USING CUTTING-EDGE UNMANNED AERIAL VEHICLES (UAVS) TECHNOLOGY FOR FLIGHT CONTROLS COURSES TEACHING

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Abstract

Unmanned Aerial Vehicles (UAVs) are gaining more and more attention during the last few years due to their important contributions and cost-effective applications in several tasks such as surveillance, search and rescue missions, geographic studies, as well as military and security applications. Compared with manned aerial vehicles, due to the requirements of autonomous flight under different flight conditions without a pilot onboard, control of UAV flight is much more challenging since all operations have to be carried out by the automated flight control, navigation and guidance algorithms embedded on the onboard flight microcomputer/microcontroller or with limited interference by a ground pilot if needed.

A team of researchers at the Department of Mechanical and Industrial Engineering of Concordia University, with the financial support from NSERC (Natural Sciences and Engineering Research Council of Canada) through a Strategic Project Grant and a Discovery Project Grant and three Canadian-based industrial partners (Quanser Inc., Opal-RT Technologies Inc., and Numerica Technologies Inc.), have been working on a research and development project on fault-tolerant and cooperative control of multiple UAVs since 2007. A quadrotor helicopter UAV physical test-bed has been developed through the projects, with the help for the UAV test-bed developed by Quanser Inc. Provided with this cutting-edge research activity and outcome as well as a special financial support made by the Department of Mechanical and Industrial Engineering and the Faculty of Engineering and Computer Science at Concordia University, since September 2010, Concordia University has for the first time made use of the developed quadrotor helicopter UAV (called as Qball-X4) for two courses teaching, which includes an undergraduate/graduate course MECH 480/6091 “Flight Control Systems” and a graduate course ENGR691X “Fault Diagnosis and Fault-Tolerant Control Systems” (please see a story and a video available at http://www.concordia.ca/now/what-we-do/research/20110321/four-times-the-fun.php). Through the use of such a cutting-edge unmanned aerial vehicle, students are able to practice and test the flight control theories learnt from the courses in such a physical and practical test-bed, which help students to link theory with engineering practice and achieve an even deeper and better understanding of the theories than would be possible without such an experimental and flyable test-bed. Students are attracted and motivated to continue in their studies and work.

In this paper, the overview on the objectives and contents covered in the two courses will be briefly introduced first. The system configuration and features of the developed Qball-X4 quadrotor helicopter UAV system are then introduced. Approaches, procedures and several flight testing results toward the use of the Qball-X4 UAV in the two courses for undergraduate lab development and graduate course projects development will be described. Achievement of using the Qball-X4 UAV in the courses labs and course projects are then presented. What we have learnt through the use of such a cutting-edge new UAV technology for the two courses teaching is summarized at the end of the paper.

Keywords: Innovation, technology, Unmanned Aerial Vehicles (UAVs), flight control systems, fault diagnosis and fault-tolerant control systems.

1 INTRODUCTION

Flight Control Systems is a core course for students in the aerospace program. The course covers the knowledge on flight dynamics, aircraft modelling and the most challenging topic of applying control theory for designing flight control laws to control aircraft with satisfactory flight qualities [1, 2]. On the other hand, the demand for reliability, safety and fault tolerance of aircraft and some safety-critical systems is generally high. It is necessary to design control systems which are capable of tolerating potential faults in these systems in order to improve the reliability and availability while providing a desirable performance. These types of control systems are often known as fault-tolerant control systems (FTCS). More precisely, FTCS are control systems which possess the ability to accommodate component failures automatically. They are capable of maintaining overall system stability and acceptable performance in the event of such failures. In other words, a closed-loop control system which can tolerate component malfunctions, while maintaining desirable performance and stability properties is said to be a fault-tolerant control system, or fault-tolerant flight control system in the case of applications to aircraft/spacecraft and UAVs [3]. Since the initial development in the 1980's, research and development on FTCS have attracted more and more attention from academic research and industrial engineering applications, as shown in a recent survey paper by the author with co-author [3], and recently published books [6-10] since the first book focused on the topic of fault-tolerant control systems published in 2003 [5].

By recognizing the importance of FTCS in the application to the future aerospace and other safety-critical and even non-safety-critical systems, the author has proposed to offer a new course on "Fault Diagnosis and Fault-Tolerant Control Systems" at the Concordia University, benefitting directly from our current research on fault diagnosis and fault-tolerant control with applications to aircraft, spacecraft/satellites, and most recently on unmanned aerial vehicles (UAVs). To test the developed theory and algorithms through an NSERC (Natural Sciences and Engineering Research Council of Canada) Strategic Project Grant (SPG) started from 2007, we have planned to build a quadrotor helicopter-type UAV for the benefit of being able to fly such a UAV in an indoor lab environment for flight testing and validating developed flight control, cooperative flight control and fault-tolerant control laws. Based on our success of the development of such a quadrotor UAV with the support of one of our NSERC-SPG industrial supporting partners, Quanser Inc., the author has proposed to the Department Chair of the Department of Mechanical and Industrial Engineering at Concordia University in 2009, when the author obtained a chance to teach the "Flight Control Systems" course offered by the department. Based on the support from department and particularly the special financial support of the Faculty of Engineering and Computer Science at Concordia University, the department with another department at the Faculty were able to purchase 5 sets of the Qball-X4 from Quanser Inc. for the courses lab development in Fall 2010, since in the past the flight control systems mostly demonstrated the theory of flight control systems in class mainly through simulations and an available flight simulator at the department. For better demonstration of flight control theory visually, many videos were presented during classes, yet the learning remained slightly dull. Even worse, the students lacked first-hand experience with implementing and testing their flight control laws in a real, flyable test-bed. There is an overriding need to engage and motivate the flight control course students through hands-on learning instead of strictly theoretical knowledge. Finding cost-efficient, practical tools for hands-on flight control teaching and research is highly needed for efficient course teaching. For such a purpose, we have been looking for a method to demonstrate concepts, and, for practical purposes, to perform such demonstrations in an indoor environment in a way that is both time-efficient and physically safe for all concerned.

Based on the support from the Faculty and the Department, we were able to start to use the Qball-X4 UAV for the MECH480/6091 "Flight Control Systems" course for undergraduate lab use and graduate course project use. We have also used the UAV testbed for a newly offered graduate course ENGR691X "Fault Diagnosis and Fault-Tolerant Control Systems" with success. Students in the classes enjoyed the use of the latest cutting-edge UAV technology in the two courses teaching and study.

The main objective of this paper is to introduce the experience we have gained through the use of such a cutting-edge UAV technology in the two flight controls courses teaching, with normal flight conditions and the most challenging aspects for the flight control laws design, implementation and flight test under different fault conditions during flight of the Qball-X4 UAV.

2 COURSES OVERVIEW

2.1 Flight Control Systems

As described in the course outline given to students at the beginning of the course: "Flight dynamics and control is the science of aircraft motion modelling and control in the air. In this course we deal with the fundamental principles of flight dynamics. In order to do so, course begins with an introduction to the airplanes configuration to discuss physical effects of configuration on aircraft motion followed by modelling acting forces either developed by wing, empennage, fuselage or engine (aero-propulsive forces), or forces generated by control surfaces (control forces). After this, six degree-of-freedom (6

DOF) equations of aircraft motion are derived and decoupled to introduce longitudinal and lateral-directional motions, trim and static stability. Since the use of quadrotor helicopter UAV (unmanned aerial vehicle) in the course labs/projectors, modelling of quadrotor UAV will also be introduced. The major objective of this course is to derive linearized equations of motion around a trim point to investigate dynamic stability of an aircraft and characteristics of flight dynamic modes such as Phugiod and Dutch roll. Finally, flying handling qualities and basic autopilots are discussed briefly at the end. Also, laboratory work is considered to provide an opportunity for students to become familiar with the real-time hardware-in-the-loop simulation and flight testing based on the new and unique Qball quadrotor UAV available at Concordia University, besides topics discussed in the class."

Tentative lecture topics are as follows:

1. Basic definitions and concepts, aircraft configuration.
2. Forces and moments acting on aircraft/helicopter, coordinate systems.
3. Aircraft/Rotorcraft equations of motion, longitudinal and lateral-directional equations of motion.
4. Linearization of equations of motion, state-space form, stability derivatives.
5. Trim, static stability (longitudinal and lateral-directional).
6. Dynamic stability (longitudinal motion).
7. Dynamic stability (lateral-directional motion).
8. Flight handling qualities, autopilots.
9. Flight control system design via classic and modern control theory.

2.2 Fault Diagnosis and Fault-Tolerant Control Systems

This is a new graduate course offered at the Concordia University for the first time in Fall 2010, although the author has offered two separate courses on "Introduction to Fault Detection and Diagnosis of Dynamic Systems" and "Introduction to Fault-Tolerant Control Systems" during 2004-2006 at Aalborg University in Denmark. As described in the course outline: "Fault Detection and Diagnosis (FDD) and Fault-Tolerant Control (FTC) in dynamic systems become increasingly important in almost all engineering systems and which covers different disciplines, including aerospace, mechanical, electrical, transportational and industrial engineering. The purpose of this course is to introduce students to the basic principles and methodologies of this active and important subject, with a main emphasis on applications to aerospace systems (in particular for newly and rapidly developing applications to unmanned aerial vehicle (UAV) systems) in consideration to the contents to be covered being suitable to one semester course. The application areas and course contents could also make corresponding adjustments based on students' background and interests during the semester of the course offering. Both the traditional and the state-of-the-art techniques will be covered. Possible directions for future research and development as well as some open problems in the fields will also be discussed."

Tentative lecture topics are as follows:

I. Introduction.
1.1 Motivation of Fault Detection and Diagnosis (FDD) and Fault-Tolerant Control (FTC) in engineering systems.
1.2 Scope and terminology of FDD and FTC.
1.3 Introduction to fault-tolerant control systems (FTCS).
1.4 Approaches to FDD.
1.5 Approaches to FTCS design.
1.6 Integration of FDD in fault-tolerant control systems.
1.7 Brief history of FTCS.
1.8 Application examples of FDD and FTC.

II. Faults and Faults Modelling.
2.1 Faults in engineering systems.
2.2 Faults modes and fault efforts analysis.
2.3 Fault modelling for fault diagnosis and FTCS design.
2.4 Summary.

III. Brief Review of Probability Theory and State and Parameter Estimation Techniques.
3.1 Review of probability theory and random processes.

3.2 Review and introduction to Kalman filters and parameter estimation techniques.

IV. Basic Principles and Techniques of Model-based FDD.
4.1 Introduction.
4.2 Principle of model-based FDD.
4.3 Fault representation in system models.
4.4 Residual generation techniques.
4.5 Residual evaluation techniques.
4.6 Summary.

V. Fault-Tolerant Control Systems Design Techniques.
5.1 Introduction.
5.2 Characteristics and special considerations in FTCS.
5.3 Classification of FTCS.
5.4 Design of active FTCS.
5.5 Design of passive FTCS.
5.6 Summary.

VI. Integration of FDD with FTC in Active FTCS.
6.1 Introduction.
6.2 Integration of FDD with FTC.
6.3 Summary.

VII. Case Studies.
7.1 Redundancy and fault-tolerance considerations in Airbus 320/340/380.
7.2 Redundancy and fault-tolerance considerations in Boeing 777.
7.3 Fault diagnosis and fault-tolerant control for a Boeing 747.
7.4 Fault diagnosis and fault-tolerant control for a quad-rotor UAV.
7.5 Fault diagnosis and fault-tolerant control for a three-tank system (optional).
7.6 Vibration-based fault detection and diagnosis for engine bearings (optional).
7.7 Summary.

3 INTRODUCTION OF THE QBALL-X4 UAV TO THE COURSES TEACHING

As can be seen from above course outlines, a newly developed quadrotor helicopter UAV was planned to be used as a testbed for the courses labs and projects. Such a newly developed UAV was originally initiated and financially supported by a NSERC (Natural Sciences and Engineering Research Council of Canada) Strategic Project Grant (SPG) lead by the author with a team of researchers from the Department of Mechanical and Industrial Engineering at Concordia University, Laval University and Defence Research and Development Canada (DRDC) and three Canadian-based industrial partners (Quanser Inc., Opal-RT Technologies Inc., and Numerica Technologies Inc.). The quadrotor UAV testbed is mainly developed by the industrial supporting partner Quanser Inc., a world leader in the design and manufacturing of advanced systems for real-time control, design and implementation used in industry, education and research, located at Toronto, Canada.

In the following sections, a general structure of quadrotor helicopters and the unique system configuration of the newly developed quadrotor UAV, named as Qball-X4, are introduced.

3.1 A General Structure of Quadrotor Helicopters

In Fig. 1, the conceptual demonstration of a quadrotor helicopter is shown. Each rotor produces a lift force and moment. The two pairs of rotors, i.e., rotors (1, 3) and rotors (2, 4) rotate in opposite directions so as to cancel the moment produced by the other pair while generating lift for flying the helicopter. To make a roll angle (φ) along the *x*-axis of the body frame, one can increase the angular velocity of rotor #2 and decrease the angular velocity of rotor #4 while keeping the whole thrust constant. Likewise, the angular velocity of rotor #3 is increased and the angular velocity of rotor #1 is decreased to produce a pitch angle (θ) along the *y*-axis of the body frame. In order to perform yawing motion (ψ) along the *z*-axis of the body frame, the speed of rotors (1, 3) is increased and the speed of rotors (2, 4) is decreased.

The quadrotor helicopter is assumed to be symmetric with respect to the *x* and *y* axes so that the center of gravity is located at the center of the quadrotor and each rotor is located at the end of bars.

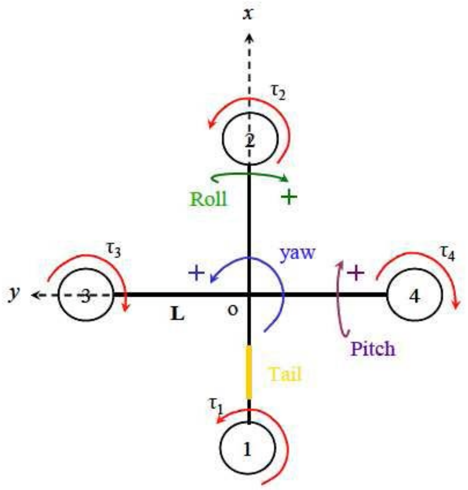

Figure 1. Quadrotor helicopter configuration with Roll-Pitch-Yaw Euler angles **[**φ**,** θ**,** ψ**]**

3.2 The Qball X-4

The quadrotor made by Quanser, known as Qball-X4 (Fig. 2), is an innovative rotary-wing vehicle platform suitable for a wide variety of UAV research, teaching and engineering applications. The Qball-X4 is a quadrotor helicopter propelled by four motors to drive four 10-inch propellers respectively. The entire quadrotor helicopter is enclosed within a protective carbon fibre cage for the safety concern to the vehicle itself and also for personnel working with the vehicle [11].

The Qball-X4's proprietary design ensures safe operation as well as opening the possibilities for a variety of novel applications. The protective cage is a crucial feature since this unmanned aerial vehicle was designed for use in an indoor environment/laboratory, where there are typically many close-range hazards (including other vehicles) and personnel doing flight tests with the Qball-X4. The cage gives the Qball-X4 a decisive advantage over other vehicles that would suffer significant damage if contact occurs between the vehicle and an obstacle. To obtain the measurement from on-board sensors and to drive the motors connected to the four propellers, the Qball-X4 utilizes Quanser's onboard avionics Data Acquisition Card (DAQ), the HiQ, and the embedded Gumstix microcomputer. The HiQ DAQ is a high-resolution Inertial Measurement Unit (IMU) and avionics Input/Output (I/O) card designed to accommodate a wide variety of research applications. QuaRC, Quanser's real-time control software, allows researchers and developers to rapidly develop and test controllers on actual hardware through a MATLAB/Simulink interface. QuaRC's open-architecture hardware and extensive Simulink blocksets provide users with powerful control development tools. QuaRC can target the Gumstix embedded single-chip computer automatically to generate code and execute flight control laws on-board the vehicle. During flights, while the flight controller is executing on the Gumstix, users can tune parameters in real-time and observe sensor measurements from a host ground station computer (PC or laptop).

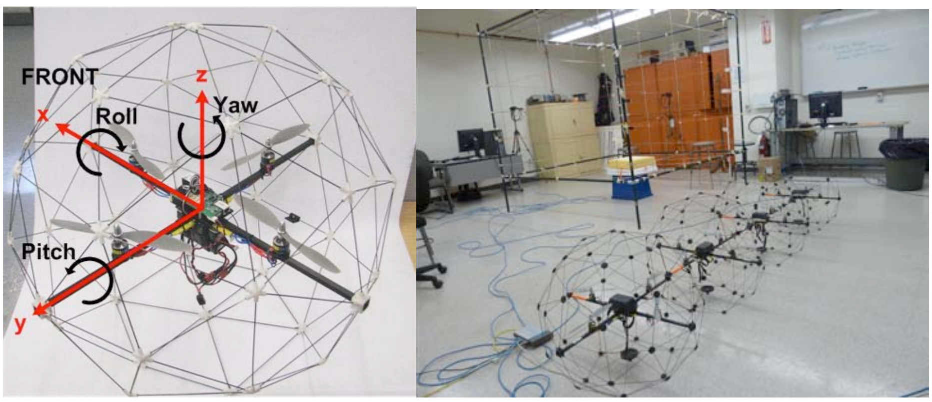

Figure 2. (a) The Quanser Qball-X4 quadrotor UAV and (b) the teaching lab at Concordia University

The interface to the Qball-X4 is MATLAB/Simulink with QuaRC. The controllers are developed in MATLAB/Simulink with QuaRC on the host computer, and these models are downloaded and compiled into executable codes on the target (Gumstix) seamlessly. A diagram of this configuration is shown in Figure 3.

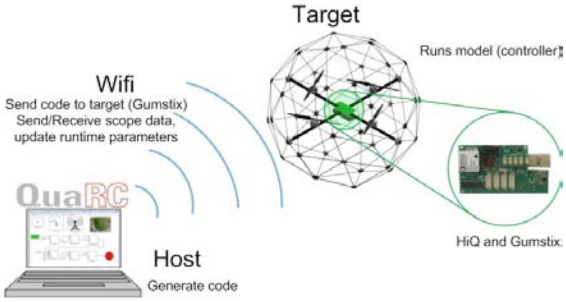

Figure 3. Qball-X4 communication hierarchy and communication diagram [11]

For Qball-X4, the following hardware and software are embedded:

- **Qball-X4:** as shown in Figure 2 above.
- **HiQ:** QuaRC aerial vehicle data acquisition card (DAQ).
- **Gumstix:** The QuaRC target computer. An embedded, Linux-based system with QuaRC runtime software installed.
- **Batteries:** Two 3-cell, 2500 mAh Lithium-Polymer batteries.
- **Real-Time Control Software:** The QuaRC-Simulink configuration.

The Qball-X4 communication hierarchy and communication diagram can be viewed in Fig. 3. It uses an ad-hoc peer-to-peer wireless TCP/IP connection for communicating with the host computer and/or other Quanser unmanned vehicles for cooperative/formation control of multiple UAVs. Before autonomously flying the Qball-X4, the complied executable flight control law codes from ground station computer will be downloaded to the on-board Gumstix microcomputer on the Qball-X4 through wireless communication. During flight of the Qball-X4, on-line and real-time transmission of the location information of the Qball-X4 will be wirelessly sent to Qball-X4 through host computer which is sensed by 6 infrared cameras in an in-door environment. For out-door flights of the Qball-X4, use of GPS (Global Positioning System) is instead applicable for Qball-X4's localization. Detailed description and operation instruction can be found in reference [11].

4 EXAMPLES OF COURSES LABS AND PROJECTS: FLIGHT CONTROL LAWS DESIGN AND FLIGHT TESTS VERIFICATION USING QBALL-X4 UAVS

4.1 Proportional-Derivative-Integral (PID) and Gain-Scheduled PID (GS-PID) Controls of the Qball-X4 under Normal and Fault Conditions

In view of the advantages of widely used Proportional-Integral-Derivative (PID) controller and gain scheduling control strategy in aerospace and other industrial applications, a control strategy by using a gain scheduling based PID controller is proposed for fault-tolerant control of the test-bed Qball-X4.

As a baseline controller and practice on implementing flight controls to the Qball-X4 during the courses, a single PID controller is designed and tuned first in both fault-free and faulty situations for the effort to control the Qball-X4 under both normal and faulty flight conditions**.** The structure of a PID controller implemented in the Qball-X4 MATLAB/Simulink software environment is shown in Fig. 4.

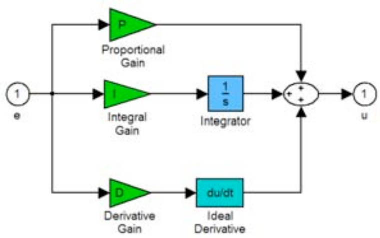

Figure 4. A PID controller structure [13]

To handle a potential actuator fault occurrence on the Qball-X4 during flight, such as a partial loss of control effectiveness in one or more rotors induced by fault(s) in DC motors and partial damage of one or more propellers, a Gain-Scheduled PID (GS-PID) control strategy has been proposed for providing fault-tolerant control for a quadrotor helicopter in [12] through a Master thesis's work. However, the work was not able to be implemented and flight tested in a physical quadrotor UAV testbed. As a course project, such an idea has been further investigated, implemented and flight-tested in the Qball-X4 testbed in [13] with the view that such a control strategy would be effective and practically-widely-acceptable control strategy to handle fault cases as for PID controller having been most widely used for most industrial applications until now. In the GS-PID controllers, several sets of pre-tuned PID controller gains are applied to control the Qball-X4 in different flight conditions under both fault-free and faulty cases respectively. To provide timely and correct switching among a set of PID controller gains, a Fault Detection and Isolation (FDI) scheme needs to be embedded with the GS-PID. Such a FDI scheme will be one of future course projects in ENGR691X course. The flight test results presented in [13] are in fact based on the assumption that such a FDI scheme was available for decision making in an overall active fault-tolerant control system loop. Analysis of the effect of control performance in the presence of different time delays due to FDI delay has been carried out.

The results based on GS-PID are also compared to the single PID controller, as shown in Fig. 5. The GS-PID proved to be fairly reliable with a high reliability, stability and improved control performance of the Qball-X4, as can be viewed in Fig. 5. For such a flight test, the objective is to maintain the desired height of 1 m even in the presence of an 18% of control effectiveness loss in all motors. As can be seen from Fig. 5(a), the Qball-X4 has been dropped as low as 0.2 m after fault occurrence, which could cause the Qball-X4 to hit the ground and cause a crash, since the operating height was considered as 0.4 m to 1 m for safety reason. However, GS-PID obtained better performance with less loss of the desired height after the fault occurrence with reconfigurable flight control law as shown in Fig. 5(b). Please watch a video also at http://users.encs.concordia.ca/~ymzhang/UAVs.htm.

More analysis on the implementation and comparison of a single PID controller and a GS-PID control strategy to the Qball-X4 UAV can be found in reference [13].

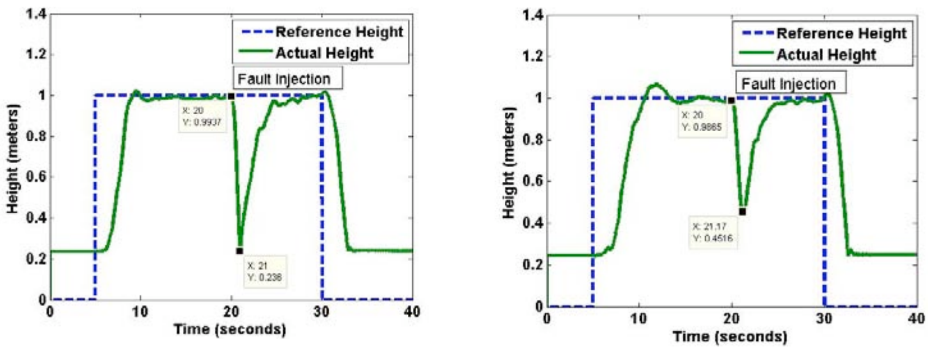

Figure 5. (a) Single PID controller with gains P=1.8, I=0.2, D=1 and (b) GS-PID control without time-delay for controller gains switching after fault occurrence [13]

4.2 Linear Quadratic (LQ) Control of the Qball-X4 under Normal and Fault Conditions

Similar to PID control, as a widely-used state-space model based control technique and for course labs and projects practice, as well as for comparison purpose with other control strategies, a Linear Quadratic Regulator (LQR) controller as a baseline controller was also developed to control the Qball-X4 UAV. Such a controller will be provided to undergraduate students for them to learn and gain the experience for controlling Qball-X4 using modern control theory, in addition to the concentional PID control techniques. To achieve tracking control, a PI (proportional-integral) action in the state-space model representation format, with a similar function as the PID controller, has been integrated in the LQR controller implementation in the Qball-X4. As it is well-known, LQR controller is a linear controller compared with the PID controller which can handle both linear and nonlinear systems.

The motivation and significance of the teaching objective is to let students investigate and gain knowledge of these two industrial-widely used control techniques, namely PID and LQR for flight control and fault-tolerant flight control applications on the Qball-X4 helicopter UAV.

As an example, details on implementation of a LQR controller with PI action can be found in [14].

4.3 Model Reference Adaptive Control (MRAC) of the Qball-X4 under Normal and Fault Conditions

Model Reference Adaptive Control (MRAC) is concerned with forcing the dynamic response of the controlled system to asymptotically approach that of a reference system, despite parametric uncertainties in the plant. Two major sub-categories of MRAC are those of *indirect methods*, in which the uncertain plant parameters are estimated and the controller is redesigned online based on the estimated parameters; and *direct methods*, in which the tracking error is forced to zero without regarding to parameter estimation accuracy (though under certain conditions related to the level of excitation in the command signal, the adaptive laws often can converge to the proper values). MRAC for linear systems has received, and continues to receive, considerable attention in the literature. In particular, several researchers have used MRAC for adaptive/fault-tolerant control of aircraft and UAVs in recent years as can be seen from recent AIAA Guidance, Navigation and Control (GNC) and AIAA Infotech@Aerospace conferences etc. Fig. 7 demonstrates the control structure of a MRAC.

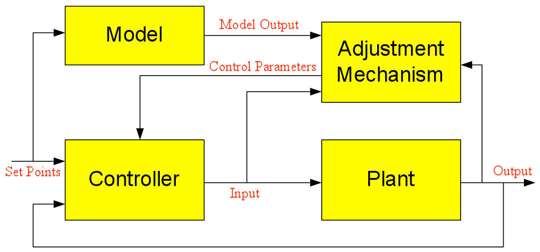

Figure 7. A model reference adaptive control (MRAC) structure [15]

There are different approaches to MRAC such as:

- The MIT rule.
- Lyapunov stability theory.
- Design of MRAC based on Lyapunov stability theory.
- Hyperstability and passivity theory.
- The error model.
- Augmented error.
- Model-following MRAC.
- Modified-MRAC (M-MRAC).
- Conventional MRAC (C-MRAC).

In the course project work presented in [15,16], a MIT rule is used to control the height of the Qball-X4. Flight test results with MRAC for fault-free and for different levels of partial loss in control effectiveness have been carried out and one fault with 18% fault are shown in Figs. 8-9.

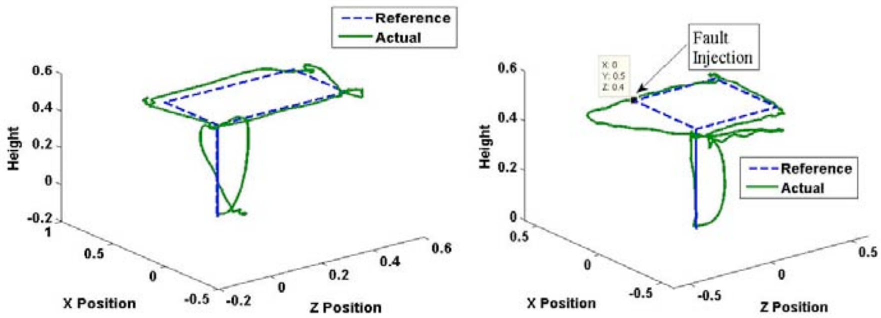

Figure 8. Square trajectory under (a) fault-free condition (b) an 18% fault in all motors with MRAC [15]

As can be seen from Fig. 8(b) and Fig. 9, with the MRAC, the square trajectory tracking were still achieved in the presence of an 18% control effectiveness loss in all four motors, although the control performance has been degraded due to the fault compared with the case without fault (Fig. 8(a)).

Comparison between a C-MRAC and a LQR controller under a 12% damage of the propeller using the mechanism for injecting a damage to one of four propellers as shown in Fig. 10 are showed in Fig. 11 for comparison between the baseline LQR controller and a C-MRAC for the *y* and *z* directions. Better performance by C-MRAC has been achieved compared to LQR with PI action.

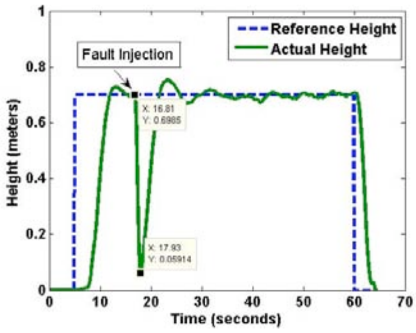

Figure 9. View on the height with MRAC under an 18% fault in all motors [15]

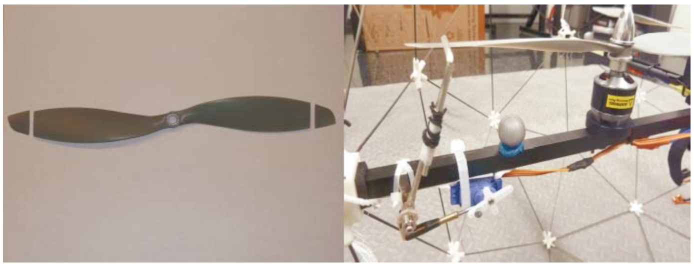

Figure 10. A 12% broken down propeller and the used mechanism to inject the damage [17]

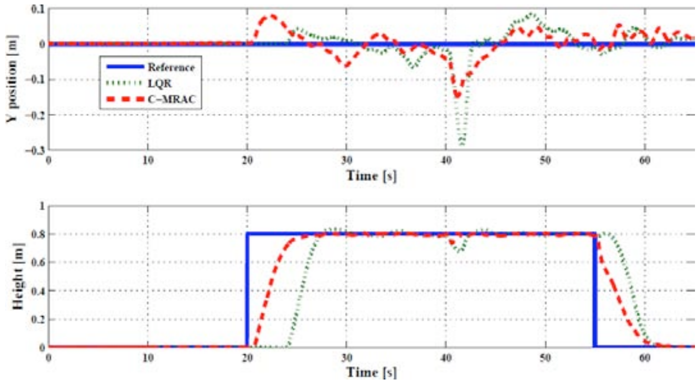

Figure 11. Performance comparison for a 12% damage of the 4th propeller with MRAC and LQR [17]

5 CONCLUSION AND FURTHER INFORMATION

This paper presented a proposal and experience on using cutting-edge unmanned aerial vehicles (UAVs) technology for “flight control systems” and “fault diagnosis and fault-tolerant control systems” courses teaching at Concordia University since Sept. 2010. A brief overview on the two courses and description on the configuration of the developed Qball-X4 UAV testbed are presented in the paper. Several typical and widely used flight control laws have been investigated and flight-tested in the UAV testbed under different flight conditions with normal flights (flight control design issue) and in the presence of different fault/damage flight conditions (fault-tolerant flight control design issue). Successful and satisfactory flight control performance in the realistic flight conditions has been achieved. Student enjoyed and learnt the course contents covered in the two courses more efficiently.

For further information on our above-mentioned teaching and research work and outcomes, an on-line version of a published article on March 21, 2011 at the “Concordia Journal” is provided as in the following website:

http://www.concordia.ca/now/what-we-do/research/20110321/four-times-the-fun.php

Other information relevant to this paper can also be found in the following web links:

http://www.encs.concordia.ca/news-and-events/entry.php?a=2011/03/quadrotor-research-takes-off-in-encs.php

http://quanser.blogspot.com/2011/02/attracting-students-with-cutting-edge.html http://users.encs.concordia.ca/~ymzhang/teaching.html (flight test videos of other courses related projects)

http://users.encs.concordia.ca/~ymzhang/UAVs.htm (flight test videos with other advanced fault-tolerant/cooperative flight control laws)

Further information published at ASEE (American Society for Engineering Education)'s PRISM Magazine in the March + April 2011 Issue and a Customer Story at the Quanser May eNEWS Issue can also be found.

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