Development of a Low Cost Autonomous Aerial Robotics System V4.0

1 June 2008

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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. A glider subvehicle enters the building, then ejects the Interior Search Vehicle (ISV), which hovers at eye-level for the building search. 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

Pima Community College has an Unmanned Aerial Vehicle (UAV) Club that is entering the International Aerial Robotics Competition. The competition is put on by The Association for Unmanned Vehicle Systems International for colleges and universities to design autonomous vehicles that are capable of completing a mission that contains four objectives. The first objective is to have an aerial vehicle autonomously fly three kilometers to a designated Global Positioning System (GPS) waypoint. The second objective is to identify a targeted building in the vicinity of the GPS waypoint and identify at least one opening in the building. The third objective is to autonomously search the interior of the building for a target and return video footage of the target. The last objective is to complete the first three objectives in fifteen minutes.

[2.b] CONCEPTUAL SOLUTION TO SOLVE THE PROBLEM

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 at this writing.

To solve the problem, our general approach is to use multiple cooperating vehicles. The primary air vehicle carries two reconnaissance cameras, as well as two subvehicles. The subvehicles consist of a drop vehicle and a hovering vehicle. 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, the UAV establishes an orbit over the building in order to relay video signals to the ground station.

An on-board accelerometer on the drop vehicle senses impact with the building. At this point a small hovering vehicle is ejected from the drop vehicle. The hovering vehicle then searches for its intended target and transmits video to the overhead UAV, which relays the video signal to the ground station.

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

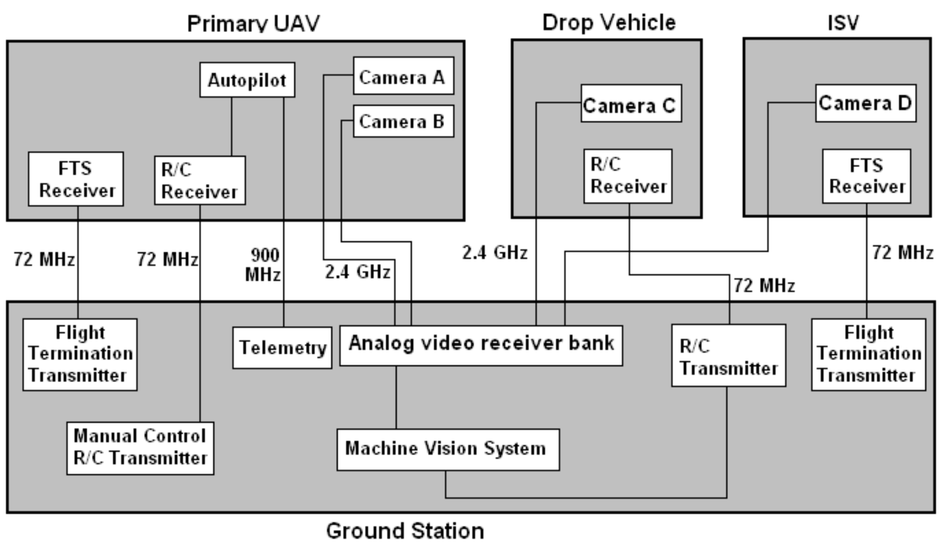

Figure 1. Overall system architecture.

[2.c] YEARLY MILESTONES

For the 2008 competition, the Pima College team concentrated on further development of a steerable tracking antenna for the ground station, as well as developing a low-cost Interior Search Vehicle (ISV) for the building search. A passive stabilization system was developed for the ISV for its roll and pitch axes, which simplifies design of the ISV autopilot. The passive stabilizer doubles as a high-gain antenna for video transmission.

[3] AIR VEHICLE

Figure 2. Primary UAV, Drop Vehicle and Interior Search Vehicle

[3.a] PROPULSION AND LIFT SYSTEM

For our primary air vehicle, we considered helicopters vs. airplanes. We chose an airplane design because airplanes tend to be cheaper to repair and easier to fly, and there is less of a safety concern with propellers relative to comparatively larger helicopter rotors.

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. The UAV's on-board autopilot uses internal PID loops to control altitude and heading. The drop vehicle is inherently stable, and a ground-based machine vision system controls the attitude of this vehicle. The hovering vehicle (ISV) is inherently stable as well, with a dish antenna doubling as a passive aerodynamic stabilizer for the roll and pitch axes.

[3.b.2] Navigation

Navigation is primarily by means of GPS waypoints for the 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 autopilot 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 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, which shares its propulsion system with the ISV, uses a switch to cut power to both motors. A separate radio system controls the switch.

[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)
- Hovering vehicle
  - MEMS gyro for yaw rate
  - Sonar rangefinders for altitude control and obstacle avoidance
  - IR rangefinder for obstacle avoidance
  - Light sensor to discriminate indoor/outdoor environment

[4.a.2] Mission Sensors

- Primary air vehicle
  - Two video cameras for symbol search and portal search
- Drop vehicle
  - Video camera for portal targeting
- Hovering vehicle
  - Video camera for target search

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.

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.

Two cameras are used in order to increase the effective resolution of the vision system. The two fields of view are adjacent to each other.

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 θ_V.

3. Maximum horizontal offset angle θ_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:

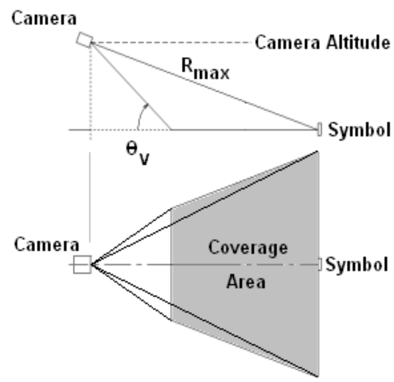

Figure 3. Coverage area of single frame.

The near boundary (relative to the camera) is determined by the offset angle θ_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 θ_H constraint. This occurs when a symbol is at a worst-case position and orientation, centered between two adjacent camera positions:

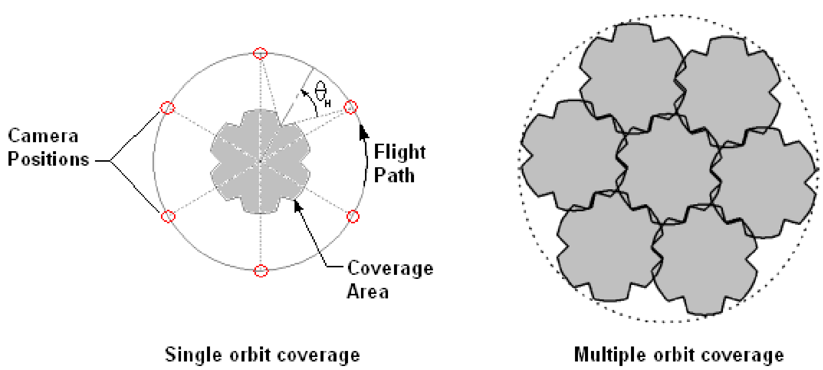

Figure 4. Notched circle coverage area, single vs. multiple orbits.

[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 5). 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.

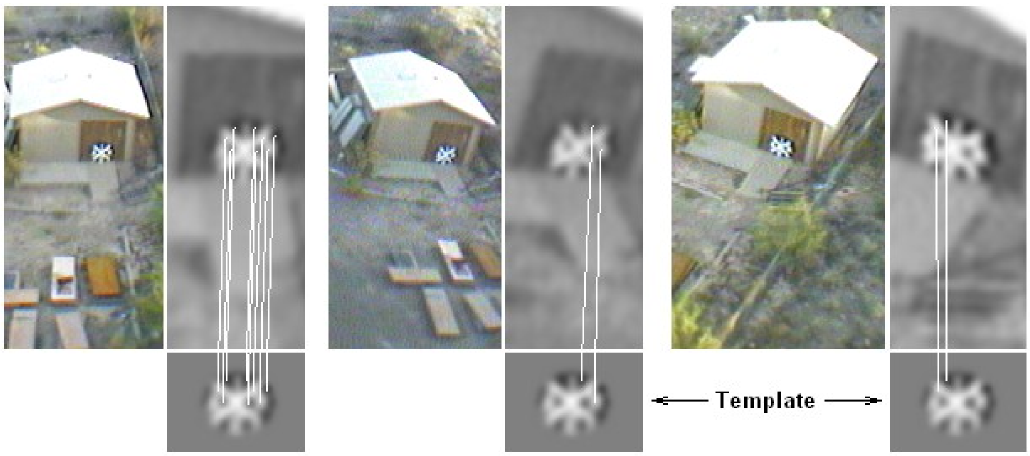

Figure 5. Symbol detected in aerial photos.

[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. The intended mission is the nuclear reactor scenario, which assumes that all windows were blown out by an explosion. Therefore windowpane detection is not necessary.

[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 3 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 900 MHz bidirectional radio modem. 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.

By contrast, the ISV control system is completely self-contained and is independent of the ground station, except for video transmitted to the ground station.

[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 ISV have separate 7.4 VDC LiPo batteries to power their own servos, cameras, sensors and other systems.

[4.d] SUBVEHICLES

The UAV carries a rigid-wing drop vehicle that is used to enter an open portal in the target building. 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.

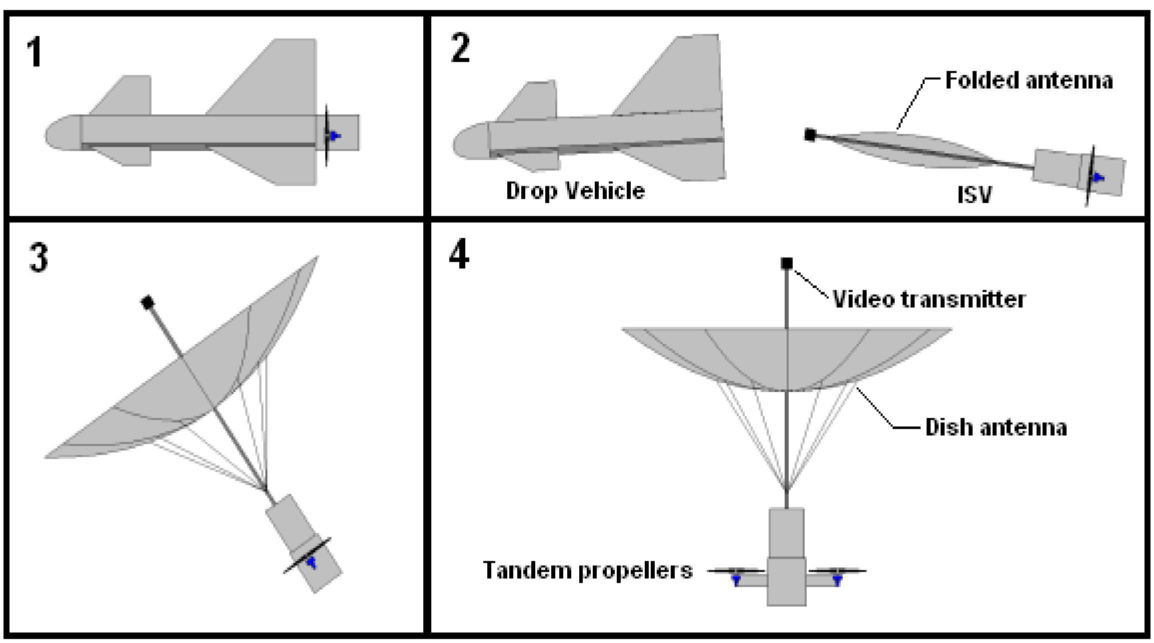

Figure 6. ISV midair deployment sequence.

The drop vehicle generally glides to the open portal, although there is enough flexibility that the ISV propulsion system could operate during descent. Once the drop vehicle enters the building, the ISV is ejected in midair and immediately begins hovering (see figure 6 above). The ISV has two counter-rotating propellers that are spun up on separation. A parabolic dish antenna also unfolds rapidly on separation. The antenna doubles as an aerodynamic stabilizer during hover. The antenna provides passive stability about the ISV's roll and pitch axes.

A relatively high gain antenna is required because the video transmitter does not otherwise have enough power to overcome substantial RF attenuation from the building structure. The antenna beam points straight up. The primary UAV flies a small-radius orbit above the building and relays video to the ground station. A small scale test was flown with a faceted approximation of the parabolic antenna (see figure 7 below) to demonstrate passive stabilization during hover.

Figure 7. Hover test with faceted stabilizer.

Design criteria for ISV control system – the ISV should be able to fly automatically according to the programming logic that is embedded in the system; therefore, the obstacle avoidance system is essential for this small UAV to fly safely in its path. Preventing the propellers from crashing into the furniture and walls inside the building is a major task of the obstacle avoidance system. Preventing the UAV from traveling outside of the building through any open windows or doors is also very important since the main mission of the UAV is able to hover inside a building. Inside a building, the hovering UAV must fly on a safe and obstacle-free path to search the target inside the building without hitting any objects. At the same time, the system must transmit the live video signal back to the ground base for monitoring to locate the reconnaissance target. The system has to control the UAV hovering horizontally at a constant velocity of 20 centimeters per second to capture necessary video resolution and to fly safely. The UAV must fly above the ground at an altitude of two meters with one meter of fluctuation up or down. The system will also need to consume little energy and must be powered by a two cell Lithium-Polymer battery at 7.4 volts. The maximum weight of the autopilot plus camera must be 30 grams.

Design of ISV control system – the design will be able to search the building autonomously while remaining in the building and avoid colliding with objects. The main components of the design will be comprised of: a TI MSP430F1610 microcontroller, two Maxbotix EZ1 ultrasonic rangefinders, one Sharp IR GP rangefinder, a small camera, a Murata gyroscope, two electronic speed controllers and a light sensor. The vehicle travels at a constant velocity of twenty centimeters per second without the ability to stop itself. The speed of the propellers will be controlled by electronic speed controllers. These electronic speed controllers will be controlled by the microcontroller and will be used to steer the vehicle. There will be one ultrasonic sensor pointing straight down that will calculate the altitude of the vehicle while the other ultrasonic sensor will be pointed straight forward. The sensor pointing straight forward will be used to detect objects in front of the vehicle. The light sensor will be used to detect sunlight if the vehicle happens to travel out of an open window or door in which case the vehicle will turn around and return inside. The gyroscope will be used to maintain the heading of the vehicle. The infrared sensor will be pointed to the left of the vehicle and will be used to detect doorways when the vehicle is following the wall.

[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. Fuselage hatch.

[6] RISK REDUCTION

[6.a] VEHICLE STATUS

Vehicle status is monitored by means of a 900 MHz radio modem. 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 polypropylene foam. In addition, most of the airframe structure is polystyrene foam. Internal electronic components are cushioned with foam rubber or mounted with Velcro, which tends to reduce vibration. Similar approaches are taken with the designs of the drop vehicle and ISV, which use small electric motors for propulsion.

[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 ISV is small and lightweight, and needs only small motors for propulsion.

[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 and subvehicles 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, 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.

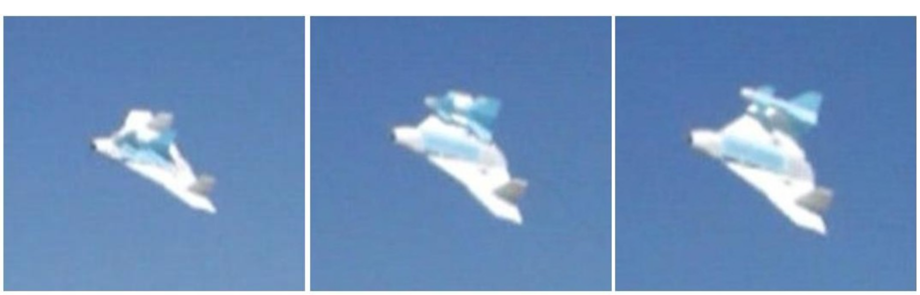

Figure 9. Drop vehicle catching on vertical tail.

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.

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