Research and Practice of a 30-class Autonomous Helicopter System

Tan Li and Jia Pie-fa

Abstract- **This paper introduces an autonomous helicopter research platform, with a customized avionics system based on embedded computing and MEMS (Micro Electro-Mechanical Systems) sensor technology. Both the weight and volume of the avionics system are small enough to be carried by a normal 30-class model helicopter. The control scheme and the experimental results of the elementary flight modes control are presented. Furthermore, real flight experiments validated the feasibility of the system design. Some of the problems that we encountered, such as vibration, attitude estimation, and some 'zero value' problems were solved in the process of designing and testing.**

Index Terms—**avionics system, elementary flight modes control, small autonomous helicopter**

I. Introduction

The small autonomous helicopter has become a hotspot in the area of robotics research since the break through of some crucial technical bottlenecks[0] in the 1990s, especially in the area of sensor, computer, and satellite positioning technology. After 20 years of research and development, there have been many successful examples, and some of them have been used in practical applications such as air photography and scientific inspection.

Looking into the existing systems, e.g., [1]-[3], we can find out that the researchers generally bought some COTS (Commercial Off The Shelf) products in the market, and assembled them so that they can construct a system rapidly and realize the elementary fight modes control in a short period of time, after which they can focus on other topics such as path planning, task planning, objects identification, and multi-helicopter cooperation.

Generally speaking, the weight of the existing avionics systems is more than 2 kilograms. As such, the airframes must be big enough to carry them. The characters of these systems can be summarized as follows:

(1) The airframes are 50-class or bigger helicopters, and sometimes the helicopters need to be modified, such as using a more powerful engine and longer propellers to carry the onboard equipments; and

(2) The sensor system includes high performance inertial navigations systems, differential GPS, and others sensors.

However, building such a system costs at least $10,000 even if the possible damage in the flight experiment is not taken into account. This is too expensive for some interested researchers and future users.

For this reason, we developed all the main hardware and software to be used in a small autonomous helicopter research platform. It is noteworthy to state that the cost of the hardware is less than 10% of that of the previous systems. The avionics system is based on embedded computing and MEMS sensor technology. Likewise, the GPS receiver that we adopted is a single point one. Moreover, all of the onboard equipments are small and light enough to be carried by a normal 30-class helicopter.

The previously existing avionics system is too heavy to be carried by a 30-class helicopter. In contrast, the avionics of this system can also be applied to bigger helicopters. It is well-known that effective payload is a very important factor for an aircraft, and being able to increase one gram of effective payload indeed offers very exciting possibilities. In this system, the weight of the avionics system is only about 500 grams. Compared with the existing systems, the weight of the avionics system decreased by 75%, and as a result, the autonomous helicopter that used our system can carry more effective payloads.

To our knowledge, this kind of avionics system had never been successfully applied in a small autonomous helicopter before. However, we also cannot confirm that it will work well in autonomous flight control before the real flight experiment. After all, the performance of the customized equipments is not

Fig.1 A 30-class autonomous helicopter in hovering

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ISBN:978-988-98671-6-4

so good compared with the COTS products. Fortunately, all the experimental results verified the feasibility of our system design and implementation. Currently, the helicopter can stabilize itself and do some basic flight actions autonomously.

II. SYSTEM ARCHITECHTURE

The system consists of the airframe, a servo control board, a sensor board, a control computer board, a vision and a communication computer board, a ground station, and a remote controller.

The airframe adopted is an unmodified Thunder Tiger Raptor V2 30-class helicopter whose shape is 1150mm x 400mm x 140mm, with the diameter of the main rotor and tail rotor at 1245mm and 237mm, respectively. The helicopter is powered by a 0.36 cubic-inch glow plug engine, with an empty take-off weight at 2950grams and a payload of about 500grams. As the 30-class model is the smallest outdoor helicopter, it is thus a challenge to design an avionics system for it.

The servo control board is based on an AVR processor, and it can convert the digital control signals from the control board to PWM(Pulse-Width Modulation) signals in order to drive the servos or receive the signals from the remote controller. The board can also switch between automatic control mode and manual control mode. In addition, samples of the PWM signals in manual control mode can be obtained and recorded to facilitate system analysis and synthesis. Another important function of this board is that the auto/manual control mode of each servo can be set up separately. Consequently, some servos can be controlled by hand and the others by computer. This function is very useful when tuning the control parameters.

The control computer is based on an Intel XScale PXA255 processor. Its main frequency is 400MHz, with a memory which includes 64MB SDRAM and 32MB flash. The OS (Operation System) is uC/OS-II, which is a strong real-time OS. The processor's synchronous serial port connects the output of the sensor system, an asynchronous port connects the GPS receiver, another one connects the communication board, and some GPIO ports are used to drive the ultrasonic sensor and receive the result. The control computer receives the sensor outputs, and then performs the computation to get the flight parameters and the feedback control gains based on the estimation and control algorithm. Afterwards, the control signals are sent to the servo control board.

The vision and communication computer is also based on PXA255 and has Linux for its OS. A USB port and a PCMCIA port are used to connect to the camera and to the wireless Ethernet card, respectively. The board simultaneously communicates with the ground station, sends the measured data, receives the command messages from the ground station, and processes the real-time vision information at the same time.

The sensor systems based on MEMS devices have been studied for a couple of years, and there have been some products in the market. However, to the authors' knowledge, none of them had been successfully used on small autonomous helicopters until now. The main reason for this could be that some devices cannot work properly in such a seriously vibrational environment on a small helicopter in flight, or that the precision of the measured data is not so good for flight control. By recursive design and test, a sensor system based on MEMS devices which can provide enough information for small helicopter control is developed. The total weight of the board is less than 100 grams, a value which can be carried easily by a normal 30-class helicopter. The sensor subsystem includes gyroscopes, accelerometers, magnetic sensors, an ultrasonic altimeter and a single point GPS receiver.

The ground station is a notebook PC running a Windows OS. The software, which is developed by Delphi, can display and record the flight data downloaded from the communication board, and upload the commands such as flight control parameters and modes setting. The 3D flight path can also be displayed in real-time.

III. ELEMENTARY FLIGHT MODES CONTROL

The hardware and software have been tested in static environment and the results are satisfying. However, it is still not known whether or not they can work well in a dynamics environment. Thus, a series of experiments are performed to test the system in real flight state. At this stage, the purpose of the experiments is just to testify the validity and feasibility of system design. Consequently, the flight modes are the elementary ones and the control algorithm is a simple one.

Elementary flight modes include: hovering, taking off and landing, ascending and descending, forward, backward, left and right flight, and turning.

The helicopter is a MIMO (Multi-Input Multi-Output), time-varying, strongly coupled complex system, but can be linearized and the coupling can be ignored when it flies near hovering. Thus, the helicopter can be seen as system composed of several SISO (Single-Input Single-Output) channels which can be controlled separately. Here, a PID (Proportional-Integral-Differential) controller is developed to control the four servo channels.

Hovering is a very useful flight mode used by helicopters. The control scheme is:

$$\begin{cases} u_a = -K_\phi(\phi-\phi_0) - K_p p - -K_{pi}\sum(\phi-\phi_0) - K_v v - K_y(y-y_0) \\ u_b = -K_\theta(\theta-\theta_0) - K_q q - K_{qi}\sum(\theta-\theta_0) - K_u u - K_x(x-x_0) \\ u_M = -K_w w - K_z(z-z_0) \\ u_T = -K_\psi(\psi-\psi_0) \end{cases}$$

Where u_a, u_b, u_T, u_M are the servo control signals; ϕ, θ, ψ are the Eular angles; ϕ_0, θ_0, ψ_0 are the expected values of the Eular angles; p, q and r are the angle rate; u, v and w are the velocity; x, y, z are the positions; and x_0, y_0, z_0 are their expected values.

Figure 2 is a group of experimental data of hovering. As can be seen, the Eular angles vary in an interval of 10 degrees, and positions vary in an interval of 2 meters. This is because the helicopter is an unstable system itself, and it is impossible for a

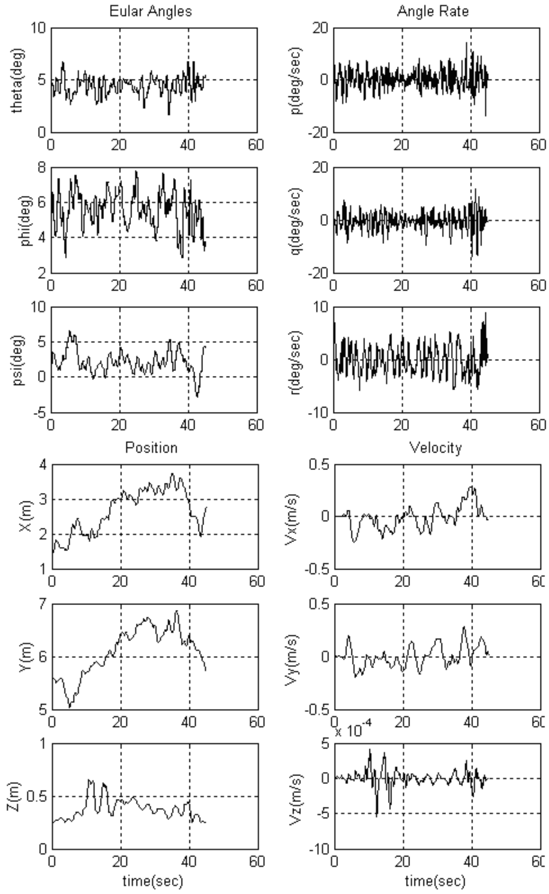

Fig. 2 A group of experimental data in hovering
(Eular angle, angle rate, velocity, and position)

helicopter to stay at a fixed attitude while hovering. In addition, the total weight of this system is only about 3.5kilograms, and its inertia is very small. As a result, it is very easy for the helicopter to deviate from the balance point.

Hovering control is the basis of other flight modes. Based on it, ascending and descending control just need to change the value of the throttle control signal. Taking off and landing control are alike. It must be noticed, however, that the balance point of the attitude angles on the ground may not be equal to the ones in the air. If they vary too much, an accident might happen while taking off and landing. Therefore, the landing gears should be adjusted to avoid any damage.

On the other hand, control of forward, backward, left, and right flight is implemented by tuning velocity feedback gain. Compared with hovering control, the position feedback is cut. To take forward flight as an example, the pitch channel control scheme is:

$$u_b = -K_\theta(\theta-\theta_0) - K_q q - K_{qi}\sum(\theta-\theta_0) - K_u(u-u_0)$$

where, u_0 is the expected velocity of forward flight.

In addition, turning control just needs to change the expected yaw angle.

All the real flight experiments are successful. The helicopter can now hover, move, and turn autonomously. The experiments indicate that the avionics system is feasible for an autonomous helicopter research platform.

IV. Problems and Solutions

An autonomous helicopter is a complex system. During our experiments, some problems were met and solved in the recursive process of design and test.

A. Vibration

The turning rotors and running engine actually cause serious vibration. For a smaller airframe, the effect of vibration to the avionics equipments is comparatively more severe, as can be found out from the experimental data which shows that the basic vibration frequency is about 25Hz. In addition, the magnitude of vibrational acceleration and angle rate are about 0.5g and 100°/s, respectively, when the helicopter is flying smoothly. If the flight mode changes rapidly then the vibration becomes more serious.

When working in such a vibrational environment, the main part of the measured data of the inertial devices is noise. The useful signal is corrupted by the noise, such that the devices may fail to work sometimes. In addition, the wireless communication signal is corrupted as well, and as a result, some data frames might be lost.

Some researchers have already paid attention to vibration problems and proposed some solutions [4]. The generally used vibration isolation materials are foam, rubber, spring, sponge and the like. Though all these materials were tried on this system, none of them had any effect. Essentially, all these methods depend on the inertial of equipments. However, the equipments of this system are too light to be isolated, making it very difficult to find the suitable material. Moreover, even if suitable materials are found, they must be very soft which might make the sensors less sensitive. Thus, the solution to the vibration problem of this system must depend on the devices themselves. In the process of system design and test, the hardest work is finding the appropriate accelerometer. As is known, most of the MEMS accelerometers in the market are based on differential capacitor. In this study, three of them are tested but none were found to work. Finally, it is found out that a piezoelectricity resistance-based accelerometer works well, and as such the problem is now considered solved.

The strapdown navigation system must be fixed on the airframe, but other equipment need not be so. Thus the communication board is suspended by rubber ropes behind the oil box in order to isolate it.

B. Attitude Estimation

Attitude estimation is the basis and premise of flight control. However, there exist some problems such as small inertial of the system, serious vibration and comparatively less sensitive sensors. All these make it difficult to estimate the attitude angles.

Meanwhile, the main sensors of attitude measurement are gyroscopes. However, the measurement error of the gyroscope increases as time goes on. The case is more remarkable for MEMS gyroscopes. For example, the static drift of the gyroscopes used in this system is about 10 degree per minute. An effective method should be taken to restrain the drift. Here, the accelerometers and magnetic sensors serve as measurement basis for pitch, roll, and yaw angles, and complementary filters [5] are used to combine the information.

Traditionally, the Kalman filter is generally used in sensor fusion. However, the complementary filter needs less calculation which is very important in real-time systems. Meanwhile, simulation and comparison have been made between the two filters, which indicate that the results are alike in this system.

C. *'Zero Values'*

There are some problems about 'zero value' which are important to autonomous flight.

The center of gravity of the airframe is on the axis of the main rotor. The case might change if the onboard equipments are not mounted properly which would, in turn, deteriorate the stability of the system. For this reason, the mounting position should be adjusted to avoid it. In this system, the GPS antenna is mounted on the nose part, while the vision and communication board is placed behind the oil box. On the other hand, the sensor and control boards are placed beneath the engine whose position can be adjusted to ensure the center of gravity on the expected axis.

The zero values of the servos often vary between manual and automatic control mode in this system, and as such, one of them should be tuned to avoid servos jumping in mode switching.

It can be found out that the pitch and roll angle are not always zero in the hovering mode because of mounting errors, so the expected values of the attitude angles must be tuned elaborately in the experiment. In addition, this work must be repeated whenever the equipments are mounted.

Some of the devices have startup errors which mean that the output values change whenever they are started up even if the environment does not change. For example, the static output value of a gyroscope changes when it is turned off and on repeatedly. The error may be related with the devices themselves, the A/D converter, or the amplifier. The simplest solution to this problem is to calculate the average value of the output after startup. These errors can also be treated as states of the Kalman filter.

V. Conclusion

The small autonomous helicopter is a versatile aerial robot. There have been many successful examples that were brought to light, but the existing avionics systems are very heavy and expensive. In this study, a 30-class model helicopter based system is developed as a small autonomous helicopter research platform. By using embedded computing, MEMS sensor, and other advanced technologies, an avionics system which is small and light with low power consumption is developed. Due to the decrease in costs, this system would dramatically favor popularization and research.

The 30-class helicopter with the small payload is the smallest one which can fly outdoors. Its size makes the system design and synthesis more difficult compared with other existing systems. The customized avionics of this system is light enough to be carried by a normal 30-class model helicopter, and it can also save more space for effective payloads such as camera and infrared equipments. However, its low-cost and low-weight scheme compromises measurement precision. Nevertheless, according to the authors' knowledge, there were no successful examples previously presented. As such, the system must be tested in practice. Experimental results which indicate that the equipment does well in autonomous flight control are presented.

The flight control parameters are tuned in real flight experiments. Although the helicopter can fly by being autonomously controlled by a PID controller now, the flight performance is not so good compared with a manually controlled helicopter. As the helicopter is a complex system, a simple PID controller and the hand-tuned parameters may confine the helicopter and not allow full utilization. As such, a mathematical model will be developed, and some advanced control schemes will be used to improve flight performance.

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