# Development of a Low Cost Autonomous Aerial Robotics System V3.0

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## [1] ABSTRACT

The Pima Community College UAV Club has designed an autonomous aerial vehicle system to compete in the International Aerial Robotics Competition (IARC). A primary air vehicle carries two cooperating subvehicles to perform the IARC mission, which consists of identifying a building, identifying and entering a portal in the building, and searching for a target inside the building. Vehicles are linked to ground-based computers, and the entire system is required to be completely autonomous.

## [2] INTRODUCTION

### [2.a] STATEMENT OF THE PROBLEM

The Association for Unmanned Vehicle Systems International has organized the International Aerial Robotics Competition (IARC) for colleges and universities to design autonomous vehicles capable of performing a specific mission. The mission is divided into four segments, or levels. For Level 1, an air vehicle must fly a 3 km course to a specified GPS waypoint. For Level 2, the system must find a building in the vicinity of the waypoint. The building is identified by a known symbol attached to the building. In addition, at least one open portal must be identified on the building. For Level 3, the system must somehow enter the building and find a target inside the building. Level 4 requires the system to perform Levels 1 to 3 sequentially and within a 15 minute time limit. All levels require the vehicles to be fully autonomous – no human interaction is allowed.

### [2.b] CONCEPTUAL SOLUTION TO SOLVE THE PROBLEM

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

To solve the problem, our general approach is to use multiple cooperating vehicles. The primary air vehicle carries reconnaissance cameras, as well as two subvehicles. The subvehicles consist of a drop vehicle and a ground rover. The primary UAV uses GPS-based navigation to fly a 3 km ingress. Upon arrival at a specified terminal GPS waypoint, the UAV establishes a search pattern in the vicinity of the waypoint. The target building is assumed to be within 100 m CEP of the waypoint, so a search pattern is designed to cover an approximate 200 m radius circle in order to achieve a 95 % probability of finding the target.

Once the symbol is found, the UAV begins a detailed search of the target building for open portals. When a portal is found, the UAV is rerouted to a racetrack pattern for approach to the portal. At the optimum position, the drop vehicle is ejected backwards from the UAV. Machine vision guides the drop vehicle to the portal. After release, carrier does an autonomous landing.

An on-board accelerometer on the drop vehicle senses impact with the building. At this point a small ground rover separates from the drop vehicle. The rover then searches for its intended target and relays video back to the ground station.

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

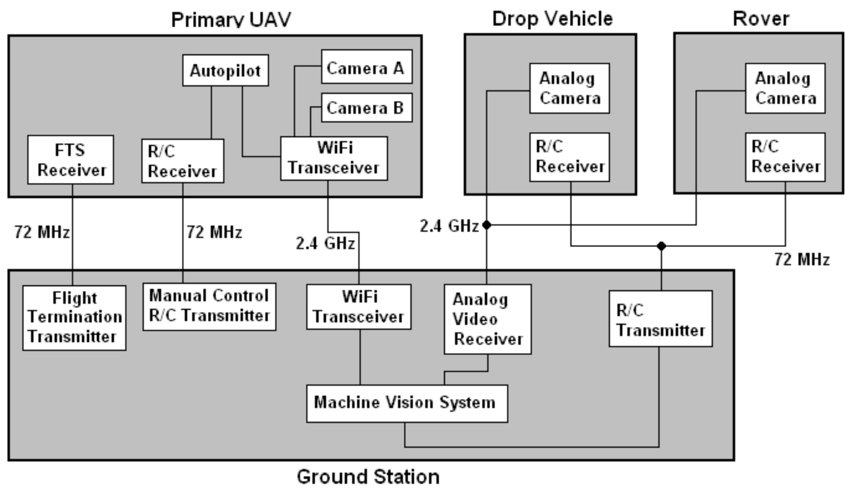


*Figure 1. Overall system architecture.*

## [2.c] YEARLY MILESTONES

For 2006/07, the goal is to design and build a system capable of performing Levels 1 and 2 of the IARC competition. For the 2007/08 competition, the plan is to build upon past results, refine software and hardware designs, and upgrade the system to perform Levels 3 and 4 at the 2008 competition.

## [3] AIR VEHICLE

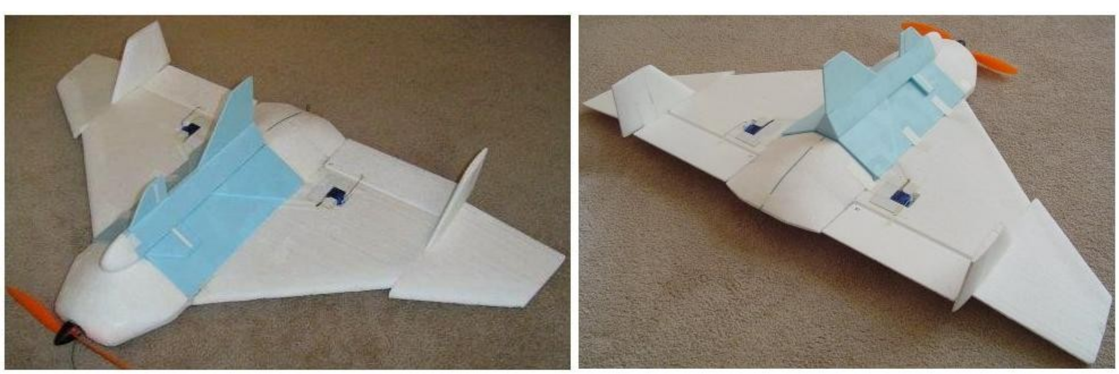

*Figure 2. Primary UAV and drop vehicle, 75 % subscale models.*

### [3.a] PROPULSION AND LIFT SYSTEM

For our primary air vehicle, we considered helicopters vs. airplanes. Although helicopters have a theoretical advantage in the ability to hover in close proximity to buildings, in practice teams have tended to keep helicopters above roof lines for safety reasons, especially since hard-to-detect powerlines are present at the competition site. If your strategy is to rely on a camera for accomplishing the mission, flying above roof lines tends to nullify the advantages of a helicopter as a camera platform, since an airplane can achieve similar camera view angles. That's one reason we chose an airplane design.

For an airplane design, we considered complex/high efficiency vs. simple/low efficiency. The IARC mission does not have particularly demanding endurance, range or speed requirements. We therefore felt we could afford reduced efficiency in exchange for lower cost and simpler geometry, so we chose a tailless airplane configuration with a flat plate delta wing. The airplane is based on an existing slowflyer design called the *Globe Delta*.

### [3.b] GUIDANCE, NAVIGATION AND CONTROL

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

The UAV is an airplane that is inherently stable. On-board autopilots use internal PID loops to control altitude and heading. The drop vehicle is also inherently stable. A ground-based machine vision system controls the attitude of this vehicle.

#### [3.b.2] Navigation

Navigation is primarily by means of GPS waypoints for the initial ingress phase of the mission, and to establish a search pattern for the IARC symbol search. Once the symbol is found, the UAV establishes a new search path that focuses on a single building in order to find open portals. After an open portal is selected, navigation changes to a machine vision mode, in which a video camera is used to target the portal and guide the drop vehicle to the building.

#### [3.b.3] Control System Architecture

The autopilots for the primary UAV is based on a PicoPilot unit. The autopilot has two PID loops that are used for flight control. Altitude is controlled by a throttle-based PID loop, where the sensor is a barometric altimeter. Heading is controlled by an aileron-based PID loop, where a GPS receiver and yaw rate sensor are used. Airspeed is controlled by the elevator trim, which is set manually. Neither elevator nor airspeed are actively controlled once the UAV is switched to autonomous mode. So far we have not seen problems with phugoid oscillations, which can be an issue with this type of altitude control.

### [3.c] FLIGHT TERMINATION SYSTEM

On the UAV, a servo-activated SPST switch cuts power to main propulsion system. A separate radio system controls the servo. The radio is powered by an independent battery. The drop vehicle is unpowered, slow, lightweight and built of a soft material, so an FTS was felt to be unnecessary.

**[3.c.1] Autonomous Landing**

The UAV is small and light enough so that non-precision autonomous landings can be done. A landing skid allows off-runway landings.

## [4] PAYLOAD

### [4.a] SENSOR SUITE

#### [4.a.1] GNC Sensors

- Primary air vehicle
  - GPS receiver
  - MEMS gyro for yaw rate
  - Pressure sensor for barometric altitude
- Drop vehicle
  - Video camera for portal targeting (also doubles as GNC sensor)
- Ground rover
  - Video camera for target search (also doubles as GNC sensor)

#### [4.a.2] Mission Sensors

- Primary air vehicle
  - Video cameras for symbol search and portal search
  - Polarization filters to help detect open portals
- Drop vehicle
  - Video camera for portal targeting
- Ground rover
  - Video camera for target search

The plan for Level 4 is to eventually use a high resolution camera for the symbol and portal searches. Due to schedule constraints, the plan for Level 2 is to use lower resolution video cameras. The low resolution cameras are described as follows.

The primary UAV carries two small color wireless cameras. Each camera measures 22 mm x 22 mm x 25 mm and weighs about 20 grams. The side-looking cameras are mounted adjacent to each other and are situated in the nose of the airplane pointing left. The intent is to fly in an approximately circular orbit, with the side-looking cameras pointing to the center of the orbit. The camera lookdown angle is about 45º. The reason for dual cameras is to detect polarized light. The cameras have mutually-orthogonal polarizer filters.

Power input is 9 VDC at about 100 mA (0.9 mW). One transmitter frequency is at 2.432 GHz and the other is at 2.450 GHz. Each has a range of about 100 meters in line-of-sight. The cameras have the capability of transmitting 30 frames per second but only 4 frames per second are being stored on a computer. The size of each frame is 320 x 240 pixels.

To increase the signal strength at the receiver, a high-gain antenna is used. Its primary function is to boost the range of the 2.4 GHz wireless signals. Since the wireless camera transmitting signal is also at 2.4 GHz, this booster antenna can also be used, as the antenna is designed to function in the same frequency range. This antenna would be rotated by two servos (azimuth/elevation) to track the flight path of the UAV. The pictures received from the camera are fed to ground-based pattern recognition software to identify the target.

The wireless camera can also make stereo images by taking two successive images a quarter of a second apart. Each image would be at a slightly different angle, and machine vision software can determine the dimensions of an object from the two images. The baseline is determined by the product of velocity and time delay between images. Velocity is derived from doppler GPS.

A contrast enhancement algorithm is applied to the images of open portals to determine what is situated inside a building. Not much sunlight reaches the inside of a building and the interior objects are poorly illuminated. When a picture is taken through an open portal, the image often has very low contrast and the details cannot be resolved. By applying a contrast enhancement algorithm, the interior objects can be better seen.

[4.a.2.1] Target Identification

[4.a.2.1.1] Camera coverage -- for the symbol search part of the mission, the objective is to find the IARC symbol in the least amount of time. The symbol is attached to the side of one building in a group of buildings, which introduces 3D geometric complications that increase the difficulty of the search. In particular, the orientation of the symbol is unknown, which implies the system needs to search over multiple angles. In addition, from the viewpoint of an airborne camera, the symbol may be occluded by nearby buildings unless the camera is guided between buildings.

For a given machine vision system, including a camera with a given field of view and resolution, the following parameters can be determined:

1. Maximum range to the symbol $R_{max}$, which is determined by the minimum number of pixels N required to reliably recognize the symbol.

2. Maximum vertical offset angle $\theta_V$.

3. Maximum horizontal offset angle $\theta_H$.

The offset angle constraints are determined by the pattern recognition software and how tolerant it is of distortion caused by out-of-plane rotation of the symbol.

The above information can be used to define the coverage area for a single image, which has the shape of a truncated wedge:

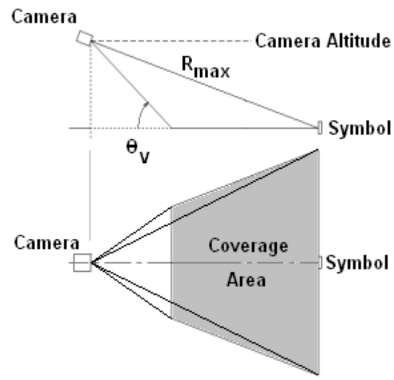


*Figure 3. Coverage area of single frame.*

The near boundary (relative to the camera) is determined by the offset angle $\theta_V$. The far boundary is determined by maximum range $R_{max}$. The top and bottom boundaries are determined by the horizontal field of view (HFOV).

Our strategy is to do an area search, ideally with multiple buildings per image, with the camera at an altitude well above the rooftops of the buildings. We believe this approach will reduce the search time compared to searching individual buildings. We considered different search pattern shapes, such as grids of various orientations. We settled on flying a circular orbit with side-looking cameras. Six images are recorded per orbit, which is a reasonable compromise between volume of image data vs. distortion caused by larger horizontal offset angles. The six images per orbit also make a honeycomb nesting pattern more convenient (see below).

Since the UAV is flying a circular orbit, the search area has the shape of a circle as defined by overlapping single-frame areas. Note that if the HFOV is wide enough, characteristic notches appear in the circle, which is caused by the $\theta_H$ constraint. This occurs when a symbol is at a worst-case position and orientation, centered between two adjacent camera positions:

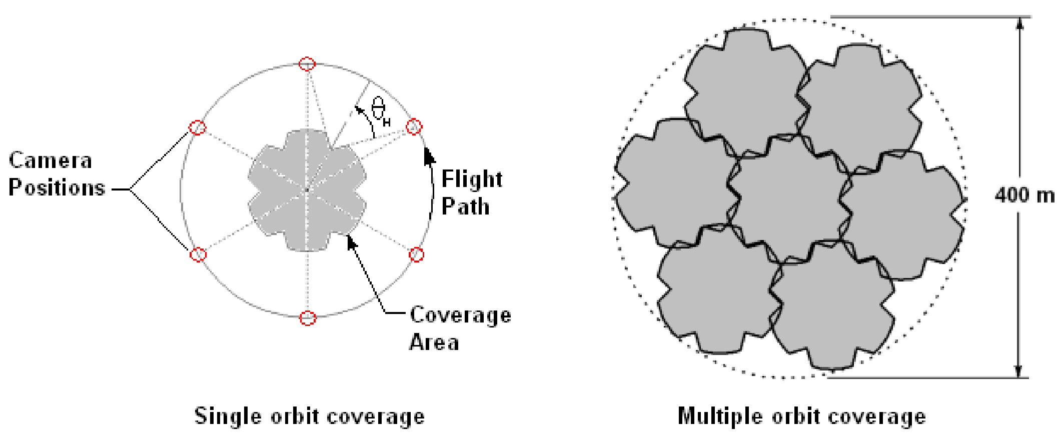


*Figure 4. Notched circle coverage area, single vs. multiple orbits.*

Our current plan for Level 4 is to use a machine vision system in combination with a high resolution camera with the following properties:

| | |
|---|---|
| Type: | Sony DSC-T10 |
| Resolution: | 3072 pixel x 2304 pixel (7.2 Mp) |
| HFOV: | 49° |
| VFOV: | 37° |
| Minimum symbol width N: | 10 pixel |
| $\theta_H$: | 45° |
| $\theta_V$: | 45° |

The search area is a function of the values shown above:

| | |
|---|---|
| UAV altitude: | 79 m |
| Orbit radius: | 151 m |
| Search area radius: | 72 m |
| Radius to notch vertex: | 56 m |

Note that the constraints on offset angles ($\theta_{H,}$ $\theta_V$) and symbol width N have not been measured at this writing. Assumed values were used in the calculations.

Note also that the notched circles can be nested in a honeycomb pattern in order to arbitrarily increase the total search area. With a 72 m search area radius, we need seven orbits (Figure 4, above) to cover most of the 400 m diameter search area.

A high resolution camera (Figure 5, below) has been tested in flight. The camera was modified for external control. Image data is stored on-board for later download. For Level 4 the camera would have to be modified to extract image data for transmission to the ground. Our current plan for Level 2 is to use lower resolution video cameras, as stated earlier.

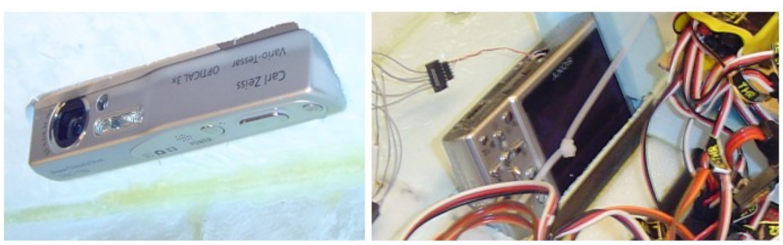

*Figure 5. High resolution camera.*

[4.a.2.1.2] Symbol search -- the search for the IARC symbol is done using SIFT (Scale Invariant Feature Transform), which was developed by David Lowe of the University of British Columbia. SIFT converts an image to a series of keypoints, and matches are found between keypoints from two images. We have successfully detected the symbol in actual images from an airborne camera (see Figure 6). In the figure, lines are drawn between matching keypoints. The symbol template was derived from the photo on the left, and the same template was used in all three test cases. Although original images are in color, the keypoint matches actually use grayscale images. Note that matches are tolerant of a moderate amount of 3D rotation.

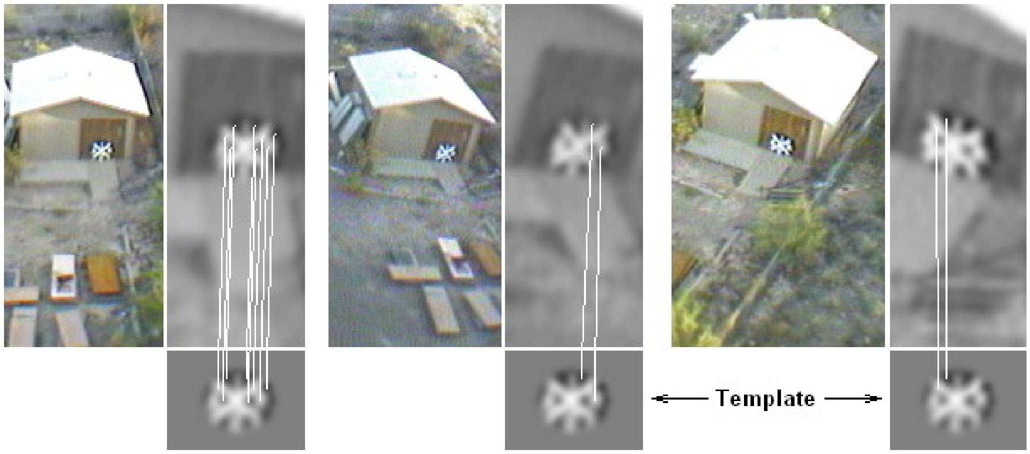


*Figure 6. Symbol detected in aerial photos.*

[4.a.2.1.3] Portal search -- once the symbol is found, a detailed search of the target building is begun. Stereo images of the building are analyzed and searched for openings that lead to internal cavities. Portals may be covered with transparent materials, which are detected by sensing polarized light. Cameras on the UAV are fitted with polarization filters that are oriented in such a way as to maximize sensitivity to polarized light reflected from vertical surfaces (such as windowpanes) that are parallel to external walls of the target building.

[4.a.2.2] Threat Avoidance

Flying above roof lines is the main way the system avoids the threat of collisions. The UAV flies at altitudes that precludes collisions with buildings or other objects. In addition, the steep approach angle of the drop vehicle minimizes the probability of collisions with adjacent buildings, powerlines or trees. Also, the UAV has a simple, rugged structure that is resistant to crash damage and is easy to repair when damage does occur.

**[4.b] COMMUNICATIONS**

For safety reasons, and to allow hand-launch takeoffs and make flight testing easier in general, the total weight of the UAV is limited to 1.5 kg. Therefore ground based computers are necessary. The ground based computers will do most of the processing needed to complete the missions. The ground station will determine flight paths, control the UAV and drop vehicle, and interpret the data received from the onboard cameras. The communication between the ground station and the UAV will be done with a 2.4 GHz bidirectional Wi-Fi network connected to a steerable, high-gain antenna. The onboard flight termination system operates on 72 MHz. The drop vehicle has a camera that transmits on 1.2 GHz to a ground station, which then responds with steering commands via a 72 MHz uplink.

**[4.c] POWER MANAGEMENT SYSTEM**

A single 11.1 VDC lithium polymer (LiPo) battery supplies power to all systems in the UAV except the FTS systems, which have independent power supplies. On the UAV, the main power is supplied directly to the powerplant and is regulated to 6 VDC for the autopilot, and 5 VDC for the servos, video cameras and other avionics.

The drop vehicle and rover have separate 7.4 VDC LiPo batteries to power their own servos, cameras and other systems. The drop vehicle has no propulsion system of its own.

### [4.d] SUBVEHICLE

The UAV carries a combination drop vehicle and ground rover that is used to enter an open portal in the target building (see Figure 7, below).

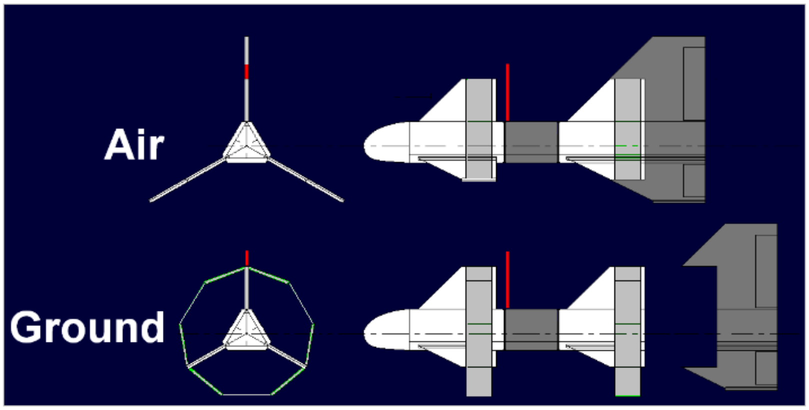


*Figure 7. Drop vehicle and ground rover.*

The drop vehicle has no propulsion system of its own. The vehicle relies on the UAV for transport to the target. After release, the vehicle glides to the portal target at a glide angle of approximately 30° to 45°. A relatively steep descent angle is used to avoid interference from nearby buildings. The vehicle has a missile configuration, with three main wings at the rear and three canards in front. This configuration is chosen for maneuverability at low speeds, and for so-called skid turn capability -- that is, the ability to turn without banking.

Although a delta wing planform has a high induced drag penalty, the additional drag is acceptable because of the steep glide angle. High drag is actually beneficial because it prevents excessive speed buildup during the steep descent.

The drop vehicle uses a machine vision system to navigate to the portal target. Before the drop vehicle is released, the ground-based vision system already knows what the building and portal look like as a result of earlier events during the mission. Since the location of the drop vehicle is also known at release, the system can predict what the drop vehicle camera will see at release. The machine vision system relies on this data to recognize the building and portal in images received from the drop vehicle camera. The vision system also controls the attitude of the drop vehicle.

After building entry, the aft wing section is jettisoned, and the forward module transforms into a ground rover. The canards and forward wing sections double as wheel spokes on the rover. On each wheel, spring-loaded flat panels are folded flush during flight. After landing the panels pop out and form nine-sided wheels. The two wheels rotate independently for steering.

To increase modularity and simplify the wheel design, all flight control surfaces are located on the aft wing module, which separates from the rover after landing.

## [5] OPERATIONS

### [5.a] FLIGHT PREPARATIONS

#### [5.a.1] Checklists

The use of checklists is critical for safety and reliability. Failure to use checklists consistently has lead to numerous problems in the past.

### [5.b] MAN/MACHINE INTERFACE

One important factor in the man/machine interface is in getting access to internal equipment in air vehicles. For the UAV, a large hatch was added to the fuselage, which allows easy access to internal equipment. The hatch was added after previous experience with typical off-the-shelf, high-wing trainer airplane designs used in the past, in which it was difficult to get access to internal equipment. The classic high wing trainer has a relatively restrictive opening in the top of the fuselage. The geometry makes it difficult and inconvenient to install and maintain equipment such as autopilots, cameras, batteries and related avionics equipment. The large hatch on our primary UAV was designed to alleviate those problems.

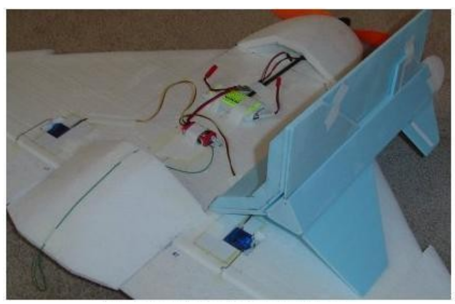

*Figure 8. Subscale model of fuselage hatch.*

## [6] RISK REDUCTION

### [6.a] VEHICLE STATUS

Vehicle status is monitored by means of a WiFi wireless network. Various parameters, such as GPS position, are monitored by the ground station.

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

On the UAV, our approach to vibration is to attack the problem at the source and use electric propulsion. Camera vibration is especially of concern -- experience with blurred camera images at a previous competition is a major reason for our adopting electric power. Landing shock loads are reduced by a skid made of styrofoam. In addition, most of the airframe structure is styrofoam. Internal electronic components are cushioned with foam rubber or mounted with Velcro, which tends to reduce vibration.

The drop vehicle is unpowered and has no appreciable vibration sources other than atmospheric turbulence. Low airspeed plus foam structure reduces shock loads on impact with building. The configuration provides a steady, controllable camera platform.

**[6.a.2] EMI/RFI Solutions**

We plan on using a number of techniques for reducing EMI problems that arise, including the use of aluminum foil for component shielding, using ground planes on antennas, and using regulated power supplies for airborne electronic components.

**[6.b] SAFETY**

The airplane and drop vehicle are made primarily of styrofoam with soft leading edges on flying surfaces, which reduces the probability of injury or property damage. In addition, the UAV's propeller is less hazardous than a helicopter rotor. The energy stored in a propeller is a small fraction of that stored in a helicopter rotor for a vehicle of equivalent payload capacity.

A relatively low wing loading allows a low stall speed for both primary and drop vehicles. In addition, the drop vehicle is unpowered. The ground rover is also expected to be small and lightweight.

**[6.c] MODELING AND SIMULATION**

A VRML math model of McKenna was downloaded from a web site operated by SRI International. The model was used to simulate various camera view angles in order to determine worst-case symbol and portal locations for design purposes.

**[6.d] TESTING**

Our UAV is small and light enough that we can do flight testing in a wide variety of locations, including parking lots adjacent to our lab. This added convenience came in handy when we were seeing problems with drop vehicle separation. For example, the drop vehicle sometimes translated sideways on separation, possibly due to a nonzero sideslip angle. During one flight test, the drop vehicle got stuck on the right vertical tail (see Figure 9 below). Redesign of the separation mechanism solved this problem. A spring-loaded rail mechanism prevented the sideways motion on separation.

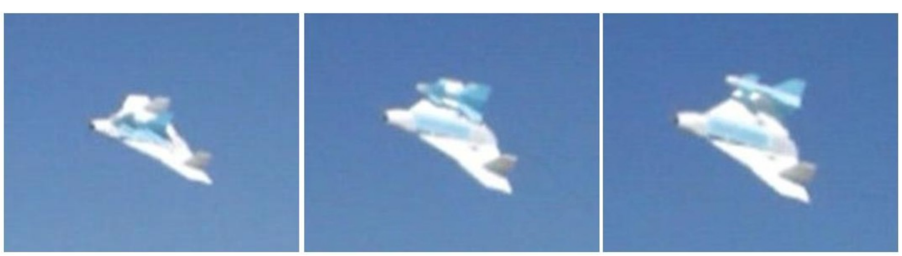

*Figure 9. Drop vehicle catching on vertical tail.*

Another issue was that the drop vehicle tended to pitch up violently on separation. This was solved by moving its center of mass forward.

## [7] CONCLUSION

An aerial robotic system was conceptually designed to perform IARC mission objectives using multiple, cooperating vehicles of simple, low cost design. A UAV with flat-plate delta wing configuration carries a lightweight drop vehicle over a 3 km ingress path, then performs a search for a target building. Once the target is found, a machine vision system steers the drop vehicle to the building, where it enters an open portal and delivers a ground-based rover.


### [7.1] ACKNOWLEDGEMENTS

We would like to thank Pima Community College for support of this project, and especially Tony Pitucco as PCC faculty advisor. Kobus Barnard of the University of Arizona also gave us valuable advice regarding machine vision. We'd also like to thank the AIAA Tucson Section for providing funding and for its support in providing air vehicle equipment for training purposes.


## [8] REFERENCES


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