Development of an Autonomous Aerial Reconnaissance System

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ABSTRACT

In preparation for the 2003 International Aerial Robotics Competition (IARC) the Aerial Robotics Club (ARC) at the University of Arizona has designed an autonomous aerial robot. This years aerial system consists of a small-scale airplane with an on-board guidance navigation control system and a ground station of networked computers for mission planning, user interface, and vision related computations. This document summarizes the IARC mission requirements, team objectives, and overall system design including guidance, navigation and control, computer vision and risk reduction strategies.

INTRODUCTION

Background

The IARC is an annual, international event organized by the Association for Unmanned Vehicle Systems designed to promote research and development of aerial robotic systems. The Aerial Robotics Club (ARC) at the University of Arizona has designed an aerial system to attempt the first two sub-missions of the IARC. The first of the required sub-missions is to demonstrate three kilometers of autonomous flight given a set of Global Positioning System (GPS) waypoints. The second sub-mission requires the aerial robot to use machine or computer vision techniques to identify a marked structure from a group of structures. Once the target structure is recognized the points of entry, including windows and doors, must be identified. The last (third sub-mission) requires the main vehicle or a sub-vehicle to enter the target structure through an opening and relay images to the ground control station for analysis of the interior by the competition judges[1].

Each of the mission requirements creates difficulties in design. For the first qualification, a platform with ease of stability and control would aid in the completion of the 3km course. While the use of an airplane meets the demands set for the first qualification, the flight capabilities of such a vehicle pose limitations during the second qualification when target identification via machine vision is needed. For the second qualification mission, a helicopter would provide an ideal platform for a computer vision system by surveying an area of interest for long periods of time while in hover. Finally, flight capabilities of a helicopter offer a more efficient way of successfully navigating a vehicle or sub-vehicle through an open portal. Alternatively, if an airplane was used for this mission, some sort of high-altitude-high-precision deployment system would be required, further complicating the system.

Competitive Strategy

The ARC has developed a multi-year strategy to use the capabilities of three aerial platforms to complete the challenging IARC missions. With the resources of a multidisciplinary group of undergraduate and graduate students from Aerospace and Mechanical Engineering, Electrical and Computer Engineering, Computer Science and Optical Science, the ARC has integrated an airplane, helicopter, and Vertical-Take-Off and Landing (VTOL) vehicle into a reconnaissance arsenal.

Fixed Wing

The Eagle2, a small-scale airplane, is the primary vehicle used to complete level 1 and level 2 of the IARC. This platform offers reliability, stability and affordability; all of which are key factors in selecting the first platform for the autonomous system. Using a kit plane also allows more time to be spent developing system components instead of concentrating on platform maintenance or repairs. Combined with a commercially available autopilot, the Eagle2 provides a flexible platform for completing the 3km ingress as well as for initial testing of aerial surveillance techniques needed for mission 2 of the IARC. As discussed in more detail in subsequent paragraphs, the Eagle2 payload will be altered to include a network camera and Ethernet transmitter during IARC mission 2 attempts.

Figure 1. Eagle2 fixed wing vehicle used for 3km, GPS waypoint navigation as well as the target identification and portal detection mission.

Helicopter

In future years, a small-scaled helicopter known as the Bergen Industrial Twin will be used to perfect computer vision techniques and a sub-vehicle deployment system. The autopilot designed to control the Bergen and similar sized helicopters is currently under development and is expected to perform in the 2004 and 2005 aerial robotics competitions.

VTOL

In addition to the fixed wing trainer and the helicopter, the ARC is developing a Vertical-take-off and Landing vehicle in order to complete mission 4 of the IARC. The VTOL combines the abilities of both the airplane and helicopter by utilizing a shrouded, rotating nacelle. When rotated in the horizontal position, the VTOL flies with the efficiency and stability of a fixed wing aircraft. With the activation of a worm gear system, the nacelle is rotated vertically to provide hover and slow moving, forward flight abilities. The VTOL's long, slender nose cone is designed to house the guidance, navigation and control computer, vision capture and transmission system, and also accommodates the sub-vehicle and sub-vehicle deployment system. To help balance the vehicle during the course of a long mission, the fuel tanks are located at the center of gravity in the booms on each side of the rotating nacelle. A wind tunnel model has been developed and is aiding in the study of nacelle rotation aerodynamics and stability and control research. While the VTOL offers a great deal of characteristics ideally suited for completion of the IARC final mission, the design may not be perfected in time for participation in the 2000 - 2004 competition schedule. With this in mind, the design of this particular VTOL has focused on the use of modular components such as different nose cones and camera mounts. In addition, multiple versions of vehicles with vertical take-off capabilities have been designed so that the concept can be utilized for a variety of missions.

Figure 2. Computer generated representation of the Vertical Take-Off and Landing (VTOL) vehicle currently under development for missions 3 and 4 of the IARC.

System Overview

The 2003 aerial robotics system has two forms, one for the 3km, GPS waypoint navigation, and a second to incorporated image capturing and computer vision for the IARC logo and portal identification mission. For the first mission, the Eagle2 is preprogrammed through the user interface to follow a GPS waypoint course. During flight, telemetry data is transmitted via radio modem to a user interface laptop running windows. However, for the second mission, the Eagle2 is also equipped with an Axis 2110 network camera mounted to a stabilizing platform, a BreezeNet SA-10D Ethernet transmitter, and a pair of mini patch antennas. After the back-up pilot performs a manual takeoff and the Eagle2 has reached the designated starting position for mission 2, the autopilot will guide the plane through a series of raster scans over the building area. During this time, video will be transmitted to the Vision base station for processing. The following hardware diagram describes the components used for the first and second missions of the IARC. Note that not all equipment is utilized during each mission.

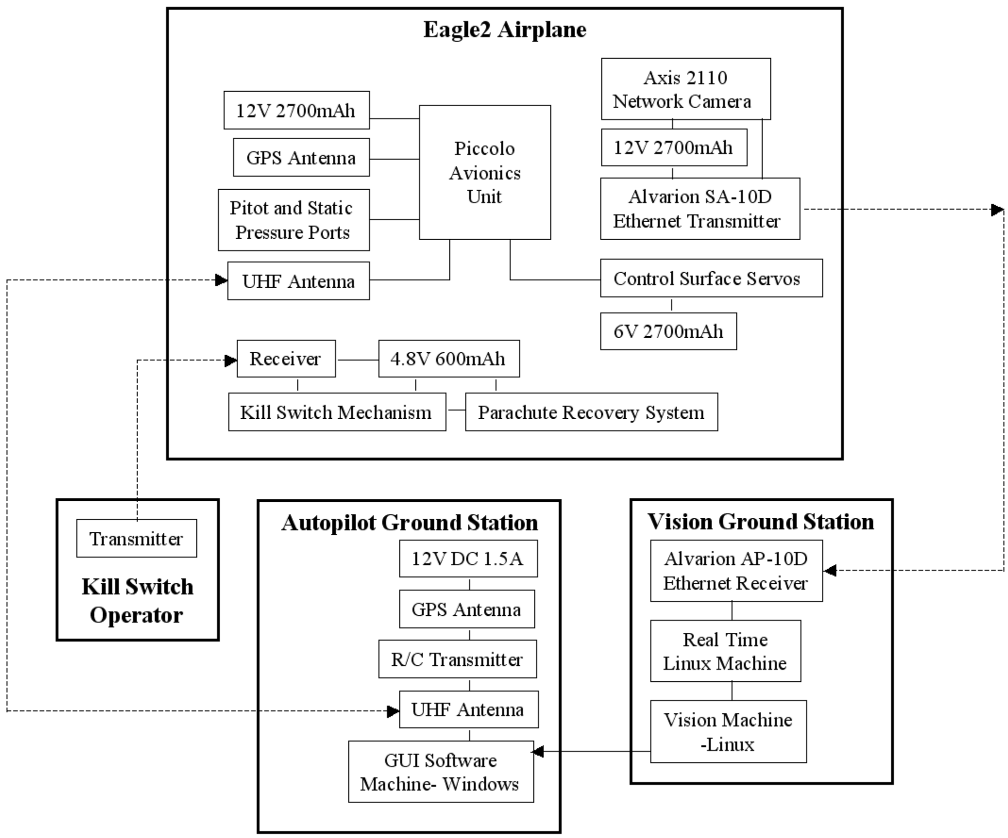


Figure 3. System Hardware Diagram

NAVIGATION AND CONTROL

To meet the requirements of the first and second IARC missions we utilize a Cloud Cap Technology Piccolo autopilot. This commercially available autopilot system is designed for small-scale Unmanned Aerial Vehicles (UAVs). The Piccolo utilizes a MPC555 micro controller, Motorola M12 GPS, MicroHard MHX 910/2400 radio modem, 3 Tokin CG-16D rate gyros, 3 Analog Devices ADXL202 accelerometers, duel ported mpxv50045 4kPa dynamic pressure sensor, absolute ported mpx4115a barometric pressure sensor, and an air temperature sensor. Unlike some autopilot designs, the single data-link is used for command and control, telemetry, and even handles commands from the pilot in the loop instead of using a standard R/C receiver onboard the plane[2].

SOFTWARE INFRASTRUCTURE

The communication between the different software modules is achieved as follows. During the second mission the Piccolo autopilot continuously sends Eagle2 telemetry data to the GUI software on the ground station laptop machine. Part of this data is then sent through ethernet connection to a designated Real-Time Linux machine. While the Piccolo is transmitting telemetry data, the network camera is continuously sending images to the Real-Time Linux machine. The Telemetry / Image Coupler module links each image with GPS coordinates and other telemetry information from the plane corresponding to the time the particular image was taken. Each image is then given the name of the corresponding custom telemetry packet, the name is stored in a mySQL database, and the image itself is sent to a flat file system database to the second Linux machine that will be accessed by the Vision System. The Database and File System module consists of a mySQL Server that stores the custom telemetry data and the corresponding image information. This is a persistent unit independent of the state of the flying vehicle, capable of resuming operation after a possible halt of another module. The Vision System continuously polls the database for new images to analyze with the IARC Symbol Recognition and Building and Window Detection algorithms. Figure 4 presents an overview of the system software.

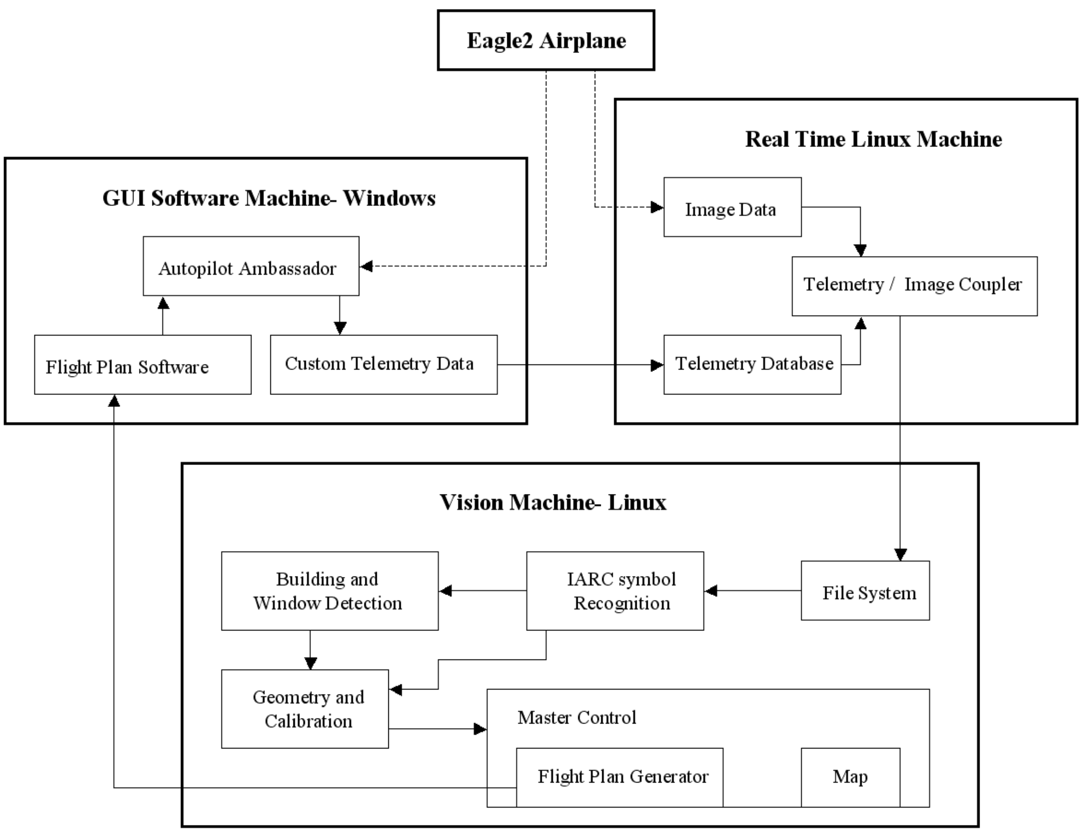


Figure 4. System Software Diagram

Vision System / Algorithms

Two main modules comprise the backbone of the vision system. One is the IARC symbol recognizer and the other is a building / window detector. The IARC symbol recognizer can be viewed as a module that localizes that region in an input image at which there is the highest probability of the IARC symbol being present. It also assigns to the image, the value of this probability. Similarly the building detector assigns to each image a probability of finding building(s) within that image. It also localizes the relative positions of the building(s) within the image. Due to the intensive computation involved in the symbol and building detection algorithms, only those images that are most likely to contain desired objects are filtered through, using strategies that require relatively lesser computation. Using the information from these two modules, the final decision as to the presence/absence of the IARC symbol in an image is made. The algorithmic flow details of the vision system are as follows.

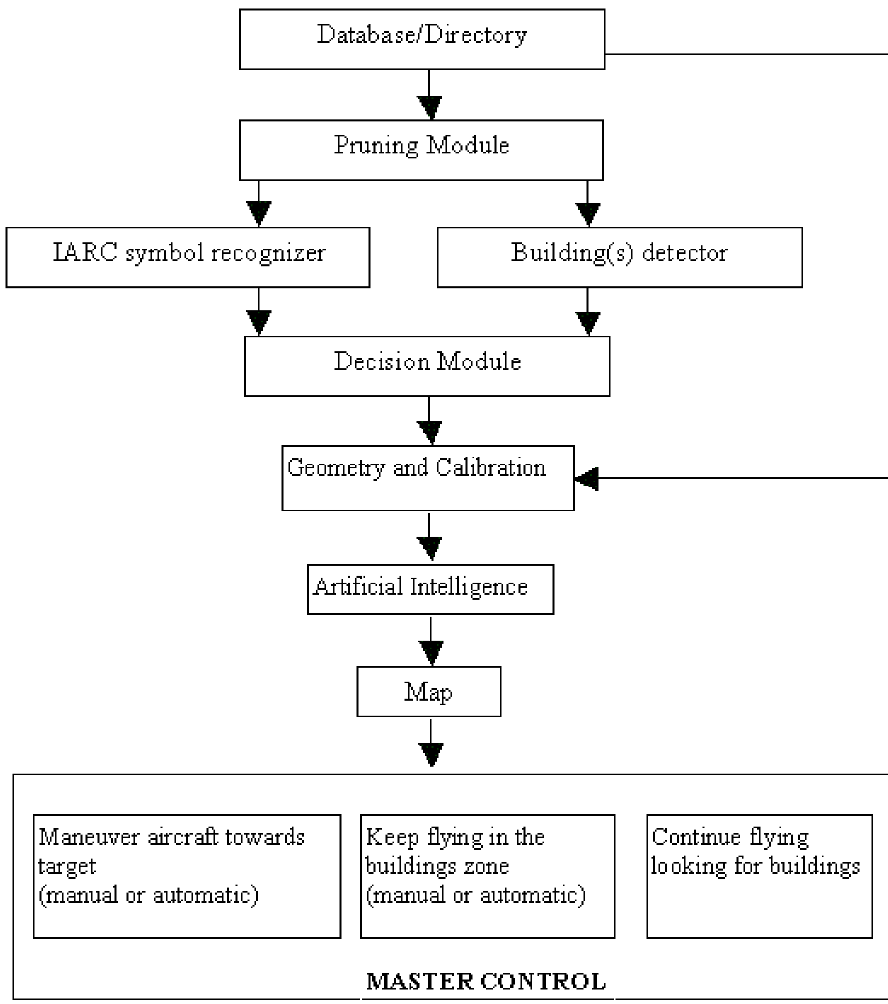


Figure 5.Vision Flow diagram

IARC Symbol Recognizer

The symbol recognition module is a pruning based template matcher. The template to be matched is the circular portion of the IARC symbol with different scales, rotations and viewing angles. Template matching is performed using the normalized correlation similarity measure. Correlation is not performed in the image domain. Instead, both the image and the template to be matched are converted into their edge maps using a homogeneity operator that detects edges at all orientations.

Figure 6. An example of the template at one scale, orientation and viewing angle and its corresponding edge map obtained using the homogeneity operator

All windows in the input image that are the same size as that of the template are considered. A pruning step eliminates most of these windows by applying simple heuristics based on the structure of the edge map of IARC symbol. Only the remaining windows are considered for correlation. The image window with the highest correlation value, with the correlation step iterated over all the templates, is the most probable location of the symbol in the image. The window location, size and the normalized correlation value are output by the recognition module.

Building / Window Detector

The building detector also works on the edge map of the input image. The detector starts by localizing straight lines in the edge map using a Hough transform for straight-line detection. In an edge map, buildings are mostly characterized by straight edges bounding the walls, windows and roof areas. Hence, presence of a large number of convex hulls formed by straight lines is an indicator to the existence of building(s) in an image. This cue is then used by the building detector to output the probability of an image containing building like structures.

The probabilities from the symbol recognizer and the building detector modules are combined to decide whether a candidate image contains the symbol or not. Then the image that contains the IARC symbol is fed to the geometry and calibration module to determine its location in real-world spatial coordinates. After using various calibrating techniques, the locations of the symbol and the possible locations of the buildings and windows are combined to generate an approximate map of the area under study. The purposes of this map include having a visual representation of the location of the symbol, the buildings, and the windows as well as to provide information to a master control unit.

Vision Hardware

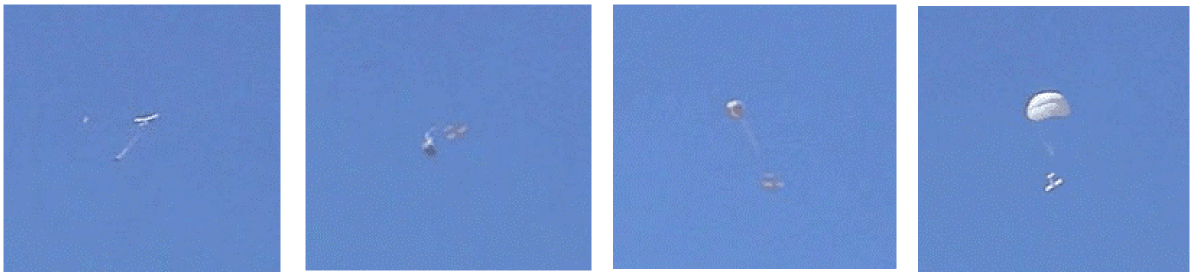
The Vision Hardware System consists of a Vision Machine - Twin 2.4 GhZ Xeon processors with 2 G of RAM, 4 IDE disks, two of which are in RAID configuration, running RedHat 8.0 ; and an AXIS 2120 24-bit color Network Digital Camera with resolution of 704x576, with rate of 25 frames/s in PAL mode.

RISK REDUCTION

Choosing an airplane as the primary vehicle instead of a helicopter considerably decreases the possibility of personal injury and hardware loss during operation of the aerial system. The large, spinning helicopter rotor presents a safety hazard to operators, more so than the small propeller of an airplane. Helicopter replacement parts are expensive and less readily available than those for airplanes. For these reasons and others we have focused our research on fixed-wing platforms. In addition to the use of a fixed-wing platform, the Piccolo autopilot has a number of fail-safes that are set prior to operation instructing the autopilot to perform a certain task when communication or GPS signal is lost for an extended period of time.

In order to better ensure spectator safety and meet all IARC requirements, an independently operated and independently powered "kill-switch" was designed in the event of disastrous system failure. A servo mounted near the Eagle2 engine acts as a fuel line termination mechanism when activated by the gear switch on a second remote control transmitter. This servo is powered by a separate battery pack and obtains signal from a receiver mounted inside the fuselage. Note that this receiver is not used for pilot in the loop commands to the Piccolo, but is designated for kill-switch operation alone.

Unlike our previous experiences with the Bergen Industrial Twin helicopter, that is rendered completely useless when the termination device is activated, the Eagle2 airplane is still capable of traveling a large distance after the independently operated transmitter activates the "kill switch." For this reason we have also designed a parachute recovery system to complement the original fuel line termination mechanism. When activated, the parachute system provides 100% recoverability of system hardware and guarantees safety of all spectators. A 16-foot diameter, spherical parachute is mounted inside a protective shell underneath the Eagle2. When the kill switch is activated with the gear switch on the second transmitter the engine fuel line is cut off with the twist of a servo arm. A few seconds later, a servo-operated pin that holds the protective shell casing to the body of the Eagle2 is released. After the casing is jettisoned, the parachute drops from the bottom of the plane, and a braided shock cord dampens the force as the plane slowly descends to the ground.



A) B) C) D)

Figure 5. Parachute recovery system in action.
A) Parachute system deploys and plane pitches up. B) Plane begins to descend, curling over parachute and chute begins to inflate. C) Shock cord elongates and chute inflation continues. D) Inflation complete and plane slowly drifts to the ground.

SUB-VEHICLE

The sub-vehicle needed for levels 3 and 4 of the competition is under development but is not the primary focus of our current research. The design is based on a ground rover approach. Both tread-based and wheeled chassis designs are utilized with a preprogrammed BasicX board for navigation and camera operation.

CONCLUSION

This paper has introduced the major components of the autonomous aerial reconnaissance system designed by the Aerial Robotics Club at the University of Arizona. The assortment of aerial platforms under development provides the ARC with payload options and flight capabilities to fit current and future IARC mission requirements. Utilization of an off-the-shelf autopilot facilitates understanding of guidance, navigation and control (GNC) techniques aiding in future development. Additionally, the current platform and GNC approach has allowed computer vision concerns to be addressed concurrently. As a result, the current setup possesses all components necessary for a successful, autonomous aerial reconnaissance system.

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