2010 8th IEEE International Conference on
Control and Automation
Xiamen, China, June 9-11, 2010

An Indoor Unmanned Coaxial Rotorcraft System with Vision Positioning

Fei Wang, Tao Wang, Ben M. Chen, Tong H. Lee

***Abstract*—We present in this paper the development of an indoor micro unmanned coaxial rotorcraft system with vision processing functions. The rotorcraft can automatically position itself based on the landmarks on the ground and perform a few indoor flight tasks. A toy rotorcraft is adopted and upgraded by adding an essential avionic system, which includes an embedded computer, an inertial measurement unit, a servo controller, and a wireless modem. In addition, a wireless camera is mounted under the rotorcraft body to capture real time image streams and send them to the ground control station. After a series of image processing at the ground station, high-level control commands are sent back to the onboard avionic system. By this mean, the rotorcraft is able to follow colored tracks on the ground and perform turning when it needs to. Experiments have been carried out to verify the accuracy of vision processing outputs and flight tests have been performed to ensure an overall good performance of the rotorcraft.**

***Index Terms*—Micro aerial vehicles, real-time systems, flight control systems, vision processing.**

I. Introduction

Unmanned aerial vehicle (UAV) helicopters are gaining more and more interests from researchers worldwide because of their unique ability of hovering and vertical taking-off and landing (VTOL) capability. UAV helicopters have useful civil applications such as disaster monitoring, environment and traffic surveillance, search and rescue, aerial mapping and cinematography [1], [2]. They also play significant roles in military and academic aspects. Advanced control laws such as non-linear control and fuzzy-based control have been tested on UAV helicopter platforms [3], [4], [5]. The potential applications of this research area are unlimited.

Driven by the rapid development of sensors, microprocessors and actuators, UAV helicopters nowadays have smaller size, lighter weight and more sophisticated functions. Hence, a term called Micro-UAV evolves and has attracted extensive attention in the academic area. Micro-UAV is able to perform indoor flights due to its miniature size. However, the conventional controller depending on GPS information can no longer be used because the GPS signals are usually blocked inside buildings. As a solution, vision sensors and vision processing algorithms are implemented as a complementary mean for the UAV to know where it is.

A typical UAV helicopter consists of three main subsystems: the bare helicopter, the onboard avionic system, and the ground control system [6]. Our Micro-UAV helicopter platform, PetiteLion (see Fig. 1) also follows this design. The bare helicopter is small in size, yet strong enough to carry the onboard hardware system. The avionic system is in charge of the helicopter low-level attitude control. The ground control system consists of two computers which can perform path planning and make high-level navigation decisions. There are both video link and data link communications between the ground control system and the onboard avionic system.

The authors are with Department of Electrical and Computer Engineering, National University of Singapore, 4 Engineering Drive 3, Singapore 117576.

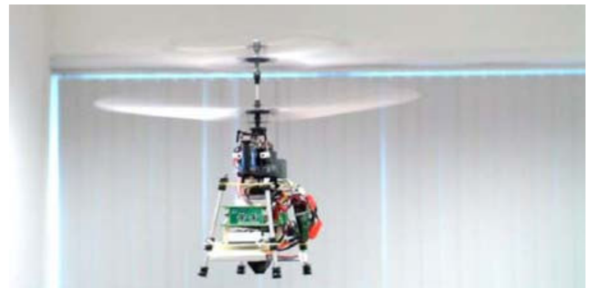

Fig. 1. Micro-UAV Coaxial Rotorcraft: PetiteLion

The organization of this paper is as follows: In Section II, the hardware design of PetiteLion is presented. Section III covers the detailed description of the individual components in the avionic system. Section IV is about the software algorithms for both attitude control and vision-based navigation. In Section V, experimental results are presented and analyzed. Finally, we draw some conclusions and discuss about future improvements in Section VI.

II. Hardware Design

A. Bare Helicopter Platform

A radio-controlled (RC) toy helicopter, E-sky Lama V4, is chosen as the skeletal helicopter for further hardware modification. Choosing this off-the-shelf product saves significant amount of time for us compared to building a miniature helicopter on our own. The E-sky Lama V4 helicopter is a low-cost toy helicopter in the hobby industry. It can perform stable hover and indoor flight under manual RC control. The most attractive feature is its coaxial design, which saves space and weight significantly compared to the conventional single rotor helicopter with a tail [7], [8].

Simple experiments have shown that the effective payload of the off-the-shelf Lama V4 is only about 50 grams, which is obviously insufficient for implementing an avionic control system onboard. Thus, hardware upgrades must be carried out to increase its payload. The helicopter's stock motors are replaced by Xtreme products to increase the torque and power. Xtreme also provides longer and better designed blades to

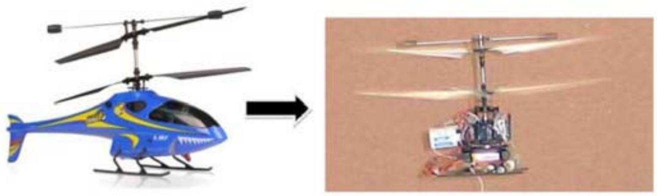

Fig. 2. Modification to E-sky Lama V4

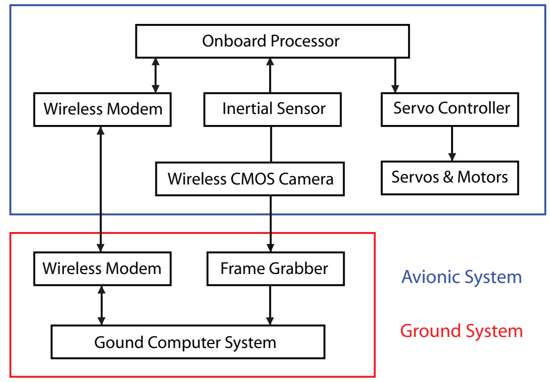

Fig. 3. Hardware Block Diagram of the Micro-UAV System

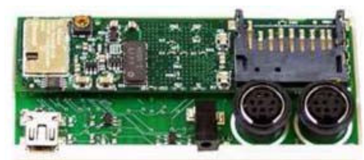

Fig. 4. Gumstix Waysmall 400-bt Computer

create more lift. To make sure the helicopter is still stable after using the longer blades, a longer inner shaft is used to increase the distance between the upper and lower blades. After these modifications, the new Lama V4 is able to carry an effective payload of 150 grams, which greatly facilitates the implementation of the onboard avionic system. Fig. 2 shows Lama V4 before and after modification.

B. Avionic Control System

The avionic system consists of an embedded microprocessor, an Inertia Measurement Unit (IMU), a servo controller, a wireless modem, and a wireless CMOS camera. The basic idea is to use the IMU to measure helicopter attitude deflections, and then the microprocessor will analyze these data and send correction signals to the servo controller. The detailed descriptions and discussion of these individual components will be presented in Section III.

C. Ground Control System

The ground control system incorporates two computers. One runs in a Linux operating system to serve as the keyboard and screen for the onboard microprocessor. It also takes care of the low-level control code development. For this code development, an online open source code package, MicroGear, is used. In addition, Gumstix Buildroot is utilized to install the arm-linux system onto the embedded computer and it also provides the cross-compilation toolchain. The other computer runs in the Windows operating system and it is in charge of image processing (further discussed in Section IV) and outputting position and heading offsets of the helicopter. It has a wireless video frame grabber which can receive real time video signal from the onboard wireless camera. The two computers are connected by a 'RS-232 to keyboard' scancode conversion cable. Thus the image processing computer can send ASCII codes with our own definitions to the former computer to realize communication. An advantage of this setup is that the ground operators can easily interrupt the Micro-UAV navigation by hitting keyboard letters of the former computer if an emergent situation happens.

III. Components of the Avionic System

Given the limited size and payload of the coaxial helicopter platform, the size and weight of the onboard components are very critical. At the same time, the processing speed and sampling rate of the components must be yet fast enough for an effective control. Hence, a comprehensive survey is done on the state-of-the-art technologies, and various components are compared based on their size, weight, performance as well as reliability.

A. Onboard Processor

Gumstix Waysmall 400-bt computer is chosen as the onboard processor (see Fig. 4). Operating at a speed of 400 MHz, Gumstix Waysmall computer only weighs 20 grams. It comes with two parts, namely, the Gumstix Basix motherboard and a data acquisition extension board. The extension board has two Mini-Din 8 RS-232 ports for interfacing with peripheral devices such as sensors, actuators and the console (keyboard and monitor for a computer). The operating system that has been installed on the Waysmall 400-bt computer comes from Gumstix Buildroot, which is built upon the Linux 2.6 kernel. Gumstix Buildroot also provides a cross-compilation toolchain to compile code in desktop Linux and generate binary executable files compatible with the Gumstix Basix processor. Fig. 5 shows the steps of using Gumstix for the first time (details can be found online at Gumstix wiki - Buildroot). A 1 GB Multimedia card (MMC) is used to transfer files from the host computer to the Gumstix computer. During flight, the MMC is also used to store flight data.

B. Inertial Measurement Unit and Servo Controller

The MNAV100CA is a compact digital sensor system integrated with servo controller (see Fig. 6). This module has highly integrated architecture which makes the overall size $5.72 \times 4.57 \times 2.54$ mm only. The MNAV100CA contains tri-axis accelerometers, tri-axis gyros, tri-axis magnetometers and a GPS receiver. While the GPS signal is absent indoor, the accelerometers and gyros can still measure the 3-Dimensional accelerations and angular rates based on inertial sensing. The integrated servo controller has 8 PWM output channels which can drive most common RC servos, and the servo positions

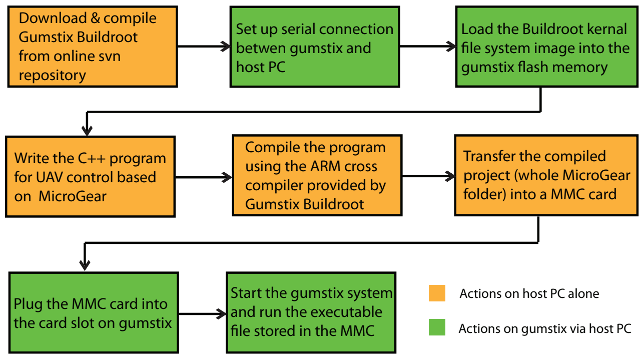

Fig. 5. Steps of using Gumstix for the first time

Fig. 6. MNAV100CA IMU + Servo Controller

can be set in software with 16-bit resolution. MNAV100CA also has a 3-pin RS-232 serial port, which allows convenient communication with the Gumstix Waysmall Computer. The output rate of MNAV100CA can be set to either 50Hz or 100Hz, which is fast enough to control PetiteLion for non-aggressive flights.

C. Wireless Communication Module

A pair of Xbee-Pro OEM RF modems (see Fig. 7) is used to establish the data link between the onboard avionic system and the ground control system. It operates at 2.4 GHz frequency and has maximum transmit power of 100 mW. The theoretical indoor range stated on its manual is 100 meters. However, the practical range for accurate transmission is below 20 meters after testing in lab condition. It is used in its Transparent Mode, which means it acts as a RS-232 serial cable replacement. The baud rate of the serial interface is selected to be 115200 bps in accordance with the Gumstix Waysmall computer console.

D. Motor Speed Controller

The Lama V4 coaxial helicopter has only two servos attached to a swash plate to control the pitch and roll angles of the fuselage. Yaw angle is controlled by changing the rotating speed of the two blades in which unbalanced torque can be generated. On the other hand, the lifting force can be also affected by the rotor speeds. Thus, the lift and the yaw

Fig. 7. Xbee-Pro Wireless Modem

Fig. 8. EFLH-1023 3-in-1 Motor Speed Controller

Fig. 9. 2.4GHz Wireless CMOS Camera

acceleration are coupled. A motor speed controller with a built-in mixer is needed to transform the throttle and rudder signals into two different current signals corresponding to the desired motor speeds. EFLH-1023 3-in-1 control unit is chosen as the motor speed controller (see Fig. 8). It contains a gyroscope, a mixer and an electronic speed controller (ESC). It reads the throttle and rudder signals from the MNAV100CA servo controller and converts them into two current signals to drive the motors. The gyroscope acts as a most inner-loop controller to ensure a stable heading of the helicopter.

E. Wireless Camera

A 2.4 GHz wireless CMOS camera (see Fig. 9) is mounted vertically downwards under the helicopter body to capture real time image streams on the ground and send these information to the ground control station. It only weighs 20 grams.

IV. Image-Supported Control Design

In order to control the helicopter attitude and navigation with high quality, accurate measurements on its 3-dimensional position, velocity, acceleration, angular position and angular rate are needed. Without GPS, the most direct way to get position and velocity is to integrate from acceleration. However, the accuracy of the acceleration measurement from MNAV100VA is not that satisfactory. In the long run, values of velocity and position will drift. The same problem occurs for measurement of angular position. As a solution, vision information from the wireless camera as well as a vision processing algorithm is needed to correct these errors periodically.

Vision-based navigation system usually depends on user-defined geometric models [9]. So we created an indoor visual reference in our lab. It is a three-color track on the ground with the red sub-track (15 cm in width) in the middle (see Fig. 10). The helicopter is ordered to fly along this track with a direction such that the green sub-track is on the left while the blue sub-track is on the right. A software program will be run on one of the ground station computers to calculate the heading, height and lateral position (left-right position) of the helicopter with respect to the track. Visual C++ working with the OpenCV library is chosen as the developing tool to solve this problem.

Fig. 10. 3-Color Track on the Ground for Vision Tracking

Fig. 11. Morphological Correction

A. Image Processing

The first agenda of our vision algorithm is to extract the red sub-track out of the background so that the helicopter heading, lateral position and height can be deduced from it. The source image captured from the wireless camera is stored as a 3-channel BGR image. Preprocessing procedures such as image smoothing, color differentiation and morphological operations need to be done to remove noises and extract the most interested features. For this case, a 9×9 median filter is applied. For easier color filtering, the original BGR image needs to be converted into an Hue-Saturation-Value (HSV) image since HSV convention can describe the perceptive color of a pixel better [10]. In OpenCV convention, red pixels have Hue values either a bit larger than 0 or a bit smaller than 180. A filter with reasonable range for the Hue value needs to be constructed, and by experiments, this range is best at Hue value smaller than 15 or Hue value larger than 165 for our setup. In real scenarios when motors and blades are spinning and wireless communication is not that perfect, some defects and overlapping of colors for the source image is unavoidable. To correct these defects, a morphological operation using OpenCV function 'MorphologyEx' is applied (see Fig. 11). This is followed by edge detection using 'cvCanny' and line detection using 'cvHoughLine2' (see Fig. 12).

After the two straight lines representing the boundaries of the middle red sub-track have been obtained, we are ready

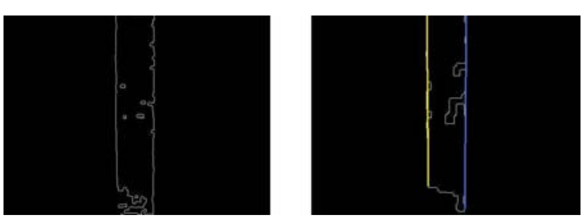

Fig. 12. Edge Detection & Line Detection

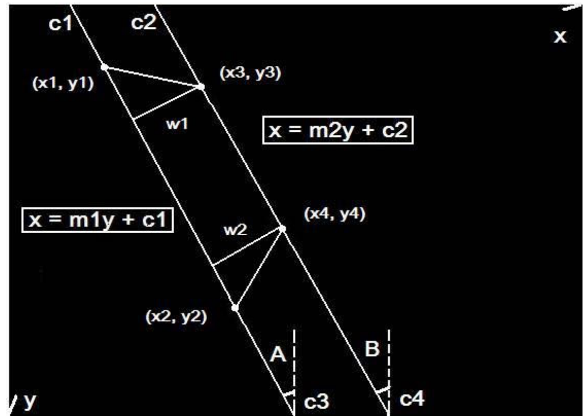

Fig. 13. Extracted 2 Lines in X-Y Frame

to calculate the parameters we need, namely, the helicopter heading, lateral position and height. By viewing the whole frame as an x-y coordinate system and treating the top-left corner as the origin (see Fig. 13), the equations of the two straight lines can be formed as follows: For Line 1,

$$x = m_1 y + c_1 \tag{1}$$

and Line 2,

$$x = m_2 y + c_2, \tag{2}$$

where

$$m_1 = \frac{x_1 - x_2}{y_1 - y_2}, \qquad c_1 = \frac{x_1 y_2 - x_2 y_1}{y_2 - y_1}, \tag{3}$$

and

$$m_2 = \frac{x_3 - x_4}{y_3 - y_4}, \qquad c_2 = \frac{x_3 y_4 - x_4 y_3}{y_4 - y_3}. \tag{4}$$

The heading of the helicopter, α can be known by calculating the offset of the track direction against the vertical direction (see angle A and B in Fig. 13). The steps are as follows:

$$A = \tan^{-1} m_1, \quad B = \tan^{-1} m_2, \quad \alpha = (A + B)/2. \tag{5}$$

If α is positive, the helicopter needs to turn anti-clockwise. Else, it should turn clockwise. Next, we calculate the image width of the track, W by taking the average value of w_1 and w_2 in Fig. 13:

$$w_1 = \sqrt{(x_1 - x_3)^2 + (y_1 - y_3)^2} \times \sin \left| \tan^{-1}\left(\frac{x_1 - x_3}{y_3 - y_1}\right) - \alpha \right|,$$

$$w_2 = \sqrt{(x_2 - x_4)^2 + (y_2 - y_4)^2} \times \sin \left| \tan^{-1}\left(\frac{x_2 - x_4}{y_4 - y_2}\right) - \alpha \right|,$$

and

$$W = \frac{w_1 + w_2}{2}. \tag{6}$$

Since the actual width of the red sub-track is known to be 15 cm, it is possible to estimate the height of the helicopter based on the image width of the red sub-track seen by the camera. This is because of the fact that when the helicopter flies higher, the red sub-track seen by the camera becomes thinner and vice versa. If we assume that the distance between the camera and

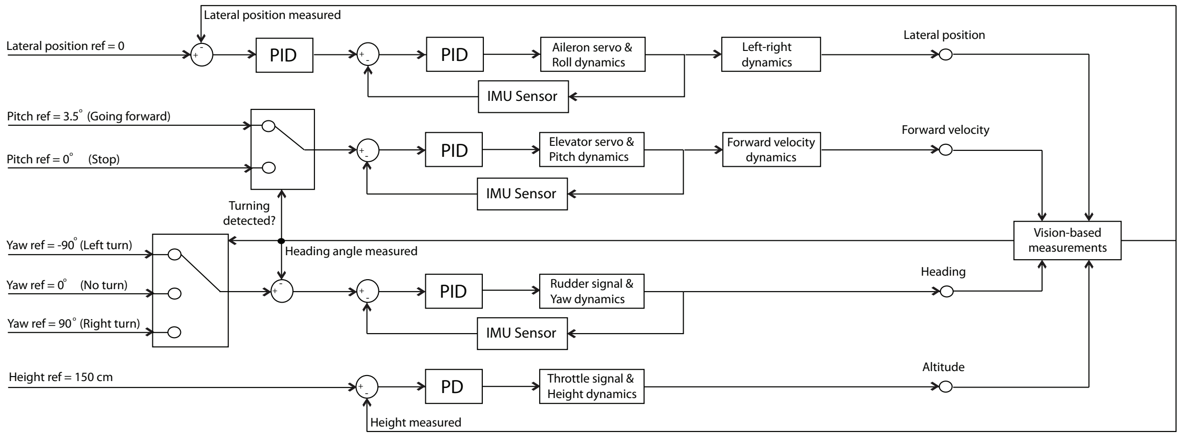

Fig. 14. The Overall Control Algorithm

the track is much longer than the focal length of the camera, then the height of the helicopter, H is approximately inversely proportional to the image width of the track, i.e.,

$$H \approx \frac{K}{W}, \tag{7}$$

where K is a constant that can be found by simple experiments. Furthermore, the lateral position of the helicopter with respect to the center of the track can be obtained also. This is done by calculating the average x value for 4 coordinates c_1, c_2, c_3, c_4. We can obtain c_1 and c_2 by substituting $y = 0$ into the two straight line equations, and obtain c_3 and c_4 by substituting $y = y_{\max}$, i.e.,

$$c_3 = m_1 y_{\max} + c_1, \quad c_4 = m_2 y_{\max} + c_2. \tag{8}$$

Hence, the actual lateral position offset, L can be calculated as:

$$L = (x_{\text{ave}} - \frac{x_{\max}}{2}) \times \frac{15}{W} \text{ cm}. \tag{9}$$

We note that $15/W$ is the ratio of actual length (in cm) against image length.

B. Control Algorithm

Once real time attitude and position measurements can be obtained accurately, an avionic control software can be implemented (based on open source MicroGear). Since the Micro-UAV helicopter will be designed to fly in near-hover condition with very small roll and pitch deviations, the roll pitch yaw dynamics are assumed to be decoupled. Hence, these three angles of the helicopters can be controlled independently. Upper part of Fig. 14 shows the block diagrams of the three sets of closed-loop PID control. Furthermore, the height of the helicopter can be controlled in a similar way. However, it is found that the integral component of the PID controller will sometimes result in too much oscillation in this case because the physical height dynamics is slow and the height measurement is relatively less accurate. Hence, a PD controller with very small D component is implemented instead (see lower part of Fig. 14).

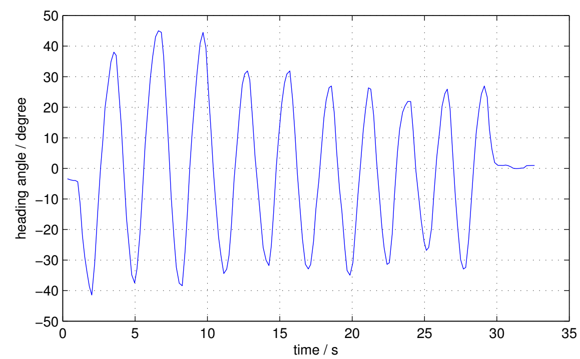

Fig. 15. Accuracy Test for Heading Measurement

V. Experimental Test Results

A. Accuracy Test for Vision Based Measurements

Three simple experiments are carried out to verify the calculated helicopter heading, height and lateral position by vision. They are done by manually oscillating the helicopter position or orientation with respect to the ground track in three different ways. Firstly, the helicopter body is turned about the vertical axis in a repeating clockwise and anticlockwise way. Fig. 15 shows the measured heading against time over about 30 s The sampling rate is about 6 Hz. There is no abrupt change between any consecutive sets of data on the curve. It generally reflects that the real time heading calculated by our image processing algorithm is accurate without any unbearable noise. Similar experiments are done towards the height and lateral position measurements. The results are quite satisfactory (see Fig. 16 and Fig. 17).

B. Real Time Flight Test

Real time flight tests are carried out in an indoor environment. The Micro-UAV helicopter took off from hands and followed the colored track on the ground. In addition to the straight-line track, there were also right angle turnings for the helicopter to make turning decisions. For each flight, the onboard avionic system is programmed to log the helicopter attitude in Euler angles. Fig. 18 shows one set of the flying

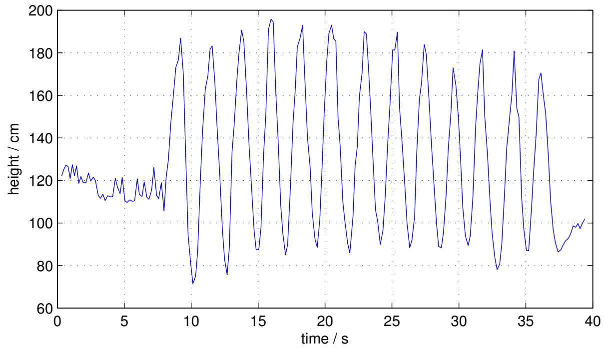

Fig. 16. Accuracy Test for Height Measurement

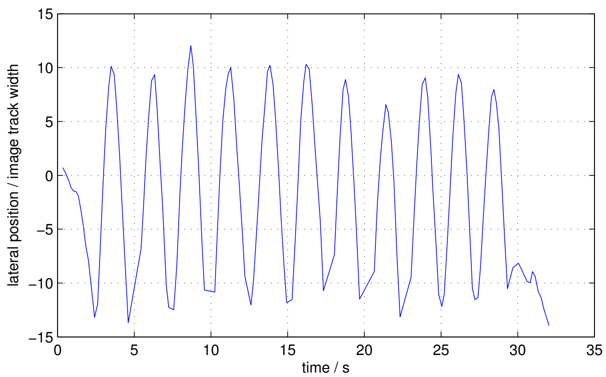

Fig. 17. Accuracy Test for Lateral Position Measurement

data which includes roll (θ), pitch (ϕ) and yaw (ψ) angle measurements, and they are plotted against time. The overall attitude of the helicopter is quite stable as all of the three angles only fluctuate within 0.5 radiance. Note that the yaw angle makes a -90° change at time = 12 s. This is because of an expected head turning of the helicopter. The large fluctuations of the pitch and roll values towards the end of the flight test are caused by the landing impact.

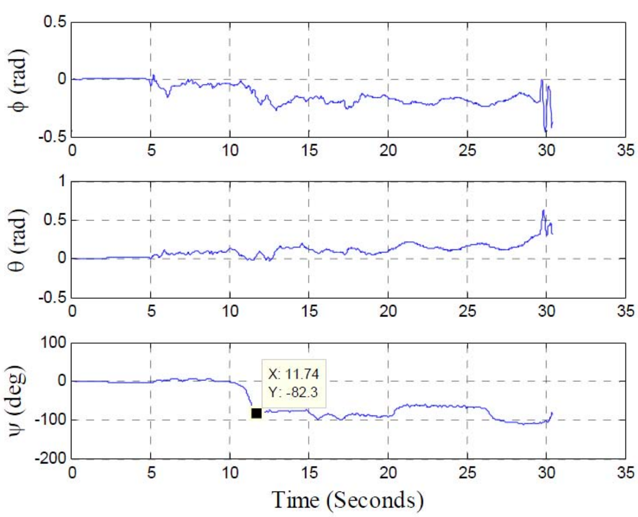

Fig. 18. Euler Angles logged during Autonomous Flight

VI. Conclusions

This paper describes the hardware structure of an originally designed Micro-UAV helicopter named as PetiteLion. From a bare E-sky Lama V4 toy helicopter, it is upgraded by a simple avionic system which includes the Gumstix Waysmall embedded computer, the MNAV100CA inertia measurement unit and servo controller, the Xbee-Pro OEM wireless modem, the EFLH 3-in-1 motor speed controller, and the wireless CMOS camera. The algorithms that run on both the avionic and the ground control systems are discussed. Such a Micro-UAV helicopter is able to perform stable hover and basic vision-based indoor navigation. It is reserved as a test bed for more advanced control technologies in the future.

Possible future improvements include implementing a more advanced inner-loop controller to substitute the current simple decoupled PID controller for a stretched performance. Additional sensors such as sonar and laser scanner can be added. The future UAV helicopter is expected to do more complicated indoor navigation such as obstacle avoidance and environment mapping. Last but not least, vision processing can be shifted from the ground control station to the onboard system so that the UAV can fly without the ground station. The trade-off is the image processing rate. More powerful embedded vision processor is needed.

Acknowledgment

Authors of this paper would like to thank Dr. G. W. Cai and Mr. F. Lin for their help and assistance throughout the course in conducting this work.

References

[1] Z. Harris, "Survey of UAV applications in civil markets," *Proceedings of the 9th Mediterranean Conference on Control and Automation*, Dubrovnik, Croatia, 2001.

[2] A. Ollero and L. Merino, "Control and perception techniques for aerial robotics," *Annual Reviews in Control*, vol. 28, pp. 167–178, 2004.

[3] S. A. Bortoff, "The University of Toronto RC helicopter: a testbed for nonlinear control," *Proceedings of the 1999 IEEE International Conference on Control Applications*, pp. 333–338, Honolulu, Hawaii, 1999.

[4] M. Sugeno, I. Hirano, S. Nakamura and S. Kotsu, "Development of an intelligent unmanned helicopter," *Proceedings of the 1995 IEEE International Conference on Fuzzy Systems*, vol. 5, pp. 34–35, Yokohama, Japan, 2007.

[5] E. N. Sanchez, H. M. Becerra and C. M. Velez, "Combining fuzzy, PID and regulation control for an autonomous mini-helicopter," *Information Sciences*, vol. 177, pp. 1999–2022, 2007.

[6] G. Cai, F. Lin, B. M. Chen and T. H. Lee, "Systematic design methodology and construction of UAV helicopters," *Mechantronics*, vol. 18, pp. 545–558, 2008.

[7] L. Chen and P. McKerrow, "Modelling the Lama coaxial helicopter," *Proceedings of Australasian Conference on Robotics and Automation*, Brisbane, Australia, 2007.

[8] C. Coleman, "A survey of theoretical and experimental coaxial rotor aerodynamic research," *NASA TP-3675 Technical Paper*, California, 1997.

[9] M. Carreras, P. Ridao, R. Garcia and T. Nicosevici, "Vision-based localization of an underwater robot in a structured environment," *Proceeding of the 2003 IEEE International Conference on Robotics and Automation* , pp. 971–976, 2003.

[10] R. I. Zaghloul and E. F. Al-Rawashdeh, "HSV image watermarking scheme based on visual cryptography," *Proceedings of World Academy of Science, Engineering and Technology*, vol. 44, pp. 482–485, 2008.