

Georgia Tech Aerial Robotics Team

2009 International Aerial Robotics Competition Entry

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ABSTRACT

This paper examines the use of low-cost range and target identification sensors on a stable flying vehicle for suitability in solving the 5th Mission proposed for the 2009 International Aerial Robotics Competition. The ability for vehicles to navigate unknown environments is critical for autonomous operation. Mapping of a vehicle's environment and self-localization within that environment are especially difficult for an Unmanned Aerial Vehicle (UAV) due to the complexity of UAV attitude and motion dynamics. Using a stable vehicle platform and taking advantage of the geometric structure typical of most indoor environments reduces the complexity of the localization and mapping problem to the point that wall and obstacle location can be determined using low-cost range sensors. Target identification is accomplished remotely using an onboard video camera with a radio transmitter. Thus complex and time-consuming image processing routines are run on a more powerful computer, enabling further miniaturization of the flight vehicle.

INTRODUCTION

Autonomous mobile robots that can effectively navigate unknown environments could be utilized for a wide range of applications, including search and rescue, disaster assessment, reconnaissance, or other tasks that would be risky or impossible for a human to perform. The problem of localization and mapping unknown environments is typically solved by using a scanning laser or other type of range finder to measure the environment. This approach has seen success for large- to medium-sized ground robots. For UAVs, traditional localization and mapping often employs Inertial Measurement Units (IMUs) for stability augmented with Global Positioning System (GPS) measurements to estimate vehicle position. Recent advances have also been made in using vision sensors for target tracking and obstacle avoidance [1] or to estimate vehicle pose [2]. These techniques have been tested using large outdoor platforms, such as the GT Max, which is based on the Yamaha R-Max UAV helicopter (see Figure 1). For lightweight indoor flying vehicles, however, these sensor suites are less effective. For example, GPS signals will likely be unavailable, and laser scanners are relatively heavy and expensive. By utilizing a stable flying platform and relying on the structured nature of most indoor environments, it is possible to simplify the localization and mapping problem to the point where lightweight, inexpensive range sensors can accomplish the task. In addition, the implementation of simple altitude-hold control reduces the complexity of mapping and localization for UAVs to essentially a two-dimensional problem.

Problem Statement

The 5th Mission of the International Aerial Robotics Competition requires that an autonomous flying vehicle weighing less than 1.5kg have the ability to enter and navigate within an unknown confined environment in search of a specific marked target. The vehicle must enter through an opening that is

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at least 1m on each side, negotiate the indoor environment without crashing into walls or obstacles, and identify a control panel gauge marked by a non-blinking blue LED. A readable image of the gauge must be transmitted to the ground station within the ten minute time limit in order for the mission to be a success.



Figure 1. The GT Max UAV performing vision-based target tracking and obstacle avoidance using a weather balloon.

Conceptual Solution

The Georgia Tech Aerial Robotics (GTAR) team designed and built a vehicle based on a commercially available stable platform. To keep the vehicle small and light, inexpensive infrared and ultrasound sensors were used for obstacle avoidance and wall-following behavior. A simple microcontroller is used onboard to handle guidance and navigation logic, as well as obstacle avoidance. An altitude-hold control loop maintains a constant altitude, simplifying the navigation problem. A video camera onboard captures images and transmits the data to a ground station, which processes the imagery and identifies potential targets. The ground station also displays vehicle health, status, and location information, and determines when the target has been successfully identified. Figure 2 shows the overall GTAR system architecture.

Yearly Milestones

For the first competition of the 5th IARC mission, the GTAR Team has set modest goals of developing a stable flying platform capable of carrying a reasonable payload mass. In 2009, the vehicle will have the ability to avoid obstacles, follow walls, and detect the blue LED and target gauge required to complete the mission. Subsequent yearly milestones include solving the simultaneous localization and mapping problem, possibly with the use of vision-based navigation, by 2010. If mission goals are not accomplished by 2011, the team will continue to refine the navigation sensors and guidance logic, as well as consider the use of multiple cooperative vehicles to make searching more efficient.

AIR VEHICLE

As the 5th mission of the IARC requires indoor operations, the GTAR team had to investigate new airframes since the vehicles currently used at the Georgia Tech UAV Research Facility are designed for outdoor flight.

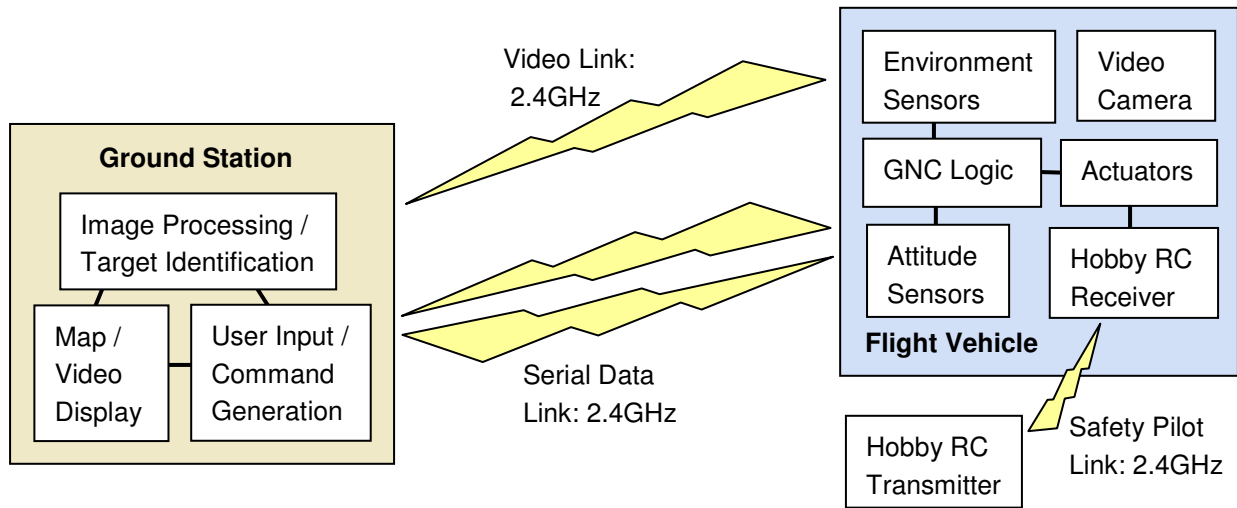


Figure 2. GTAR system architecture.

The GTAR team composed a list of requirements during vehicle conceptual design:

1. Overall size and weight as regulated by official IARC rules: largest dimension less than 1m, maximum takeoff weight less than 1.5kg
2. Flight Endurance at least 10min
3. All-electric aircraft
4. Payload capacity of 100g or more
5. Hover-and-stare capabilities
6. Preferably with inherently stable flight dynamics

After considering various airframes and comparing them against the design criteria, the GTAR team selected the Esky Big Lama as a base airframe (see Figure 3 below).



Figure 3. The Esky E020 “Big Lama” coaxial helicopter. Note: the tail rotor on this aircraft is neither functional nor required for flight.

Propulsion and Lift System

The vehicle is a counter-rotating coaxial helicopter with no tail rotor. The upper rotor is stabilized by a Bell stabilizer and is RPM controlled. The lower rotor is connected to a 2-servo swash plate and

also has RPM control. The system is a four channel helicopter with pitch, roll, yaw, and throttle control, with a yaw-damping gyro to improve handling qualities. Some additional technical specifications for the stock aircraft: main rotor diameter of 460mm, takeoff weight 410g, 800mAh 11.1V LiPo Battery, 75MHz FM radio.

In order to meet the requirements of the current IARC mission, the stock vehicle had to be modified in several aspects. To increase payload capability and flight time, the stock brushed motors and speed controllers were replaced with brushless motors and speed controllers. To further improve handling, the stock rate-damping gyro was replaced with a heading hold gyro. Other changes to the stock vehicle included modifications to the airframe and the addition of sensors and an onboard control system as discussed below.

Guidance, Navigation, and Control (GNC)

Significant technological challenges exist in order to ensure reliable autonomous operation of miniature air vehicles in cluttered indoor environments. The combination of cost-effective sensors and avionics, along with proximity to sources of electromagnetic and radio frequency interference, can result in significant measurement error and noise. Although challenges to miniaturization and cost reduction are often met through eventual progress in microelectronic technology, indoor navigation and control is also hindered by the unavailability of GPS signals. Most current algorithms for UAV GNC rely heavily on GPS, and hence are not suitable for indoor navigation where GPS signal is normally not available.

Given the state of the art in sensor technology, the above constraints limit the number and type of sensors that can be used, and limit the reliability of the sensor data. Since the available information to the control system is reduced, a reasonable strategy is to use simple and robust GNC laws that have been proven to function well under such conditions. In this section is a discussion of the solutions used by the GTAR team to tackle these challenges. The driving theme for this solution is the simple requirement that the UAV be able to explore a maximum amount of indoor area in a reasonable amount of time while relying on simple and robust guidance, navigation and control strategies.

Stability Augmentation System

Fulfilling one of the desired requirements, the stock vehicle already has a remarkable passive stabilization system. The primary disturbance rejection is accomplished by the Bell stabilizer, sometimes called a flybar, on the top rotor. Without going into details of helicopter stability, the Bell stabilizer essentially consists of a decoupled gyroscopic element that holds its attitude in space. If the vehicle encounters a disturbance that changes the attitude of the airframe, the Bell stabilizer remains fixed in space and the resulting attitude difference between the main part of the airframe and the Bell stabilizer causes a restoring effect on the airframe. To augment the passive stabilization on the stock vehicle, the baseline platform was upgraded with a heading hold gyro. This greatly aids the pilot during manual flight, and improves overall handling during autonomous flight. The resulting system is easily controlled with simple control laws.

Navigation

The vehicle has several modes of autonomous operation, including: random flight with obstacle avoidance, flight to the center of a room, wall-following, and target tracking modes. The most basic flight mode is random flight. When the vehicle is in random flight mode, it will fly in the forward

direction for a short random amount of time, then it will turn to a new random heading and the cycle repeats. During random flight, the vehicle always maintains a minimum safe distance from all obstacles and walls using the sonar and infrared range sensors for detection.

Flight to the center of a room can be initiated at any time. In order to fly to the center of a room, the vehicle measures the range from the four sonar pointing to the front, back, and sides of the vehicle. The control algorithm then attempts to equalize the relative range between the two lateral and the two longitudinal sensors. Once the vehicle is approximately in the middle of a room, the vehicle stops and can then pan the room looking for a possible target.

To ensure full coverage of an indoor environment, a wall-following technique is used. The vehicle has two forward-facing infrared sensors spaced approximately 40cm apart. These sensors are used to “lock on” to a wall by flying forward until a wall is detected, then adjusting the vehicle’s heading until the two range sensors read the same value. A stand-off distance of approximately 1.5m is established, and the vehicle flies in either lateral direction while maintaining its heading relative to the wall using the two infrared sensors. When an oncoming wall or obstacle is detected, the vehicle turns to continue tracking around the corner or obstacle. Thus, the entire contiguous wall surface may be traversed. During wall-following mode, a basic map of the vehicle’s flight path is drawn by integrating estimated velocity. Heading is assumed based on the assumption that all walls in the environment make right angles. Once the initial heading is set, a yaw rate gyro is used to determine each time the vehicle turns a corner. Future versions of the system may employ vision-based approaches such as optical flow to determine vehicle speed relative to the fixed environment.

During any of the navigation modes described above, the camera may detect the blue LED target indicator, at which time the ground station, which is performing image processing on the video data, instructs the vehicle to enter target tracking mode. During this mode, the ground station transmits the two-dimensional row and column of the detected LED in the video image reference frame. The vehicle flies forward toward the target, while using yaw control to keep the target centered in the video frame. Once the vehicle has determined that it is within a specified distance from the target, it hovers in front of the target to record images of the target gauge reading.

Control System Architecture

The GTAR system relies on active range sensors such as ultrasound sonar sensors, and infra-red sensors to obtain range information in the immediate vicinity of the vehicle. Leveraging the inherent stability properties of the coaxial rotorcraft platform, the control system directly command servo deflections based on error between the commanded relative position and observed relative position. This allows for great simplicity in the control system design. For the current system, flight tests have shown that proper location of the vehicle’s center of mass (centered beneath the rotor shaft) prevent any unstable oscillation or other detrimental performance characteristics.

A novel implementation of Proportional Integral Derivative (PID) control architecture is used for vehicle position control. The strategy is to simply augment the dynamically stable platform with active obstacle avoidance and position hold. Three position control loops are used: an altitude loop, a longitudinal relative position control loop, and lateral relative position control loop. These three loops work together to ensure that the vehicle maintains a constant relative altitude and follows position commands from the outer loop navigation logic as discussed above. Due to vehicle

sensitivity to proportional control and time delay between the servo commands and actuation, derivative control is also needed. A Kalman filter based approach is used, which functions similar to a second order observer system to estimate the relative velocity of the vehicle. This estimate is used as the input to the derivative control which attempts to regulate the system velocity. The resulting system is less susceptible to oscillations. During vehicle operation, varying battery voltage level affects the throttle trim value. To counter this effect, an integral part is included in the controller. Instead of integrating the position as is traditionally done, the servo commands output by the controller are integrated. In this way the system can inherently handle actuator saturation and integration windup. Furthermore, servo commands are easier to measure since they are assigned by the controller. Figure 4 shows the schematic of the altitude control loop. The lateral and the longitudinal loop have similar architecture.

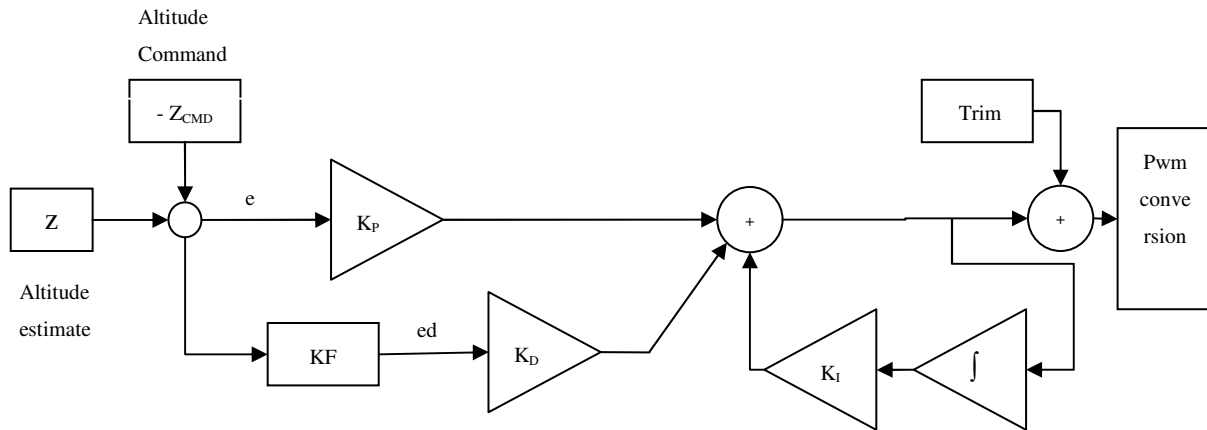


Figure 4. Schematic of Altitude Hold Control System

Flight Termination System (FTS)

As required by the IARC official rules, the vehicle has a built in FTS to allow a judge or operator to remove electrical power from the motors during flight if necessary. The GTAR FTS is actually a complete safety pilot system, whereby a judge or operator can take complete control of the vehicle at any time. In addition to the onboard avionics that provide autonomous control, a separate hobby radio control receiver is included on the vehicle. In addition to the four channels used to fly the vehicle manually, a fifth channel is used to switch from automatic to manual control. The four flight control servo signals, along with the servo commands generated by the autonomous system, are input to a two-channel, four-input multiplexer. The fifth control channel on the hobby radio transmitter is used to select which multiplexer channel is sent to the actuators (servos) for flight control.

PAYLOAD

Since the avionics system is embedded on a small expendable UAV, it needs to be compact, lightweight and inexpensive while enabling the UAV to accomplish the mission. The embedded avionics package consists of the sensors, the microcontroller, and the communication devices.

Sensors

Several sensors are used for Guidance, Navigation and Control purposes which are quite common to UAVs and other small autonomous vehicles. Some sensors are also used for specific tasks related to

the mission (e.g. obstacle avoidance and target detection). The vehicle has four MaxBotix® LV-MaxSonar®-EZ4 in the front, back, right and left for longitudinal and lateral control. An additional MaxSonar®-EZ1 is used for altitude control. These sonar have a range of 6.5m, a resolution 2.5cm, and a wide beamwidth, providing obstacle detection in all directions.

For wall-following behavior, two Sharp GP2Y0A02YK0F infrared range sensors are mounted facing forward, spaced 40cm apart. They have a narrow beam and a shorter range (1.5m), but a better resolution (1cm) than the MaxBotix® sonar. An Analog Devices ADIS16100 gyro is used to determine the yaw rate for estimating the vehicle heading. Target acquisition is accomplished using a Draganfly Eyecam Extreme NTSC video camera mounted in the front of the UAV. See Figure 5 for pictures of the primary range sensors.



Figure 5. Primary range sensors are the MaxBotix® LV-MaxSonar® (on the left), and the SHARP GP2Y0A02YK0F infrared range sensor (on the right). Photos courtesy SparkFun Electronics: www.sparkfun.com.

Microcontroller

An Atmel® ATmega128 microcontroller is used to interface with all the sensors, accomplish all GNC functions, and interface with the radio transceiver to communicate with the ground station. It is a lightweight, inexpensive microcontroller, which can interface with all the required sensors via analog to digital converters, Serial Peripheral Interface, and external interrupts for reading pulse width modulated signals. It also has two serial communications ports, which are used to interface with the sonar altimeter and the XBee radio data link. The ATmega128 runs at 16MHz, which is fast enough to run the required GNC algorithm.

Communications

A communication link to and from the aircraft is accomplished between Xbee Pro wireless radio modules at the ground station and on the vehicle. The units operate on a frequency of 2.4GHz and transmit at a power of 60mW. The bi-directional data link sends sensor telemetry and vehicle status to the ground station and target tracking data from the ground station to the vehicle, both at 38.4kbps. The data link can also be used to send messages from the ground station to the vehicle, which allows control system tuning before and after autonomous flights.

Link Budget

The following link budget calculation ensures that the XBee Pro data link provides adequate performance at a range of 100m in the presence of 6dBm of building attenuation. The values in Table 1 below were used in the calculation.

Table 1: Constants for Link Budget Calculation

	Symbol	Value
Range (m)	R	100
Frequency (Hz)	F	2400000000
Wavelength (m)	λ	0.125
Link margin required (dBm)		10

The equation used to determine the signal-to-noise ratio (S/N) for the datalink at this range is given as

$$\frac{S}{N} = P_{tx} - Rx \text{ sensitivity} + Gain_{trans} + Gain_{receiver} - Path \text{ loss} - Misc. \text{ loss} \quad (1)$$

where P_{tx} is the transmit power, Rx sensitivity is a characteristic of the receiver, $Gain_{tx}$ and $Gain_{rx}$ are the transmit antenna gain and receiver antenna gain, the miscellaneous loss is the building attenuation of 6dBm and finally, path loss is given by

$$Path \text{ loss} = \left(\frac{4\pi R}{\lambda} \right)^2 \quad (2)$$

The terms in the equation are added to get the available S/N in Table 2 below. After finding the available S/N, a required S/N of 10dB is subtracted, leaving a fade margin of 24.74dB. This value exceeds the required link margin of 10dB, so the data link is expected to have an adequate signal-to-noise ratio for the application.

Table 2: Link Budget Calculation

	Symbol	Ratio	unit	dB	unit
Transmit power [3]	P_{tx}	60	mW	17.78	dbm
Tx antenna gain [3]	$Gain_{tx}$			1.5	dBi
Rx antenna gain [3]	$Gain_{rx}$			1.5	dBi
Path loss		101064749.07		-80.05	dB
Receiver sensitivity [3]				100	dBm
Misc loss (building loss) [4]				-6	dBm
		Available S/N		34.74	dB
		Required S/N		10	dB
		Fade Margin		24.74	dB

Power Management System

Aircraft power is provided by an 11.1V, 1320mAh Lithium polymer battery. The battery is connected to two brushless speed controllers rated at 10A each. The speed controllers also provide separate 5V power. The servos and safety pilot circuit are powered by one of the 5V supplies, while the microcontroller, sensors, and video camera/transmitter are powered by the other 5V supply. In addition, the flight avionics package provides a 3.3V supply to power the XBee radio data link. Battery voltage is monitored continuously and transmitted to the ground station to prevent over discharging the batteries during flight.

OPERATIONS

Flight Preparations

Before each autonomous flight test or competition trial, a checklist of preparations must be followed. The steps listed below in Table 3 ensure the safe and efficient operation of the vehicle.

Table 3. Flight preparation checklist.

Steps completed days before flight session	Charge flight batteries, transmitter batteries
	Load new software onboard and ground station
	Complete hardware-in-the-loop (HITL) tests to ensure proper operation of any code changes
Steps completed day of flight session	Ensure all flight test equipment is present.
	Set up ground station.
Steps completed before each flight	Clearly brief safety pilot of intention of flight
	Check structural integrity of vehicle and ensure proper center-of-gravity position.
During flight test	Pilot has primary discretion on whether to take manual control if vehicle is in jeopardy. Besides this discretion, safety pilot will only obey judges or ground station operator.
	Once the low voltage warning tone is heard, safety pilot takes control and lands the aircraft.

Man/Machine Interface

A ground station will continuously monitor the flight vehicle and display health and status information during the flight. The flight vehicle will send its current estimated position/heading, obstacle locations, and battery voltage via the XBee serial data link. In addition, a frame-grabber is used to retrieve images from the incoming video stream for processing. The ground station will analyze the images to detect the target, and send instructions to the ground vehicle upon target acquisition. Instructions from the ground station, including the adjustment of system parameters during manual flight, are transmitted over the XBee serial data link. A safety pilot / FTS is included, which operates via a separate 2.4GHz radio uplink.

RISK REDUCTION

Vehicle Status

The flight vehicle will continually monitor its surroundings for potential hazards. Obstacle detection information, as well as altitude and battery health are all transmitted to the ground station for viewing by observers.

Shock and Vibration Isolation

The onboard electronics are somewhat insensitive to shock and vibration from a mechanical perspective. As such, no special matters other than a careful mounting are necessary to protect the avionics from physical damage to shock or vibration. However, in order to improve sensor readings, care must be given to isolating the sensors from vibrations occurring during operations.

The avionics of the vehicle hence have been split up in a sensor and a non-sensor group. The non-sensor group (essentially the CPU, data and video links, and power circuitry) is very insensitive to the occurring vibrations and is mounted close to the overall CG of the vehicle in an effort to reduce moment of inertia and to keep the vehicle balanced.

The other items making up the sensor group (five sonar, two infrared range finders, and the camera) are directly mounted onto the shroud of the vehicle. The shroud (as described in detail below) provides an extra layer of vibration isolation between the sensors and the rotors. This is accomplished by mounting the vibrating part of the vehicle (the motor, shaft, and rotor assembly) to a more flexible part of the shroud. The relatively large inertia of the (stiffer) rest of the shroud helps in damping higher frequency vibrations which tend to deteriorate sensors the most. Furthermore, the camera, heading lock gyro, and yaw rate gyro (for heading estimation) each have their own custom mounts which specifically aim at vibration isolation through the use of specialized foam padding.

Electromagnetic Interference (EMI)/Radio Frequency Interference (RFI) Solutions

Typical electric UAVs have two primary sources of interference: electric motors (for propulsion and servo actuation), and radio transmitters (for data and video links). To reduce the effect of EMI, the stock brushed motors were replaced with brushless motors and any potentially sensitive parts were relocated away from the motors and servos if possible. Ensuring proper electrical grounding and adding capacitors where needed on power circuitry proved sufficient protection against EMI. For the radio links, 2.4GHz transmitters were chosen for the video link, the safety pilot radio control link, and the data link. This eliminates the typical “servo jitter” that plagues UAVs operating with 900MHz transmitters nearby. Possible interference between the 2.4GHz systems can be reduced by proper shielding and location of antennas.

Safety

Indoor operation poses several major paradigm shifts in UAV operation. Among others, the general assumption that the space surrounding the UAV is not occupied can no longer be made. The GTAR team addresses this problem not only with a vehicle that has obstacle detection and avoidance capabilities, but also one that can survive minor impacts during horizontal flight. To improve resilience against collisions in flight, the stock canopy was replaced with a custom safety shroud. The shroud is multi-purpose structure that combines a rotor guard with a wide stance landing gear, as well as providing for vibration isolated mounting space for the sensors. The four main struts of the shroud

are aligned with the cardinal directions of the vehicle carried coordinate frame. With the rotor guard ring, the structure provides a stiff but flexible cage surrounding the vehicle.

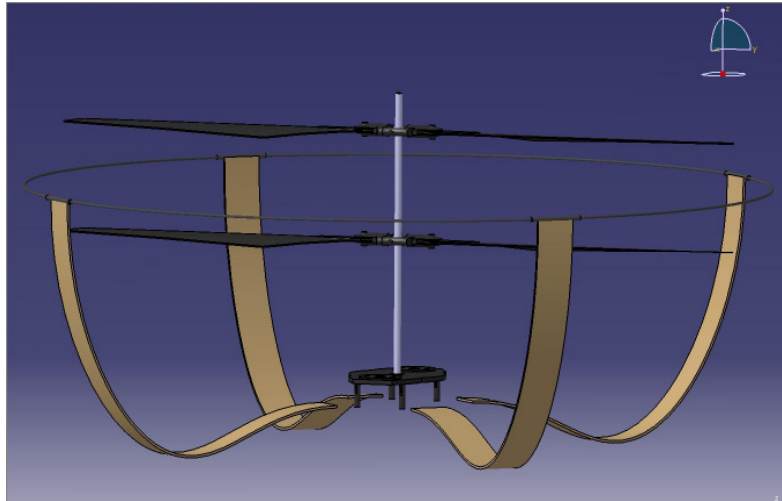


Figure 6. Safety Shroud and Rotor Guard

In addition to the collision prevention and protection system built into the airframe, the vehicle may be brought completely under manual control by a judge or operator at any time via the FTS/safety pilot system mentioned above.

Modeling and Simulation

A simulation was developed using the free open-source modeling and animation software Blender. In the simulation, coaxial helicopter vehicle dynamics are simulated, as well as the range sensors mentioned above. The simulation allowed for easy configuration of different test environments, with variable opening and obstacle placement. In addition, the control and navigation algorithms were easily tested and improved before attempting to fly the actual hardware.

shows a screen capture from the simulation.

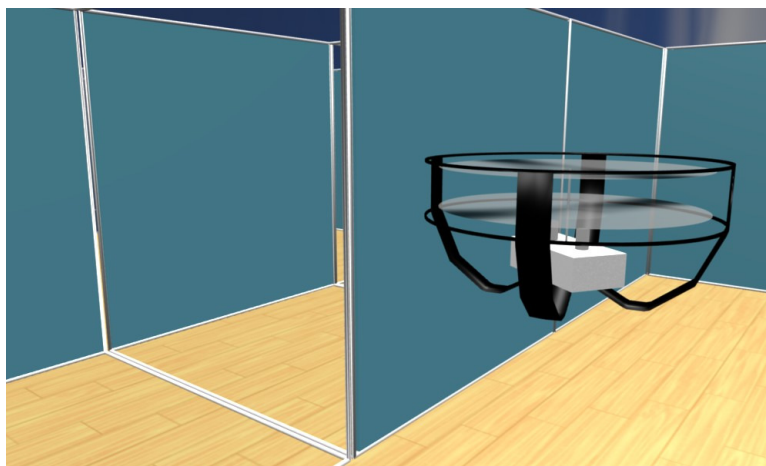


Figure 7. Screen capture from GTAR Blender simulation.

Testing

The GTAR system has been rigorously subjected to flight testing at the indoor test flight facility at Georgia Tech. The development of GNC algorithms and the hardware has been tremendously aided by flight testing. A MATLAB based interface is used to plot and record data in real time. To perform rapid prototyping of control algorithms, a MATLAB based off-board controller was also been designed; this allows easy and low-risk testing of new concepts before integrating them into the onboard code. A protocol for ensuring safety, efficiency, and reliability in flight tests has also been developed.

CONCLUSION

This paper reports the progress made by the GTAR team towards developing an indoor UAV for attempting the IARC 5th mission in the year 2009. A low cost alternative to developing UAV systems capable of operating in GPS denied environments was described. Leveraging the inherent stability of a coaxial rotorcraft platform, the system relies on simple Guidance Navigation and Control concepts to accomplish the mission. The unique aspect of this approach is that the system does not rely on building elaborate global map for navigation. Rather, it uses simple random walk concepts for ensuring that maximum area is covered in reasonable amount of time. Solutions were posed to the typical technological challenges faced when using compact low cost sensors on a UAV. A cost flight system and communication hardware suitable for an indoor UAV were also discussed.

In conclusion, a low cost solution to indoor UAV navigation and target identification was proposed. The system relies on simple and robust control laws and smart navigation logic without having to resort to any sort of global mapping or a GPS global position fix. Flight tests continue as the system is further developed in order to successfully attempt the IARC 5th mission.

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