# A Low Cost Indoor Aerial Robot with Passive Aerodynamic Stabilization

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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 should 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 should be either avoided or deactivated. Floor sensor alarms should 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] 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.

[2] 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*

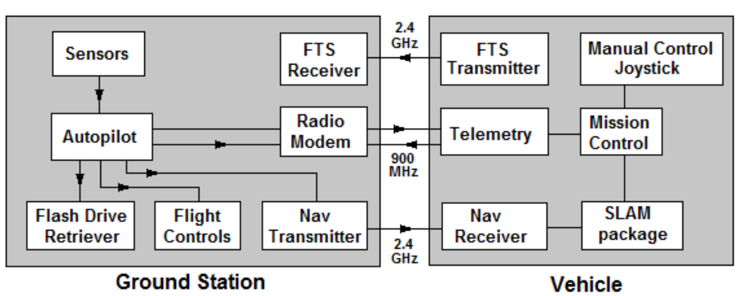


*Figure 1. Overall system architecture.*

## [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

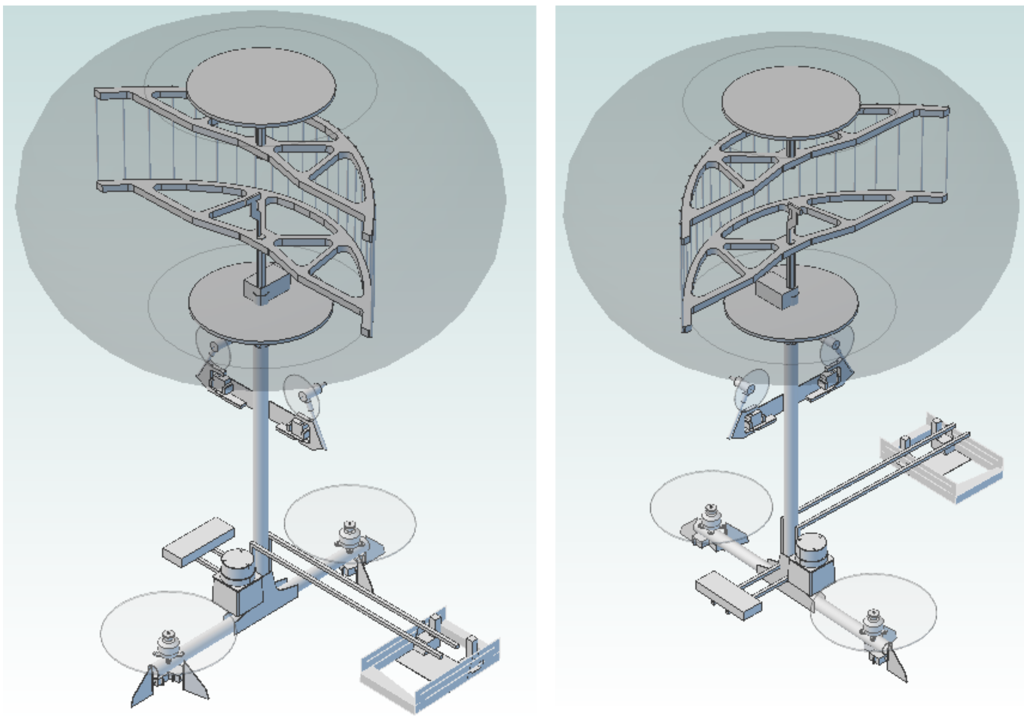

*Figure 2. Air vehicle.*

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

Propulsion is provided in two modes depending on the desired airspeed.

*Mode 1 -- Low airspeed*

In this mode, propulsion is provided by a separate thruster (Figure 3) that generates horizontal forces for precise maneuvering in close quarters. The thruster consists of 2 small counterrotating propellers, each of which pivots about a vertical axis, allowing for Thrust Vector Control (TVC).

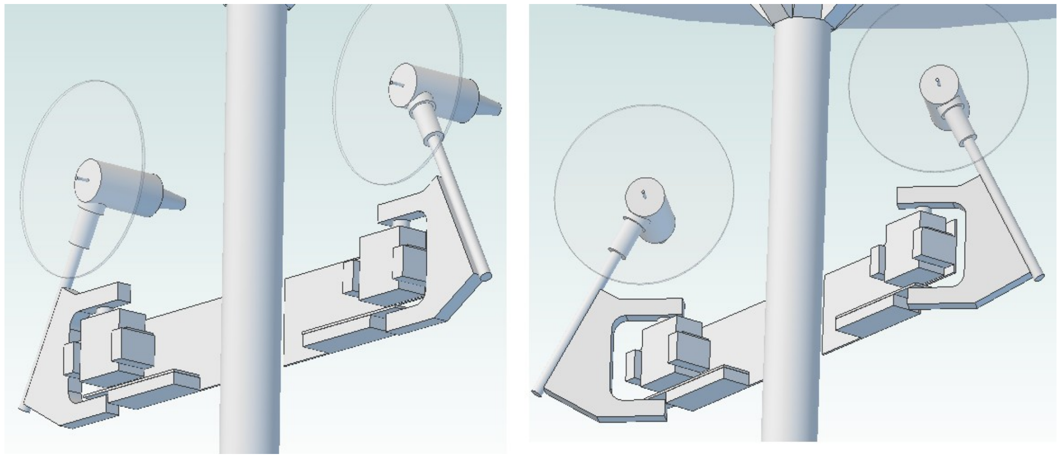

*Figure 3. Propulsion thrust vector control. At left, thruster is centered. At right, thruster is deflected 45°.*

The thruster motors are rigidly attached directly to servo output shafts with no intervening mechanisms such as pushrods or control horns. The thruster motors and propellers are cannibalized from a small quadrotor.

In mode 1, the vehicle-fixed Z axis is always held vertical, parallel to the gravity vector. Constant roll and pitch angles simplify the use of cameras, lidar scanners, directional antennas and other devices.

*Mode 2 -- High airspeed*

In this mode the entire vehicle is tilted about the pitch axis in order to generate a horizontal component of the lift vector. Tilting the lift vector is similar to the way conventional rotorcraft control horizontal acceleration.

Tilting is accomplished by using differential thrust on the two lift propellers in order to generate a pitching moment. Separate yaw vanes counteract the undesirable yawing moment that is a side effect of the differential thrust.

Mode 2 is intended only for counteracting air motion generated by sources such as HVAC systems or open windows. In other words, mode 2 is used only for high airspeed, not high groundspeed. High groundspeed is not required to accomplish the mission.

The lift system consists of two counter-rotating propellers driven by E-flite Park 370 brushless outrunner motors. Both motors run at the same speed.

**[3.b] Guidance, Navigation and Control**

*Attitude control*

The vehicle Euler angles are controlled by a total of four vanes, consisting of two yaw/roll vanes plus two pitch vanes (see Figure 4).

Yaw and roll angles are controlled by a combined yaw/roll vane outboard of each of the two lift propellers. The two vanes have independently controlled deflection angles. Yaw is controlled by the difference between the angles, roll by the sum of the angles.

The pitch angle is controlled by two pitch vanes, one per lift motor. The vanes extend to the left of the motors. Each pitch vane is tilted inwards slightly such that the lift vector goes through the vehicle centerline. This tilt minimizes undesirable yaw/pitch coupling when the pitch vanes are deflected.

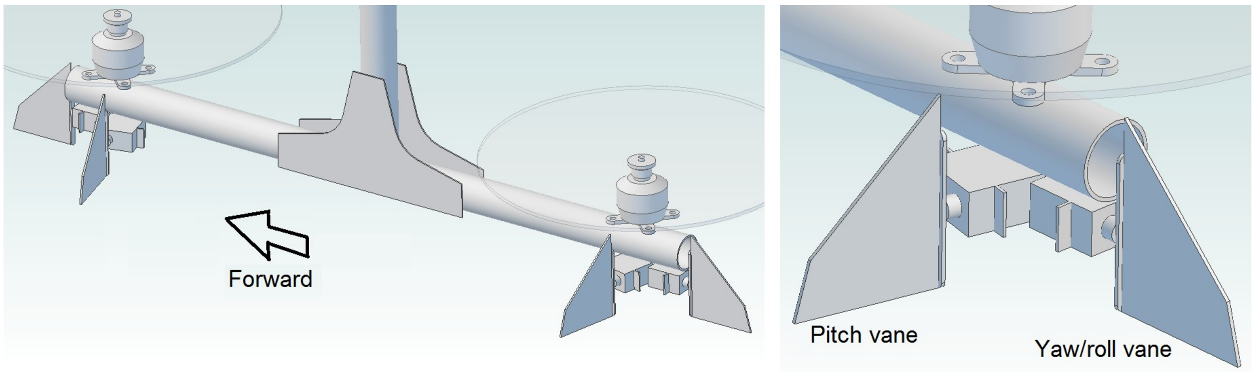


*Figure 4. Attitude control vanes.*

Each vane is attached directly to a servo output spline using friction fit only. No screws are used. This allows the vanes to pop off undamaged in a crash. The delta wing geometry allows a large angle of attack without stalling. The shape turns out to be a good match for typical servos, allowing a larger usable rotation range that would otherwise stall vanes of more conventional shapes.

*[3.b.1] Stability Augmentation System*

The balloon provides passive stability that reduces complexity and cost barriers to getting a controllable vehicle in the air. However, empirically we've found it beneficial to use gyros to actively damp attitude oscillations. This makes it easier to achieve precise control in hover.

One mode in particular has been troublesome -- due to the vehicle configuration, the gondola is prone to swinging like a pendulum, and once the oscillation gets started, there is very little damping to stop it. Originally the hope was to prevent the mode from getting started in the first place. This has proven unrealistic. Gyros have helped considerably in this case.

Another problem is slight thrust imbalances between the two lift propellers. A small thrust imbalance can lead to a noticeable and unwanted horizontal velocity. Plans are to use an orientation sensor to solve the problem.

The strategy would be to exploit the pitch vanes as follows -- the function of each pitch vane is to use attitude data from the orientation sensor to keep the vehicle Z axis vertical. The autopilot would keep track of the average deflection angle of the pitch vane. If the angle starts drifting away from neutral, that's an indication of unequal thrust on the lift propellers. Differential thrust would be adjusted to compensate.

*[3.b.2] Navigation*

A Hokuyo URG-04LX scanning laser rangefinder is the primary naviation sensor. The device has a 240º sweep. Maximum range is 4 meters, angular resolution is 0.36º and the maximum scan rate is 10 Hz. Open source SLAM software is used to create a global map of the arena for navigation purposes.

Altitude is measured using a low-cost Sharp IR rangefinder pointed at the floor, in parallel with a sonar sensor. Altitude readings from the two sensors are compared. Any difference beyond a specified threshold value indicates floor clutter such as trash cans or other objects. The general strategy is to avoid areas with floor clutter in order to maintain constant altitude. An exception is when retrieving the flash drive, when the vehicle needs to hover over a table.

Sonar rangefinders are also used as proximity sensors for low-level obstacle avoidance.

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

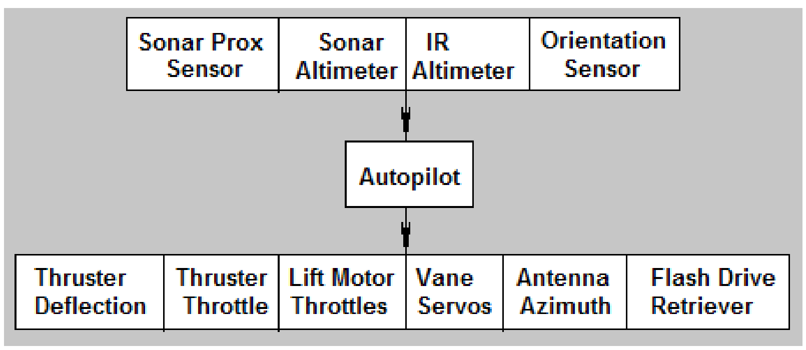


*Figure 5. Control system architecture.*

**[3.c] Flight Termination System**

The flight termination system (FTS) allows an operator to remotely cut power to the entire vehicle in an emergency. This is a crucial safety feature intended to prevent injury and property damage. The FTS consists of a conventional R/C system on 2.4 GHz spread spectrum. The R/C system is connected through an electronic interface to a FET that cuts power from the flight battery.

**[4] PAYLOAD**

**[4.a] Sensor Suite**

[4.a.1] GNC Sensors

Laser rangefinder scanner -- Hokuyo scanner is used for SLAM.

Sharp IR rangefinder -- measures altitude above the floor.

Sonar rangefinders – for obstacle detection, also as a secondary altimeter.

Orientation sensor – a CH Robotics UM6 Orientation Sensor includes 3-axis accelerometers, gyros and magnetometers. An internal ARM chip runs an EKF (Extended Kalman Filter).

*[4.a.2] Mission Sensors*

*[4.a.2.1] Target Identification*

The search for the flash drive is done using a CMUcam camera combined with a laser line generator. Structured light is used because the 2D appearance of the flash drive is ill-defined due to unknown color and logo. The 3D shape of the device is much better defined.

*[4.a.2.1.a] Flash Drive Retrieval Mechanism*

The Retrieval Mechanism is designed to retrieve the target flash drive, after the navigation system located it. Based on the existing aerial vehicle we had, we designed a rectangular shape one, which is installed underneath the vehicle in order to make it land on the area where the target flash drive is. We considered the stability of the vehicle, it is better to land on the working area instead of hovering on it. According to the payload of the vehicle and the weight limitation of the competition, we had to minimize the weight for the Retrieval mechanism. Therefore all materials are lightweight.

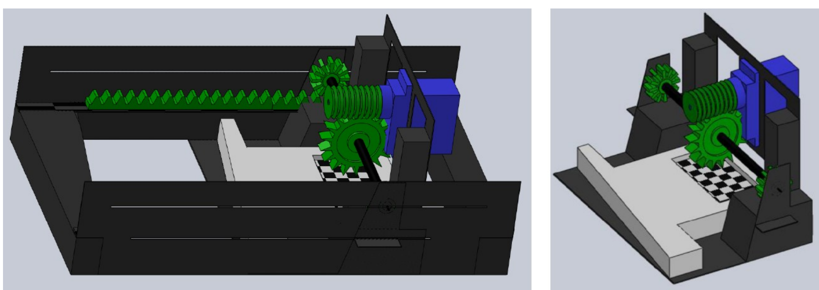

*Figure 6. Flash drive retrieval mechanism, scoop on right. The checkerboard pattern denotes a groove that holds the decoy.*

**Frame** – the frame (Figure 6 above) has a 160 mm x 96 mm rectangular shape and 39 mm height, it is the main assembly to cover the working area for retrieving the target flash drive. There are two hard plastic slide tracks on both sides of frame, the lower slide tracks are for the main scooper to move on the surface, the upper ones are for the gears the rotates while it is moving. Moreover there are two gear racks on both sides that are railway for small gears move on them. Two long side frames are made of 0.3 mm carbon fiber plates and short side frames are made of foam.

**Scoop** -- The scoop is the main mechanism to capture the target flash drive. It has a 9 g micro continuous rotation servo mounted on it. When it works, the servo rotates the worm to drive the worm gear in the middle, at the same time, the small gears will move on the gear racks. While it is retrieving the flash drive, the foam slider on the polycarbonate will be pushed backward by the flash drive, there is a rectangular groove where we keep the decoy, when the foam slider is pushed to the end, the decoy flash drive will be dropped at the working area instead of the target flash drive.

This Retrieval mechanism meets all functional requirements for the competition, it is able to drop a decoy flash drive while it is retrieving the target flash drive, and also able to do repeatable work once it didn't get the flash drive at first time, it will rework in that area till it grabs the flash-drive. The groove we designed for the decoy flash drive ensured that it wouldn't drop it occasionally on the way to the office or in case it didn't obtain the target at first time. It only will place the decoy flash drive while the foam slider is being pushed by the target flash drive.

*[4.a.2.1.b] Deployment of Retrieval Mechanism*

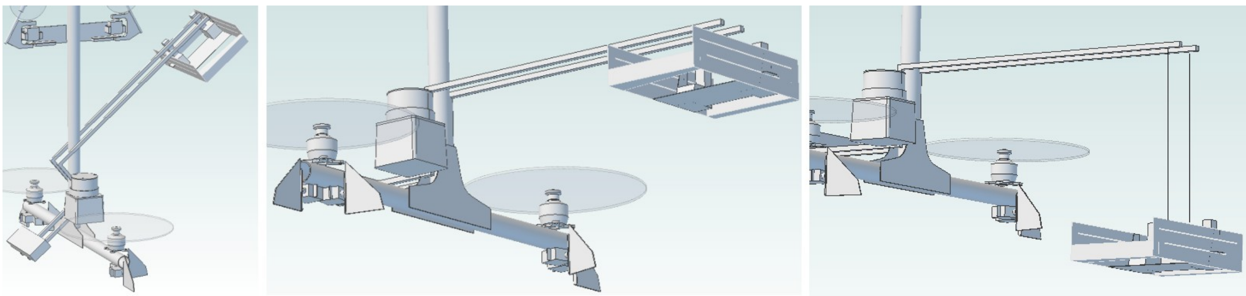

*Figure 7. Positions of retriever on vehicle. From left, stowed during flight, deployed over flash drive, lowered onto flash drive.*

In Figure 7 above, the retriever is lowered onto the table where the drive is located. The retriever is carried on an arm that extends sideways from the vehicle. The lateral offset is needed in order to keep the propeller slipstream away from the tray where the drive is located. The flight battery acts as a counterweight in order to keep the vehicle center of mass within allowable limits, as well as to minimize the torque necessary to rotate the arm from its stowed position.

*[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. |
| 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. Lidar data is transmitted over 2.4 GHz using a Bluetooth radio. The Bluetooth antenna is a large directional antenna inside the balloon stabilizer. The balloon doubles as a radome.

### [4.c] Power Management System

A 11.1 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.

## [5] OPERATIONS

### [5.a] Flight Preparations

[5.a.1] Checklists

- **Mechanical**
  - Gondola
    - Check for damage
  - Balloon stabilizer
    - Attachment points
    - Check for leaks
  - Lift propellers
    - Propeller integrity
  - Vane/pylon
    - Pylon damage
    - Vane structure
    - Vane mounting
  - Thruster
    - Servo condition
    - Mechanical integrity
    - 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:

IR altitude
Sonar range
Voltage of flight battery

*[6.a.1] Shock/Vibration Isolation*

The orientation  sensor is mounted on soft foam to isolate the internal gyros and accelerometers. 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*

*[6.a.2.1] Communications Risk Reduction*

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

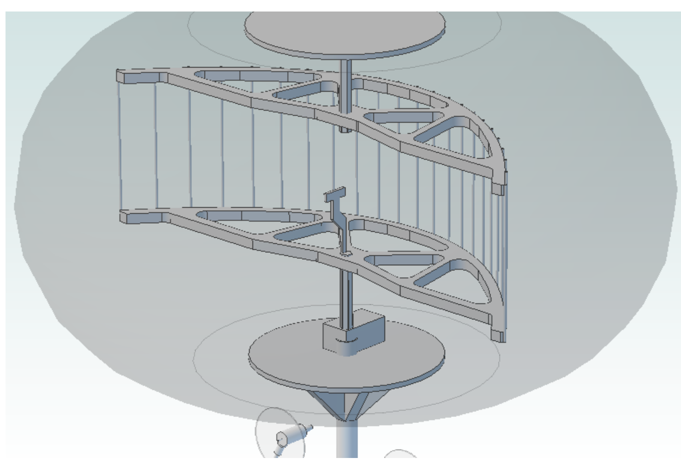

*Figure 8. Balloon antenna.*

The balloon stabilizer on the vehicle has a sizable and protected internal volume -- an ideal location for a large directional antenna (Figure 8). 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.[2] 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 about 600 g. 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. 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 boilerplate version of the vehicle was built out of wood and was used for gyro testing and vane development (see below). This test configuration makes it easy to tune various PID control loops.

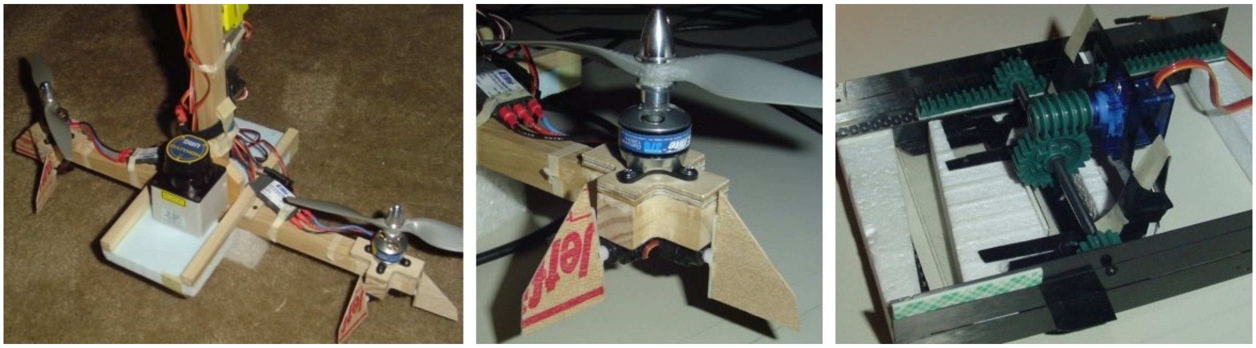

*Figure 9. Left to right -- boilerplate vehicle, vane setup, flash drive retriever.*

**[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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