Ongoing Development of an Autonomous Aerial Reconnaissance System at Georgia Tech

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ABSTRACT

The Georgia Tech aerial robotics team has developed a system to compete in the International Aerial Robotics Competition, organized by the Association for Unmanned Vehicle Systems, International. The team is a multi-disciplinary group of students who have developed a multi-year strategy to complete all levels and the overall mission. The approach taken to achieve the objectives of the required missions has evolved to incorporate new ideas and lessons learned. This document summarizes the approach taken, the current status of the project, and the design of the components and subsystems.

INTRODUCTION

This paper describes Georgia Tech's entry to the 2003 Aerial Robotics Competition. The teams past accomplishments in the context of the current mission scenario include successful completion of the Level 1 requirements (Way Point Navigation) using a fixed wing aircraft in the year 2001. In 2002, the primary vehicle was changed to Georgia Tech UAVLab's GTMax rotorcraft, and in 2003, the GTMax successfully completed the level 2 requirements. The GTMax continues to provide the team with a robust autonomous flight platform capable of way point navigation, precision hover, high-speed flight and auto takeoff and landing. For the 2004 entry, the GTMax has both hardware and software improvements and two new vehicles have been added to the system, an autonomous ground vehicle, GTRover, and an autonomous ducted fan, GTSpy. The GTRover is capable of maneuvering in unknown terrain and relaying video back to the ground station, and the GTSpy is capable of high precision flight. These developments and additions will allow the team to complete level 3 and reliably incorporate the level 2 behavior in an attempt at the completing the entire mission.

SYSTEM OVERVIEW

The overall reconnaissance system consists of 5 major components:

1. The GTMax helicopter from the Georgia Tech UAVLab
2. The GTRover ground vehicle from the Georgia Tech UAVLab
3. The GTSpy ducted fan from the Georgia Tech UAVLab
4. The Image Processing and Object Tracking Subsystems
5. Mission Planning and Trajectory Generation subsystem

The attempt at level 3 will be made using the GTRover . The rover is equipped with infra-red sensors for mapping unknown terrain and a wireless video link for transmitting images back to the Ground Control Station (GCS). The attempt will be made using the ground based launch mechanism. The GTRover will be launched into a window inside of a self-righting canister, after which it will make it's way through the building transmitting video of the interior walls.

Upon successful completion of level three an attempt will be made to complete level four. Completing level 4 will require coordinated movement among all of the vehicles. The GTMax will act as the primary vehicle, and will carrying the GTSpyThe GTMax will navigate the 3 km ingress, locate the correct building, and choose a satisfactory opening. Once an entrance has been located, the GTSpy will be deployed and begin a descent towards the window. Upon reaching the window the GTSpy will enter the building and begin transmitting imagery back to the GCS, and the final phase of the mission will begin. At the time this paper was written, the exact configuration of vehicles to enter the building had not been determined. The entire approach is outline in Figure 1.

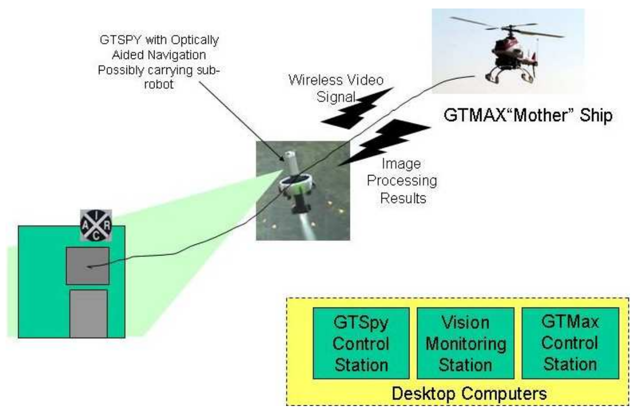


Figure. 1. Approach for completing level 4

A diagram showing the interaction between the different components onboard the GTMax is shown in Figure 2. The GTMax helicopter is the primary air vehicle and is used during all parts of the mission. It is capable of full autonomous flight and may be commanded using waypoints. The GTMax carries two computers in addition to inertial and other sensors. The primary flight computer (PFC) runs the guidance, navigation and control algorithms. The waypoints maybe uploaded to the PFC over the network from a GCS or from any other computer on the network. The secondary flight computer (SFC) is normally used at the UAVLab to fly experimental flight control algorithms. For the aerial robotics mission, the SFC will run the image processing and object tracking routines, and provide image processing to the GTSpy for optically aided navigation. In addition, the GTMax will provide a relay for the wireless video from the GTRover. Since coordination between several vehicles is required, the mission planning routines are located in a centralized location on the ground and commands are relayed to the appropriate vehicle via the wireless network. Hence, once activated the entire system is autonomous with onboard processing for all aspects of the mission, and a centralized command center for the mission planning. Then the ground control station (GCS) can be used to view the progress of the mission and monitor telemetry.

The primary interface to the system is via the GCS computers. Each vehicle has a dedicated notebook computer running OpenGL based visualization and telemetry software. The GCS is also used for all vehicle modelling, simulation, controller development and hardware in the loop testing[2].

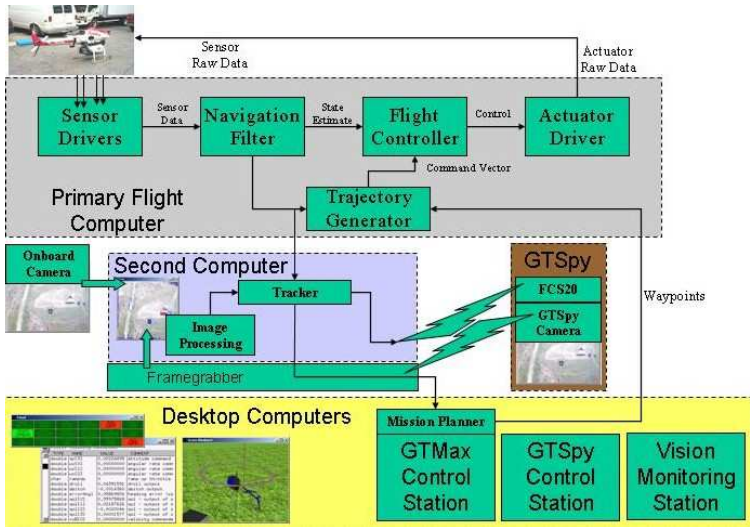


Figure. 2. System Overview

The GTMax is equipped with a pan-tilt network camera with zoom that can provide images to the SFC at 4Hz. There are, also, analog cameras and video transmitters onboard both the GTSpy and GTRover. These video signals are received onboard the GTMax and either relayed to the ground or feed into a framegrabber attached to the SFC for image processing.

SAFETY

Each of the aerial vehicles involved in this mission have multiple features that provide various levels of safety. A few of those are discussed here.

- During any point in the mission the operator at the GCS may press a *Trajectory Stop* button which puts the vehicle immediately into hover. The mission may be resumed from this point without having to restart.
- At any point in the mission the safety pilot may take over manual control of the vehicle.
- A novel safety feature is the ability of the GCS operator to take over direct control of the vehicle and fly it using a joystick or mouse. This feature is critical in situations when the pilots radio link has failed. This feature is implemented through the wireless modem link which generally has a higher range of operation than the pilots radio.
- The final safety feature is the Kill Switch as required by the competition rules.

GTMAX

The primary air vehicle is based on a Yamaha R-Max helicopter, shown in Figure 3. The GTMax helicopter weighs about 128 lbs (empty) and has a main rotor radius of 5.05ft. Nominal rotor speed is 700 revolutions per minute. Its practical payload capability is about 66 lbs with flight endurance of greater than 60 minutes.

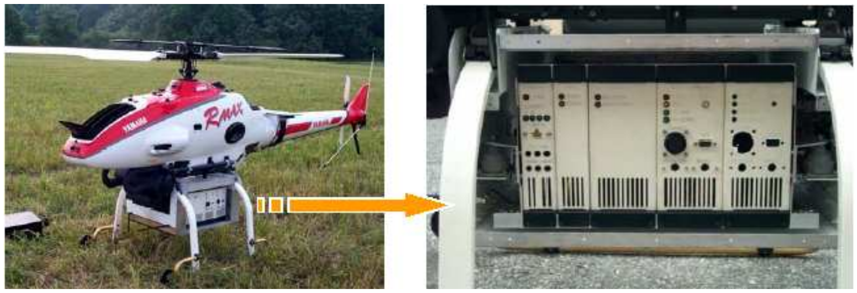


Figure. 3. GTMax Airframe and Avionics Box

AVIONICS

Figure 3 shows the airframe and associated avionics box. The avionics bay is modular and hosts sensors and computing hardware including,

- Flight Computer - *Embedded 233 MHz Pentium PC-104 SBC, 8 RS-232 ports, Ethernet, Flash Drive*
- Sensors - *Inertial Measurement Unit, Novatel D-GPS, Magnetometer, Sonar Altimeter, Vehicle Telemetry (RPM, Voltage, Pilot Inputs)*
- Data Links - *11 Mbps Ethernet Data Link,RS-232 Serial Data Link*
- Mission Payload - *Embedded 833 MHz Pentium 4 PC-104 SBC with Sensoray 311 Framegrabber, Axis Video Server, Axis Web Camera, and Analog camera*

The main avionics rack is shock mounted onto the helicopter. Each module has self-contained power regulation and EMI shielding. The overall architecture of the primary air vehicle avionics is shown in Figure 4. A particular advantage of this platform is that it is equipped with an onboard generator, which can provide for all power requirements onboard. Thus, the flight endurance of the helicopter is only limited by the amount of onboard fuel the vehicle can carry.

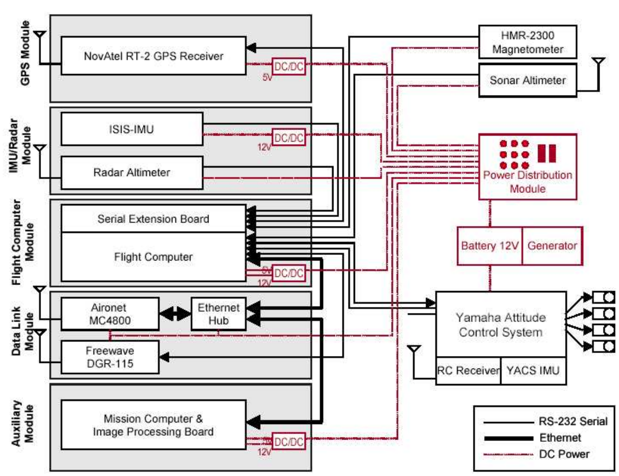
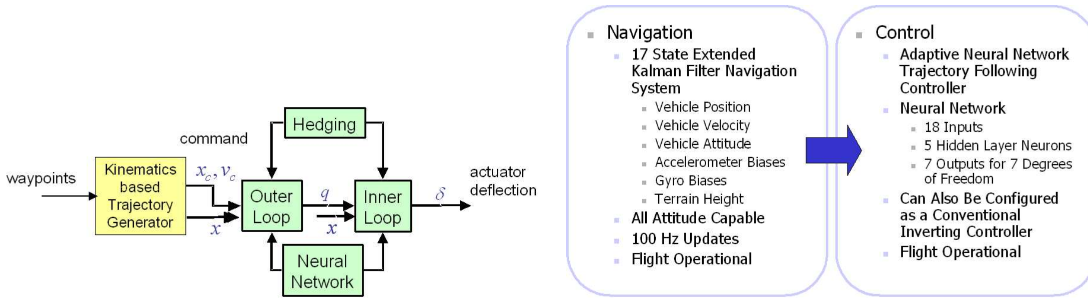


Figure. 4. GTMax Schematic of Avionics Box

GUIDANCE, NAVIGATION AND CONTROL

A summary of the Navigation and Control architecture is illustrated in Figure 5-a.



(a) **(b)**

Figure. 5. Control and Navigation Architecture

Trajectory Generator

Commands to the helicopter take the form of different types of waypoints. All trajectories generated are assumed to be physically feasible by the helicopter. The kinematic model used for trajectory generation uses specifiable limits on the maximum speed and acceleration the aircraft may have during a maneuver. The various kinds of maneuvers are summarized below.

- CUT - takes three waypoints and generates a position and velocity profile that includes a turn to go from waypoint 1 to waypoint 3. The trajectory does not pass through waypoint 2.
- THRU - the trajectory will pass through the given waypoint without stopping
- STOPAT - the trajectory will end at the waypoint and bring the speed of the helicopter to 0.
- LAND - the trajectory will end at the given north, east position with commanded altitude being 0. This includes a slow descent until landing

The flight controller takes smooth bounded position, velocity and attitude commands (heading)as inputs; details of the controller may be found in [1]. The navigation functions are performed at 100Hz and are based on the update rate of the IMU, which is used to trigger navigation and control calculations on the PFC. The interaction between the navigation and control modules is shown in Figure 5-b.

Navigation and Control

All sensor output is collected via serial connection. This required adding a serial port expansion card (RS-232), resulting in a total of 8 serial ports on the PFC. The actuator commands are sent to the helicopter via an RS-232 interface, which forms the primary interface to the physical vehicle. The navigation system consists of a 17 State Kalman filter that outputs a consolidated state vector of the vehicle to memory. This is then used by the flight controller for control calculations.

The flight controller consists of an outerloop and an innerloop. The innerloop performs attitude tracking and generates the required actuator deflections. The outerloop is used to generate the attitude quaternion 'q', required to follow a commanded translational trajectory given by denoting desired position and velocity. The controllers themselves are based on feedback linearization through dynamic inversion of a linear model of the helicopter in hover. The state feedback is denoted by 'x'. The Neural Network is used to correct for any inaccuracies in the dynamic inversion. It is through adaptation in the neural network that the problem of flight control at different flight conditions (such as high speed flight) is addressed. Finally, the hedging block is used to protect the neural network from actuator saturation or other known nonlinearities to which we do not want adaptation to occur. However, due to significant time-delay the bandwidth of the closed loop system is limited. Time delay is handled using an integrated Smith predictor, which is described in [3], and has allowed an increase of position tracking bandwidth up to 2.5 rad/s.

GTSPY

The GTSpy is the small ducted fan shown in Figure 6. This vehicle is a relatively new addition to the UAVLab fleet. The shroud is 11 inches in diameter, and without avionics it weighs 5lbs. It has a payload capacity of 1 lb which is reduced to about 4 oz with the fuel and avionics onboard. The fuel capacity limits the maximum flight time to about 10 minutes.

Figure. 6. GTSpy

FCS20 FLIGHT CONTROL SYSTEM

Due to the limited payload capacity of the GTSpy, it is equipped with an FCS20 as the primary flight control computer. The FCS20 was developed as a part of ongoing research activities at the Georgia Institute of Technology's UAV Research Lab. The FCS20 is a small Integrated Adaptive Flight Control System, which uses FPGA/DSP technology coupled with a small sensor array to satisfy the requirements necessary for advanced vehicle behavior, while satisfying strict size, weight and power constraints.

The FCS20 uses a Texas Instruments C6713 DSP for most of the data processing as well as sensor data handling. It interfaces with an Field Programmable Gate Array (FPGA) via a 32-bit, high-speed data bus. The FPGA handles all input/output operations to and from the sensors as well as all communication with the outside world. Furthermore, it feeds a FIFO queue with data for processing by the DSP. The board support package, the FPGA image, and the flight controller application are all held in Flash memory.

The sensor board hosts accelerometers and rate gyros for all three axes, absolute and differential air pressure sensors, a magnetometer, and a GPS receiver. Most of the sensors are located directly within reach of the DSP and FPGA; therefore, there is no need for expensive serial communication to and from the sensors. A picture of the unit is displayed in Figure 7.

Figure. 7. FCS20 custom flight computer

The GTSpy also has a dedicated Freewave wireless serial datalink, an analog camera, and an analog video transmitter.

GUIDANCE, NAVIGATION AND CONTROL

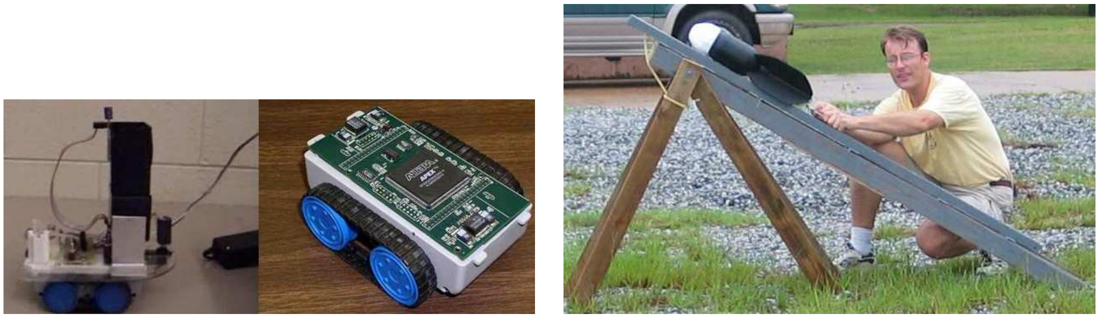
The GTSpy uses the same flight control software which runs onboard the GTMax, which was described in the GTMax section. Accordingly, it has the same ability to follow waypoints and execute other pre-programmed maneuvers. The GTSpy has an independent GCS, and a dedicated datalink between the GCS and the vehicle. This ensures the GCS operator can take over control of the vehicle at any point in the mission.

The standard navigation sensors and capabilities onboard both the GTSpy and GTMax have been enhanced to include navigation using vision. Details of the image processing algorithms can be found in [4]. Since it is necessary for the GTSpy to fly between buildings and indoors during this mission, a strong GPS signal will probably not be available. To combat drift in the navigation solution, position updates based on vision are used. It is not currently possible to connect a camera directly to the FCS20; therefore, it is necessary to do the image processing off-board. The present configuration transmits the video signal to the SFC on the GTMax for all image processing and then the results are relayed back to the GTSpy as inputs to the navigation filter running on the FCS20.

GTROVER

The GTRover shown in Figure 8-a, is a fully autonomous reconnaissance robot designed to be launched into an unfamiliar area and comprehensively explore the environment while communicating intelligence in real-time to a ground control station (GCS). The robot design consists of a small robust frame connected to drive motors, tank-tread wheels, a mechanical lifting arm, SONAR, two infrared sensors, on-board video camera, and a powerful custom built microcontroller which operates each device to execute its high level objectives. It is designed to be launched using the capsule shown in Figure 8-b

The GTRover interfaces with the GCS using a wireless datalink. It continuously provides navigational data to the graphical interface shown in Figure 9, allowing the operator to monitor the vehicles progress. In addition to this information, the video footage from the GTRover will be displayed on a separate screen.



(a) **(b)**

Figure. 8. GTRoverand with the launching mechanism

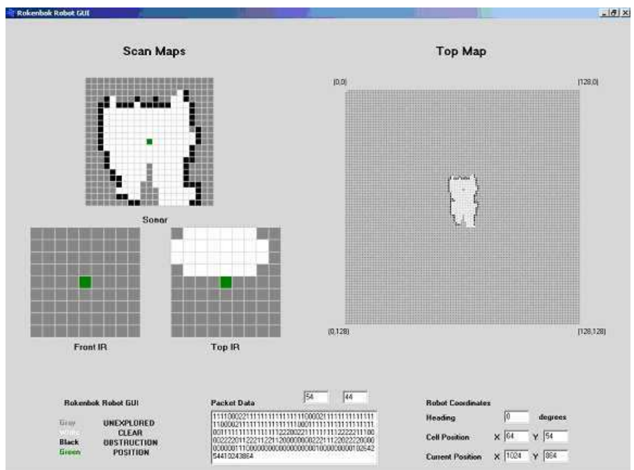


Figure. 9. Graphical User Interface for the GTRover

SCANNING AND MAPPING

The GTRover employs a variety of proximity sensors to gather information about its environment, which are positioned at different heights on the robot's frame. The top arrangement of devices consists of sonar and an infrared sensor that collect long and short-range proximity measurements at a high altitude. These sensors rest on a turret with 360° of motion; this allows data to be collected in any direction around the robot. The lower system consists of one infrared sensor resting upon a servo, which provides 140° of motion. This sensor is used to obtain short-range measurements in front of the robot. Proximity distance measurements are coupled with their respective degree location; then the data is reduced and mathematically fitted to a map containing 128X128 cells, each cell representing an area of 256 square inches of the surrounding environment.

Scan maps for each individual sensor are created based on the range of the sensor and the data that it provides. Based on the results of the scan each cell in the scan map is labelled as *obstructed*, *open* (no obstruction), or *unexplored*. The information within each scan map is then input into the main mapping system based the current position of the robot. To account for errors in the scan maps and changes within the environment, the main mapping system uses the scan data to increases or decreases the confidence level of a particular map cell. Then once the confidence levels of a cell move above or below a particular threshold, the status of that cell will change.

Errors in the mapping that remain unchecked prior to a drive sequence are handled by the low altitude proximity sensor system. If the robot suddenly approaches an object that is higher than the wheel base, the lower infrared sensor will trigger an emergency brake, and perform a quick horizon scan of 64 inches. Then the new information will be re-mapped, and an updated drive sequence will be calculated. After each mapping update, the robot calculates an *unexplored* or *openness* score for each cell within the map, therefore describing the amount of open or unexplored cells around each point in its memory.

EXPLORATION AND NAVIGATION

Once the GTRover has entered the environment of interest, its main exploration algorithm commences, consisting of scanning, mapping, target calculation, and then driving. This activity is separated into two distinct exploration modes, *Unexplored* and *Openness*. These modes determine the drive length and direction. After the robot first scan of its surroundings, it enters into *Unexplored* mode and begins searching for the largest unexplored area.

In *Unexplored* mode, the robot traverses its memory map to establish the cell with the highest unexplored score, and a target coordinate is determined based on the cell index. A coordinate-course system then determines the shortest unobstructed path to the cell through an open area. If such a path exists, the direction and length of the first step of the path is calculated and travelled by the robot. If a path does not exist, the cell is flagged and the next untargeted cell containing the highest unexplored score is then considered. The process repeats itself until all map cells have been targeted, in which the mode then changes from *Unexplored* to *Openness* exploration.

Openness exploration is similar to *Unexplored* mode except the robot seeks out the cells containing the highest openness score. The cells with the highest openness score are assumed to be the center of a room within the structure. Once the target has been reached, the robot will turn slowly 360° in order to collect and transmit images of the visible walls to the GCS via on-board video camera. This process will continue until all open cells have been visited. At this point, the robot remains idle, hidden away in an area of the smallest possible openness. This method removes the need for a wall following mechanism; therefore, allowing the robotic system to have expandable application to a wide variety of alternate environments and missions.

DESCRIPTION OF THE LEVEL 1 APPROACH

The Level 1 mission requirements are to use an autonomous aerial vehicle to navigate through predefined waypoints for 3km. This portion of the mission will be performed using the GTMax. The waypoint tracking capabilities of the GTMax are described in the GTMax section.

MISSION MANAGEMENT

For the Level 1 mission, the vehicle will have the autopilot engaged and be in a hover. The GCS operator will dictate when to commence the mission. Then the mission planner will initiate the pre-programmed waypoint sequence. Once the flight is complete, the GTMax will hover at the final waypoint waiting to begin the level 2 behavior.

DESCRIPTION OF THE LEVEL 2 APPROACH

The Level 2 mission requirements are to use an autonomous aerial vehicle to locate a building with an identifying symbol within a designated search area. Once the correct building is identified, an opening in the building must be found, through which the third level of the mission could be commenced. The mission coordination and flight path generation is done at a centralized location on the ground, and the commands are transmitted to the various vehicles via wireless datalink. The GTMax GCS interfaces with the primary flight computer and displays vehicle information, the object tracker information, and the flight plans generated by the mission planner. The Vision Monitoring Station receives streaming video from the camera and results from image processor. This allows the operator to monitor the efficiency of the image processing as well as visually document the results of the search in the final phase of the Level 2 mission.

IMAGE PROCESSING AND OBJECT TRACKING

The image processor has three modes, building detection, symbol detection, and window detection. To detect buildings the image processor scans each image for closed polygon contours. The contours sent to the tracker, which converts the pixel location of the contours into local geographical coordinates using the state estimate from the GN&C. Then it reduces the contour into a characteristic four sided polygon, and determines the probability that it is a valid building through a series of comparison test. The tracker keeps a list of objects with the highest probabilities of being buildings, and transmits the results to the GCS for display.

Symbol detection and tracking is accomplished by passing each image through a pattern matching routine to find candidate symbol locations. These candidate symbols are then examined to determine if they have the correct color content for the symbol. Then each positive symbol identification is fed into a probabilistic tracking algorithm. Once all of the buildings have been searched, the best symbol candidate is chosen, and the tracker determines which building it is located on.

The final mode is window detection, this is done using a level set edge detection algorithm. In this mode, the building fills most of the image. To enhance the image, it is passed through a color filter. This filter generates a black and white image which contains only dark features without color in them. Therefore, most of the contours that are detected will be either window and door edges. These potential portals are then classified based on size, darkness, and uniformity.

MISSION MANAGEMENT

To complete the Level 2 mission, the vision system on the primary air vehicle needs to track and locate buildings and the open portals. The mission is broken up into three phases. The first phase is to map the buildings. This is done by initiating a predetermined a high altitude flight pattern over the search area to look for buildings. After all of the buildings are mapped with adequate precision, the second phase of the search, to look for the symbol, is initiated at a lower altitude. In addition to planning the trajectory of the helicopter, camera direction and zoom must also be chosen. During this phase the mission planner needs to ensure that each building is visited to look for the symbol. Once the correct building is located a flight plan to search for portals must be generated. This includes the flight path to the building and a portal search pattern. The search pattern is a low altitude circling of the building. Once the most suitable opening is determined, the final phase of the Level 2 mission is to plan an approach to the chosen portal, to put the GTMax in position to launch a sub-vehicle into the structure.

DESCRIPTION OF THE LEVEL 3 APPROACH

The Level 3 mission requires the collection of visual information from within a building structure. An autonomous vehicle must be able to navigate inside the building, capture images of desired objects and transmit these images to monitoring personnel at the launch site up to 3 km away.

The strategy for Level 3 is to launch the GTRover through a portal with the ground based launch mechanism shown in Figure 8-b. The ground based launcher is used to ensure that the level 3 attempt is not disrupted by outside factors. Once inside the structure the GTRover will begin it mission and start transmitting video back to the GCS.

MISSION MANAGEMENT

The Level 3 mission begins with the GTRover in flight 10m away from the chosen portal. Upon landing in the room the it must orient itself. At this point the main exploration algorithm onboard the GTRover commences in *Unexplored* mode. Once all the all map cells have been explored, the mode then changes to *Openness* Exploration, and the robot then seeks out the cells containing the highest openness score. Once the robot reaches the desired location, it slowly turns 360° in order to collect and transmit a full image of the environment via the on-board video camera. This process will continue until all open cells have been visited, ensuring that an unobstructed view of each wall is obtained.

DESCRIPTION OF THE LEVEL 4 APPROACH

The level 4 mission ties each of the levels together. The primary addition for level 4 is the sub-vehicle delivery mechanism. In level 2, an opening to the building is located with the GTMax. However, in level 3 the GTRover is simply delivered using a ground based launcher. The final design for completing level 4 is still under development; however, in the current configuration the GTSpy is launched from the GTMax in front of the portal. Since the GTSpy under controlled flight, it can ensure the safe delivery of the sub-vehicle into the building under varying environmental conditions. Once the GTSpy has been launched, the GTMax will back away to a surveillance position, and begin its support tasks. Then exploration of the interior will commence.

CONTROLLED FLIGHT INTO THE STRUCTURE

After being launched, the GTSpy will attain a hover at a pre-determined location relative to the launch site. Once the GTSpy is in hover, it will orient itself such that the chosen portal is in view of the camera. During this phase of the mission, the images from the camera onboard the GTMax will be compared with the images being transmitted from the camera onboard the GTSpy. Once the correct opening has been located in the image from the GTSpy, it will begin its flight towards the window. The GTSpy will the navigate from the hover location towards the opening using the FCS20 sensor suite. As the vehicle approaches the building and the GPS signal becomes weaker, the position fix from the image processing will become dominant. Once it is inside the structure then the level 3 behavior can commence.

MISSION MANAGEMENT

The mission planner for the Level 4 mission must preform complex tasks and make decisions about the launch and flight of the GTSpy. The steps that the mission planner will carry out are outlined below.

1. Initiate a flight along the predetermined waypoints for the 3 km ingress.
2. Based on the final waypoint location, initiate a predetermined search pattern over the search area to look for buildings.
3. Determine and initiate the second phase of the search at a lower altitude. During this phase the mission planner needs to ensure that each building is visited to look for the symbol.
4. Choose the correct building. Generate and initiate a flight plan to search the building for opening.
5. Choose the best opening. Generate and initiate an approach to the chosen portal, to put the GTMax in position to launch the GTSpy.
6. Launch the GTSpy and initiate a controlled flight towards the chosen opening.
7. Collect imagery from the interior of the structure.

CONCLUSIONS

The Georgia Tech aerial robotics team has developed a multi-year approach to complete all levels of the International Aerial Robotics Competition mission. The program approach is flexible enough to allow lessons learned to be incorporated into the design as the project moves forward. Improvements in the GTMax avionics and the addition of two new vehicles, GTSpy and GTRover, has allowed work on the level 3 and 4 missions to proceed. Although, the approach for completing level 4 of this mission is intricate, it provides a very high level of robustness to changing environmental conditions and uncertainty.

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