A Low Cost Indoor Aerial Robot with Passive Stabilization and Structured Light Navigation

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[1] Abstract

The Pima Community College UAV Club has designed an air vehicle system to compete in the International Aerial Robotics Competition (IARC). The rules require an autonomous air vehicle to fly through an open portal into a cluttered indoor environment, search for a small flash drive and exchange the drive with a decoy while evading or deactivating various security systems. The mission deadline is between 5 and 10 minutes, depending on whether security alarms are triggered. The team designed a low cost air vehicle with a jellyfish configuration, on which a balloon stabilizer provides passive stability. The balloon also doubles as a radome and encloses a large directional antenna. Twin propellers suspended beneath the balloon provide lift, and a separate modular 2D thrust vector control system provides precise horizontal positioning, allowing the vehicle to respond rapidly to changes in HVAC air movement.

[2] Introduction

[2.a] Statement of the Problem

The overall objective is for an autonomous aerial robot to covertly retrieve a flash drive located in a cluttered office environment. The robot gets access to the building through an open window, and must evade various security elements on ingress and egress.

The mission begins from a starting point at least 3 m from the building, where the air vehicle searches for an open window. Next, the vehicle searches for an LED on a security camera near the window. When the camera becomes inactive, as indicated by the LED, the vehicle enters the building through the window.

While navigating the confined environment, the vehicle searches for the office of the Chief of Security, as defined by various signs posted on interior walls. During the search, a laser intrusion detector must be either avoided or deactivated. Floor sensor alarms must also be avoided. Once the security office is found, the vehicle searches for a flash drive resting on a stack of papers.

The drive is swapped with a decoy.

At this point the vehicle exits the building through the window, delaying egress until the security camera is off. The vehicle then delivers the flash drive after flying a minimum of 3 m beyond the building. The time limit for delivery is 10 minutes maximum, which may be reduced depending on whether alarms are triggered.

[2.b] Conceptual Solution to Solve the Problem

PHASE 1 -- Pre-position vehicle. Initiate hover, orient sensors toward approximate window location. Search for window opening while maintaining 3 m minimum distance from building. On finding window, hold position and search for blue LED.

PHASE 2 -- Ingress. Wait for falling edge on blue LED. On edge detection, record time and enter window within 30 s deadline.

PHASE 3 -- Search for security office. Search for "Chief of Security" sign. Also search for switch plate label on laser barrier. If label is found, either avoid barrier or deactivate it by applying force to pressure plate.

PHASE 4 -- Enter security office. Search for office entryway, enter office.

PHASE 5 -- Search for flash drive. Search for drive, swap with decoy when found. During the swap the vehicle positions itself to keep the propeller downwash away from the stack of papers.

PHASE 6 -- Egress. Reverse course, fly to window. Hold position just inside window until blue LED turns off, as determined by integer multiple of 60 s period after falling edge recorded in Phase 2. Exit window, fly minimum 3 m beyond window to deliver flash drive.

Notes:

[1] Vision-based SLAM handles high-level navigation.

[2] During all phases, keep track of alarm activation and elapsed mission time. Determine deadline as function of alarm activation. If deadline passes without egress, trigger self-destruction of vehicle.

[3] This paper describes a conceptual solution that is intended to perform the full IARC mission at a future date. Only a small part of the solution has actually been implemented in hardware and software as of this writing.

[2.b.1] Figure of Overall System Architecture

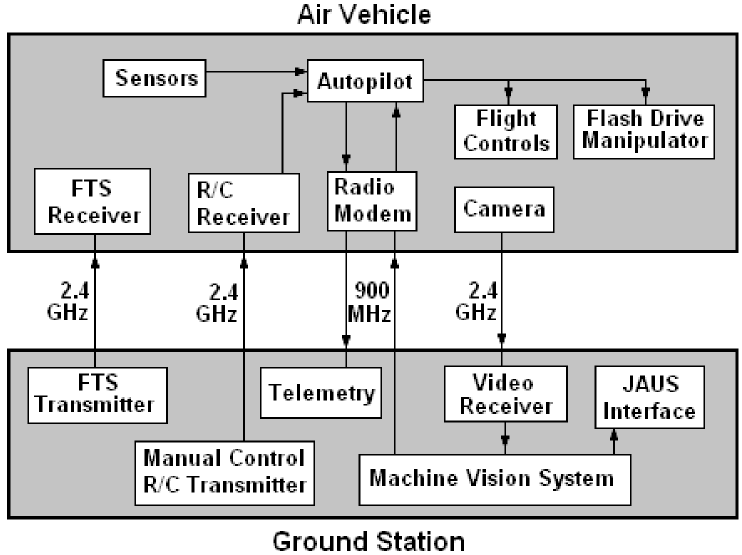

Figure 1. Overall system architecture.

[2.c] Yearly Milestones

Low-level obstacle avoidance and antenna development will be emphasized in 2011/12. SLAM, optical flow, camera imaging and machine vision will be done in 2012/13.

[3] AIR VEHICLE

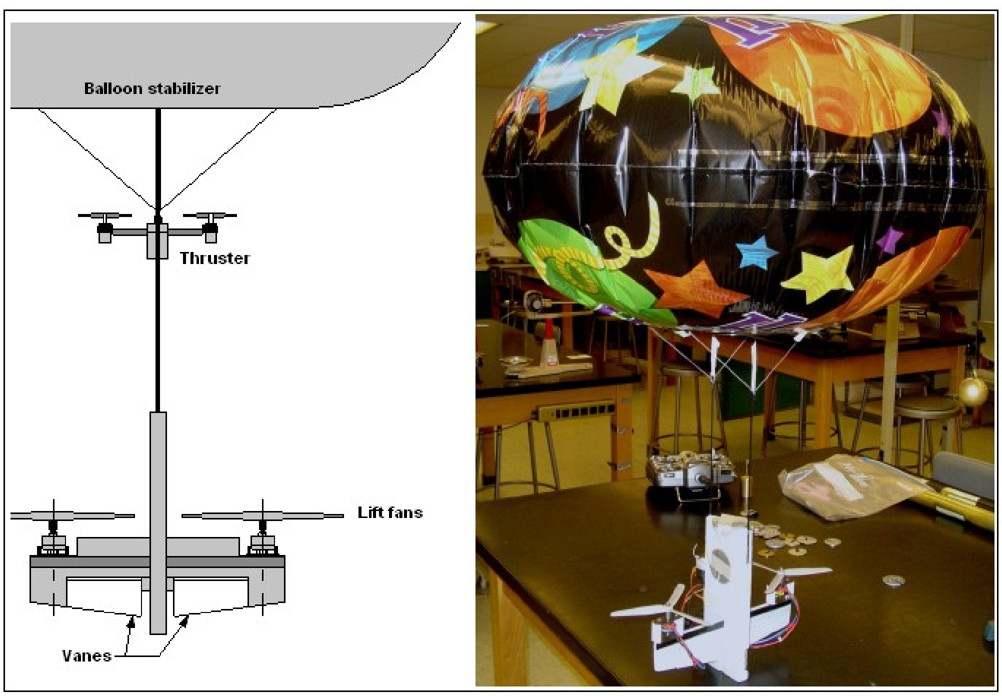

Figure 2. Air vehicle.

The air vehicle uses a jellyfish configuration, with lift fans suspended underneath a balloon stabilizer. The hybrid design combines the inherent stability of balloon with payload capacity of quadrotor. Thrust Vector Control near the CM allows precision stationkeeping while minimizing attitude transients. Ideally vehicle Z axis is always vertical.

[3.a] Propulsion and Lift System

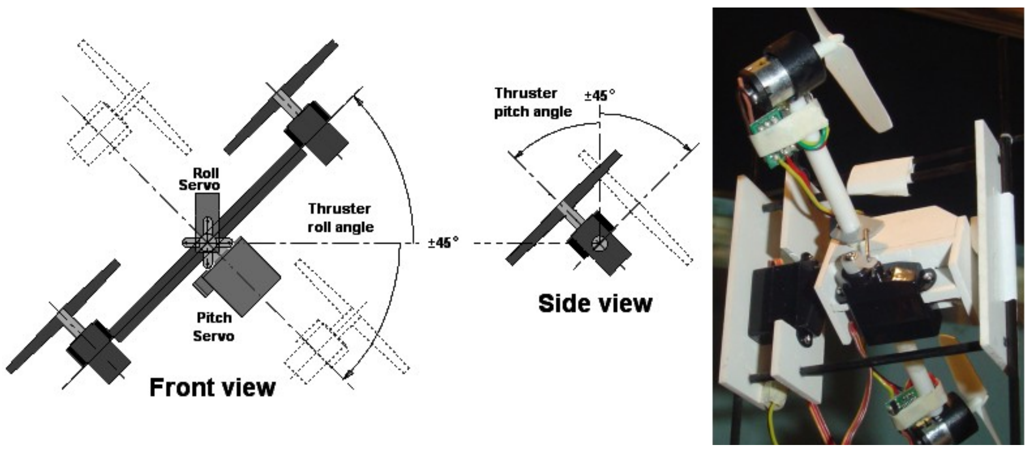

Figure 3. Propulsion thrust vector control.

The propulsion system consists of a thruster with a 2D thrust vector control (TVC) mechanism. The thruster is comprised of two propellers driven by brushed electric motors (see Figure 3 above). The motors are separated by a pylon. By varying the roll and pitch angles of the device, a force can be generated in an arbitrary horizontal direction relative to the vehicle-fixed coordinate frame. The thruster roll angle modulates side force (F_y), and the pitch angle modulates longitudinal force (F_x).

The thruster is cannibalized from an R/C blimp. Motor controllers are cannibalized from servo amplifiers.

Ideally the thruster is intended to produce a purely horizontal force. However, in order to reduce mechanical complexity, the pitch and roll angles are limited to ±45° from vertical. Consequently a significant vertical component exists, which contributes to lift and reduces the load on the lift motors.

The thruster is located near the center of mass of the vehicle in order to minimize attitude transients when the thrust vector changes in either magnitude or direction. Attitude transients are further reduced by using counter-rotating propellers, which minimize gyroscopic moments that are otherwise caused by rapid slew rates of the TVC mechanism.

The thrust vector can be changed rapidly without rotating the vehicle as a whole. This allows the vehicle to respond rapidly to changes in air movement caused by HVAC or other sources.

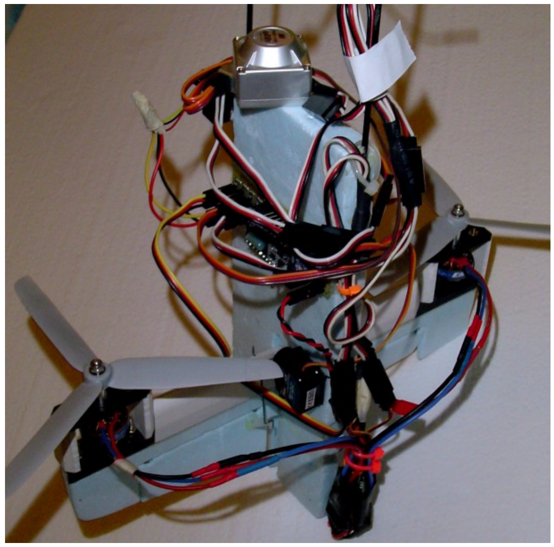

Figure 4. Gondola with lift fans and vanes.

The lift system consists of two counter-rotating propellers driven by E-flite Park 250 brushless outrunner motors. Both motors run at the same speed.

[3.b] Guidance, Navigation and Control

[3.b.1] Stability Augmentation System

Pitch and roll stability -- a balloon provides passive stability in pitch and roll. When the vehicle tilts to one side, the lift vector has a nonzero horizontal component, which causes the vehicle to accelerate horizontally. The resulting aerodynamic drag on the balloon generates a moment about the vehicle center of mass. Since the CM is well underneath the balloon, the moment acts in such a way as to drive the tilt angle toward zero.

The balloon is filled with helium, which has only a minor effect on stability. Although helium increases the payload capacity slightly, helium's main practical advantage is to keep the vehicle upright when it's shut down and sitting on the floor.

Yaw stability -- vanes control the yaw rate. An off-the-shelf R/C rate gyro damps the yaw rate and is quite simple to implement.

Altitude is controlled by a conventional throttle PID loop. Altitude is measured by an IR rangefinder altimeter.

[3.b.2] Navigation

Stereo cameras are used for vision-based SLAM, augmented by structured light[4]. A green laser line generator will be used, possibly combined with a second red laser line to increase immunity to color variations in the environment. On-board vision processing will be used initially, using a monocular CMUcam3, with a transition to stereo and ground-based processing in later versions.

[3.b.3] Figure of Control System Architecture

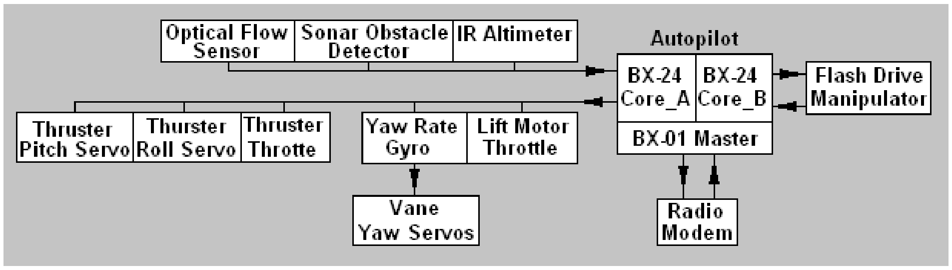

Figure 5. Control system architecture.

The autopilot is a mulitcore BasicX system with three processors. A BX-01 master communicates with the ground station through a radio modem. One of the two slave BX-24 processors handles fast control loops for the flight sensors, lift control, thruster control and yaw control. The other slave BX-24 handles the flash drive manipulator.

[3.c] Flight Termination System

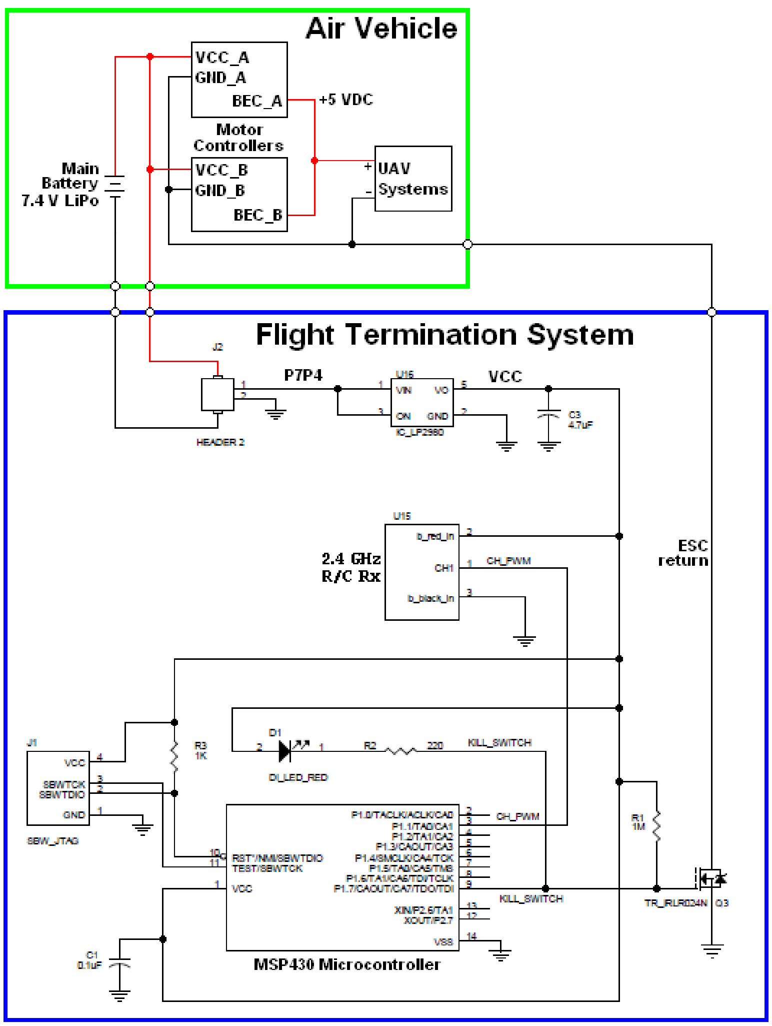

Figure 6. Flight termination system.

The following section was copied from reference 5.

The purpose of the flight termination system is to cut off the supply power to the ISV immediately by a radio transmitter in an emergency situation to prevent the ISV from injuring people. A detailed schematic of the flight termination system is included. Our team's flight termination system is comprised of two components. The first component is a Spektrum DX6i RC transmitter, the second a Spektrum AR6300 RC receiver and a Texas Instruments MSP430 microcontroller connected to a field effect transistor that acts as a switch. Flight Termination can be achieved by simply flipping the kill switch on the transmitter.

1) A Spektrum DX6i RC transmitter sends a 2.4 GHz Pulse Width Modulated (PWM) signal that represents the state of the kill switch

2) This signal is received by a Spectrum AR6300 RC receiver and is recreated at the output of the receiver.

3) Next, a TI MSP430 microprocessor is used to detect and analyze the PWM signal, the PWM signal is fed in to the timer_A module of the MSP430 where the microcontroller examines the rising and falling edges of the PWM signal to determine the duration of the pulse.

4) When the when the kill switch is in the up position the PWM signal transmitted is longer than 1.5 milliseconds, when the microprocessor detects this the output on pin P1.7 is set high (3.3 volts). When the kill switch is in the down position a PWM signal of less than 1.5 milliseconds is transmitted and P1.7 is set low (0 volt).

5) Finally, an N-type MOSFET is connected to act like a switch between the batteries and speed controllers for the UAV. P1.7 is connected to the gate and of an N-type MOSFET and acts as the control for the switch, when P1.7 is High electricity flows from the battery to the speed controllers and then through the MOSFET back to the negative terminal of the battery. If P1.7 is brought low then the circuit is opened and electricity can no longer flow to the speed controllers thus terminating flight.

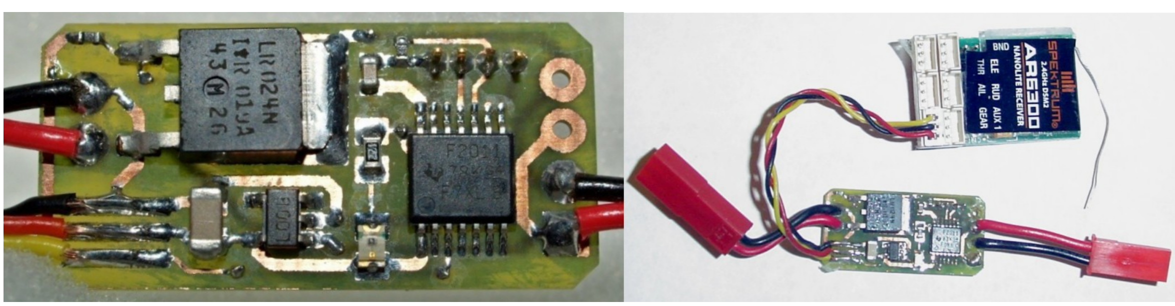

Figure 7. Flight Termination System board (left). Board with radio receiver (right).

[4] PAYLOAD

[4.a] Sensor Suite

[4.a.1] GNC Sensors

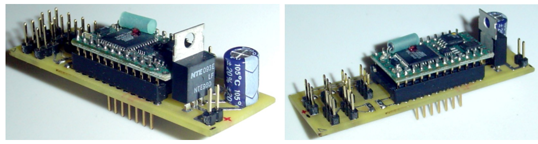

Figure 8. Autopilot, based on NetMedia BX-24.

The autopilot is a multicore BasicX system with three processors. Figure 8 (above) shows an single core version of the autopilot. At this writing a dual core version has been tested in a breadboard configuration.

Sharp IR rangefinder -- measures altitude above the floor.

Sonar rangefinder -- for obstacle detection.

Magnetometer -- for heading.

Camera -- for vision-based SLAM. The camera also detects floor clutter, defined as obstacles too low for the sonar detector, but high enough to confuse the IR altimeter. A small trash can is an example of floor clutter. The camera will be used with a laser line to detect the window and the distance from the walls.

Optical flow sensors -- for odometry and stationkeeping.

[4.a.2] Mission Sensors

[4.a.2.1] Target Identification

Cameras identify the laser security barrier and wall signs during the search for the security office. SIFT (Scale Invariant Feature Transform) is used for the search. By contrast, since the flash drive has a poorly-defined 2D appearance (variable color and logo) but well-defined 3D shape, it is detected using structured light.

[4.a.2.2] Threat Avoidance

Threat	**Sensor**
Laser barrier	Camera identifies label on pressure plate.
Floor sensor alarms	IR rangefinder measures altitude above floor.
Video surveillance	Camera identifies blue LED.
Air movement from HVAC, windows, etc.	Optical flow sensors sense air movement indirectly from vehicle motion.

Security guards	Mission clock keeps track of mission time in order to avoid the security guards, who patrol at 10 minute intervals.
Obstacles (walls, furniture, etc.)	Sonar and camera sense obstacles.

Also, to avoid the threat of capture and traceback, the UAV has a built in (simulated) self-destruct routine in case the mission runs out of time. If the UAV fails to exit the building in less than 10 minutes it will power off the motors and sound an alarm. The alarm is a small piezo speaker (buzzer). In addition to the timer we would like to trigger the self-destruct if the battery voltage gets too low. In this case the motors would shut off and the alarm would sound.

[4.b] Communications

A radio modem allows two-way data communications between the vehicle and ground station. The modem operates on 900 MHz spread spectrum.

Video is transmitted over 2.4 GHz. The video antenna is a large directional antenna inside the balloon stabilizer. The balloon doubles as a radome.

[4.c] Power Management System

A 7.4 VDC lithium-polymer battery powers the propulsion and lift systems, as well as all electronics on the vehicle.

Twin motor controllers drive the lift fans. Each controller has a regulated 5 VDC BEC output that powers the UAV autopilot, sensors, servos and data links.

[4.d] Sub-Vehicles

No sub-vehicle is used.

[4.e] Effector Suite

The Flash Drive Manipulator (FDM) exchanges the flash drive with a decoy. The FDM has a lateral offset from the propeller downwash in order to minimize disturbance of the stack of papers on which the flash drive is located. The FDM also deactivates the laser barrier.

[5] OPERATIONS

[5.a] Flight Preparations

[5.a.1] Checklists

Mechanical
- Gondola
  - Check for damage
- Vane/pylon
  - Pylon damage
  - Vane control horns
  - Vane pushrods

Balloon stabilizer
  Attachment points
  Check for leaks
Lift propellers
  Propeller integrity

Thruster
  Servo condition
  Control horns
  Propeller integrity

Communications
  Check Data link integrity
Controls
  Exercise controls in sequence
  Check for proper operation

[5.b] Man/Machine Interface

Since the vehicle spends most of its time hovering or flying at low airspeeds, it's not required to have a low drag coefficient. Therefore the structure of the vehicle is open, with equipment easily accessible for operation, maintenance and replacement.

[6] RISK REDUCTION

[6.a] Vehicle Status

The following real time sensor data transmitted from vehicle to ground station over the radio modem:
  IR altitude
  Sonar range
  Camera video
  Voltage of flight battery

[6.a.1] Shock/Vibration Isolation

The structure of the gondola is mainly styrofoam with a small amount of reinforcement by carbon composite. The styrofoam inherently damps vibration. In addition, all propeller blades are balanced in order to reduce vibration. The large lift motors use an outrunner configuration with no mechanical gear reduction, which further reduces vibration.

[6.a.2] EMI/RFI Solutions

RFI and EMI are minimized in the following ways (this section was copied from reference 5 with modifications):

o Both the FTS and video system operate around 2.4 GHz. Because of this care must be taken when selecting the appropriate frequency over which to transmit video. Video is transmitted on 2.432 GHz while the FTS control signals are transmitted at 2.402 MHz allowing roughly 30 MHz of bandwidth between the signals. The video bandwidth is 20 MHz and the bandwidth of the control signal is 2 MHz. To avoid interference the space between the signals must be greater than at least half of the bandwidth of the signals.

o Physical proximity between transmitters and receivers can also contribute to RFI in the form of front end overload. This problem is reduced by using a highly directional antenna for video.

[6.a.2.1] Communications Risk Reduction

Indoor radio communications can be a major challenge. Problems include reflection, refraction, diffraction, scattering, multipath and attenuation.

The balloon stabilizer on the vehicle has a sizable and protected internal volume -- an ideal location for a large directional antenna. Combined with a similar antenna on the ground station, the two antennas reduce the risk of communication failure. Flexibility is key -- directional antennas on both nodes allow communications to be tailored to the mission.

At one extreme of difficulty, there might be an extensive mix of objects consisting of walls enclosing internal clutter, where the objects have some random mix of reflective and attenuating properties. Directional antennas can be used to improve communications after empirically searching for the best orientations. An optimum orientation might require bouncing the signal off one or more surfaces, for example.[3] Beam path searches can be time consuming, so the vehicle would periodically halt, hover in place, do the search, then download accumulated image data for offline processing by the ground station.

At the other extreme, in a benign environment with RF-transparent walls and minimal clutter, directional antennas can be used in line-of-sight mode in order to minimize the transmit power on the vehicle, allowing us to reroute power to the propulsions system to better counteract HVAC air movement.

For intermediate levels of difficulty, such as environments with uncontrolled RF radiation, directional antennas give us the flexibility to operate lightweight, low-cost radios that would otherwise be unusable because of frequency conflicts.

[6.a.2.2] Software Risk Reduction

Software reliability increased by Ada 2012 in ground station software. In the future Ada is planned for airborne processors as well.

[6.b] Safety

Safety is enhanced due to the low weight of the vehicle at 334 g maximum. The low weight is partly due to helium in the balloon, accounting for 50 g due to buoyancy. Light weight allows low power motors, which minimizes injury potential from spinning propellers. The primary structure of the gondola is relatively soft, consisting mostly of styrofoam. Also, the large balloon stabilizer intentionally has high drag, thus limiting airspeed if the vehicle goes out of control.

[6.c] Modeling and Simulation

A software test harness was utilized to accomplish unit tests of software components.

[6.d] Testing

Flight testing lends itself to an academic lab environment, since testing can occur indoors in cluttered environments. Large outdoor flight test areas are not required. A BasicX Development Station is used as a breadboard setup for the vehicle electronics, which lends itself to easy testing. The vehicle itself can be connected to the breadboard through flexible wires, allowing limited hovering capability. This test configuration makes it easy to tune various PID control loops.

[7] CONCLUSION

The Pima Community College UAV Club has designed an air vehicle system to navigate in a cluttered indoor environment and swap a flash drive while evading security elements. For the task the team designed a low-cost air vehicle with a jellyfish configuration, with lift fans suspended underneath a balloon stabilizer. The hybrid design combines the inherent stability of balloon with payload capacity of quadrotor. Thrust Vector Control near the CM allows precision stationkeeping while minimizing attitude transients.

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[8] REFERENCES

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[6] Manning, Frank. Miller, Christopher. Worden, Tim. A Low Cost Indoor Aerial Robot with Passive Stabilization and Structured Light Navigation, Pima Community College, Tucson, Arizona, 1 June 2011. This was copied verbatim except for the following changes -- removed fig. 9, modified sections [1], [2.c], [4.a.2.1], [4.a.2.2], [4.b], [6.a.2], [6.d], added sections [6.a.2.1], [6.a.2.2].