Co-Axial Helicopter for Autonomous Navigation and Exploration in GPS-denied indoor missions

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ABSTRACT. This paper details a Co-axial helicopter capable of autonomous navigation and exploration of unknown indoor areas without relying on any external navigational aids like GPS. The problem statement of the competition is reviewed as well as the overall system architecture that was implemented to solve this challenge. Motion vector and depth measurement data are gathered from cameras in the front and the bottom of the vehicle, in order to elaborate a Simultaneous Localization And Mapping (SLAM) algorithm. Each task of the helicopter runs on a separate process and is distributed according to its priority and each processing power between on-board and ground station devices. This vehicle is intended to be UTFSM team's entry for the 2011 International Aerial Robotics Competition.

1. INTRODUCTION

Development and application of UAV technologies have taken a higher priority for many governments, universities and institutes. This interest is due to the wide variety of applications in civil and military fields, and an effect of this interest can be found in the significant increase of major projects, international events and media outreach achieved by this area of research.

Indoor reconnaissance and surveillance by UAV can be utilized for terrain inspection, search and rescue or disaster assistance, including undercover penetration of enemy territories.

Most current UAV implementations are based on GPS signals [1][2] and rely on a previously given map [3][4], but the GPS signal is not reliable and becomes necessary the usage of system like SLAM or vision-based when navigating indoors. Indoor navigation requires the UAV to be small in order to safely move inside the building, resulting in limitations of maximum load and therefore heavy limitations in the batteries, sensors and computational power that can be carried onboard. Additionally, the application in dangerous tasks and the high risk of losing the UAV leads to a low-cost expendable design.

These technical challenges are addressed by utilizing a stable flying platform, relying in a robust altitude-hold control and simplified SLAM algorithms, to obtain an UAV capable of navigating cluttered areas for indoor reconnaissance in GPS unreliable environments.

1.1 Statement of the problem

The sixth mission of the International Aerial Robotics Competition (IARC) is to create an UAV capable of entering a building through a window of 1 square meter, then navigate within an unknown confined environment, locate a specific target, replace a flash drive without being detected and exit the building.

1.2 Conceptual solution to solve the problem

The UTFSM "Chincol" team has developed a flight vehicle that is stable, low-cost and easy to maintain. This consists of a Fixed Pitch Co-Axial Helicopter that uses Walkera Lama 400D as a base airframe. The Lama 400D motors have been replaced with more powerful brushless motors. The vehicle uses an ultrasonic sonar sensor for height control, a Futaba gyroscope for tail control and a flybar for horizontal stability. It uses an AVR Xmega microcontroller and runs an Overo Fire with a camera CMOS Caspa from Gumstix and an array of Sharp infra-red sensors for obstacle avoidance. The Overo will provide guidance with optic flow from the CMOS camera pointed toward the floor and uses a Kinect camera for navigation. Navigation is based on SLAM and route planning algorithms. Tasks are distributed between on-board and off-board processing through a wireless data bridge.

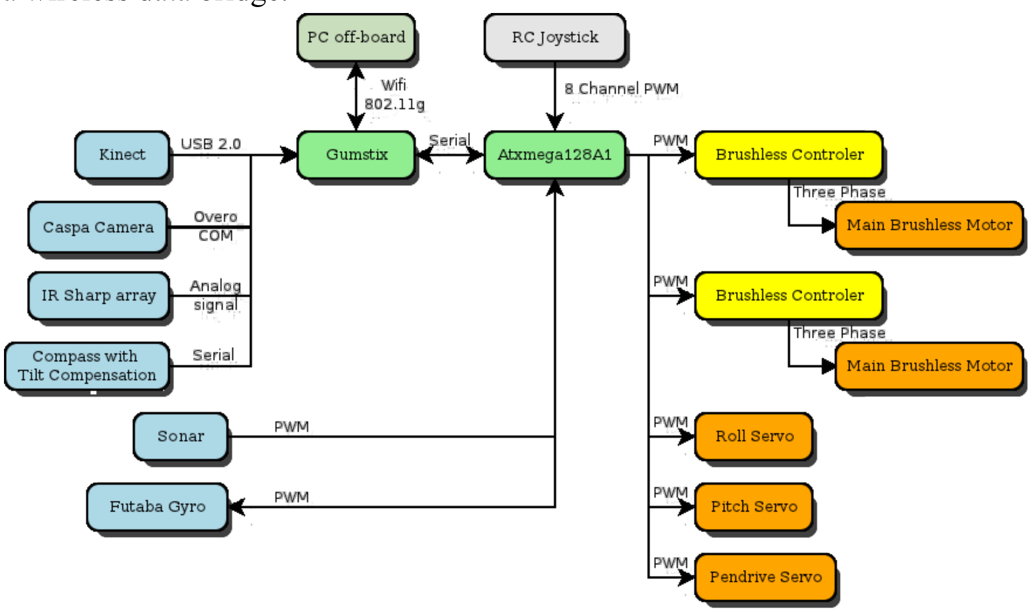

Figure 1: Overall system architecture

1.3 Yearly milestones

In 2009, some students developing different autonomous vehicles projects, e.g. a quadrotor and a submarine, began to gather and working together to set up the first laboratory of unmanned vehicles at UTFSM. In 2010 the development team was formed and the first goal is to compete in the International Aerial Robotics Competition (IARC). In 2011, the first team from UTFSM named "Chincol" plans to accomplish the sixth mission of IARC.

2. AIR VEHICLE

The vehicle used for the mission is a co-axial helicopter with fixed pitch angles, making the vehicle robust so that it can outlast inevitable crashes during experiments without getting seriously damaged. The design enables the helicopter to carry a sensor payload of 1.1 Kg, as described in section 3, for a little more than the mission time (10 minutes). The bottom and sides of the helicopter was used as a rack to mount the components and keep a low center of gravity for better stability.

2.1 Propulsion and lift system

The axial helicopter has two main rotors of 50cm of diameter with two blades each. One rotor turns clock wise and the other on the opposite direction so that the difference in speed of each rotor makes the tail turn and the sum of the thrust of each rotor affects the height of the helicopter. [16]

The original DC motors of the Lama 400D helicopter have been replaced by two brushless motors to obtain more payload capacity and flight time because of the high efficiency inherited to the brushless motors.

Each motor is driven by a Castle Creations Phoenix 25 speed controller. Approximately 55% of the total thrust is sufficient for the vehicle to hover with all equipment at fixed-height. On average, each motor drain 5 amperes with a maximum peak of 25 amperes limited by the speed controller.

The motor has a weight of 40g, 28mm length, 25.9mm diameter, 2.3mm shaft, 3000RPM/V, a free load current of 2.5A, 13A max current and 80% max efficiency.

2.2 Guidance, navigation and control

2.2.1 Stability augmentation system

The helicopter has a flybar for horizontal stability that came with the Walkera Lama 400D. This mechanical stability coupled with a proper balance of the components is enough for an adequate horizontal stability.

The tail movement is controlled by a Futaba GY240 that works with an internal proprietary control loop with a gyroscope.

These greatly improve the overall handling during manual and autonomous flight, allowing the resulting system to be easily controlled by the on-board processor without involving more complex methods [5].

2.2.2 Level control system

The six degrees of freedom of the helicopter are controlled by four degrees through time: pitch, roll, yaw and height. This is done by adjusting the angle of the blades and the torque of both main rotors.

In order to decrease the complexity of the problem, the vehicle works with fixed height so that the 3D navigation is simplified to a 2D system as described in section 2.2.4 except for the landing, takeoff and taking the flash drive from the desk.

The fixed height is achieved through a cascade control composed of two stages. The first stage is the control loop of the speed of each blade and the second one is the control loop of the height.

We considered the following points to simplify the simulation of the helicopter height control in order to analyze what controller is sufficient and easy to implement for the application:

- The values used to define the model of the helicopter are an ideal representation of the helicopter model; hence the architecture of the controller was adjusted according to experimental results. For example the mass of the helicopter in the simulation is 1.5 and not a measured value.
- Because the height is controlled by the sum of the trust of both main rotors, we will represent it as if it was only one.
- The operating point will be the RPM necessary to make the helicopter rise.
- We will represent Phoenix 25 speed controller from Castle Creations by a P controller.
- We will not analyze the delays on the system caused by the discrete system nor the sensors.

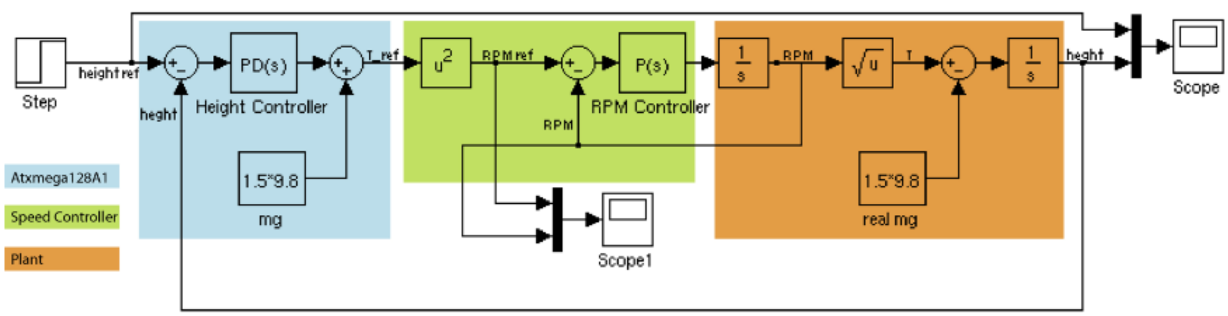

Figure 2: Height controller simulation

We first tried with a PD controller because a root locus analysis showed stability and good time response and because the PID controller is much used in this type of aplication. But in our case the stationary error does not matter.

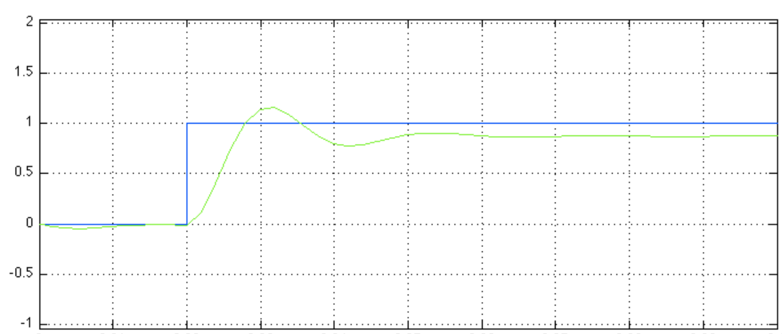

Figure 3: Result of the simulation of figure 2. Height (green) and Height Ref (blue) vs. time.

2.2.3 Obstacle avoidance system

There are two systems to avoid obstacles. The first system works on the navigation system described in 2.2.4 and the second one is a reactive fuzzy system [11]. The navigation system has a path planner fed with mapping and obstacle information in order to build routes that avoids the current obstacles. In case of the sensors spot and unexpected obstacle due to navigation errors or blind points, the reactive system takes control of the helicopter. The reactive system is based on a fuzzy system with the IR sensors as inputs, and a danger level value and a proposed direction as output. When the danger level rises above a threshold the proposed direction is achieved. The height and orientation does not change, but seeks for a new position distant from the obstacle. This is a simplification of other fuzzy systems that also controls the height [6].

2.2.4 Navigation system

The navigation system is based on a Kinect camera and depth sensor attached to the helicopter. The data from the Kinect is sent through the 802.11g wireless connection to the base station which has enough processing power to perform a SLAM algorithm.

The Kinect is a low-cost device as reliable as many other stereo-vision systems [7] that gives depth information of the obstacles on the front of the helicopter which is used to determine the environment. The Caspa camera pointing towards the floor is used to calculate the motion vector of the vehicle[8][9][10]. That improves the hover of the helicopter and the direction when moving. The combination of both systems generates the map through a SLAM method that spots the structure of the building and leads to the path planning strategy.

In order to verify that all systems work well, prior to the preparation of the mission-specific algorithms, the helicopter was tested with different modes of autonomous and semi-autonomous flight. To test the fixed-height control, the vehicle direction was commanded by the RF joystick while the height control was working. To test the obstacle avoidance system, the vehicle navigates in random flight mode, moving forward for a random time and then turning for a random degree, while the height control and the obstacle avoidance system are working. The same random flight mode is used to test the SLAM algorithm. To test the landmark recognition system, the helicopter works in target-tracking mode, where the movement always seeks to keep the recognized landmark in the center of the camera.

As well as the object avoidance system, the navigation system works as an agent based system. In this case, each process, i.e. optic-flow, slam, landmark recognition and movement executor, are independent agents that share a common data area and has a monitor to enable or disable each agent according to the motivations of each stage of the mission. This approach is a simplification of autonomous motivation based agents [11][17] in which motivations drive the planning of agents and their corresponding actions.

2.3 Flight termination system

There is a monitor process responsible for updating the mission status, and also to check the

health of the helicopter. When the battery level drops below the safety threshold or if the ground station sends an abort signal, the helicopter seeks the closest safe spot (without obstacles) to land. The same procedure is performed if the mission time ends, but in this case the helicopter also “explodes” with a beep sound.
After a successful mission, if the helicopter is outside and 3 meters away from the building, it lands.
At any moment, the manual control can override the autonomous flight mode if in an emergency.

3. PAYLOAD

3.1 Sensor suite

The helicopter is outfitted with an ultrasonic sonar sensor, a Futaba gyroscope, an array of infra-red sensors, a CMOS Caspa Camera and a Kinect camera.
The Futaba gyroscope is used for tail control as described in 2.2.1 and the ultrasonic sonar sensor is used for height control as described in 2.2.2.
The IR array consists of six Sharp sensors pointing in the horizontal plane to six equidistant directions. This information of the surroundings is used for obstacle avoidance as described in 2.2.3.
The CMOS Caspa from Gumstix is mounted in the helicopter pointing towards the floor and is used to get the movement vector as described in 2.2.4 and to locate the flash drive as described in 3.1.2.2.
The Kinect camera reads depth information of the obstacles in the front of the helicopter. These 4D images are transmitted through the wireless link to the ground station as input information for the SLAM algorithm as described in 2.2.4 and to get RGB images for landmark recognition as described 3.1.2.1.

3.1.1 Guidance, Navigation and Control sensors

3.1.1.1 Ultra-sound sensor

This sensor is a XL-MaxSonar-EZ4 MB1240. It operates at 42kHz and takes 100ms to make a measurement. It has an error of 1 cm and measures from 20 cm to 645 cm.
The EZ4 generates a high power, narrow beam of sonic energy, and then measures the returning echo. This narrow beam width allows it to accurately measure the distance to even small objects and the high power allows the object to be detected at a greater distance. Its maximum range is 765cm with a resolution of 1cm. The EZ4 operates at up to 42kHz and communicates serially at a speed of 9600 baud using RS232 protocols. Each time the EZ4 takes a range reading it calibrates itself. The sensor then uses this data to properly range the distance from the ground.
This sensor is employed to give very accurate information about the elevation of the aircraft when it is coming in to land and taking off since the GPS can only give an elevation to about 10 meters of accuracy. When trying to land an aircraft moving at high speed on a possibly uneven surface a much more accurate system was needed and the EZ4 fills this role perfectly.

3.1.1.2 Caspa camera

This a full color spectrum computer vision camera specially designed for UAV and surveillance. It uses an optical filter to cut out the IR range, and thus receives only visible spectrum light. It has an Aptina MT9V032 CMOS sensor with 752H x 480v active pixels and 60 fps at full resolution. A 3.6mm fixed focal length lens contains a IR filter so that only visible spectrum light can pass.

As mentioned in 2.2.4 this camera pointing towards the floor is used to measure the motion vector through optic-flow by feature tracking. Although SIFT[13] and SURF[14] features are popular algorithms for visual feature recognition, the computing power required for this purpose is restrictive. Instead we used BRIEF [10] feature detector, which is very fast both to build and to match. When compared to SURF and U-SURF on standard benchmarks[10], it shows a similar or better recognition performance, while running in a fraction of the time required by either. The BRIEF descriptor is used over FAST[12] keypoints to find a projective consistency and measure the motion vector.

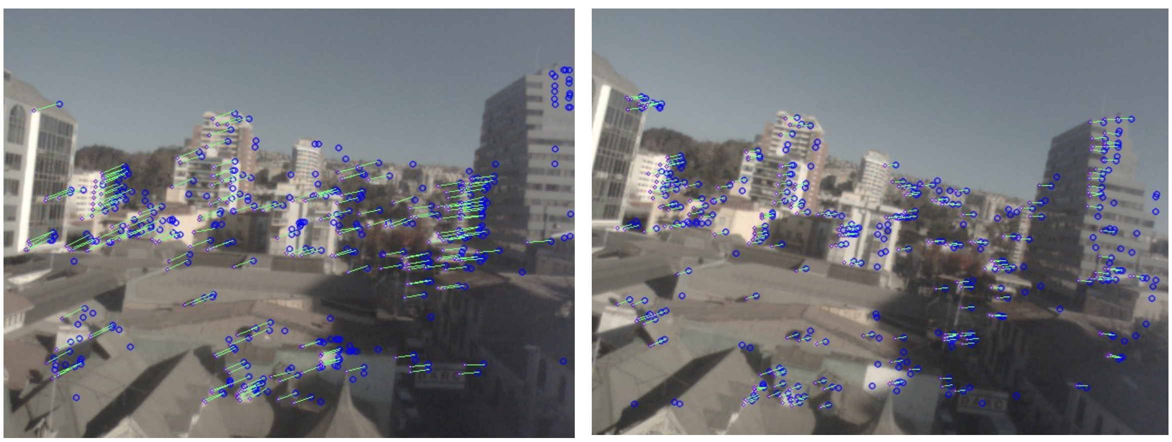

Figure 5: FAST BRIEF optic-flow test looking out the window. The blue circles are the details that are followed and the green lines are the same details found on the next frame.

3.1.1.3 Kinect camera

Kinect is an Xbox 360 peripheral formerly known as Project Natal that uses IR to track objects in 3D space. It has a field of view of 57 degrees horizontal and 43 degrees vertical. The depth sensor range is between 1.2m and 3.5m. The max resolution is 640x480 pixels, 32-bit color and 30fps.

From the 4D image given by this camera (RGBD), the depth measurement (D) is used as input for the SLAM algorithm.

3.1.1.4 Infra-red Sharp sensors

These are infrared proximity sensors GP2Y0A02YK0F by Sharp. It has an analog output that varies from 2.8V at 15cm to 0.4V at 150cm with a supply voltage between 4.5 and 5.5VDC. It’s used to get information from the surroundings for object avoidance.

3.1.2 Mission sensors

3.1.2.1 Kinect camera

The depth information (D) from the Kinect camera is used to detect the obstacles from the environment as described in 2.2.4. The image information (RGB) is used to recognize landmarks from the walls of the building. When searching for the signs that indicate the route to the Chief of Security's office, the recognition of the signs is performed by the Phony-Ferns method [12].

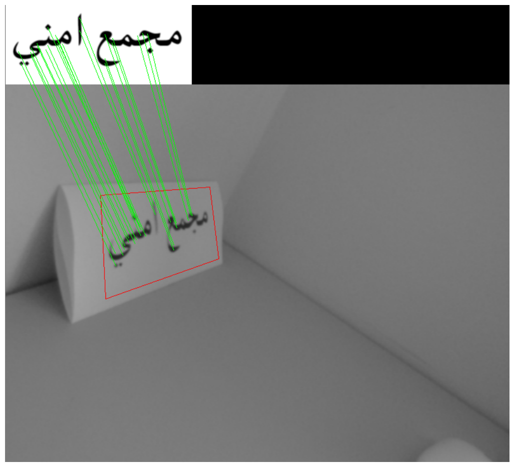

Figure 6: A sign recognized using Phony-Ferns

3.1.2.2 Caspa camera

The Caspa camera is used to obtain the motion vector of the helicopter as described in 3.1.1.2. The same image is used when searching for the flash drive. The object detection is achieved with the Viola-Jones method [15].

3.2 Communications

The communications system is an IEEE 802.11g infrastructure connection. There is a Cisco router as bridge which will work to connect the base station with the helicopter.
The on-board Gumstix has chip W2CBW003B that is based on Marvell's 88W8686 for Wi2Wi and brings both 802.11(b/g) and Bluetooth. This transceiver can work up to 54Mbps at -74 dBm with OFDM or 1Mbps at -90dBm with DSSS. It has a power save mode and a transmit power up to +15dBm for both 802.11b and g.
The base station can be any laptop with a standard WIFI antenna and with Linux operating system. Also it needs to have enough processing power to run the algorithms.
The Walkera radio controller uses a proprietary protocol with a 2.4GHz spectrum technology that features fast reaction and strong anti-jamming protection. The receiver has a double receiving circuit that effectively assures the stability of receiving signal.

3.3 Power management system

The helicopter is powered from 4 cell 14.8V lipo-polymerer battery for powering the main motors and all the electronics involved. As shown on figure 5, the brushless controllers power the motors by connecting directly to the battery. The Kinect is powered up by a 12V lineal regulator connected to the battery. All the other electronics are connected by a 5V lineal regulator except for the Atxmega128A1 that needs a 3.3V lineal regulator.

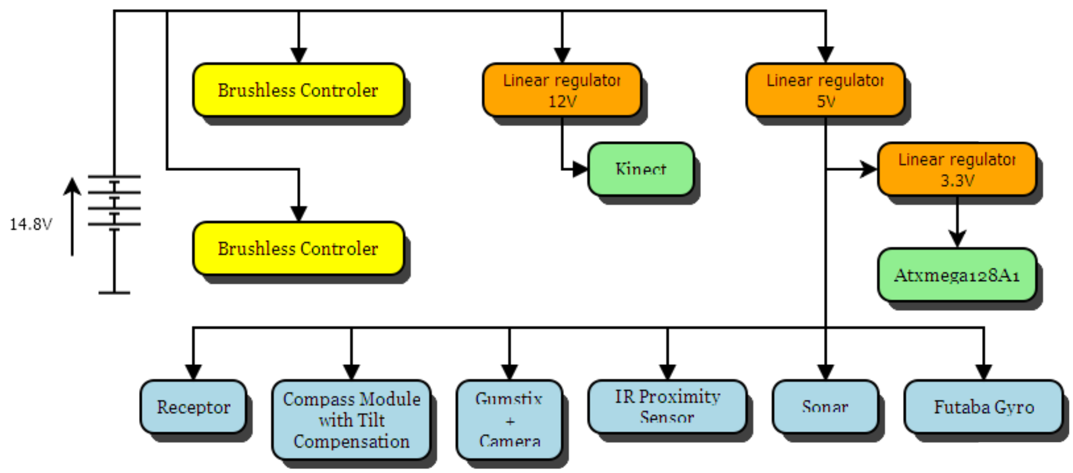

Figure 7: Power management

4. OPERATIONS

4.1 Flight preparations

A procedure has been established to ensure safety and proper operation when initializing the system before executing a mission. The process reviews the hardware, ensuring the electro-mechanical integrity of the vehicle; and the software, initializing all the processes and the data-link.

4.1.1 Flight checklist

1. Helicopter motors and linkages
2. Batteries
3. Power-on the ground station and wireless communication system
4. Power-on the helicopter and check the manual control communication link
5. Start all processes
6. Test communication between on-board and off-board processes
7. Ensure health of all processes (parameters, data gathering and synchronization)
8. Start vehicle and ensure health of the motoring process
9. Start mission via ground station operator
10. Flight termination upon mission completion, mission abort or manual control override

4.2 Man-machine interface

There is a graphical user interface used for monitoring mission progress, which provides a datarich single screen about mission information. Also, low-level information is gathered through a terminal console, which provides information about the helicopter status and processes health. The operator can send a start or termination instructions to the monitoring process to initiate or abort the mission. Each process has a configuration file which is loaded on start-up to set all parameters. If a file is missed, the default parameters are selected. Another console terminal shows the status of the wireless communication link, CPU statistics and memory utilization.

5. RISK REDUCTION

In order to manage the safety risks of the operation of the helicopter, a number of measures have been taken.

5.1 Vehicle status

5.1.1 Sock/vibration isolation

The flybar on top of the blades filters mechanically the high frequency oscillations and works as a good isolation system for the vibrations produces by the main motors.
Following the recommendations of Futaba, the Gyro was mounted on a vibration absorbing pad and far from the motors, which is factory set to isolate the gyro from the vibrations of the vehicle.
The compass signal is filtered through a sixth-order low-pass filter at a frequency cut of 10 Hz.

5.1.2 EMI/RFI solutions

During the component selection stage, quality and robustness have been a priority together with versatility and prize. Each one of the helicopter components has the proper EMI/RFI industrial shielding.

5.2 Safety

The helicopter is equipped with a highly reliable system to activate and deactivate the autonomous system. When the autonomous system is turned off, the manual control takes place which uses a conventional remote control to control the helicopter. The only control that remains active is the tail control and the height control that can be enabled or disable on flight.
It is very important to follow the procedure set out to reduce risks. And also to always have a proper operator in case the manual flight is required.
The on-board processor constantly monitors the wireless link connection. If the connection is lost, the vehicle will hover until the wireless link is recovered or manual control is enabled.

5.3 Modeling and simulation

The only modeling and simulation we used is for the height controller seen on point 2.2.2.
Everything else is tested on the helicopter itself under controlled conditions.

5.4 Testing

As we skipped simulation, we needed to make a lot of on-ground testing before on-flight testing. First, we created dummy data and tested the algorithms code off-board. Then we tested the code on-board with the main motors turned off and moving the helicopter with our hands so that there was coherent data to test the application. Afterwards, we tested the code on manual flight and finally with the autonomous flight.

This procedure is faster and helps to detect any failure when testing the helicopter in a wide range of real conditions. Also, it helps to test the overall system, like the batteries and power system, the WIFI connection, and processes health, so that we can have a reliable system.

6. CONCLUSIONS

“Chincol” team from UTFSM has developed a helicopter that is capable of autonomous navigation in unknown and GPS-denied indoor environments using on-board sensors. We have also developed a multi-agent system that enables a proficient method for incorporating or removing independent algorithms to solve each specific task of the mission.

The helicopter is stable, low-cost and easy to maintain, and uses Walkera Lama 400D replacement parts.

The on-board processes runs over an AVR Xmega microcontroller and an Overo Fire Gumstix, which have proven to be very reliable systems, with high processing power, low power consumption and small weight.

The 3-dimensional situation was reduced to a 2-dimensional navigation process by using a fixed-height controller, but in the future we plan to extend the navigation based on FAST BRIEF optic-flow and SLAM capabilities to enable a dynamic height control.

With this overall system, “Chincol” team will compete in the 2011 International Aerial Robotics Competition.

7. ACKNOWLEDGMENTS

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