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DESIGN AND CONSTRUCTION METHODOLOGY OF AN INDOOR UAV SYSTEM WITH EMBEDDED VISION

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Abstract

This paper describes the design and construction of an autonomous indoor coaxial rotorcraft system with onboard vision processing capability. A radio-controlled (RC) helicopter was modified and upgraded with essential avionics and processing elements for autonomous flight. This paper shows that in an indoor environment, where GPS signals are unavailable, vision-based navigation system can be used as a substitution. An embedded vision system that is compact and light enough to be carried by indoor UAVs is integrated into the control loop. The system has been successfully tested and the UAV was able to follow a painted track on the ground autonomously.

Key Words

Micro-aerial vehicles, real-time systems, flight control systems, embedded vision processing

1. Introduction

Unmanned aerial vehicle (UAV) has been gaining increased attention in fields of academia, industry and military. Compared to unmanned ground vehicles, UAVs are less limited by difficult terrains and obstacles, have greater degrees of freedom, as well as larger field of vision. These features have led to applications in disaster monitoring, environment and traffic surveillance, search and rescue, aerial mapping and cinematography [1]. Furthermore, UAVs can serve as excellent platforms for testing advanced control theories such as state feedback control, fuzzy control and nonlinear control [2]–[5]. The classes of UAVs include fixed wing, vertical takeoff and landing (rotorcraft) and airships [6]. The rotorcraft class was chosen as the platform for exploration in this paper.

Driven by the rapid developments in sensors, microprocessors and actuators, UAVs can now be built smaller and lighter while at the same time having more advanced functions. Micro aerial vehicle (MAV) is the cumulative result of such developments and it has shown great potentials in wide range of research applications. Compared to conventional UAVs, MAVs are more agile due to their size and are thus able to meet the challenges of navigating through complicated indoor environments.

Indoor flight poses several unique challenges that are difficult to solve. Firstly, the indoor environment is GPS denied. Navigation techniques commonly employed on UAVs rely heavily on GPS for localization and path planning [7]. Examples of these include MicroPilot® and MicroKopter. Secondly, narrow spaces in indoor environments constraint the physical size of UAVs. As the carrying limit of an aircraft is proportional to its wingspan, this indirectly constraints the weight of sensors, processing elements and power supply that may be carried onboard. Lastly, electrical appliances and other modern day conveniences contribute to a noisy RF environment. This greatly diminishes the successfulness of a popular UAV design paradigm [8], [9], which is to offload processing to a ground control station (GCS) through a 2-way radio link. To demonstrate how each of these challenges may be overcome, the construction of a vision-enabled UAV is discussed in this paper. Vision-based navigation is used to replace GPS-based techniques. Furthermore, recent developments in microprocessors, sensors and actuators are used to achieve low take off weight and small physical profile.

In the design prior to current, the UAV, PetiteLion, operates by transmitting raw video footages during flight to a GCS for processing. The resulting navigation guidance is sent back *via* radio to the UAV [10]. This design, while successful in controlled environments, suffers from unreliable data link in more realistic deployments. In the updated design, KingLion, all critical processes are kept onboard to sidestep problems induced by noisy RF backdrops. Drawing from experience, additional sensors have been included and the design methodology has been improved upon. This UAV participated in the 2010 Singapore Amazing Flying Machine Competition (SAFMC) and won the Best Performance Award.

There are a few existing embedded vision processing systems being used on UAVs or other applications prior or on par to this work with varying degree of cost and

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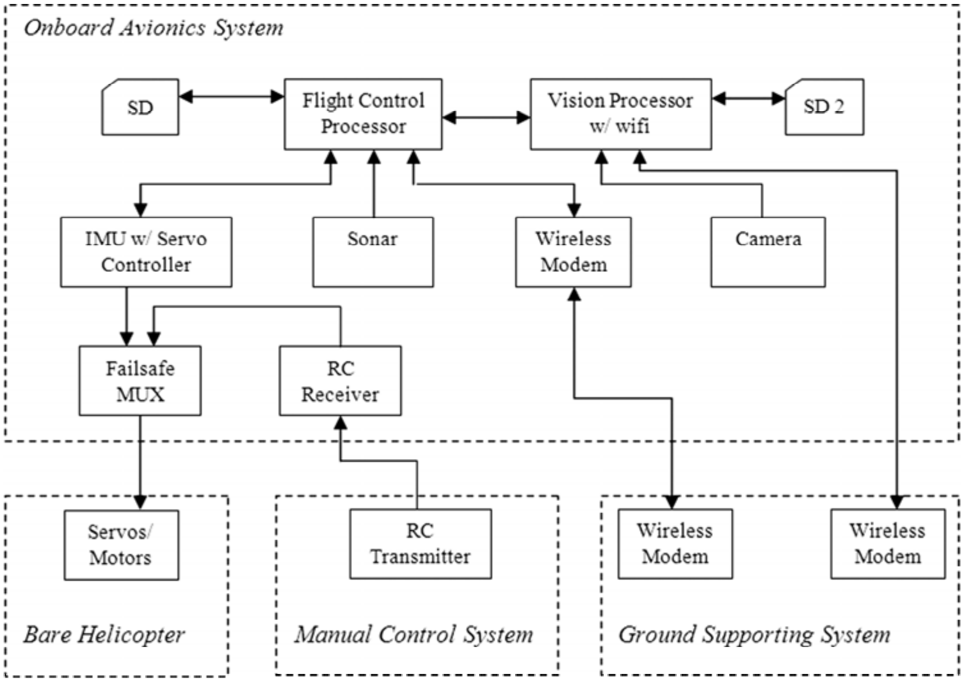


Figure 1. Overall working principle of the KingLion system.

capabilities. Examples include the PIXHAWK Pioneer, Acadia II and CMUcam3. Comparing to all these similar UAV platforms or embedded computer vision systems, this work is unique in the way that all hardware components are commercially off-the-shelf. Linux is used for software development and is freely available. Overall, the MAV is relatively low cost and reproducible.

The organization of this paper is as follows. Section 2 describes the hardware system design with focus on individual components. Then the embedded vision supported controller is described and analysed in Section 3. In Section 4, accuracy test results of the vision system and the real time flight performance results of the UAV are provided. Finally in Section 5, conclusions from all the above sections are drawn and possible future improvements are discussed.

2. Platform Design

According to [11], [12], a typical UAV consists of the following essential parts:

1. A physical aircraft with engines
2. An on-board avionic system to realize automatic flight control. This includes
   (a) An onboard processor to collect data, implements control laws, drives actuators and communication with ground stations;
   (b) An IMU to measure the attitudes of the vehicles;
   (c) A good communication system to provide communication link with ground stations; and
   (d) Power supply system sufficient to power up the whole UAV for a respectable duration.
3. GCS to monitor and schedule flight courses and to collect in-flight data.

Our UAV system is designed in a similar structure. However, less attention has been placed on GCS design as critical components are not dependent on it. The overall picture is shown in Fig. 1.

Table 1
Specifications of the Upgraded ESky Big Lama Co-Axial Helicopter

Specifications	Big Lama Co-Axial
Main rotor diameter	460 mm
Full length without tail	160 mm
Full width	110 mm
Weight	352 g
Maximum flight time	15 min

2.1 Bare Helicopter

A high quality RC helicopter, ESky Big Lama Co-Axial was chosen as the starting platform. It originally comes with normal brushed motors and a plastic swashplate. The following upgrades were made to improve payload and robustness of the platform to meet design requirements:

1. *Brushless DC motors*: Brushless motors have many advantages over the brushed motors. They have higher efficiency, better reliability and longer lifetime. In KingLion, two Brushless Motors rated at 3900 kV were used to increase the take-off weight of the helicopter from the original 500 g to 900 g.
2. *Shaft and swashplate*: Stronger shaft and metal swashplate were used to replace the original ones. This greatly reduces undesirable vibrations, especially when the helicopter carries heavy loads.

Some key physical parameters of the upgraded helicopter are listed in Table 1.

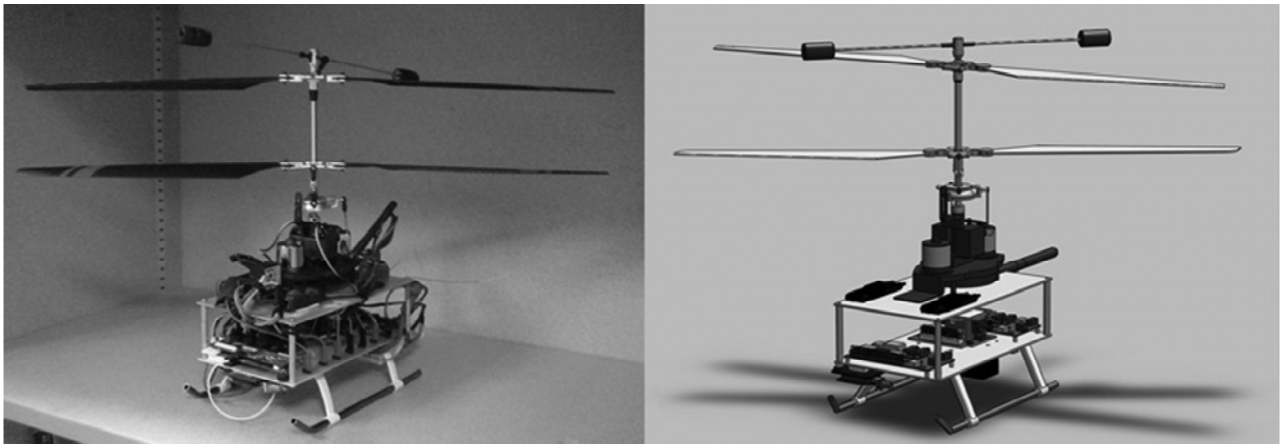


Figure 2. KingLion and its virtual counterpart.

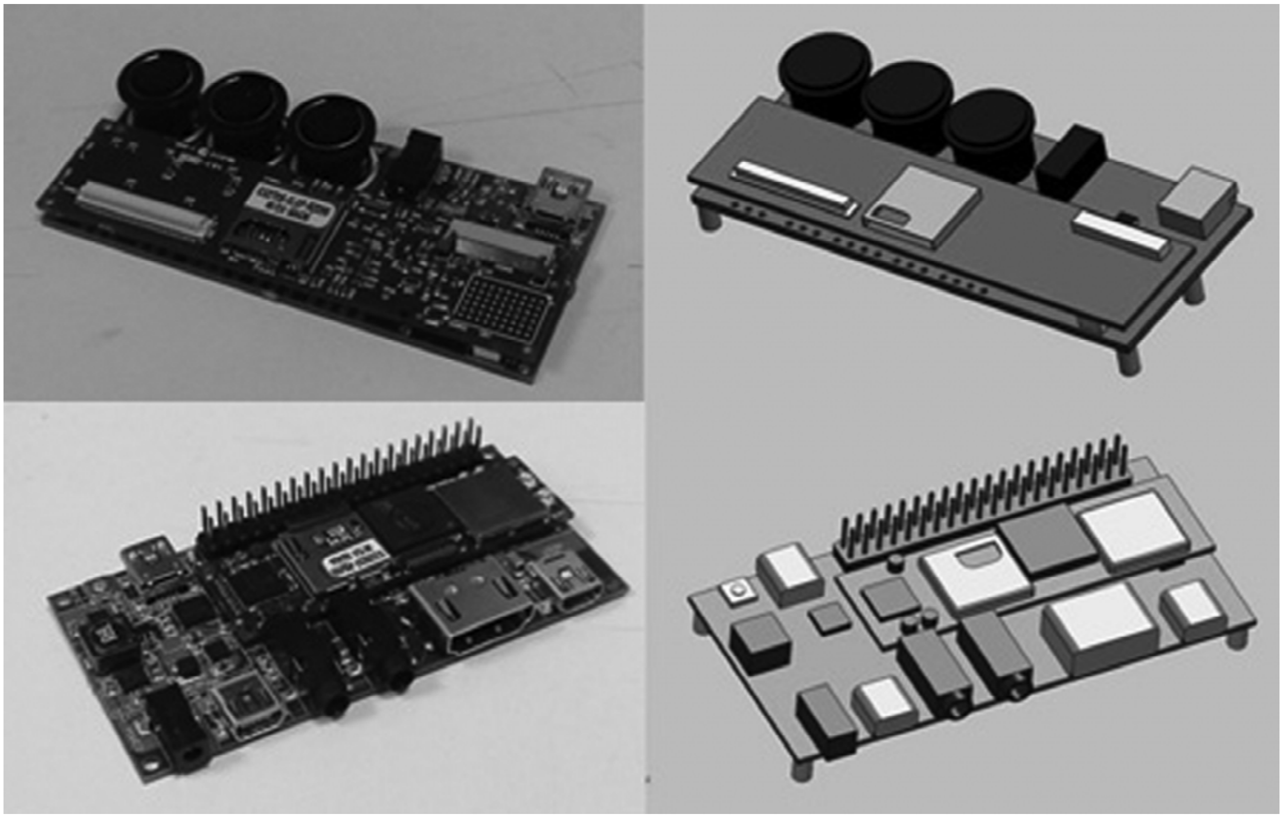


Figure 3. Gumstix Verdex Pro (left) and Gumstix Overo Fire (right).

2.2 Avionic System

At system level, the avionic system consists of a flight control processor, a vision navigation processor, an IMU with servo control capability, an ultrasonic range finder, a wireless modem and a web camera. Given the limited size and payload of the rotorcraft platform, weight and size of onboard components have to be minimized while guaranteeing performance. A survey on the state-of-the-art was conducted to source for the components. The selected components were further modelled in SolidWorks as shown in Fig. 2.

2.2.1 Embedded Computers

Being the brain of the whole system, the onboard embedded processor is the most important component. It collects data from various sensors, processes the data and sends information to the servo controller to execute the final control actions. Selecting suitable processors out of the available products in the market is crucial to ensuring a successful implementation of the UAV system.

Gumstix Verdex Pro (Fig. 3) was chosen as the onboard processor for implementing the flight control algorithm. Operating at a speed of 600 MHz, Gumstix Verdex Pro

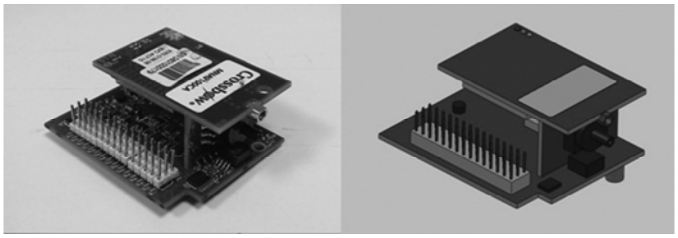


Figure 4. MNAV100CA.

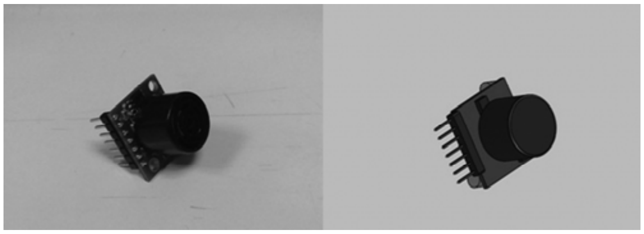


Figure 5. MaxSonar EZ4.

together with its expansion board (Gumstix consoleLCD-vx) weighs only 23 g. The expansion board has three RS-232 ports for interfacing with peripheral components. A 2 GB Multimedia Card (MMC) is inserted to the card slot to enable file transferring and flight data logging.

To realize vision based navigation, a high performance embedded computer is needed for vision processing. Gumstix Overo Fire coupled with its Overo Summit expansion board (Fig. 3) was chosen for this purpose. This unit has a 600 MHz main processor, a DSP coprocessor and a WiFi module. At the core of this system is a Texas Instruments OMAP3530 ARM processor and is one of the fastest low powered embedded systems as of writing. This unit is small in physical dimensions and weighs 18 g in total.

2.2.2 Inertia Measurement Unit and Servo Controller

IMU is the primary sensor for UAVs. It outputs linear accelerations and angular rates which are important raw measurements for stabilizing UAVs in flight. In this paper, the MNAV100CA was chosen (see Fig. 4). This module has a compact dimension of $5.72 \times 4.57 \times 2.54$ mm with the weight of 33 g. MNAV100CA is also embedded with a servo controller, which is able to drive up to 8 RC servos *via* PWM channels. It has a 3-pin RS-232 serial port which enables convenient communication with the onboard processor.

2.2.3 Ultrasonic Sonar Sensor

In this paper, an ultrasonic sonar sensor is used to measure the height of the UAV with reference to the ground. The MaxSonar EZ4 (Fig. 5) offers range detection and ranging in a small package of $19.9 \times 21.1 \times 16.4$ mm and 4.3 g. It is capable to detect objects and provides sonar range information ranging up to 645 cm with the resolution of 2.5 cm. It has three interface output formats – pulse width output, analog voltage output and asynchronous serial digital output.

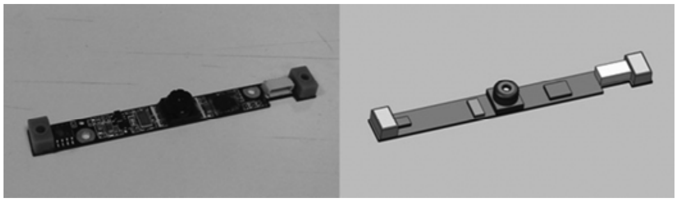


Figure 6. Onboard camera taken from HP Pavilion dv5 series laptop.

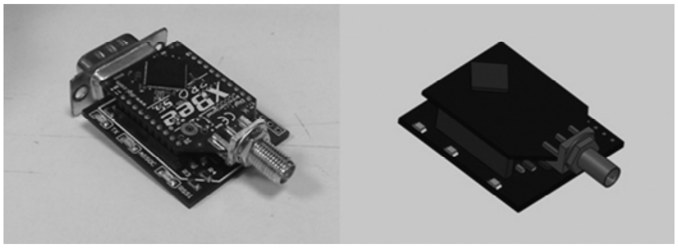


Figure 7. XBee-Pro wireless module.

2.2.4 Onboard Camera

A camera is used to capture video for navigation guidance. A HP Pavilion DV5 series laptop webcam module (Fig. 6) was chosen to be mounted under the UAV. This colour CMOS camera has a dimensions of $8 \times 80 \times 6$ mm and weight of 3 g. Despite its small size, it is capable for providing 30 FPS at 320×240 resolutions. It is mounted below the platform of the UAV body and faces vertically downwards.

2.2.5 Wireless Communication Modules

Wireless communication modules are needed to form communication links between the onboard systems and the GCS. A pair of Xbee-Pro OEM RF modules is used to establish the data link between the onboard flight control system and the GCS, while the built-in WiFi module in Gumstix Overo is used to establish the video link between the onboard vision system and the GCS. XBee-Pro wireless module (Fig. 7) operates at 2.4 GHz. Its indoor range of 100 m and miniature size of 24.4×32.9 mm makes it an ideal wireless module to be implemented in the UAV.

2.3 Ground Control Station

The GCS incorporates a personal computer running GNU/Linux. It wirelessly gives high-level commands and collects in-flight data from the onboard system for monitoring purpose. Live video streaming from the camera on the UAV will be sent back at a reasonable frame rate and displayed for observation and debugging.

3. Vision Supported Controller

3.1 Vision Processing

The simple mission given to the UAV was to follow a track that has been painted on the ground. As seen in Fig. 8, the track is formed by the primary colours red, green and

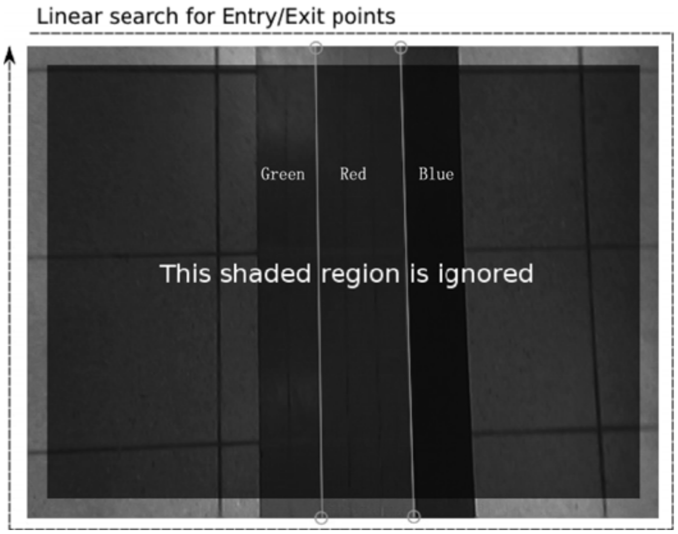


Figure 8. Path detection strategy that saves computation time by focusing its search on the image perimeter.

blue. The different colours allow an observer to distinguish right from left, forwards from backwards.

The algorithm designed for PetiteLion leveraged on large amounts of processing resources available on the GCS. In the updated design, the algorithm had to be redesigned to meet processing constraints of the embedded system.

The key idea behind simplifying computation is to focus on a small strip of pixels that make up the frame of the image. By finding the points of intersection between the tracks and the image frame, the rest of the track that lies within the image body may be interpolated (see Fig. 8).

To realize this strategy, the pixels forming the image frame are stripped and unwrapped to form a single row of pixels. This strip is segmented using edge detection and each segment is assigned a colour through a colour classifier. The problem of finding points of intersection thus reduces to matching the colour pattern of the track to the colour pattern in the segments. This can be accomplished by a simple state machine.

The chosen edge detection algorithm is colour edge detection with adaptive thresholding as proposed in [13]. An improved measure of edge strength was introduced to reduce effects of colour bleeding typical of low-cost plastic optics. Instead of computing the difference in pixel value of its immediate neighbour, pixels in the wider neighbourhood are also used. Suppose $I_x = [R_x \quad G_x \quad B_x]^T$ be the RGB value at x, edge strength is defined as:

$$D_x = \lfloor \max\left[\left|I_x - I_{x+1}\right|, \left|I_x - I_{x+2}\right|\right] \rfloor \tag{1}$$

Determination of the threshold value follows the original scheme of maximizing entropy. The pixels are divided into two sets. Those passing the threshold, $\{E \in D | D \geq T\}$, forms an edge while those falling below the threshold, $\{\overline{E} \in D | D < T\}$, do not belong to an edge. A good threshold value, $\hat{T}$, is sought by maximizing the total information in these two sets:

$$\hat{T} = \arg\max_{T} \left(H(E_T) + H(\overline{E_T})\right) \tag{2}$$

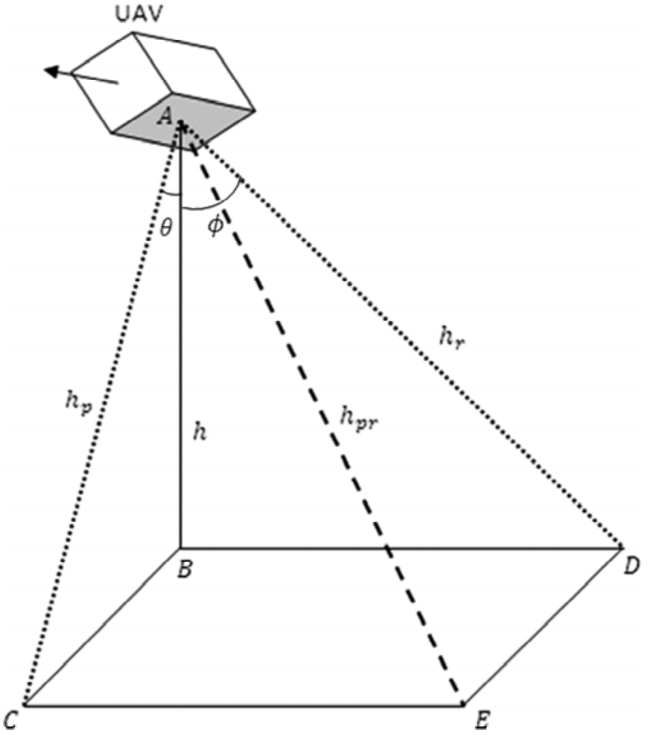


Figure 9. The error in measuring actual height.

Information is quantified using the well-known Shannon's entropy measure:

$$H(X) = -\sum_{i=1} P(x_i) \log_2(P(x_i)) \tag{3}$$

At first glance, this is a tedious operation. However, common terms in computing $H(E_T)$ and $H(\overline{E_T})$ can be factored out. This leads to a $O(n)$ implementation where n is the search space for $\hat{T}$.

3.2 Data Filtering and Correction

To enhance the flying performance of KingLion, all sensor measurements are filtered and compensated. There are three main sensors on KingLion, namely IMU, sonar and camera.

3.2.1 IMU

Accumulation of angular rates, $(\omega_x,\ \omega_y,\ \omega_z)$, leads to drift errors when used to determined the Euler angles that describe the attitude of the UAV. Extended Kalman filter is used to combine angular rates, magnetometer reading and linear acceleration to achieve an optimal estimate of Euler angles.

3.2.2 Ultrasonic Range Finder

Sonar is used to measure the vertical position of the UAV with respect to the ground. Experimental results show that high frequency noise is present in the measurement. Hence, a simple first order low pass filter with cut-off frequency at 5 Hz was designed and implemented.

Besides the low pass filter, a compensator is used to overcome the measurement error caused by pitch and roll of the UAV. As shown in Fig. 9, the apparent height, h_{pr},

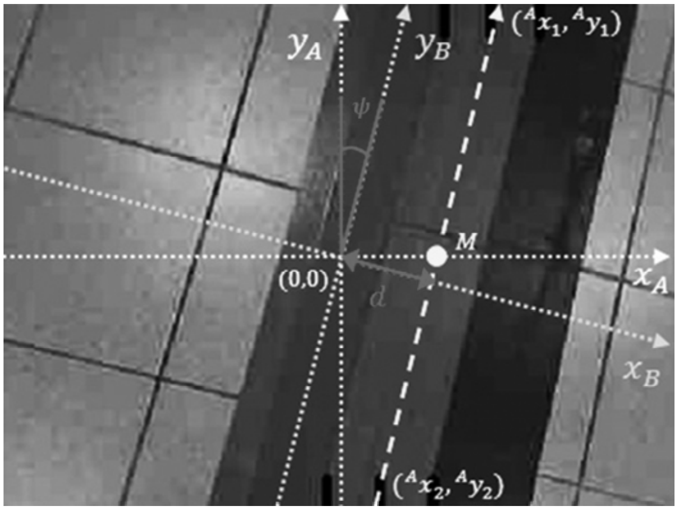


Figure 10. The assigned frames for easy calculation of heading angle and lateral position.

of the UAV is larger when it pitches or rolls. Taking pitch and roll of angle as θ and ϕ, respectively, the actual height can then be recovered using:

$$h = \frac{h_{pr}}{\sqrt{1+\tan^2\theta+\tan^2\phi}} \tag{4}$$

3.2.3 Vision-Based Measurement

Vision sensor provides the location of the coloured track in unit pixel. Two coordinates, (A_{x_1}, A_{y_1}) and (A_{x_2}, A_{y_2}) are communicated across the navigation and flight control subsystems. They correspond to the midpoints of the track in the forward and backward direction, respectively (see Fig 10). Based on these two coordinates, the heading and lateral position of the UAV with respect to the track are calculated. Two reference frames are used in the computation (see Fig. 10). Frame A represents the body frame of the UAV with x_A-axis pointed to the right and y_A-axis pointed to the front of the UAV. Frame B has y_B-axis pointing in the forward direction of the coloured track. Heading angle, ψ, and lateral distance, d, are obtained by:

$$\psi = a\tan 2(A_{x_1} - A_{x_2}, A_{y_1} - A_{y_2}) \tag{5}$$

$$d = \frac{1}{2}\left[(A_{x_1} + A_{x_2})\cos\psi - (A_{y_1} + A_{y_2})\sin\psi\right] \tag{6}$$

Similar to height measurements, a compensator is used to correct the error introduced by roll deviation. The lateral position measurement is affected by the roll angle (ϕ) as shown in Fig. 11. The error caused by roll, e, is

$$e = h \times \tan\phi \tag{7}$$

where h is the current height of the UAV.

The actual position of the coloured track is recovered by subtracting the error term.

3.3 Control Law Design

The flight control laws were developed on the assumption that sensor measurements have been corrected for, as outlined in previous sections. As the UAV is designed to fly in near-hovering conditions with minimal pitch and roll deviations, yaw, pitch and roll motions of the UAV are

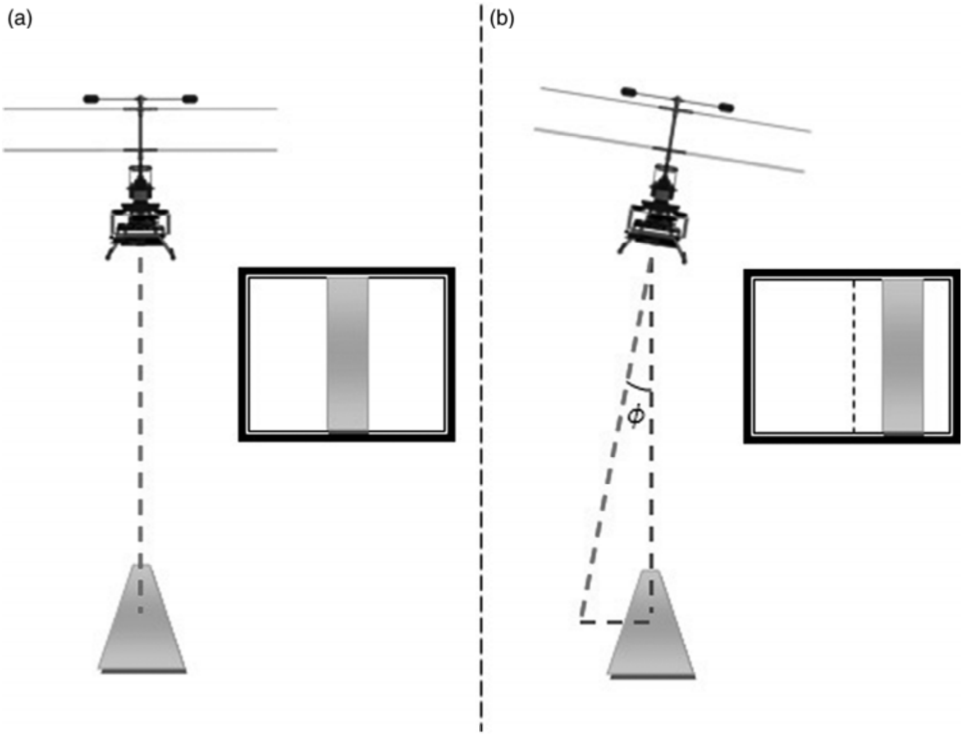


Figure 11. (a) Without roll tilt and (b) with roll tilt.

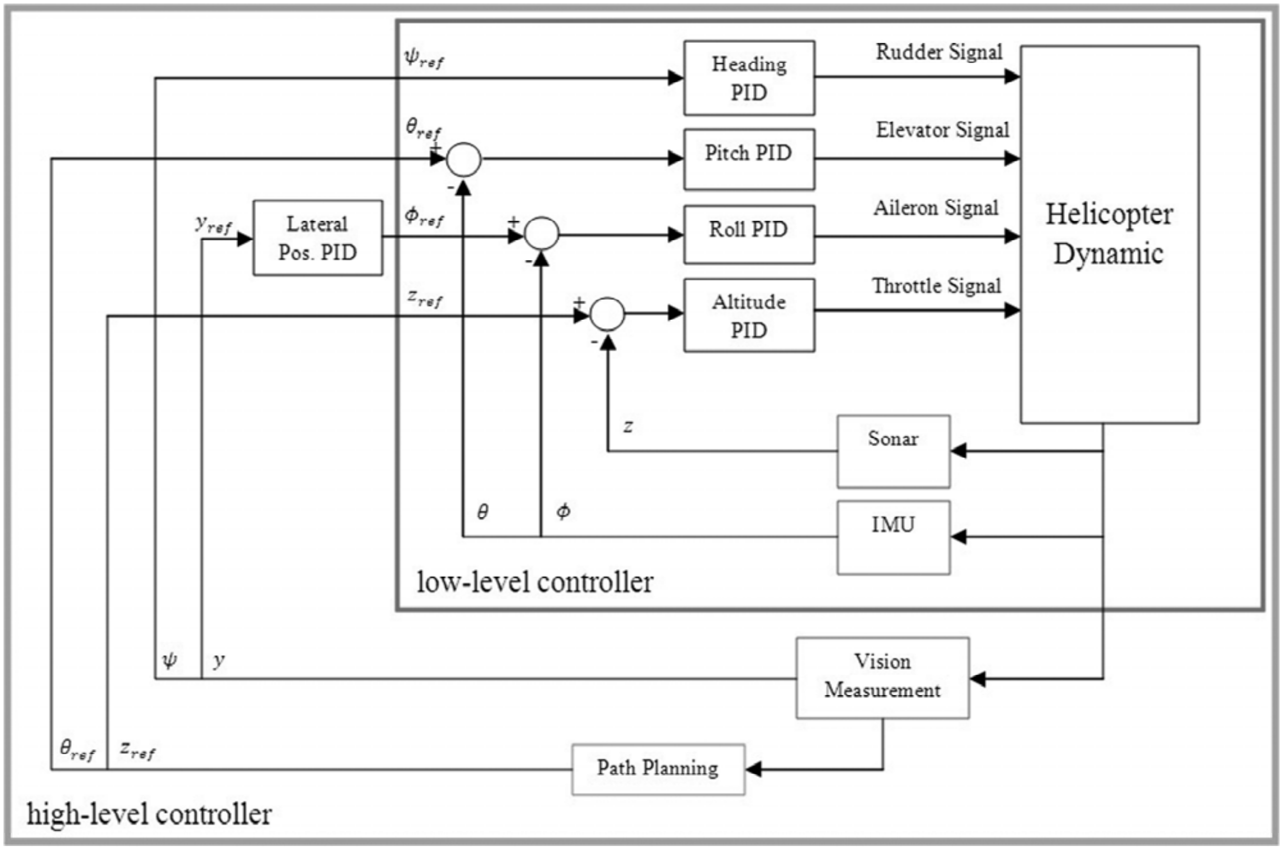


Figure 12. Overall control block diagram of KingLion.

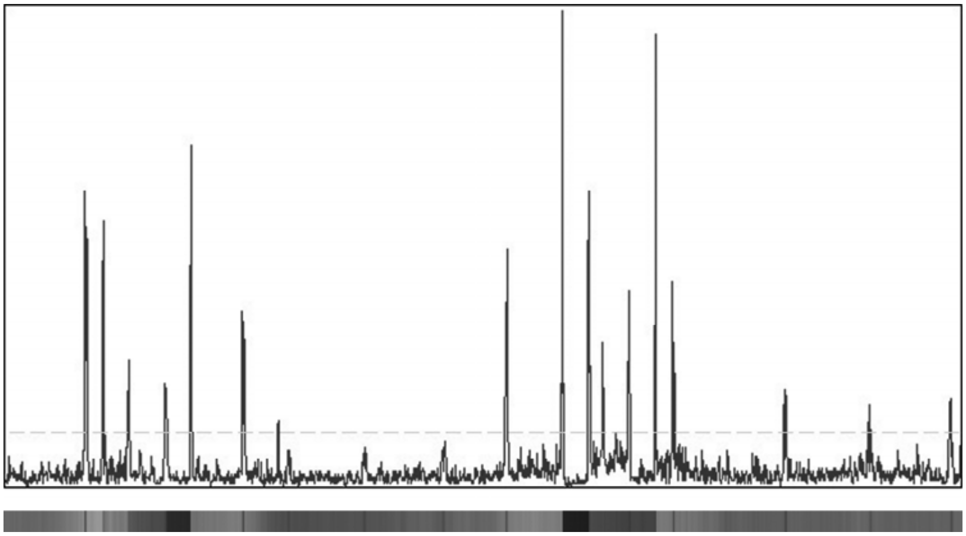


Figure 13. Image strip and corresponding strength of each location as an edge. The horizontal dashed line denotes the optimal threshold.

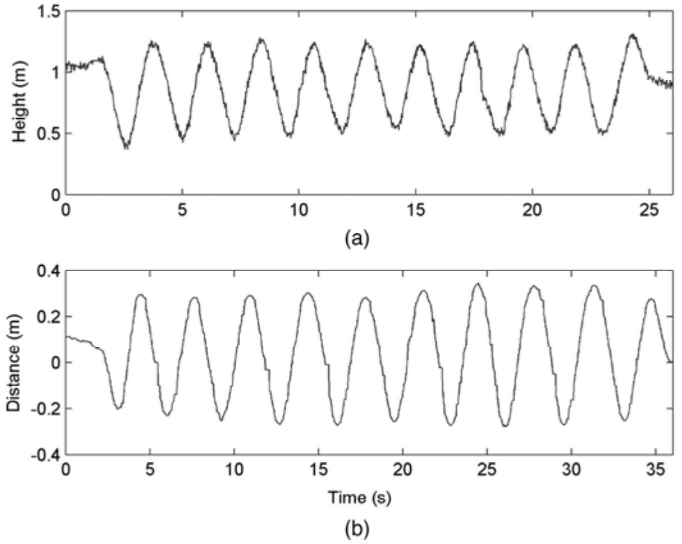


Figure 14. (a) height measured by the sonar range finder under oscillation motion. (b) lateral position calculated by the vision algorithms under oscillation motion.

assumed to be decoupled. Three PID controllers were used for each axis of motion.

The flight control algorithm comprises of two portions: the low- and the high-level controller. IMU sensors provide feedback to the low-level controller to stabilize the UAV, while vision measurements provide feedback to the high-level controller to adjust the heading and position of the UAV. The overall control system of the UAV is summarized in Fig. 12.

Once the control law has been implemented, it has to be translated into software language to run on the onboard processor. An open source autopilot software – MicroGear – is utilized. MicroGear is an aerial robotics application that is robust, highly capable, highly configurable and interfaceable. Along with high levels of capability, MicroGear focuses on robustness, high performance, and minimal memory and disk footprints, which is an obvious advantage over the other autopilot softwares. The original MicroGear was modified to adapt to KingLion. It uses polling method to obtain data from individual components. The main loop runs precisely at 50 Hz rate. The

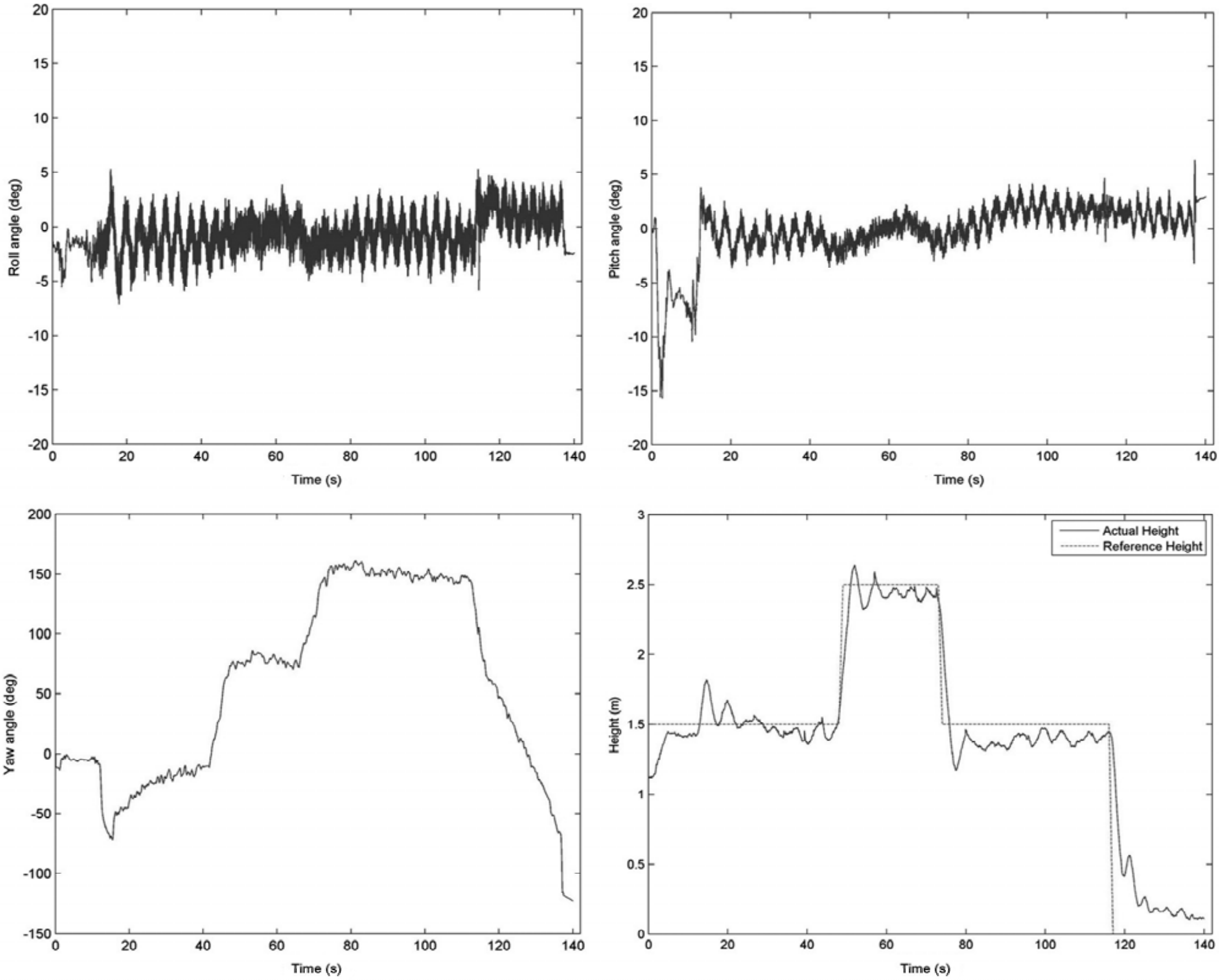


Figure 15. Euler angles and height of KingLion measured by sonar sensor during the flight test.

code will access data received from the IMU at every loop, the ultrasonic sonar sensor every two loops and the vision processor every three loops. As for path planning, control decisions will be accessed on demand.

For the ease of tuning the PID controllers, an XML file in the MicroGear package is modified to include the parameters of individual PID controllers. When the program starts, it will read in the parameters from the XML file and assign them to each individual controllers. Thus, it saves the effort of re-compiling of the whole program.

4. Experimental Result

4.1 Accuracy Tests

Several tests have been carried out to examine the accuracy of sensors (after filtering) and to verify the overall flight control methodology. Test results for each category are presented as follows.

1. *Path Detection*: Adaptive colour edge detection is applied to a thin strip around a camera frame. Figure 13 shows the edge strength of each pixel, intersected by the optimal threshold computed. The algorithm efficiently distinguishes edges from non-edges with only one false alarm.
2. *Height Measurement*: A simple experiment is carried out to verify the height measurements from the ultrasonic sonar sensor. It is done by manually oscillating the UAV position with respect to ground. Figure 14(a) shows that the measurement result are generally accurate since there is no abrupt changes between any consecutive data point on the curve.
3. *Lateral Position Based on Vision*: A similar experiment is done to verify the accuracy of vision-based positioning. The UAV is displaced laterally above the coloured track in a oscillatory motion. The distance from the coloured track is plotted in Fig. 14(b). The result shows that the lateral positions calculated by the image processing algorithm is accurate without any unbearable noise.

4.2 Flight Test

Flight tests were carried out in an indoor environment. KingLion was hand lauched and performed navigation by following the coloured track on the ground. The Euler angles and the height of the UAV were recorded by the onboard computer. Figure 15 shows the height and Euler angles of the UAV during the flight test.

In this flight test, while following the track on the ground, KingLion was also programmed to fly at different heights after each cornering. Note that the UAV was launched at $t = 10\,\mathrm{s}$. It underwent two right turns at $t = 44\,\mathrm{s}$ and $85\,\mathrm{s}$ and a final left turn at $t = 113\,\mathrm{s}$. The video clip captured during the above mentioned flight test is available at the NUS UAV group's website: http://uav.ece.nus.edu.sg/video/Door-Best%20Height-Object-Landing.mpg.

5. Conclusion

This paper has summarized the design and construction methodology of an indoor UAV rotorcraft, KingLion, with onboard vision functionality. From a simple RC co-axial helicopter, essential avionic components were added to the platform to enable fully autonomous flight. Choices of major hardware components have been explained and reasoned. Vision processing algorithms such as the fast path detection method have been discussed in detail. With all sensor measurements filtered and refined, the overall control strategy has also been shown. The performance of the UAV system has been verified through experiments and actual flight tests. Possible future improvements include more advanced control law design and hardware upgrades. As technology advances, better processors, sensors and actuators can be used to improve the performance of the UAV while further reducing its size and weight. In the near future, this UAV system is expected to perform more complicated indoor navigation tasks such as obstacle avoidance and environmental mapping.

References

[1] Z. Sarris, Survey of UAV applications in civil markets, *Proc. 9th Mediterranean Conf. Control and Automation*, Dubrovnik, Croatia, 2001.

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

[3] S.A. Bortoff, The University of Toronto RC helicopter: A testbed for nonlinear control, *Proc. 1999 IEEE International Conf. Control Applications*, Honolulu, Hawaii, 1999, 333–338.

[4] J. Yao, X. Zhu, and Z. Zhou, The design of sliding mode control system based on backstepping theory for BTT UAV, *Control and Intelligent Systems*, *36*(4), 2008, 347–354.

[5] M. Saffarian and F. Fahimi, A model predictive framework for autonomous 3D formation flight of helicopter groups, *Control and Intelligent Systems*, *37*(4), 2009, 220–226.

[6] M. Sugeno, I. Hirano, S. Nakamura, and S. Kotsu, Development of an intelligent unmanned helicopter, *Proc. 1995 IEEE International Conf. Fuzzy Systems*, *5*, Yokohama, Japan, 2007, 34–35.

[7] H. Chao, Y. Cao, and Y.Q. Chen, Autopilots for small fixed-wing unmanned air vehicles: A survey, *Proc. 2007 IEEE International Conf. Mechatronics and Automation*, Harbin, China, 2007, 3144–3149.

[8] R.J.D. Moore, S. Thurrowgood, D. Bland, D. Soccol, and M.V. Srinivasan, A stereo vision system for UAV guidance, *Proc. 2009 IEEE International Conf. Intelligent Robots and Systems*, October 2009, 3386–3391.

[9] A. Cesetti, E. Frontoni, A. Mancini, P. Zingaretti, and S. Longhi, A visionbased guidance system for UAV navigation and safe landing using natural landmarks, *Journal of Intelligent and Robotic Systems: Theory and Applications*, *57*, 2010, 233–257.

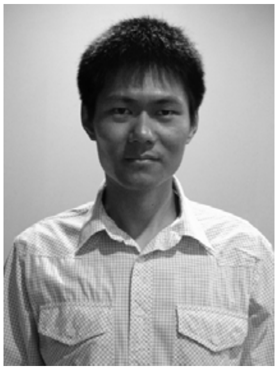
[10] F. Wang, T. Wang, B.M. Chen, and T.H. Lee, An indoor unmanned coaxial rotorcraft system with vision positioning, *Proc. 8th IEEE International Conf. Control and Automation*, Xiamen, China, 2010, 291–296.

[11] G. Cai, K. Peng, B.M. Chen, and T.H. Lee, Design and assembling of a uav helicopter system, *Proc. 5th IEEE International Conf. Control and Automation*, *2*, 2005, 697–702.

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

[13] R. Ji, B. Kong, F. Zheng, and J. Gao, Colour edge detection based on yuv space and minimal spanning tree, *Proc. 2006 IEEE International Conf. Information Acquisition*, 2006, 941–945.

Biographies



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