Development of a Low Cost Autonomous Aerial Robotics System

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[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 a drop vehicle that will be used in the competition. They were designed with autopilots that will work closely with Global Positioning Systems (GPS) 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 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 mission two.

Mission two 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.

Mission three is an extension of the second mission. 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, the fourth mission can be attempted. Mission four 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. A primary air vehicle acts as a carrier of two subvehicles. The subvehicles consist of a drop vehicle and a ground rover. The ground rover is carried inside the drop vehicle.

The primary UAV uses GPS-based navigation to fly a 3 km ingress. Upon arrival at a specified terminal GPS waypoint, a search pattern is established 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 UAV begins a detailed search of the target building for open portals. When a portal is found, the drop vehicle is ejected backwards from the UAV. Machine vision guides the drop vehicle to the portal.

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

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

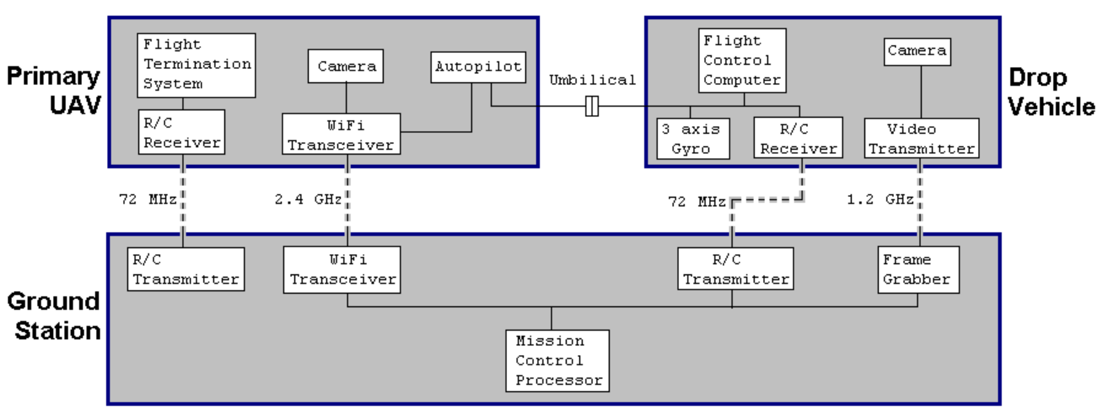

Figure 1. Overall system architecture

[2.c] YEARLY MILESTONES

For 2004/05, the goal is to design and build a system capable of performing levels 1 and 2 of the IARC competition. For the 2005/06 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 2006 competition.

[3] AIR VEHICLE

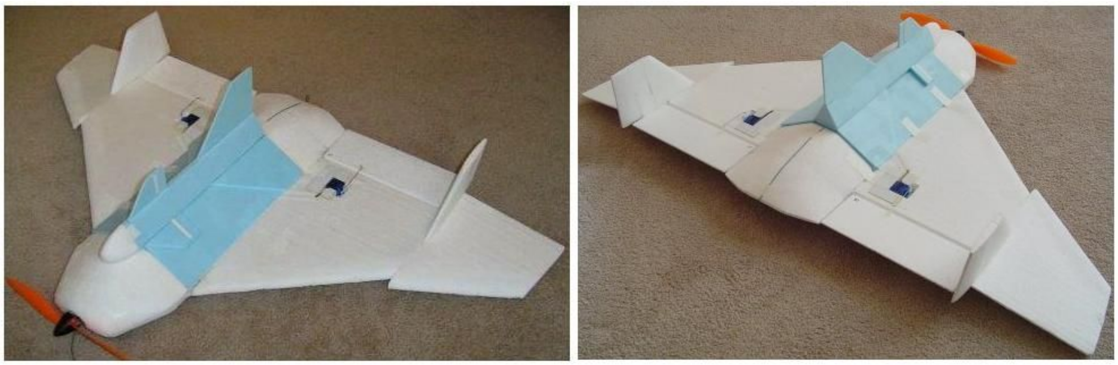

Figure 2. Primary UAV and drop vehicle, 41% subscale models

[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 competiton 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, and in fact teams have historically tended to use helicopters festooned with externally-attached, high-drag electronic boxes. 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*.

Flat plate airfoils have obvious disadvantages. For example, a 2D flat plate airfoil has C_{Lmax} approximately 0.7. This is about half that of more conventional airfoils, such as a NACA 4421, with a C_{Lmax} of about 1.4 [1, p. 297].

But you can substantially increase C_{Lmax} of a 2D flat plate, at the expense of high drag, by shaping it into a 3D delta wing. For example, C_{Lmax} increases to a more reasonable 1.3 for a flat plate delta wing with a 60º leading edge sweep [1, p. 363] or 75º sweep [2].

Additional lift augmentation can be attained by drooping the wingtips. In particular, Traub measured lift increments of 7 % and 9 % at $\alpha = 15º$ and 25º, respectively, compared to a planar wing[2]. This was for a 75º delta wing with anhedral breaks at 2/3 span. Our wing has smaller sweep and anhedral angles, but it is reasonable to expect that anhedral may increase lift to some extent.

Rounding the leading edge of a delta wing tends to increase lift-to-drag ratio L/D [1, p. 363..364]. Our wing is relatively thin, which limits the LE radius, but we attempt to round the LE as much as possible.

To summarize, we chose a simple tailless, flat-plate delta design with an L/D target somewhere between a conventional airplane and the usual high-drag IARC helicopter.

[3.b] GUIDANCE, NAVIGATION AND CONTROL

[3.b.1] Stability Augmentation System

The primary UAV is based on an airplane, which is inherently stable. The on-board autopilot uses 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 the vehicle, except for a wing-levelling function, which is handled on board. Wing levelling is done by integrating a 3 axis gyro and using a PID loop to for aileron control.

[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 focusses 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.

[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

We considered parachute recovery for autonomous landing, which is worth 200 points in level 3. Parachutes are great in theory but reliability in the field is questionable. At a previous competition, experience by one of us with unsuccessful parachute deployments was not encouraging. Also, from a practical point of view, packing parachutes is labor-intensive -- not something to take lightly in the heat of competition. So we decided not to use parachute recovery.

Alternative approach -- in past subscale flight tests, the airplane has been able to fly under certain conditions in a high-lift, high-drag mode at a high angle of attack. The angle of attack in this mode was estimated at greater than 30º, probably because of the delta wing configuration. In the future we plan on further exploring this capability as an alternative to parachutes for autonomous landings.

[4] PAYLOAD

[4.a] SENSOR SUITE

[4.a.1] GNC Sensors

- Primary UAV
  - GPS receiver
  - MEMS gyro for yaw rate
  - Pressure sensor for barometric altitude
- Drop vehicle
  - 3 axis MEMS gyro for attitude
  - 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
  - Video camera for symbol search and portal search
  - Polarization filter to help detect open portals
- Drop vehicle
  - Video camera for portal targeting
- Ground rover
  - Video camera for target search

[4.a.2.1] Target Identification

The machine vision system uses a template-matching algorithm to search for the IARC symbol. Once the symbol is found, a detailed search of the target building is begun. The following 4 paragraphs are adapted, with slight changes, from reference [6]. The paragraphs were originally written by one of us (Manning):

The vision system searches building walls for closed shapes that are either dark or change internally as a function of view angle, indicating an internal 3D cavity. The search is not limited to dark shapes. Since the view angle is 30º to 60º below horizontal, sunlit objects such as floors are potentially visible through a portal. Note in particular that portals may be covered in partially-reflective transparent materials (such as glass or plastic) that may reflect light from the external environment. Reflected images may mimic a 3D internal cavity and spoof the vision system. This problem is handled by detecting light polarization.

Window detection -- light reflecting off a transparent material can be polarized, depending on the incidence angle. Maximum polarization occurs at Brewster's angle, which for light passing through two materials is a function of the indexes of refraction for each material. Brewster's angles for glass and plastic is approximately 56º and 53º respectively [4,5]. Thus the objective is to determine whether a feature consists of polarized light. If it is, the feature is rejected as an open portal.

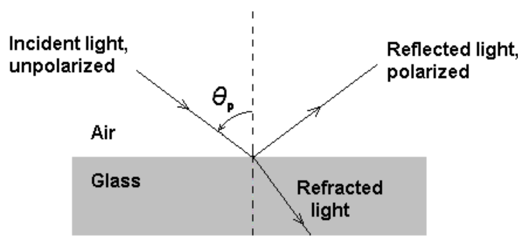

Figure 3. Brewster's Angle.

Detecting polarized reflections -- the key question is how to detect polarized reflections. When the UAV is searching for open portals, it approaches the target building at an altitude well above the building, which means the flight path is such that the camera sweeps through a range of angles relative to portals on the building. If the frame rate is high enough, we can record multiple frames that are close to Brewster's angle. Since the camera is above the building, reflections are typically of the ground adjacent to the building, at least for portals that are oriented vertically.

The UAV camera is equipped with a continuously-rotating polarizing filter. The rotation rate is 600°/s (see below). The vision system searches frame sequences for maximum and minimum brightness values in features that are candidates for portals. If the difference in brightness exceeds a certain threshold, the feature is deemed to be polarized, and is rejected as an open portal. False positives and false negatives are possible. A false negative can occur if a window reflects light from a dark surface, which makes it difficult to detect if the reflected light is polarized. A false positive can occur if the interior of an open portal generates polarized light. This does not occur often, given that most light sources are unpolarized (sunlight, incandescent light, fluorescent light, LEDs), and given that most internal surfaces are diffuse reflectors, which also generate unpolarized light.

[4.a.2.2] Threat Avoidance

Stealth is our primary approach towards threat avoidance. The UAV primary vehicle is powered by an electric motor with a gear reduction unit. Gear reduction allows us to use a large, slow-moving propeller that minimizes acoustic noise. Altitude is restricted to above-rooftop-level for the UAV, which also increases stealth.

The drop vehicle is unpowered and flies at relatively low speed, which allows silent entry. The approach path is steep in order to minimize flight time and to reduce likelihood of collisions with adjacent buildings, or with difficult-to-detect powerlines.

[4.b] COMMUNICATIONS

For safety reasons, and to allow hand-launch takeoffs and make flight testing easier in general, the total weight of the primary air vehicle is limited. 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 autopilot on the UAV and drop vehicle, and will 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. 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

The main power supply is the power to the motor. This consists of a 26 volt lithium polymer (LiPo) battery pack. This will provide the UAV with enough power for a 30 minute flight at cruise speed. A separate 6 V NiMH battery operates servos for the control surfaces. An additional 11 V LiPo battery operates all other avionics on the UAV.

Meanwhile, the drop vehicle has a separate 6 V NiMH battery to power its flight control servos, plus an 11 V LiPo battery for all other avionics. The drop vehicle has no propulsion system of its own.

[4.d] SUBVEHICLE

The primary UAV carries a drop vehicle (below) that is used to enter an open portal in the target building.

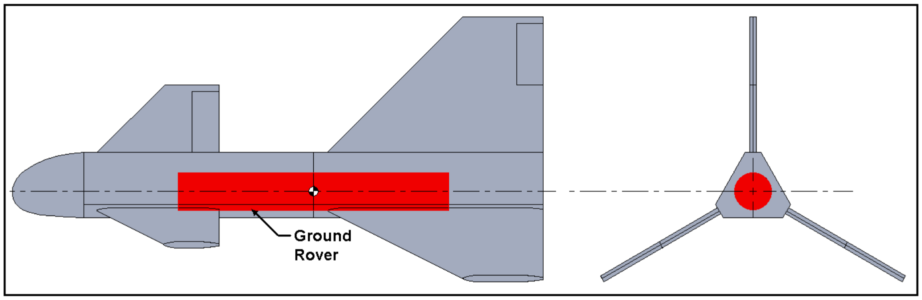

Figure 4. Drop vehicle

The following 4 paragraphs are adapted, with slight changes, from reference [6]. The paragraphs were originally written by one of us (Manning):

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. Aerodynamic surfaces (wings and canards) use low aspect ratio delta wing planforms for the following reasons:

- High maximum lift coefficient
- Light weight
- Structural simplicity.
- Overall wedge shape makes portal entry easier
- Low lift curve slope ($\delta C_l / \delta\alpha$) reduces sensitivity to wind gusts

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 lightweight three-axis rate gyroscope to control angular rates. Just before release from the carrier UAV, the drop vehicle receives an attitude update from the UAV through an umbilical. After release, an onboard flight computer integrates data from the rate gyros to keep track of attitude. Determining attitude solely by integrating rate gyros results in a relatively high drift rate. The drift rate is acceptable because the flight time is very short -- on the order of a few seconds. 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.

Navigation is a four-step process that relies on internal gyro data, as well as video data transmitted to the ground station from a camera on the drop vehicle. (1) A three axis gyro is used initially to point the drop vehicle in the approximate direction of the portal target. (2) Once the drop vehicle is on its intended heading, video data from an on-board camera is received by a ground-based computer, and a machine vision system uses a template-matching algorithm to search for the target building. (3) Once the building is found, the vision system searches for the portal target. (4) When the vision system locks on to the portal, it is tracked in real time and the drop vehicle is steered to the portal. After the imaging system locks on to the target, pitch and yaw are controlled externally, by the drop vehicle ground controller. The roll angle is controlled internally such that the wings are kept level. Note that all three axes of the rate gyro must be integrated in order to keep the wings level.

[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. For example, at the 2004 competition, one the authors (who was a member of another team at the time) (and who as a *licensed pilot* should have known better) (you know who you are) failed to plug in a laptop computer that was responsible for machine vision processing. The laptop's internal batteries ran out in the middle of an attempt. This failure could have been prevented by using a checklist.

The following checklist is intended for future flight operations:

```
Flight Prep (To be done well before flight)
   Assemble UAV
   Check center of mass
   All outer surfaces flush with one another
   Place all electrical components to their intended positions
       Make sure all batteries are charged to full capacity
   Look at wing:
       Check for cracks or fractures
       Tape all exposed joints
       Check for air leaks
           Connect the servos to the control surfaces
       Upper body
           Assemble upper body
               Cover all internal components
           Tape the pieces down firmly
               Leave access to the avionics for final connections
       Motor
           Check motor mount
           Check battery mount
           Verify motor batteries disconnected
           Mount the propeller
   Second Flight Check (to be done before preceding flight is completed)
       Check electrical connections and mounts
           Batteries, avionics, autopilot, computer
       Check battery charge
       Turn on all systems
           Check avionics are working
           Check communication between UAV and ground station
           Motor
               Make sure the propeller is on in the right direction
               Mounts securely fastened
           Drop Vehicle
               All communications ready
               Check all avionics
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        Check deployment mechanism, test for a clean launch
    Turn all systems off until just before flight
Final Flight Check
    All systems on and ready
        All communications with ground station are working properly
        All communications with avionics working properly
        All control surfaces working properly
        Set takeoff trim
        See that all systems securely fastened
        Check center of gravity
    Securely fasten all remaining service panels
    Check the body for any exposed openings, fasten down openings
    Uplink initial data
    Secure the drop vehicle to primary vehicle
Launch
```

[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.

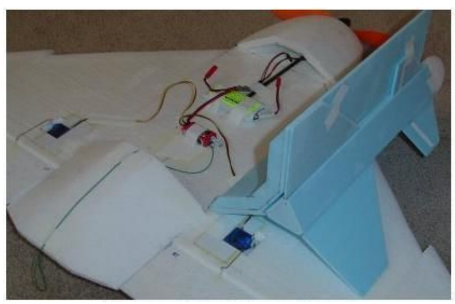

Figure 5. Subscale model of fuselage hatch

[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 -- Arizona's experience with blurred camera images at the 2004 competition is a major reason for our adopting electric power. During the competition the prevailing opinion was that image blur was due to a focussing problem, but it was later discovered to be vibration rather than a focussing issue.

Landing shock loads are reduced by a skid partially made of polypropylene foam. 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 separate power supplies on for airborne electronic components. The main propulsion battery in particular is entirely separate from other power supplies in order to minimize EMI generated by the high-current motor as well as brushless motor controller.

[6.b] SAFETY

The primary 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. The UAV's wing loading is expected to be no greater than 4.3 kg/m^2 (14 oz/ft^2). 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

The primary UAV was initially tested as a 41 percent scale model. The UAV actually started out as a modification of an existing slowflyer design. This approach allowed us to start flight testing very early, back in September 2004. Both primary and drop vehicles have undergone subscale flight testing in parallel with full scale testing.

The full scale UAV is light enough and has a low enough wing loading to allow hand launch takeoffs. In addition, we were able to do initial glide tests in parking lots, both with and without an operating flight control system.

A wing bending test was done to verify the wing bending strength. Water ballast was used to apply the bending loads:

Figure 6. Wing bending test

[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 primary UAV with a 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 injects 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.

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