Development of a Low Cost Autonomous Aerial Robotics System V2.0

Frank Manning
AIAA Tucson Section
Gerardo Cornejo
University of Arizona
Chien-Wei Han
Pima Community College
Felix Zimba
University of Arizona
Jason Lewis
Pima Community College

[1] ABSTRACT

The International Aerial Robotics Competition (IARC) is designed for colleges and universities to compete in the design and construction of an autonomous aerial vehicle. Pima Community College is being represented by the Unmanned Aerial Vehicle (UAV) Club. The UAV Club has designed a primary vehicle and three subvehicles that will be used in the competition. The vehicles were designed with autopilots that will work closely with GPS navigation and ground-based computers to control the aircraft. The following will explain the mission objectives and their purposes, the purpose of the design of the vehicles, the problems encountered and solved, design of software and the use of optical sensors to achieve success.

[2] INTRODUCTION

[2.a] STATEMENT OF THE PROBLEM

The Association for Unmanned Vehicle Systems started the IARC as an annual competition to get colleges and universities involved in the future of unmanned aerial vehicles. The competition is a rigorous one consisting of three sub-missions and a final fourth mission that combines the first three missions to be completed uninterrupted.

The first mission (so-called Level 1) is designed to see if the aerial vehicle can complete a three kilometer course as specified by GPS waypoints. Once this is completed the team can advance to Level 2. Level 2 requires an air vehicle to fly and seek out the IARC symbol that is situated on the side of a target building that is within a complex of buildings. The UAV then must find and identify at least one open portal that is one meter by one meter or larger. This can be any opening that is in a normal building, be it a door, window, or similar opening. In order to earn the maximum amount of points the open portal must be located to an accuracy of ±0.25 m in GPS coordinates.

Level 3 is an extension of Level 2. This requires a vehicle of some sort (which may be the primary vehicle or subvehicle) to be dropped or flown into an open portal. Once inside the target building, the vehicle must provide the judges with information, via video or photographs, of one of three scenarios; a hostage situation, a wall tapestry, or a control panel from a nuclear reactor.

After the completion of the first three missions, Level 4 can be attempted. Level 4 requires the UAV to do the first three missions in order and within a 15 minute time limit. All four missions must be fully autonomous, with no human interaction 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 is specialized for reconnaissance. A carrier subvehicle flies in parallel with the primary air vehicle, and carries an additional two subvehicles, which consist of a drop vehicle and a ground rover. The reconnaissance and carrier UAVs use GPS-based navigation to fly a 3 km ingress. Upon arrival at a specified terminal GPS waypoint, the recon 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 diameter circle.

Once the symbol is found, the recon UAV begins a detailed search of the target building for open portals. When a portal is found, the mission is handed off to the carrier UAV, and recon does an autonomous landing. Carrier 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

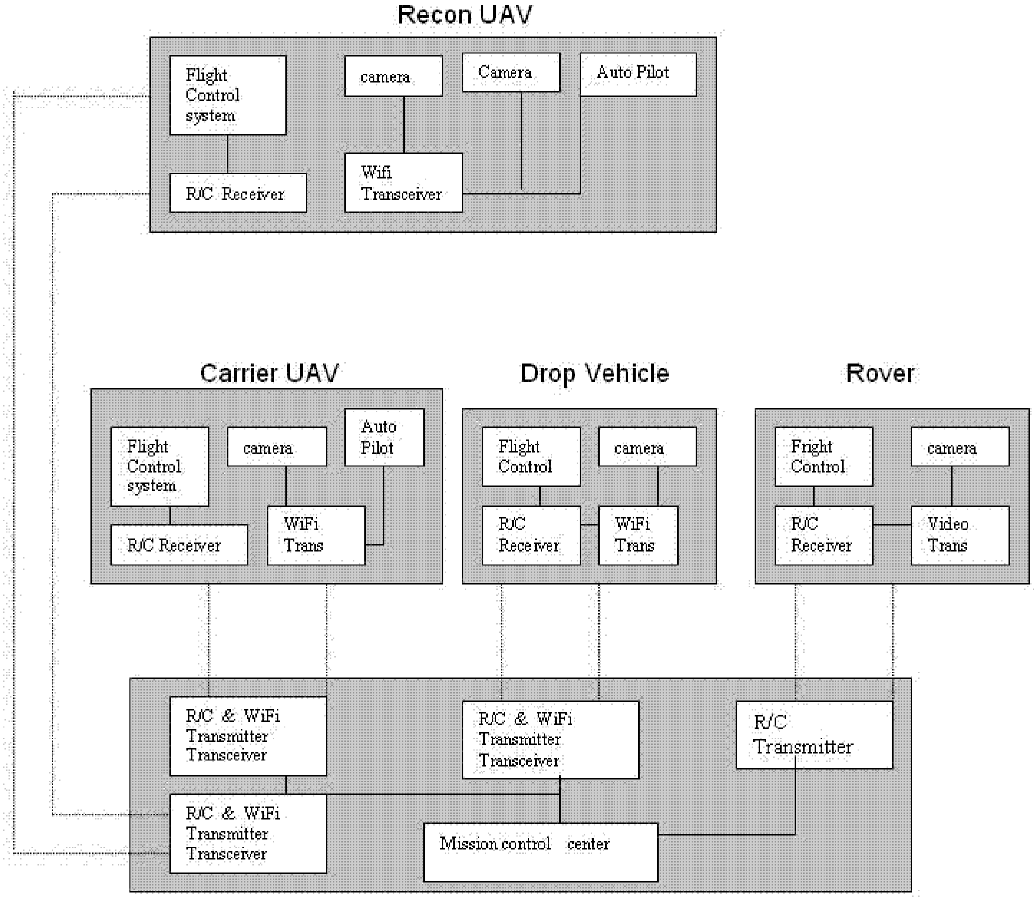

Figure 1. Overall system architecture

[2.c] YEARLY MILESTONES

For 2005/06, the goal is to design and build a system capable of performing Levels 1 and 2 of the IARC competition. For the 2006/07 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 2007 competition.

[3] AIR VEHICLE

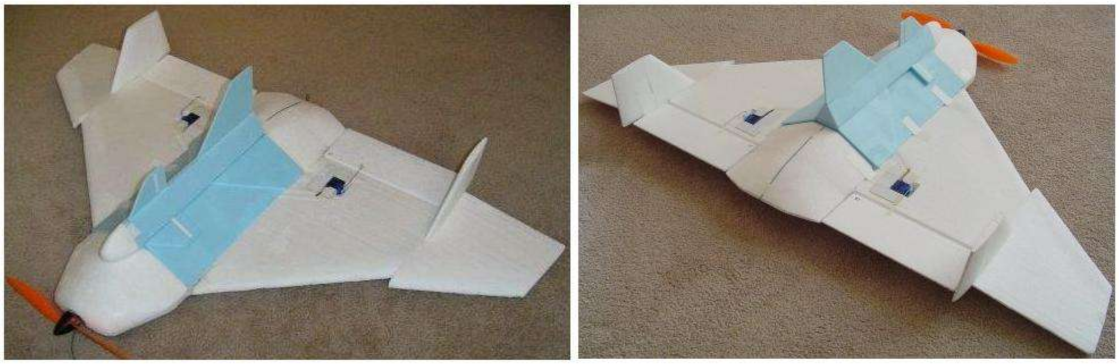

Figure 2. Primary UAV and drop vehicle, 75 % subscale models

[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 recon and carrier UAVs are airplanes that are 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 primary 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 recon and carrier UAVs are 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.

[3.c] FLIGHT TERMINATION SYSTEM

On each of the two airplanes, 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 recon and carrier UAVs are small and light enough so that non-precision autonomous landings can be done. Landing skids on both UAVs allow off-runway landings.

[4] PAYLOAD

[4.a] SENSOR SUITE

[4.a.1] GNC Sensors

- Recon and carrier UAV
  - 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 UAV (recon)
  - Video cameras for symbol search and portal search
  - Polarization filters to help detect open portals
- Carrier UAV subvehicle
  - Video camera for portal targeting
- Drop vehicle
  - Video camera for portal targeting
- Ground rover
  - Video camera for target search

The recon UAV carries two small color wireless cameras that were purchased at Radio Shack for about $120 each. Each camera measures 22 mm x 22 mm x 25 mm and weighs about 20 grams. The side-looking cameras are mounted vertically-adjacent to each other to increase the viewing angle, 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 reduce the need for a mechanical pan/tilt mechanism.

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 booster antenna made of a circular metal tube is used. The tube measures 304.8 mm in length and 8.5 mm in diameter. Its primary function is to boost the receiving range of the wireless network signal at 2.4 GHz. Since the wireless camera transmitting signal is also at 2.4 GHz, this booster antenna can also be used. This cylindrical antenna would be rotated by a servo 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 a computer 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.

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 program, the interior objects can be better seen.

[4.a.2.1] Target Identification

Symbol search pattern -- the reconnaissance UAV, when searching for the IARC symbol must fly in a predetermined flight pattern that will maximize the amount of ground coverage and minimize the amount of time that it takes to locate the symbol. The team decided that we would go with a search pattern that was based around a “rose curve” mathematical formula, $R = A\sin(N\theta)$, where R and theta are the dependent and independent variables, respectively; A defines the radius of one of the petals in the curve; and N defines the number of petals in the curve.

If we use an even number for N, we get a curve that has 2N petals; if N is an odd number, we get N number of curves. To pick an appropriate value for N we need to keep in mind that if N becomes too large, the possible viewing angles produced by the curve will be large, but also the curve will be become too cumbersome to navigate, and will hinder the performance of the reconnaissance vehicle; and if N is too small the area covered by the flight path will be insufficient to locate the symbol. With that in mind we decided to go with a value of 3 for N since this curve will be relatively easy to navigate and will also cover a wide area (see below).

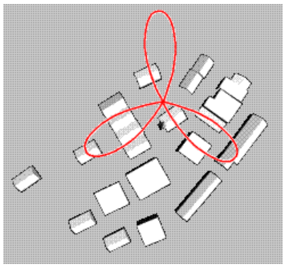

Figure 3 – Symbol search pattern

If the symbol were to be in the intersection point of the three curves, or in a place that whose view would be obstructed, we have the option of either centering the curve at another point(s), or we could also alternate the 'sin' to a 'cos,' or we could also alternate between a positive and negative function for the two trigonometric functions; all of which would change the location and/or the orientation of the curve. Since the diameter of the circle that needs to be covered is 200 meters according to the CEP stipulation, the corresponding value for A becomes 100, since the 100 denotes a radius of the circle.

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. We have successfully detected the symbol in actual images from an airborne camera (see figure X below). So far the empirical success rate using low resolution images and a relatively crude algorithm has been about 30 %, with no false positives. This was with a set of 5 test images, 3 of which included the IARC symbol. Three templates were used. The successful hit is shown below.

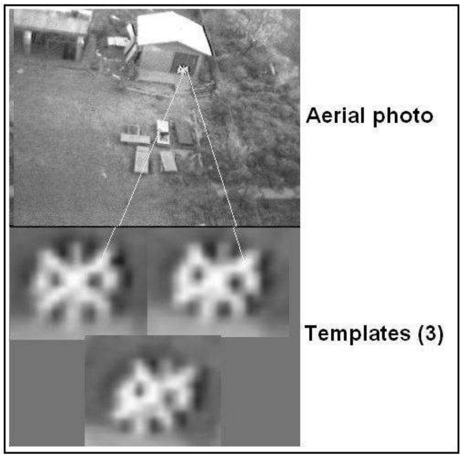

Figure 4. Symbol detected from aerial photo

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 Recon 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. Both Recon and Carrier UAVs fly at altitudes that preclude 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.

[4.b] COMMUNICATIONS

For safety reasons, and to allow hand-launch takeoffs and make flight testing easier in general, the total weight of each of the two airplanes 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 autopilots on the UAVs and drop vehicle, and will interpret the data received from the onboard cameras. The communication between the ground station and the UAVs will be done with a 2.4 GHz bidirectional Wi-Fi network. The onboard flight termination systems operate 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 recon and carrier UAVs except the FTS systems, which have independent power supplies. On each 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 carrier UAV carries a combination drop vehicle and ground rover that is used to enter an open portal in the target building (see Figure 5, below).

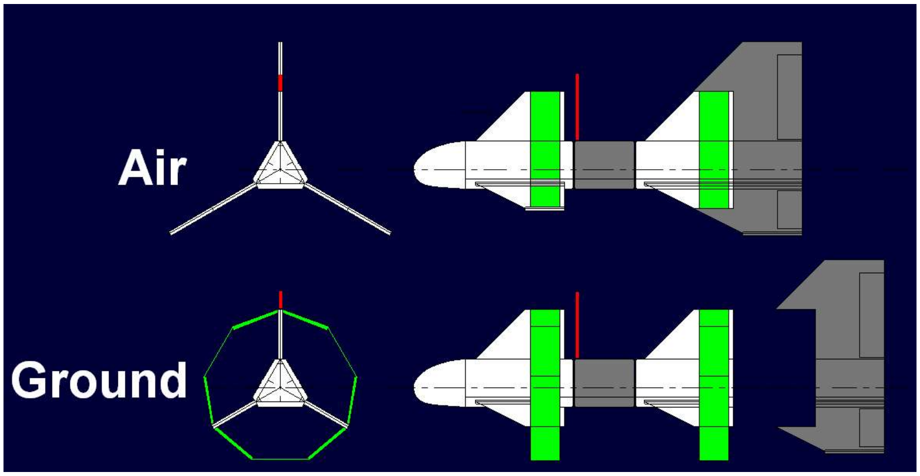

Figure 5. Drop vehicle and ground rover

The drop vehicle has no propulsion system of its own. The vehicle relies on the carrier 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. The following checklist is intended for future flight operations:

```
Preflight checklist
   Assemble all vehicles
   Check center of mass
   Make sure all batteries are charged to full capacity
   Look at wing -- Check for cracks or fractures
   Check servo control horns
   Check motor mount
   Make sure the propeller is on in the right direction
   Check battery mount
   Check electrical connections and mounts
   Check battery charge
   Turn on all systems
   Check avionics are working
   Check communication between UAV and ground station
   Check drop vehicle deployment mechanism, test for a clean launch
   Securely fasten all remaining service panels
   Set takeoff trim
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[5.b] MAN/MACHINE INTERFACE

One important factor in the man/machine interface is in getting access to internal equipment in air vehicles. For our primary 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.

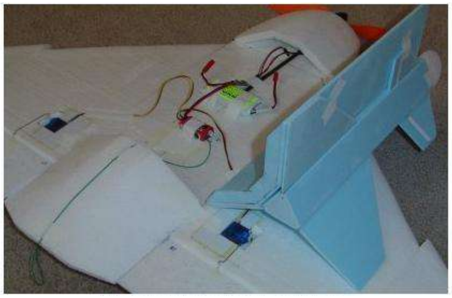

Figure 6. Subscale model of fuselage hatch

[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 recon and carrier UAVs, 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 airplanes and drop vehicles 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 primary UAVs are 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, sometimes the vehicle would not go towards the rear but rather to the sides of the plane and become stuck on the vertical stabilizers. This was probably caused by a nonzero sideslip angle during release (see Figure 7 below).

Figure 7. Drop vehicle catching on vertical tail

Wind tunnel testing done on the plane and the Drop Vehicle confirmed these experimental findings. This lead to a spring loaded release mechanism being placed in the midsection of the plane, ensuring positive separation.

Another issues 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 air 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, while a similar UAV 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. Kate Taralova and Tim Spriggs of the UA also gave us permission to use their symbol recognition software. We'd also like to thank the AIAA Tucson Section for its support in providing air vehicle equipment for training purposes.

[8] REFERENCES

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