and weight W and are sketched in Figure 4. θ , Ψ and ϕ are the rigid body rotations about the x , y and z axes respectively. τ_1 is the propeller's reaction force and the angle between the free-stream velocity and the thrust vector is ε . The four forces of flight and the moment of inertia J are about the airplane's center of gravity. Thus, the Newtonian equations of motion for a fixed wing aircraft in three-dimensional space are:

$$\begin{aligned} m_x a_x &= T \cos \theta \cos \Psi \cos \phi - D \cos \varepsilon \cos \theta \cos \Psi \cos \phi \\ &\quad - L \cos \theta \sin \Psi \cos \phi + F_{3_x} \\ m_y a_y &= -T \cos \theta \cos \Psi \sin \phi + D \cos \varepsilon \cos \theta \cos \Psi \sin \phi \\ &\quad - L \sin \theta \cos \Psi \cos \phi + F_{3_y} \\ m_z a_z &= T \cos \theta \sin \Psi \cos \phi - D \cos \varepsilon \cos \theta \sin \Psi \cos \phi \\ &\quad - W + L \cos \theta \cos \Psi \cos \phi + F_{3_z} \end{aligned}$$

$$\begin{aligned} J_x \dot{\omega}_x &= \tau_{1_x} + F_{3_z} l_y + F_{3_y} l_z \\ J_y \dot{\omega}_y &= \tau_{1_y} + F_{3_z} l_x + F_{3_x} l_z \\ J_z \dot{\omega}_z &= \tau_{1_z} + F_{3_x} l_y + F_{3_y} l_x \end{aligned}$$

It can be seen from the equations above that $L = W$ and $T = D$ during cruise flight ($a_x = a_y = a_z = \theta = \Psi = \phi = 0$).

3.1 CQAR Prototype

Employing fixed-wing aircraft design, a prototype with a 46 cm wing span and 26 g mass (about 3 U.S. quarter coins) was constructed. The resulting vehicle can carry a 14 g sensor payload and navigate in a $10 \times 10 \text{ m}^2$ area (about 1/3 the size of a basketball court) when flying at a maximum speed of 2 m/s (about the speed of a slow jogging person).

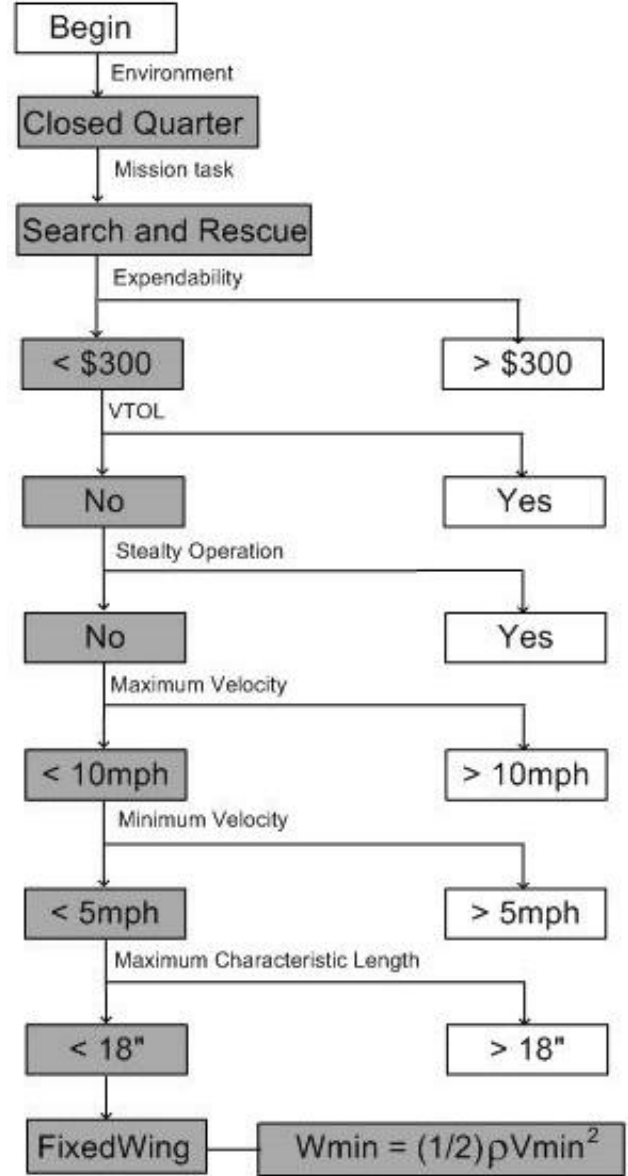


Figure 3: Flow chart detailing execution of commands

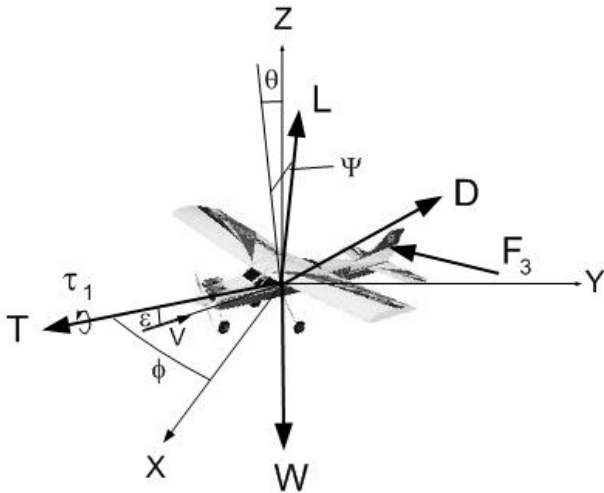


Figure 4: Free-body diagram of fixed-wing vehicle

The fuselage and airfoil frame were constructed out of carbon fiber rods with a $3 \mu m$ mylar covering, while the tail is made from mylar covered balsa wood. With a payload capacity of $14 g$, the aircraft can carry a light-weight mini wireless camera and power supply as shown in Figure 5 (left). The middle photo is a frame captured by the on-board camera while flying in the atrium (Figure 1). A table can be identified, but the image is noisy. For comparison, the actual table is depicted in the right photo. The noise is due to both interference from the university’s 802.11b wireless network and the wireless camera’s poor performance. We are currently testing more robust light-weight wireless cameras.

4 Optic Flow for Navigation

Collision avoidance is especially crucial in navigating through closed quarters. Infrared proximity sensors and ultrasonic sensors are often used by ground-based mobile robots to steer around obstacles [4]. The CQAR prototype has a minimum flying speed of $2 m/s$ and a turning radius of about 2.5 meters. To avoid large obstacles, it is preferable to detect them and initiate a turn at least two turning radii away (5 meters). This distance is generally out of range or accuracy of small, lightweight ultrasonic or infrared sensors. Processing of images captured by an aerial robot’s on-board camera has been performed on outdoor aerial robots. Common methods exploit image features provided by the horizon [9] or flying field [11] which are both absent in closed quarters. The net

effect is that conventional sensors and methods, although successful outdoors, have limitations indoors and thus demand alternative approaches.

Insects make heavy use of vision, especially optic flow, for perceiving the environment. Optic flow is essentially the apparent visual motion experienced by an insect as it travels through the environment. Objects that are close will tend to appear to move faster than objects that are far away, and objects with which the insect are on a collision course will tend to appear as if they are rapidly increasing in size. Figure 6 (top) depicts optic flow as it might be seen by an aerial robot traveling a straight line above the ground. The robot can estimate its height from the optic flow in the downward direction. The robot is able to detect the presence of obstacles by expansion in the forward direction. Through the use of multiple optic flow sensors, it is possible to estimate the aircraft’s self-motion with respect to the Earth, including rotation information and sideslip.

Optic flow has been applied to outdoor flying vehicles for terrain-following and altitude control [10]. For smaller sized vehicles, Centeye has developed the *Ladybug* optic flow microsensor, shown in Figure 6 (bottom). The resulting sensor is composed of two parts: a mixed-mode “vision chip” images the environment and performs low-level processing using analog VLSI circuitry. Then an off-the-shelf microcontroller performs mid- and high-level processing using standard digital techniques. 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 $20 rad/s$, and functions even when texture contrast is just several percent. Details of the current sensor are unpublished, but earlier generations are described in [1]. Such Ladybug sensors have been used to provide 1-meter outdoor RC aircraft with reliable autonomous altitude hold, terrain following, and obstacle detection.

4.1 Autonomous Takeoff and Landing

Optic flow can be used to autonomously land an aerial robot in closed quarters. To simplify this task, the rotational component of optic flow arising from changes in aircraft pitch are assumed smaller than the translational component. Srinivasan observed that honeybees land by keeping the optic flow on the landing surface constant (v/d , where d is the altitude). Mimicking this behavior demands the fixed-wing aircraft decrease forward speed in proportion to altitude. Au-

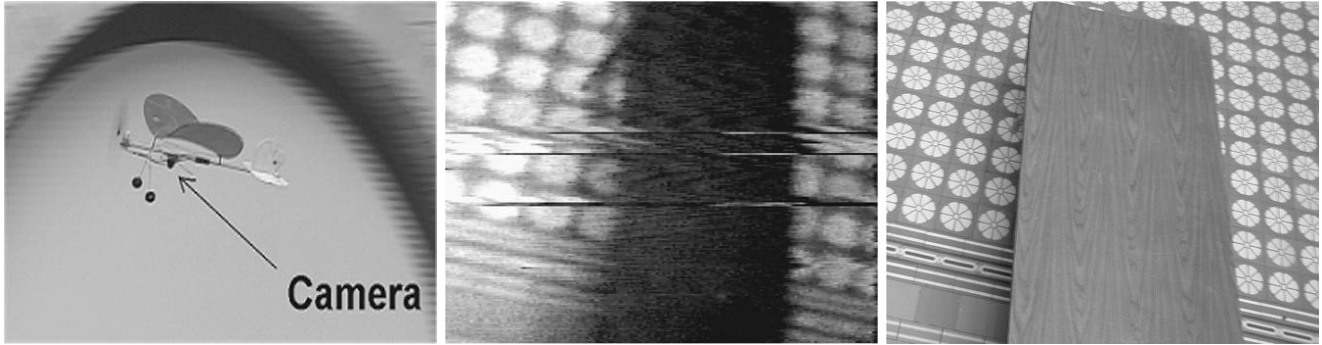


Figure 5: An on-board wireless camera mounted on the flying prototype (left) can acquire video and transmit images (middle). Such images, although noisy, compare well with regular cameras (right).

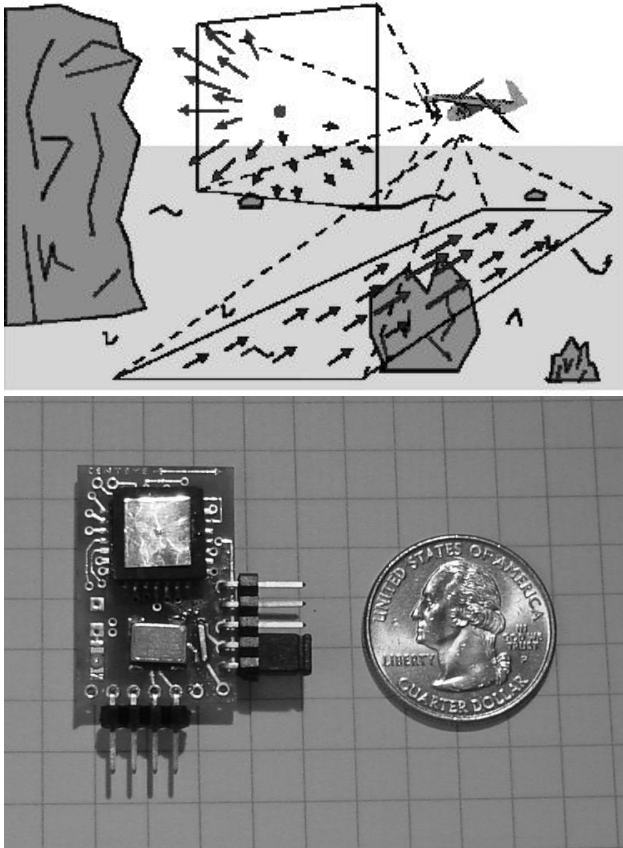


Figure 6: Top: Optic flow as seen by an aerial robot flying above ground. Bottom: the mixed-mode VLSI optic flow microsensor is slightly bigger than a US quarter.

tonomous takeoff is simpler and can be achieved by applying full throttle with elevator deflection.

The optic flow control system block diagram and flow chart are shown in Figure 7. When approaching a landing, a microprocessor, or controller, will take an initial optic flow reading and set that as the desired value, $o_i(t)$. The controller will continue to take readings throughout the landing process and compute the error, $e(t)$, between the desired and actual values, $o_i(t) - o_f(t)$. When the optic flow on the landing surface becomes larger than the desired optic flow, the error is negative and two conditions are possible. One, the forward velocity, v , could be significantly increasing. However, this is not likely during a landing sequence and can be ruled out. Two, the altitude, d , can be decreasing at a faster rate than v . Here, the controller will send a signal to the elevator, K_a , to slightly deflect it upwards to give a small increase in altitude. The other possibility is that the optic flow could start to dip below the desired level causing the error to be positive. The two possible cases that arise here are one, d is increasing but again this is not practical while in landing mode and two, v is decreasing faster than d . In this case, the controller will need to increase the propeller speed slightly by giving an output, K_m to the motor. After either control sequence has been implemented to force the optic flow back to the desired value, the throttle and elevator should be reset to its initial settings (i.e. $K_a = K_m = 1$).

5 Conclusions and Future Work

Closed quarters which are enclosed but spacious areas like warehouses, stadiums, underground parking lots and tunnels, are time consuming and labor intensive to patrol and safe keep. A robot designed to

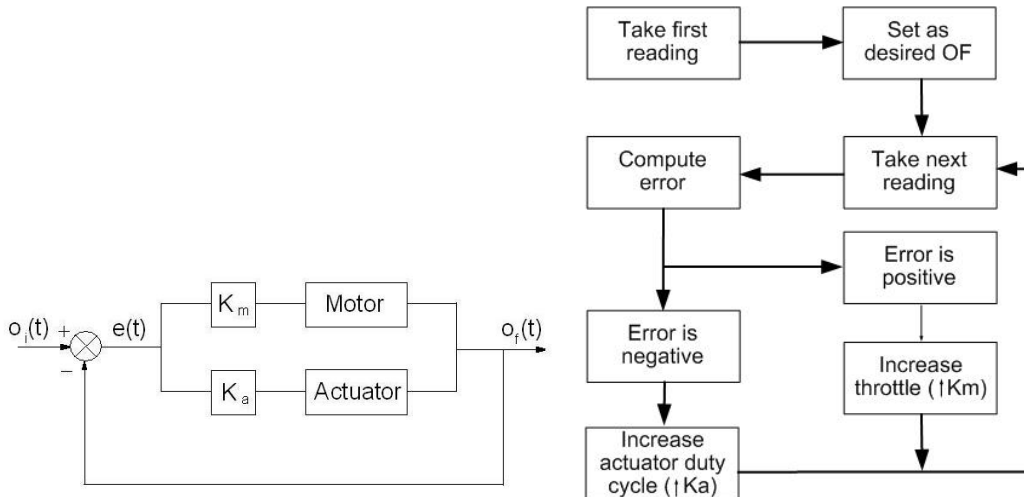


Figure 7: Left: Optic flow control system block diagram. Right: Flow chart of how control system operates.

fly in closed quarters and deliver situational awareness would benefit homeland security, disaster mitigation and military operations. Applications could include biochemical detection, search-and-rescue and reconnaissance. This paper presented a working prototype based on output from a optimization matrix that parameterized design variables. The resulting closed quarter aerial robot (CQAR) can fly safely and slowly in an area as small as 10×10 square meters and deliver wireless video with its on-board camera. Optic flow, often used in insect navigation, can be captured using VLSI hardware. This paper describes how such a sensor can be used for autonomous take-off and landing. Flight tests using this approach are currently underway and will be accomplished before Fall 2003.

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