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Design, Implement and Testing of a Rotorcraft UAV System

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1. Introduction

Unmanned aerial vehicles (UAV) are useful for many applications where human intervention is considered difficult or dangerous. Traditionally, the fixed-wing UAV has been served as the unit for these dangerous tasks because the control is easy. Rotorcraft UAV (RUAV), on the other hand, can operate in many different flight modes which the fixed-wing one is unable to achieve, such as vertical take-off/landing, hovering, lateral flight, pirouette, and bank-to-turn. Due to the versatility in maneuverability, helicopters are capable to fly in and out of restricted areas and hover efficiently for long periods of time. These characteristics make RUAV applicable for many military and civil applications.
However, the control of RUAV is difficult. Although some control algorithms have been proposed (Sanders et al., 1998, Garratt et al., 2003, Enns et al., 2000, Bijnens et al., 2005, Koo et al., 1998, Jiang et al., 2006), most of them were verified by simulation instead of real experiments. One reason for this is due to the complicate, nonlinear and inherently unstable dynamics, which has cross coupling between main and tail rotor, and lots of time-varying aerodynamic parameters. Another reason is that the flight test is in high risk. If a RUAV lost its control, it would never be stabilized.
Shenyang Institute of Automation, Chinese Academy of Sciences (SIA, CAS) as a national research institute focus its future research on RUAV 5 years ago. Until now, we have 3 types of experimental platforms for advanced control algorithm research demonstration. ServoHeli-20 (Fig.1) is a model class platform which has 20 kilograms takeoff weight. ServoHeli-40 (Fig.2) and ServoHeli-110 (Fig.3) are engineering class platforms for highway patrol, electrical line patrol and photography. They have 40 and 110 kilograms takeoff weight and have finished full autonomous flight control experimental demonstration. In SIA, the control algorithm research on RUAV involves in navigation, advanced flight control, 3D path planning and fault tolerant control.
This paper details the development of an unmanned helicopter testbed – ServoHeli-20 (Qi et al., 2006) (Fig.3), and the experiments performed toward achieving full autonomous flight. The brief of this paper is as follow: the ServoHeli-20 platform is introduced in Section II. The introduction of sensor package is in Section III. The modeling of the RUAV system is presented in the Section IV. In Section V, we introduce an independent-channel control scheme as a baseline control of the platform. In Section VI, an overview of fault tolerant

control research is presented. In the end, we conclude our work and discuss some future research issues.

Figure 1. ServoHeli-20 airframe

Figure 2. ServoHeli-40 airframe

Figure 3. ServoHeli-110 airframe

2. ServoHeli-20 Platform Description

As the basic airframe of the RUAV system, we chose the small-scaled model helicopter which is available in the market. Such a choice is easy for us to exchange the accessories and cost low price.

ServoHeli-20 aerial vehicle (Fig.4) is a high quality helicopter which is changed by us using a RC model helicopter operating with a remote controller. The modified system allows the payload of more than 5 kilograms, which is sufficient to take the whole airborne avionics box and the communication units. The fuselage of the helicopter is constructed with sturdy ABS composite body and the main rotor blades are replaced with heavy-duty carbon fiber reinforced ones to accommodate extra payloads. The vehicle is powered by a 90-class glow plug engine which generates 3.0hp at about 15000 rpm, a displacement of 14.95cc and practical angular rate ranging 2,000 to 16,000 rpm. The full length of the fuselage is 1260mm as well as the full width of it is 160mm. The total height of the helicopter is 410mm, the main rotor is 1600mm and the tail rotor is 260mm.

Designing the avionics box and packing the box appropriately under the fuselage of the helicopter are two main tasks to implement of the UAV helicopter system. In the actual flight environment, the weight and the size of the avionics box are strict limited. Our airborne control box, which is shown in Fig.5, is a compact aluminum alloy package mounted on the landing gear. The center of gravity of the box lies on the IMU device where is not the geometry center of the system that ensure the navigation data form IMU accurate. The digital compass and the IMU which are taken as the horizontal center of the gravity of the avionics system to locate and the other components are installed on the same line.

Figure 4. Implemented rotorcraft UAV

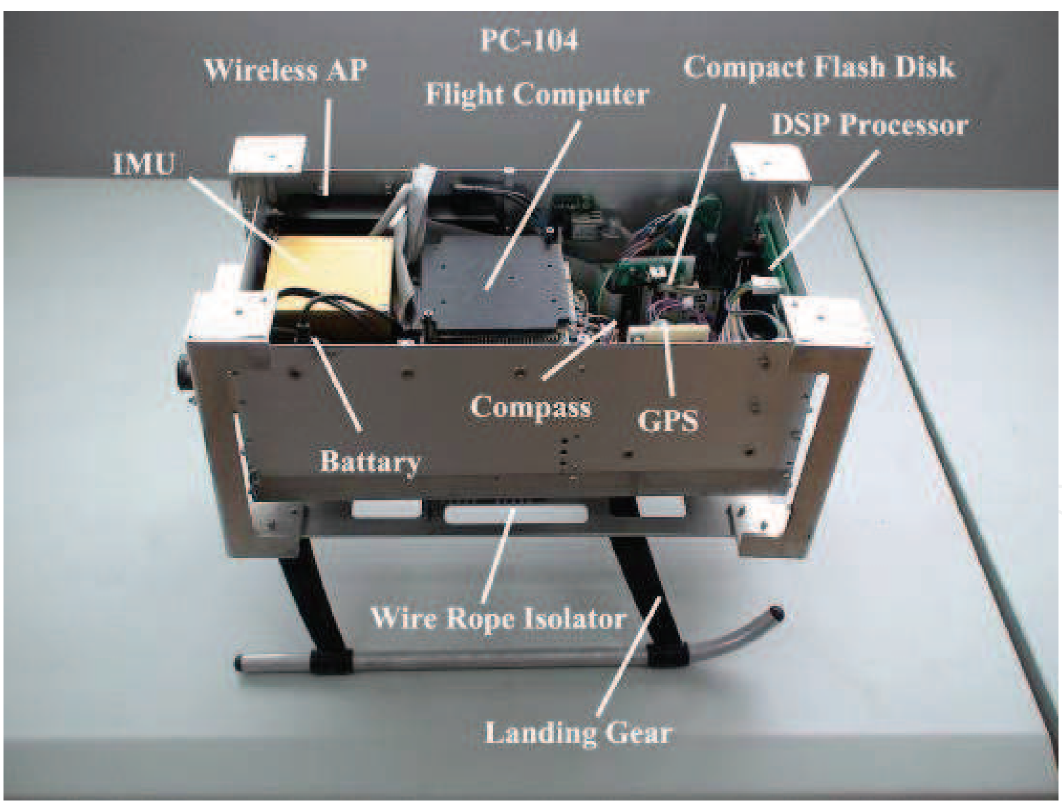

Figure 5. The avionics control system

The original landing gear of the model helicopter is plastic, which is no enough room to install the designed avionics system in the fuselage of the helicopter. While, we re-design a landing gear with aluminum alloy and make a larger room under the fuselage of the model helicopter for the control box. To avoid the disciplinary vibration about 20Hz caused by characteristic of the helicopter, ENIDINE® aviation wire rope isolators which are mounted between the avionics box and the changed landing gear are chosen. They are comprised of stainless steel stranded cable, threaded through aluminum alloy retaining bars, crimped and mounted for effective vibration isolation.

3. Flight Control System of the ServoHeli-20

3.1 Flight Control Computer

The onboard avionics system is responsible for the overall RUAV's main managements including navigation, autonomous control, communication and so on. The PC-104 flight computer, communication components and sensor units including inertial measure unit, global position system (GPS), digital compass, air-press altimeter, ultrasonic sensor are installed onboard.

In our research in the project, PC-104 computer system is used as the onboard computer which is shown in Fig.6.

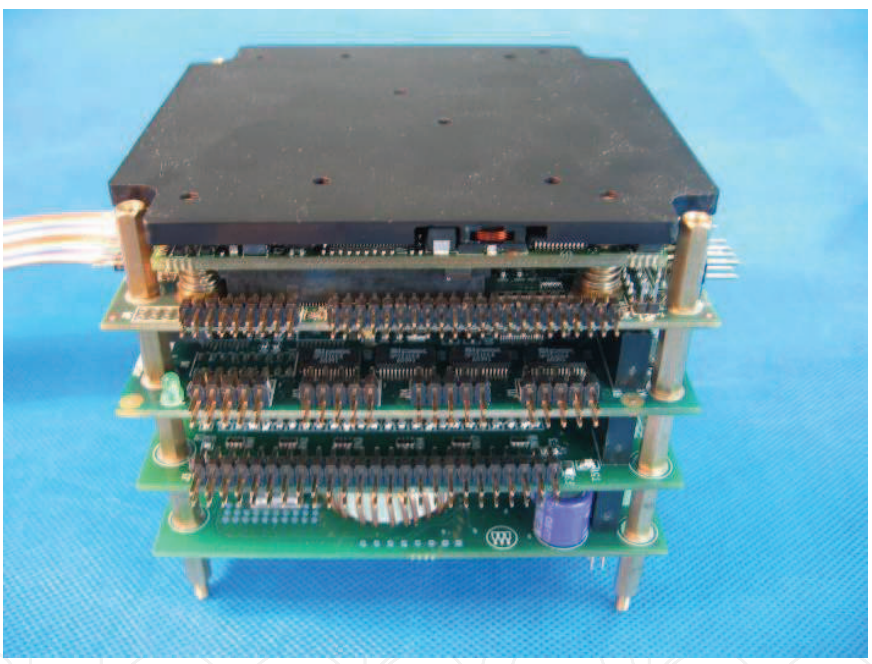

Figure 6. PC-104 computer system

The flight computer installed in avionics box is a typical industrial embedded computer system, so-called PC-104 which the whole system is kept as compact and light-weight as possible. The PC-104 has the ISA or PCI bus which features a 108.2cm×115.06cm footprint circuit board. Our flight computer system consists of a main CPU board and some other peripheral boards such as DC-DC power supply board, 8-channel serial communication device and PWM generation board.

The main CPU board has a Celeron processor at 400MHz with 256MB SDRAM, fully compatible with the real-time operation system such as QNX. Hard drive or other equivalent mass-storage device for booting and running an operation system and storing useful sensor data is needed to the flight computer. The Compact Flash (CF) card by KingStone® is a 1GB flash RAM device and is suitable for air environment. The Eurotech®

PC-104 processor board has only two serial ports, which are not enough for collection data from more than two sensors that communicate with serial port. As a result, a serial port expender is packed with the main CPU board providing RS-232 / 485 communications. In order to control the Futaba® model helicopter servos, a PWM generation board is needed. Take price and reliable as consideration, DSP board is chosen to generate 5-channel PWM signal as well as capture the PWM signal encoded by remote controller when the system run at manual mode. Such a design is to ensure that the system can run independently at manual mode, which the close loop of the servo control is not through PC-104 processor except for receiving the commands of servos from serial port. Li-Ion battery serves as a power supplement to the overall onboard system such as flight computer system, sensors, communication units and servos through DC-DC converter. Eurotech® ACS DC-DC converter is mounted to meet the system design requirement of converting a 9-40V DC input voltage to multi-voltage power outputs including +5V, +3.3V and +12V with overload protection. An optional onboard microprocessor monitors the temperature of the module and protects it by turning the module off when temperatures exceed 85 centigrade-degree. The power supplement of the overall avionics system as well as five servos that control the helicopter is powered by a Li-Ion battery pack which has the capacity of 78WH at the output of 19V.

3.2 QNX Real-Time Operation System

To our flight control system, a real-time operation system (RTOS) is required for the onboard computer system. After carefully consideration and comparison, QNX Neutrino RTOS is selected as the operation system, which is ideal for embedded real-time applications. It can be scaled to very small size and provides multitasking, threads, priority-driven preemptive scheduling, and fast context-switching – all essential ingredients of an embedded real-time system. The applied program can be coded and debugged in the remote windows-host computers and can be executed in the airborne computer system independently, which provides great convenience during the flight experiments without modify the program in onboard computer.

3.3 Ground Control Station

The ground station mainly includes the ground control computer, the ground development computer, model helicopter remote controller, wireless-LAN access point, video signal receiver, the antennas of the communication devices and ground power source. The role of the ground station is to issue control commands to the onboard avionics system and monitor its real-time status. The pre-scheduled trajectory and commands as well as the synchronized sensor data are transmitted and received by wireless APs.

The ground control computer is a laptop, which sends the pre-scheduled commands and trajectory to the airborne flight computer. The program of the ground control computer is developed by Visual C++.The interface of it is presented in the Fig.7. The whole picture of ground station is shown in the Fig.8.

The development computer is used for the onboard software development of QNX Neutrino RTOS as well as the DSP processor. QNX Momentics IDE which is an integrated development environment of the QNX system is installed in the computer as a windows-host to modify the remote flight computer programme. As the same to the QNX system, Code Composer Studio IDE (CCS) is also setup in the development computer to change the programme in the DSP which is the PWM signal generator in avionics box. The 9-channel RC controller which is at 72MHz radio communication signal is used in manual mode in system modelling.

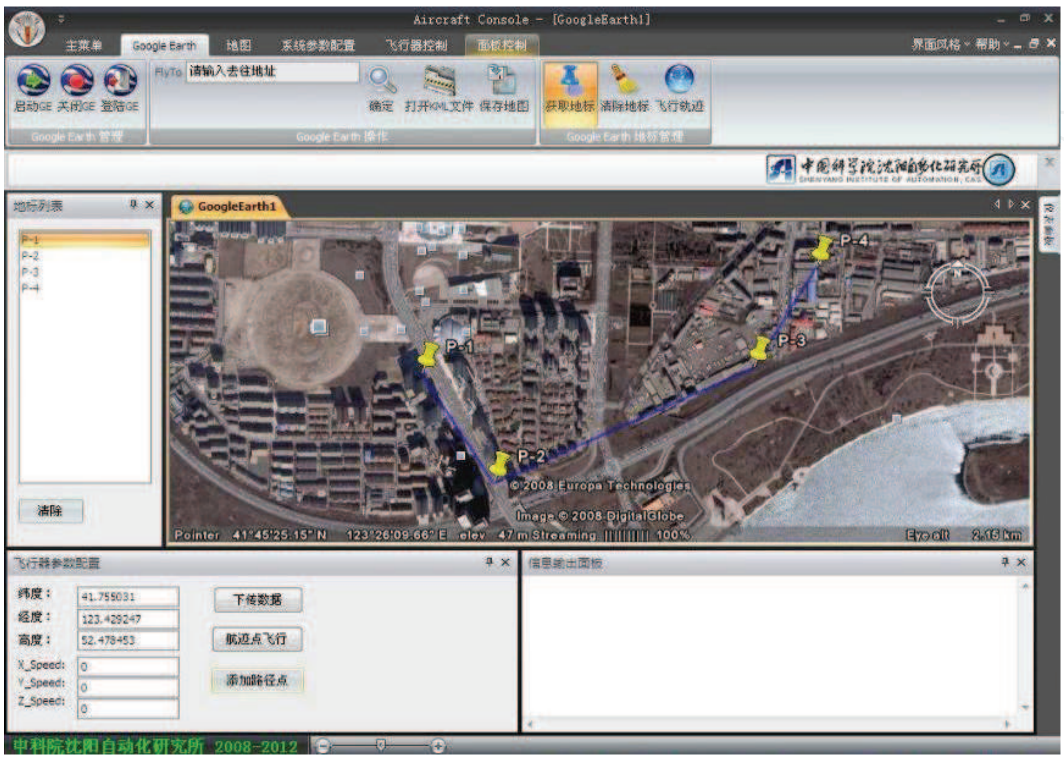

Figure 7. Interface of the ground control computer

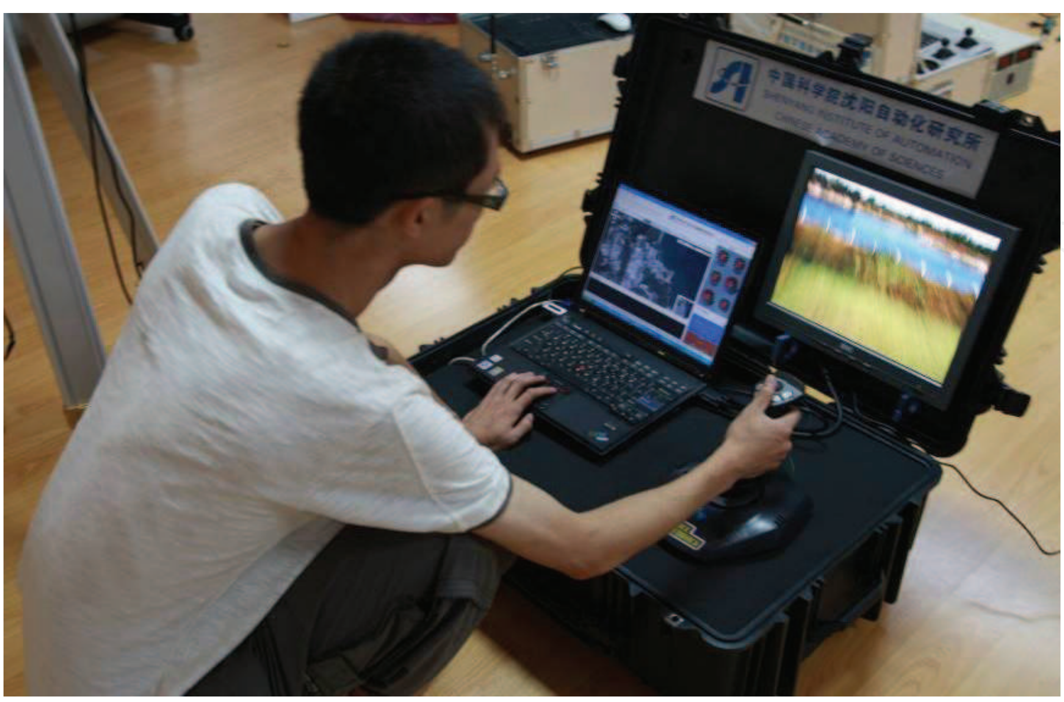
Figure 8. Ground station interface

3.4 Sensors for Attitude and Position Estimation

In order to navigate following a desired trajectory while stabilizing the vehicle, the information about helicopter position, velocity, acceleration, attitude, and the angular rates should be known to the guidance and control system. The rotorcraft UAV system is equipped with sensors including inertial sensor unit, GPS, digital compass, rotor speed sensor, air-press altimeter and ultrasonic sensor to obtain above accurate information about the motion of the helicopter in association with environmental information.

The Crossbow IMU300, which is shown in Fig.9, is a six-axis measurement system designed to measure the linear acceleration along three orthogonal axes and rotation rate around three orthogonal axes. It employs on board digital processing to provide application-specific outputs and to compensate for deterministic error sources with in the unit. Solid-state MEMS sensors make the IMU300 product responsive and reliable.

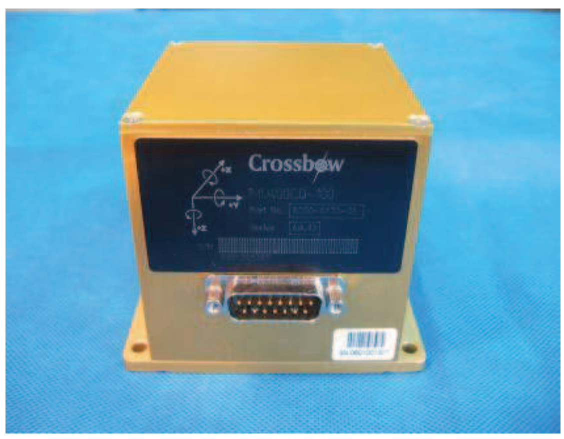

Figure 9. Crossbow IMU

Hemisphere GPS, which is shown in Fig.10, is a space-based satellite radio navigation system developed by a Canada company. GPS provides three-dimensional position and time with the deduced estimates of velocity and heading. The GPS provides position estimates at up to 10 Hz. For operation, the GPS and the antenna are installed on the host aerial vehicle.

Figure 10. Hemisphere OEM GPS

HMR3000 digital compass, which is presented in Fig.11, is an electronic compass module that provides heading, pitch and roll output for navigation and guidance systems. This compass provides fast response time up to 20 Hz and high heading accuracy of 0.5 degree with 0.1 degree resolution.

Figure 11. HMR3000 digital compass

In order to get the accurate altitude information of the vehicle, an air-pressure altimeter that collecting data higher than 5 meters as well as an ultrasonic sensor that getting the information on other situations is equipped under the avionics box.

The update rate of all sensors is ranging from 10-100Hz, which is enough for implementation for advanced control algorithms.

3.5 Passive and Active Vibrations Isolation

In our avionics box, we use rate gyros and accelerometers to measure rates about three axes, and accelerations along 3 axes; processor is used to extract absolute roll and pitch. However, in the real flight environment, the sensors will subjected to rotor frequency vibrations; both the rate and acceleration readings are grossly inaccurate; consequential, so to is the attitude estimation.

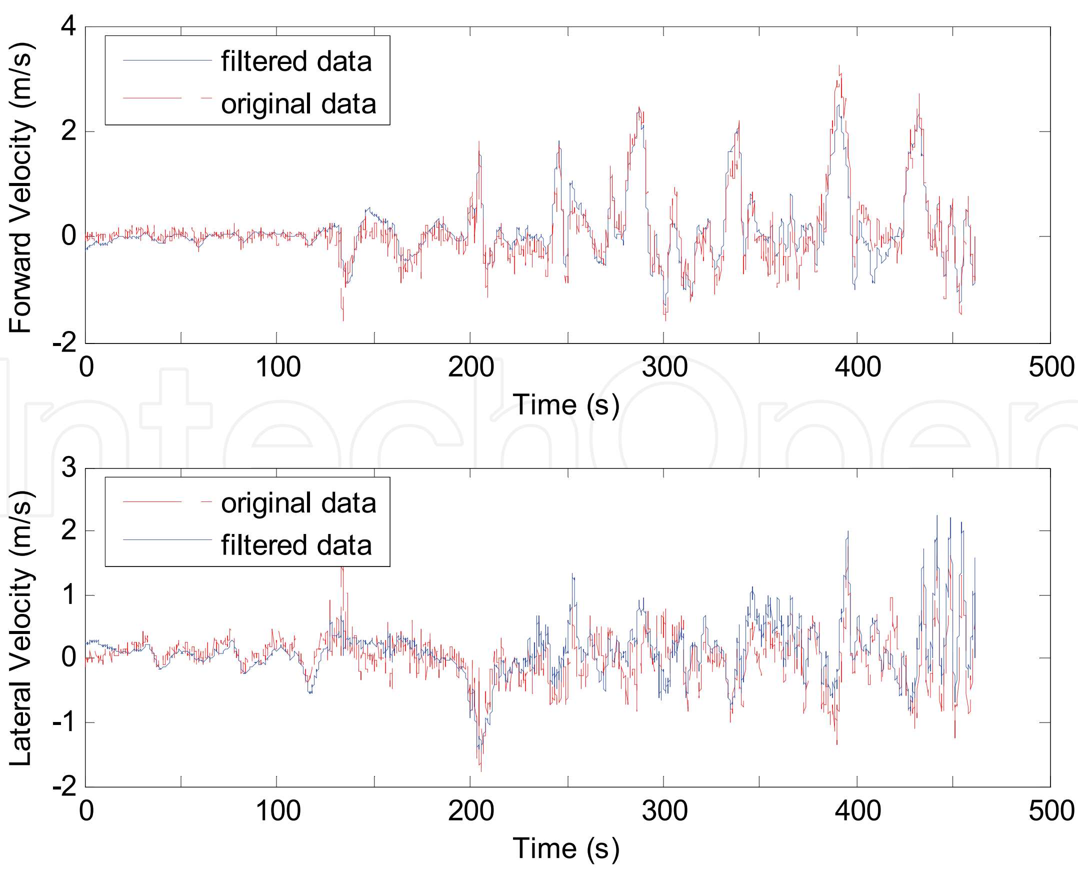

Figure 12. Velocities before and after isolation

In order to isolate the unit from these frequencies, we use the passive and active isolation method. The passive method is that the sensors are spring mounted inside the main avionics box. With the foam damping included, the isolation can act as a passive effect. However, the active method is the Kalman filter way to isolate the vibrations and biases. A typical plot of the forward and lateral velocities before and after isolation is given in Fig.12.

4. Rotorcraft UAV Modelling

For effective hovering identification, the original model in reference (Mettler et al., 2004) is decomposed into three groups (longitudinal, lateral, and yaw-heave coupling), and a semi-decoupled model is obtained. Each group has a decoupled system matrix, and the coupling characteristics is presented only in the control matrix. Thus, the number of unknown parameters and control inputs are reduced and the control loops are semi-decoupled. Then, to identify the unknown parameters in the MIMO semi-decoupled model, a new cost function is proposed to make the traditional method of SISO system frequency estimation (Bendat et al., 1993) applicable to the MIMO state-space models. The proposed cost function is presented in the addition form of the frequency error of every input-output pair for transfer matrix, and the parameters are identified by minimizing the cost function. The simplified model and proposed identification method free the selection of initial estimation and constraint is not required.
Take the yaw – heave model for example. We have got the numerical model, and then other serial of input data was verified using the proposed model. The blue line is the measurement of the yaw rate from the real flight as well as the red line is calculated by the numerical model and the real flight input. As is shown in the Fig13, the estimation output is similar to the real flight data and we can conclude that the proposed modeling method is useful to the rotorcraft UAV.

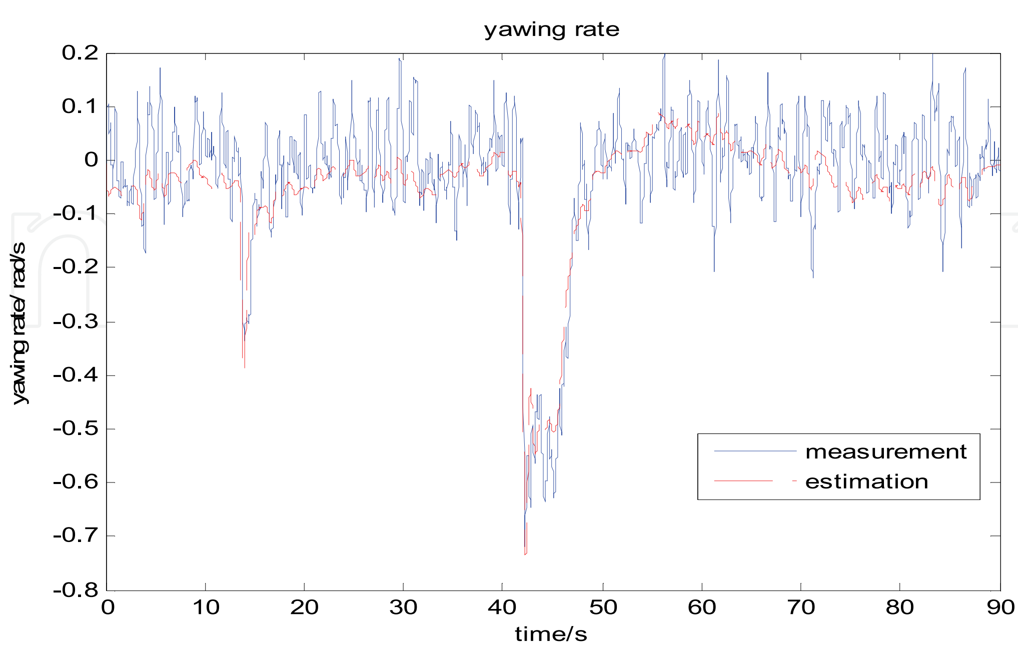

Figure 13. Rotorcraft UAV modeling verification

5. Independent-Channel Control Scheme

Simulation studies have shown that a better strategy for the control of a small-scaled helicopter is to use the flight controller as consisting of two cascaded controllers: an inner loop and an outer loop. The inner loop, that has the faster dynamics, is designed as the attitude controller which takes desired attitude angles as inputs and generates the actuator commands that will result in the desired attitude. The outer-loop controller, which controls the slower translational rate variables, takes desired velocity or position as input and generates desired angels to the inner loop. The overall flight control scheme is shown in Fig.14, while five linear controllers are designed to control the engine speed, height, yaw, lateral and longitudinal motion.

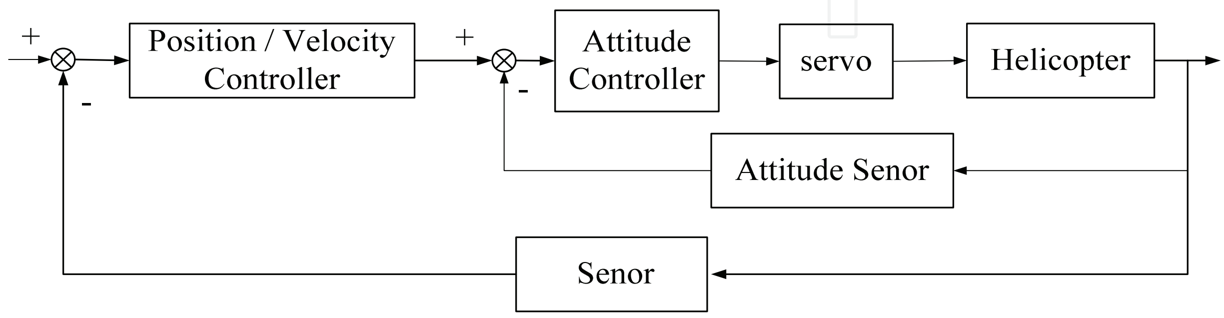

Figure 14. Overall fight control scheme

5.1 Engine Speed Control

The engine speed during the hover-envelope flights is maintained at 1200 rpm as a result of the experiments in manual mode. To get a steady rotary speed of the engine, a PID controller is used in feedback control which from the speed sensor to the throttle demands. When collective pitch changing, the power of the engine will change as a result of it. A feed forward term from the collective pitch is introduced to compensate for the extra loading experienced. The engine control scheme is shown in Fig.15.

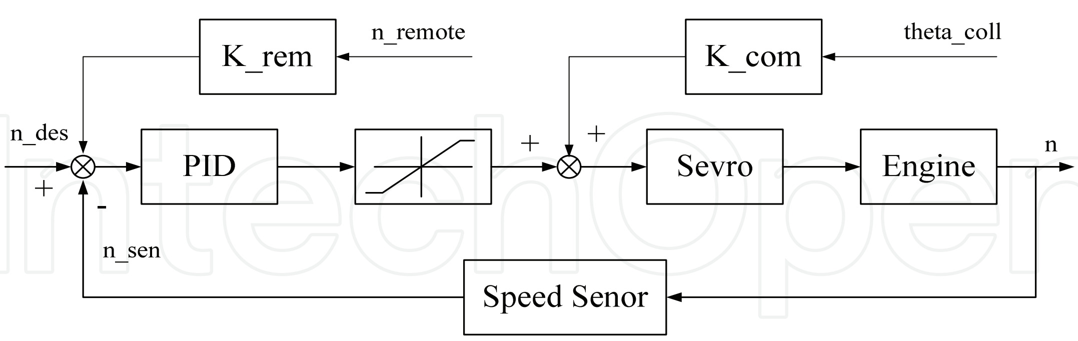

Figure 15. Engine speed control scheme

5.2 Height Control

The height control is a one loop scheme which a PI controller using feedback from the height sensor generates collective pitch demands in Fig.16.

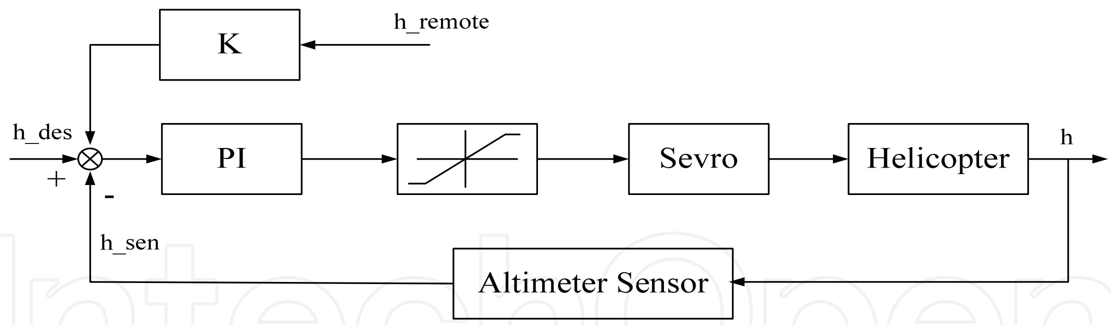

Figure 16. Height control scheme

5.3 Yaw Control

The yaw control two loop structure is presented in Fig.17. As is shown in this figure, the inner loop is a yaw rate stabilization loop which proportional control using yaw rate feedback from the IMU output demands to the rudder servo and the outer loop uses the scheme from the digital compass output to the yaw rate input.

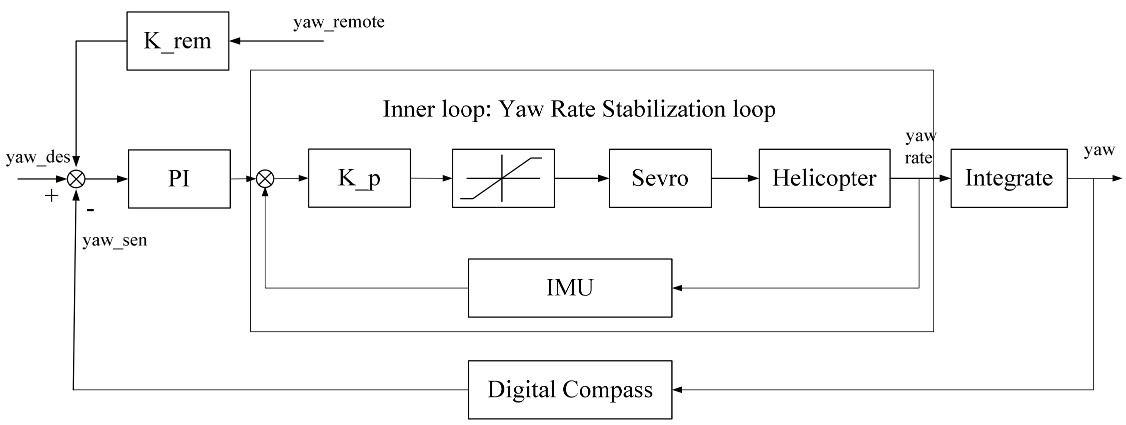

Figure 17. Yaw control scheme

5.4 Lateral and Longitudinal Motion Control

Similar to the yaw control scheme, IMU, digital compass and GPS are used as the feedback sensors to maintain the lateral and longitudinal position with simple proportional and PI controllers. The inner loop is pitch / roll rate stabilization component as well as the outer loop serves as the position feedback unit which is shown in Fig.18.

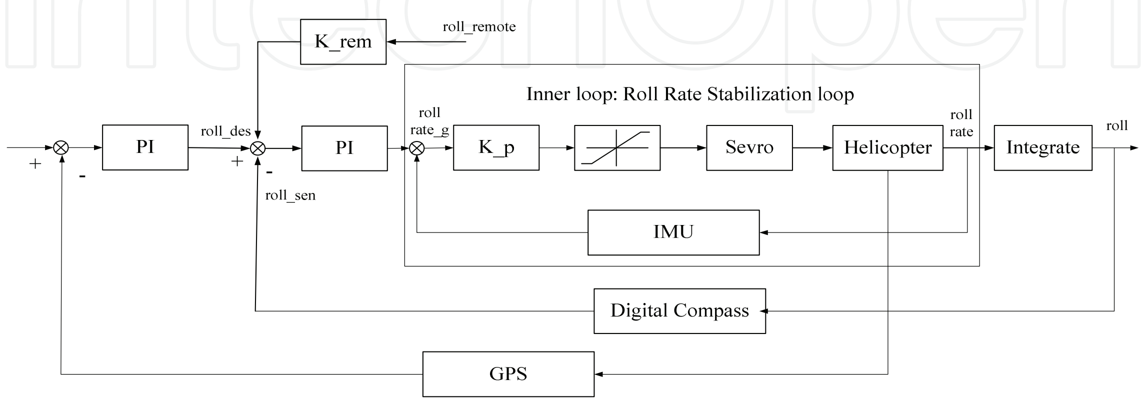

Figure 18. Roll control scheme

5.5 Autonomous Flight Result

A two-loop control scheme for the rotorcraft UAV system was design and tested using the ServoHeli-20 platform. We design some specified trajectories to be flown. These trajectories were selected in order to evaluate the inner loop and outer loop response over several different sequences of inputs. We selected a tunnel way to be followed, as is shown in the Fig.21. The proposed controller handled this flight trajectory with minimal error, Fig.22. Fig.19 and Fig.20 show that the angles and velocities which controlled by inner loops are also get a stable response.

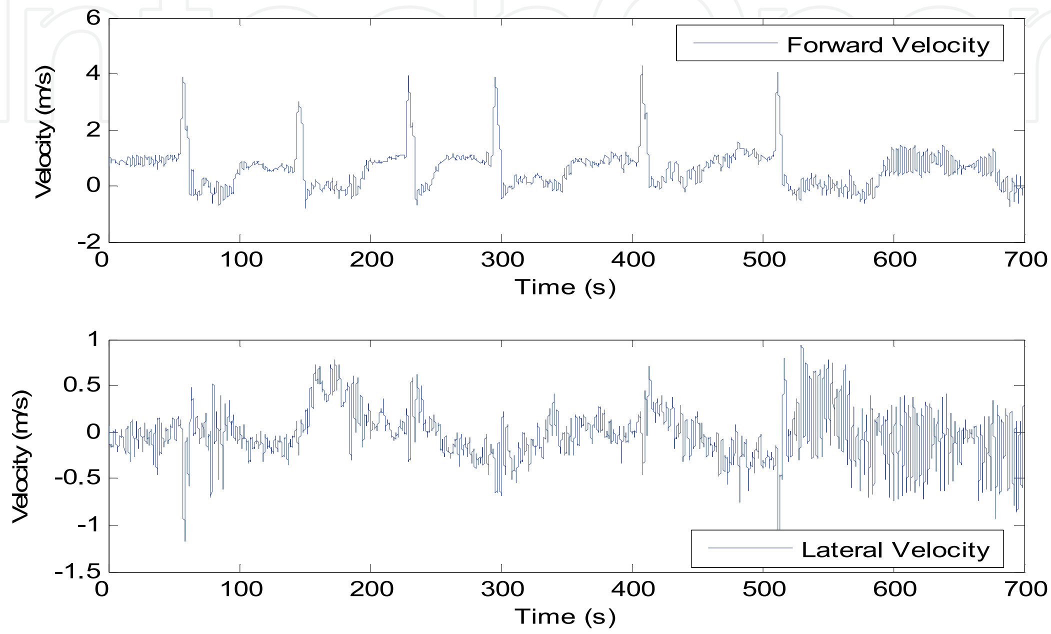

Figure 19. Forward and lateral velocity during the flight

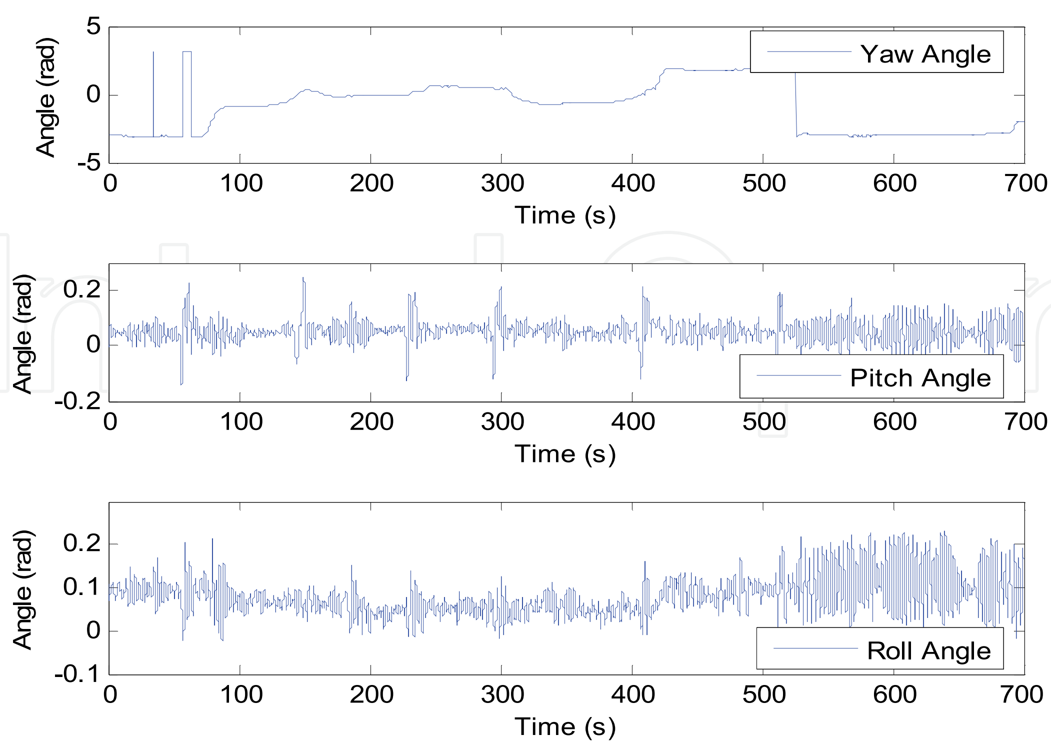

Figure 20. 3-axes angles during the flight

Figure 21. Trajectory in the Google Map

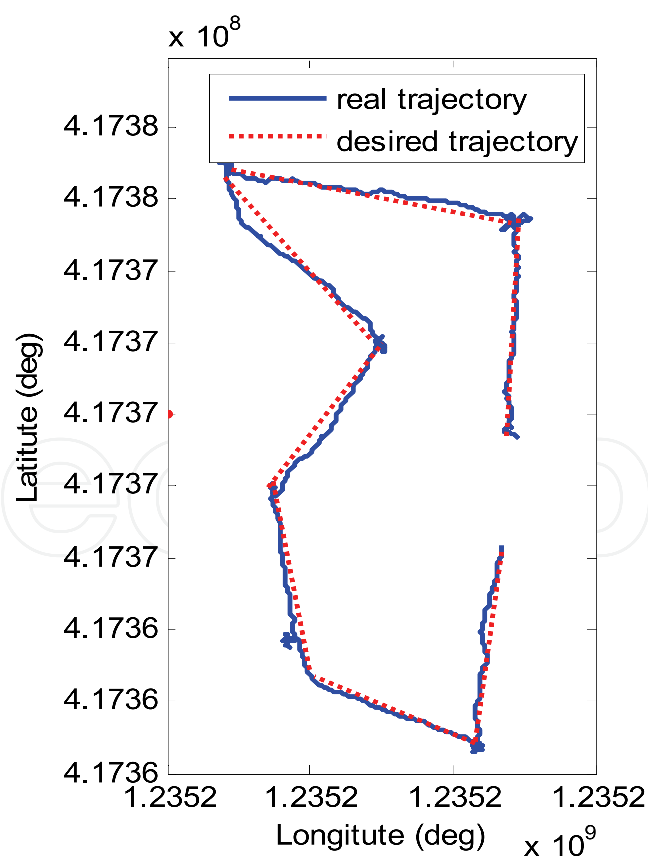

Figure 22. Desired and real trajectory

6. Fault Tolerant Control Research on Rotorcraft UAV

6.1 Fault Tolerant Control Architecture for RUAV

Fig.23 is the overall architecture for RUAV fault tolerant control. The white part is the conventional 3-layer UAV control architecture which including mission planning, path planning and robust flight control. Based on this part, we introduce the mission re-planning and path re-planning to the upper and middle level as while as a reconfigurable flight control to the lower level. In this section, we propose the sensors and actuators failure detection algorithms and demonstrate their effectiveness with simulations.

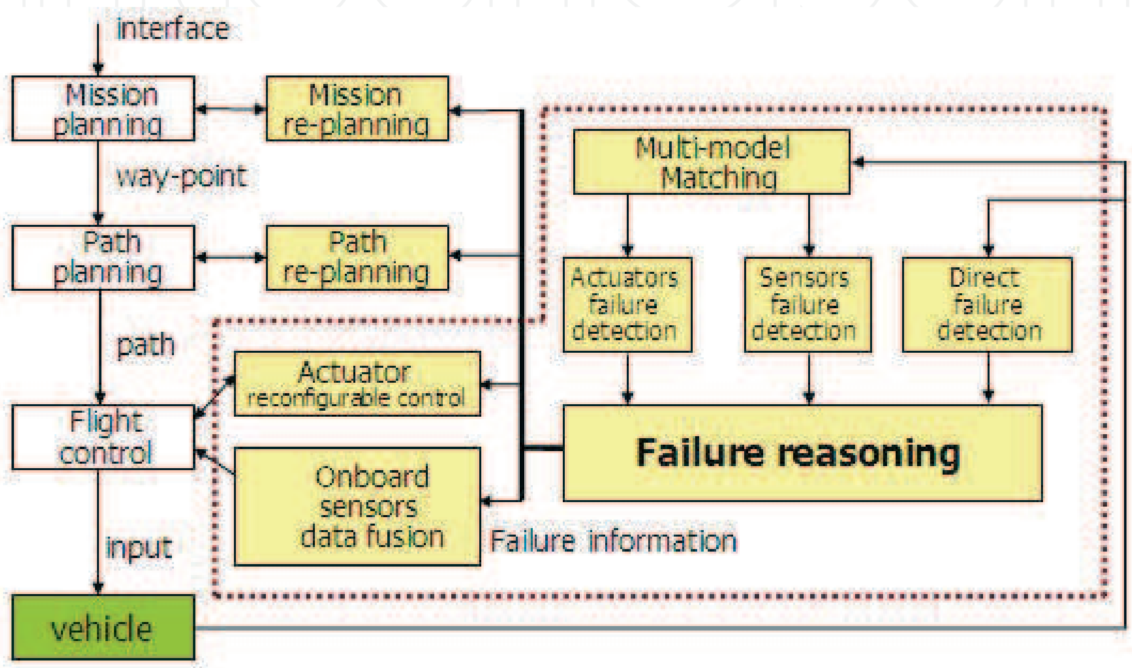

Figure 23. Overall fight control scheme

6.2 Wavelet Transform Based Sensors Failure Detection Algorithms

By use of wavelet transforms that accurately localize the characteristics of a signal both in the time and frequency domains, the occurring instants of abnormal status of a sensor in the output signal can be identified by the multiscale representation of the signal. Once the instants are detected, the distribution differences of the signal energy on all decomposed wavelet scales of the signal before and after the instants are used to claim and classify the sensor faults. Synthetic data simulated by means of a computer using real flight data from ServoHeli-20 RUAV, which is designed and implemented by ourselves, have verified the effectiveness of the proposed method. (Qi et al., 2006, 2007)

The sensors of the navigation system with different mechanism also have different performance. We can not get the ideal fault detection results using the traditional fault detection techniques. In order to accompany the short control period and the highly update rate, we use the parallel wavelet analyzer, which is shown as Fig.24.

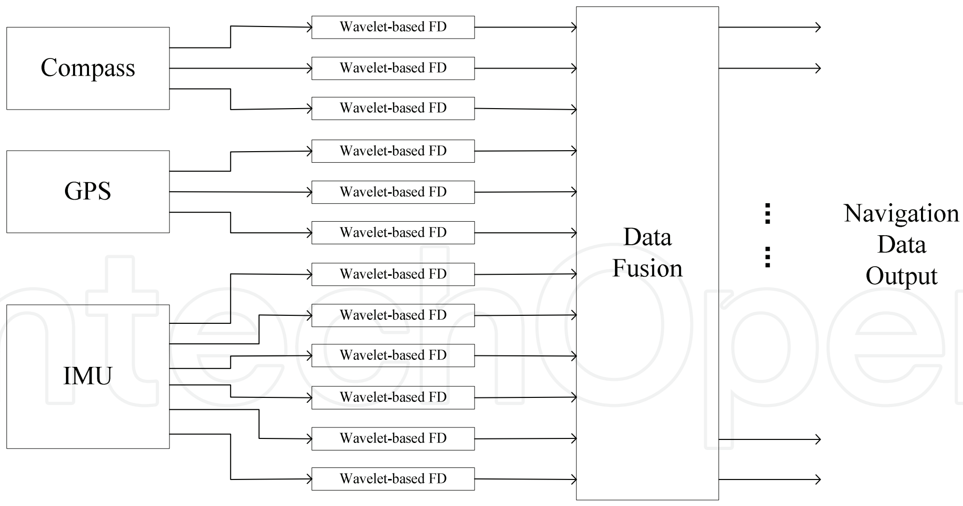

Figure 24. Wavelet-transform based sensors failure detection

6.3 Adaptive Filter Based Actuators Failure Tolerant Control Algorithms

Due to the inherently unstable dynamics, either flight test or real application of a RUAV is in high risk while a minimal failure may lead to the whole system collapse. In our recent research (Qi et al., 2007, 2008), a novel adaptive unscented Kalman filter (AUKF) is proposed for onboard failure coefficient estimation and a new fault tolerant control method is designed against the actuator failure of RUAV. The filter method with adaptability to statistical characteristic of noise is presented to improve the estimation accuracy of traditional UKF. The algorithm with the adaptability to statistical characteristic of noise, named Kalman Filter (KF)–based adaptive UKF (Fig.25), is proposed to improve the UKF performance. Such an adaptive mechanism is intended to compensate the lack of a prior knowledge. By introducing the actuator health coefficients (AHCs) into the dynamics equation of a RUAV, the proposed AUKF is utilized to online estimate both the flight states and the AHCs (Fig.26). A fault adaptive control is further designed based on the estimated states and AHCs. The comparisons between the adaptive-UKF-based fault tolerant control and the normal-UKF-based one show the effectiveness and improvements of the proposed method.

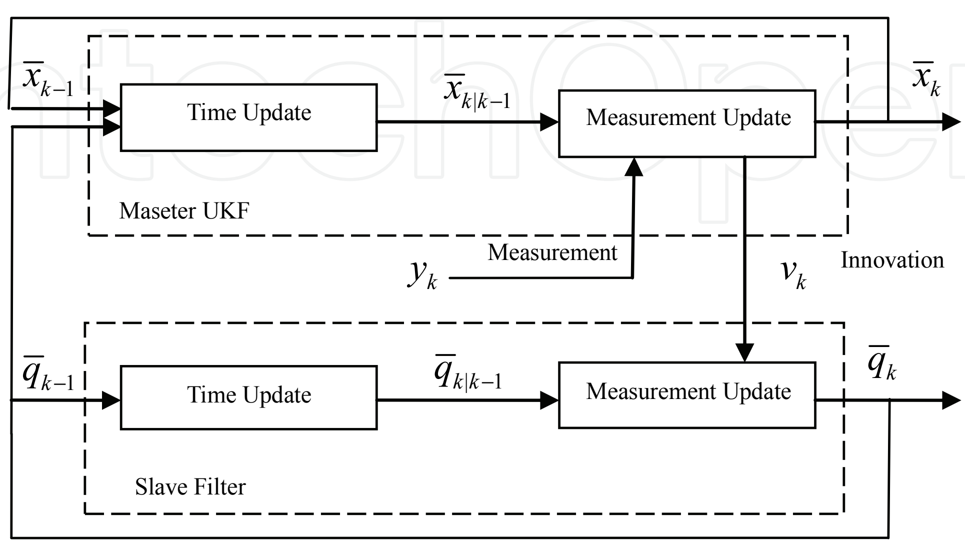

Figure 25. KF-based adaptive UKF

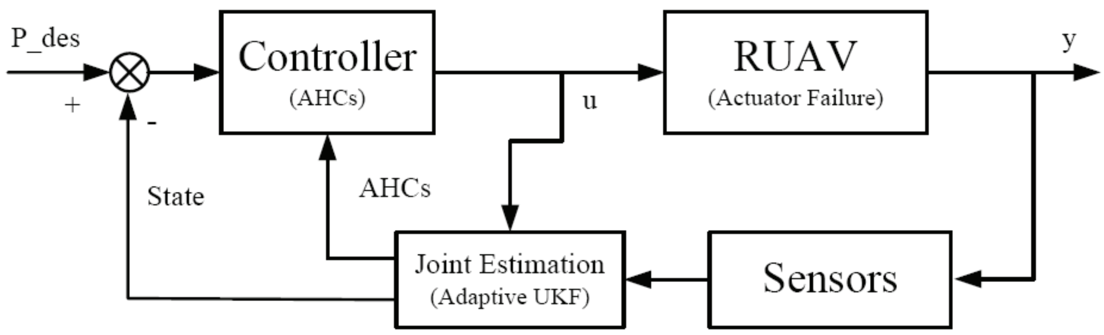

Figure 26. Actuator fault tolerant control scheme

7. Conclusions

This paper describes the current status of the ServoHeli-20 autonomous helicopter. We have introduced the system implementation of the rotorcraft UAV and control scheme for model scaled helicopter. A remote-controlled model helicopter is selected as the basic helicopter, which is changed to adapt to the heavy load. We also introduce the sensors and algorithm for attitude and position estimation. The two loop linear control scheme is presented in this paper for RUAV system and is a simple but useful control law in unmanned aerial vehicle experiments. Then we introduce our recent research in RUAV fault tolerant control algorithms.

The rotorcraft UAV system has been tested successfully for full autonomous flight including autonomous take off and landing. The next step is to integrate the visual and IMU estimation into a unified sensor suite and to develop advantage autonomous flight control algorithm for maneuverable fight.

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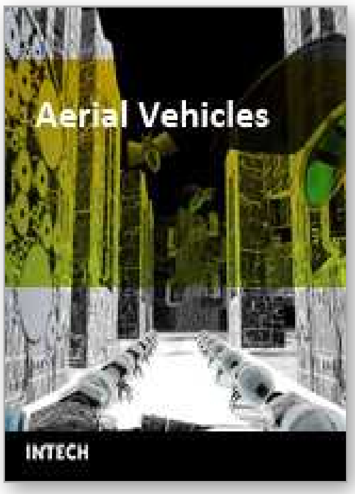

Aerial Vehicles
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This book contains 35 chapters written by experts in developing techniques for making aerial vehicles more intelligent, more reliable, more flexible in use, and safer in operation.It will also serve as an inspiration for further improvement of the design and application of aeral vehicles. The advanced techniques and research described here may also be applicable to other high-tech areas such as robotics, avionics, vetronics, and space.