REAL-TIME LONGITUDINAL CONTROL SYSTEM FOR THE KADET SENIOR RADIO-CONTROLLED AIRPLANE: A LOW-COST EDUCATIONAL TESTBED

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Abstract: In research and education, experimental platforms and testbeds make experimentation process easier and safer. In this paper, the design and development of a testbed for controlling the altitude and speed of a radio-controlled airplane is presented. This hardware-in-the-loop, low-cost platform lets students to test different control systems in a motivating, high-impact experience. This paper shows the design, development and test process, and includes information about the airplane mathematical model, sensors and communications system design, PID controller tests, and application in classes with educational purposes.

Classification Code: H3
Keywords: Unmanned Air Vehicles, Longitudinal Control, Electronic Design.

1. INTRODUCTION

In this paper, a M. Sc. Thesis project in electrical engineering is presented. The project's main objective was to design and develop a low-cost, hardware-in-the-loop experimental platform for controlling the altitude and speed of a radio-controlled (RC) airplane in a real-time Simulink environment. This testbed, useful for research and educational purposes, allows users to easily test different control strategies in a nonlinear and high-impact dynamic system.

In order to achieve the project objectives, several stages needed to be completed in this two-year research. Firstly, the airplane was chosen and built. After that, its mathematical model was developed and used for simulating its behavior in a safe environment. Then the sensors and electronic systems were developed and tested. Communication systems, required to transmit information from and to the airplane, were also implemented. Finally, the experimental platform was successfully tested for different control strategies. All of these topics are presented in this paper.

2. THE AIRPLANE

For this project, it was preferred to buy and modify a commercial RC model than designing a whole new airplane, due to the lack of time and know-how on aerodynamics. The airplane chosen for this development was the *Kadet Senior* (figure 1), a 1.98 m wingspan, 4 kg weight, commercial RC airplane characterized for its inherent stability and low flight speeds. Its medium size makes it feasible for carrying sensors and other electronic devices. The airplane was built and modified to make enough room for carrying additional electronic systems.

In this point of the development, it would have been helpful to enlarge the airplane nose in order to move ahead the airplane center of gravity; when loaded with electronics, the airplane would have its center of gravity (cog) where expected. This modification was not done in this project, and the airplane had to carry extra load to compensate the cog shifting.

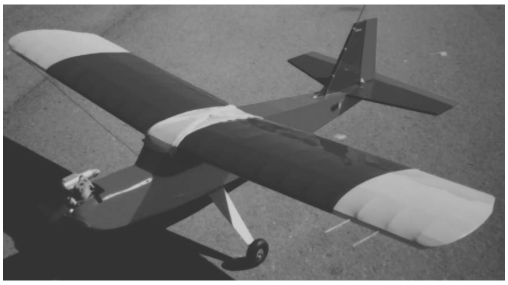

Fig. 1. The Kadet Senior Radio-Controlled Airplane.

3. AIRPLANE MATHEMATICAL MODEL

In order to test the airplane behavior and control algorithms under a safe environment, a mathematical model for the airplane longitudinal dynamics was required.

Standard airplane mathematical models are usually obtained from wind tunnel tests on the airplane or a scale model. These tests generate extensive tables for aerodynamic coefficients and stability derivatives, which define local linear models (Blakelock, 1991; McRuer *et al.*, 1973; Nelson, 1997). The high cost of these tests encouraged the authors to develop an analytic mathematical model, based on the airfoil aerodynamic forces (previously known from tables), the airplane structure and weight distribution, and Newton laws. Some of the model parameters could not be analytically obtained, so they were estimated and corrected to match airplane simulations and real flights.

As seen in the model block diagram of figure 2, the model inputs the engine duty cycle δ_T and the elevator deflection δ_e (gray blocks). These variables, combined with the state variables of airspeed (V_T), angle of attack (α) and pitch angle (θ) are introduced in aerodynamic equations to obtain the airplane forces (thrust, lift and drag) and moments. These forces can be related to the airplane coordinate system using the following equations:

$$\sum F_X = T\cos(\alpha_T) + L\sin(\alpha) - D\cos(\alpha) - mg\sin(\theta), \quad (1)$$

$$\sum F_Z = T\sin(\alpha_T) - L\cos(\alpha) - D\sin(\alpha) + mg\cos(\theta), \quad (2)$$

$$\text{and} \sum M_Y = M_T + M_w + M_t + M_\alpha. \quad (3)$$

The mathematical model for the airplane longitudinal dynamics outputs the airplane longitudinal speed U_A and ground vertical speed V_Z (gray blocks in figure 2), which can be integrated to obtain the airplane altitude Z. This nonlinear, global model is valid for most flight conditions, including stall and inverted flights. The model, as a faithful representation of the airplane dynamics, was useful for simulating the airplane behavior and developing the control algorithms.

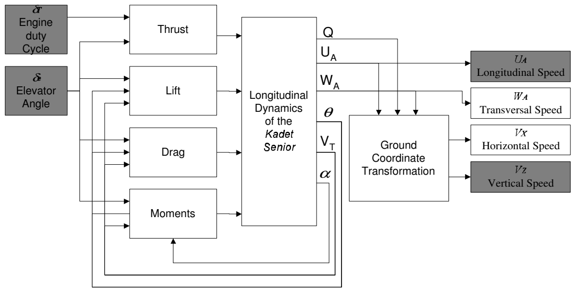

Fig. 2. Longitudinal Mathematical Model Block Diagram for the Kadet Senior RC Airplane.

4. SENSORS DESIGN

Standard airplanes and unmanned air vehicles use altitude, attitude, speed, climb rate and angular speed sensors to detect their condition and control their dynamics. However, for this low-cost project, multiple sensor integration would increment the airplane load, the system complexity and the overall cost; in the other hand, simulations of the airplane longitudinal dynamics control showed that only the altitude, the speed and their derivatives were absolutely needed to achieve the control goals. For this reason, the minimum necessary sensors for controlling the airplane longitudinal dynamics (speed and altitude sensors) were developed and included in the platform. It was also added a sonar, to detect the distance to ground when flying low.

When designing the sensors, it was also known that the absence of inertial sensors (accelerometers, gyroscopes) would make even more difficult and challenging the airplane control.

4.1 Speed Sensor

The speed sensor, needed to detect the airplane airspeed, was designed based on the Bernoulli principle using a Pitot tube (figure 3). A micromachined mechatronic device, the Motorola MPX5010DP differential pressure sensor, was used to measure the difference between static and dynamic pressures in the Pitot. The analog signal obtained from this device is signal conditioned using low-noise operational amplifiers, then digitized using the PIC16F876 microcontroller 10 bit A/D converter, and finally sent to ground in serial data packets.

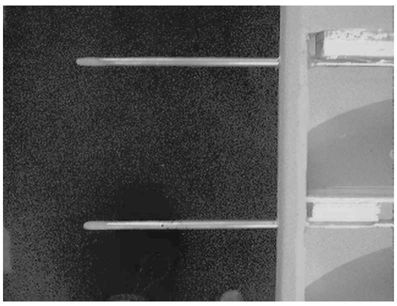

Fig. 3. Airplane Pitot tube, mounted in the wing.

The speed sensor was first calibrated in a wind tunnel, and then tested in the real airplane, showing a good performance; however, some noise in the output could not be filtered. Due to the wide range of operating temperatures, the speed sensor requires manual calibration before each flight. A high-precision potentiometer was specially dedicated for this process.

4.2 Altitude Sensor

The airplane was expected to fly below 70 m over ground level, thereby an altitude sensor for that range was needed. To reduce costs, the barometric pressure measuring principle was chosen for this application. A micromachined sensing element - the Motorola MPX4100AP 105 kPa absolute pressure sensor - was employed for detecting the airplane altitude. The signal-conditioner circuit, which compares the measured pressure with a calibration offset voltage, makes the output voltage to be proportional to the airplane altitude.

The circuit scale was adjusted using a high building as a reference. To calibrate the sensor for different pressure, altitude and temperature initial conditions, a special routine was programmed in the microcontroller. That routine, which is executed in the airfield before each airplane flight, measures the ground barometric pressure considering it as a zero-altitude pressure. This is done by adjusting the offset voltage for the signal-conditioner circuit as the actual measured voltage. With this routine, each time the airplane starts flying, independently on the weather condition, the initial altitude or the geographic location, the measured altitude is zero. The sensor output is digitized at 10 Hz using the PIC microcontroller, and then sent to ground using the developed communication system. The circuits board including both differential and absolute pressure sensors, the acquisition microcontroller and signal conditioners, shown in figure 4, was mounted in the airplane wingtip, next to the Pitot.

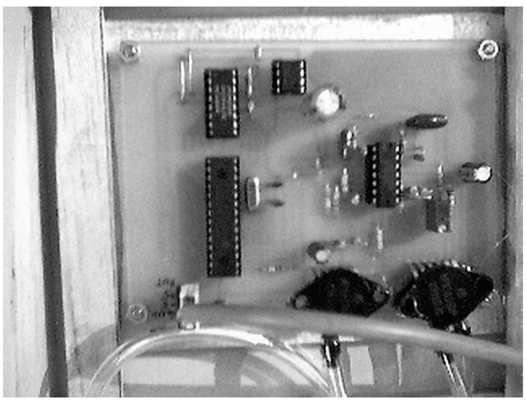

Fig. 4. Differential and Absolute Pressure Measuring Board.

This sensor was tested in the real airplane during complete flights, showing an excellent performance. Figure 5 shows a record for the airplane altitude during a 140-sec flight. That signal has not been digitally filtered; it only has been processed with the signal-conditioner lowpass filter. There can be appreciated that the sensor has no drift and its sensibility is excellent. To compensate any ambient pressure changes, another pressure sensor was mounted in the ground control base.

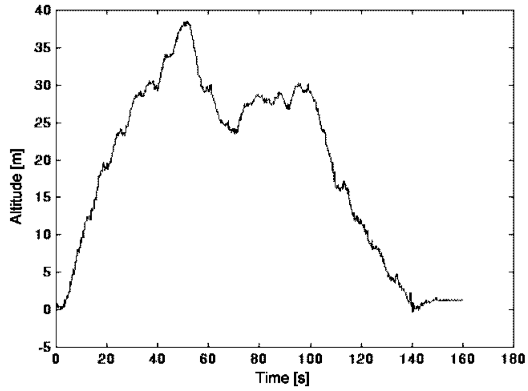

Fig. 5. Non-filtered Altitude Measurement during a Complete Flight, using the Developed Altitude Sensor.

4.3 Ground Distance Sensor

Although the altitude sensor has an excellent performance, it is not faithful enough to be considered in low-altitude flights. These cases, particularized in takeoffs and landings, require a more sensitive sensor. A Polaroid 6500 ultrasonic sonar was chosen for this purpose. This sensor, usually found in robotics applications, can detect objects at distances up to 10 m by measuring the time that an ultrasonic pulse sequence needs to get to the object and return back to the transducer. The sensor was mounted in the airplane, and a special microcontroller routine was programmed to measure the time interval; working with a 10 bit counter, the minimum measurable distance is as low as 1 cm.

The sensor was tested during real takeoffs and landings. When flying at low speeds over the asphalt airstrip, and for different pitch angles, the sensor was able to measure the airplane distance to ground up to 6 m. However, when flying over grass or sound-absorbing surfaces, or at high speed or altitude, its performance substantially decreases. Figure 6 shows a record of the airplane altitude during takeoff using this sensor. The steps of the curve show the slow 10 Hz sampling rate.

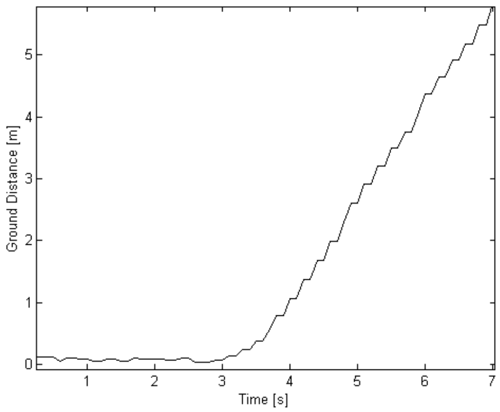

Fig. 6. Non-filtered Ground Distance Measurement during Takeoff, using the Polaroid Sonar.

5. COMMUNICATION SYSTEMS

One of the first logistic problems of the project was to decide the controller location. There were two choices: inside the airplane or in a ground base. The first option is a simpler solution, because it does not require a communications system to transmit the sensors information to ground; however, the limited processing speed, the difficulty for adjusting the controller parameters or control law, and the impossibility of switching to manual control in case of system failure makes it risky and inconvenient. Because of these reasons, for developing this project it was decided to set all the control systems in a ground base. The airplane could be controlled using any of two different methods: for taking off, landing and every risky situation, the pilot would be able to control the airplane manually by selecting a switch; when flying in normal conditions at high altitudes (40 m), the pilot would be able to control the lateral dynamics of the airplane, while the ground computer controls the airplane altitude and speed. This controller configuration can be appreciated in the system block diagram of figure 7.

The design and implementation for both air-to-ground and ground-to-air communication systems is described in next section.

5.1 Air-to-Ground Communications System

This system is used to send the serial data packets generated in the airplane sensors to a ground computer, running under Simulink real-time environment. A Hitec RC transmitter/receiver pair sends the 1 kbps data packets to the ground base; in that device, a PIC16F877 microcontroller stores the last measured values, and sends them to the computer when requested, using a SPORT232 acquisition serial card. The computer, running in a Simulink real-time environment, processes the sensors information and generates the three manipulated variables, δ_e, elevator deflection; δ_r, rudder deflection; and δ_T, thrust, needed to control the airplane. Among the

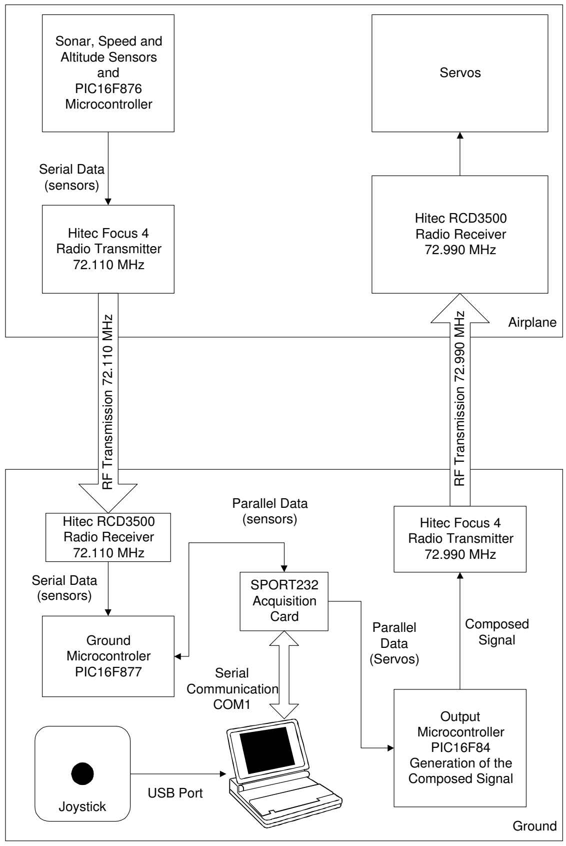

Fig. 7. Airplane's Communications Systems and Control Architecture.

three manipulated variables, only δ_r, rudder deflection is always operated manually; the other two controlled variables can be either manually or automatically governed.

5.2 Ground-to-Air Communications System

The 8-bit manipulated variables are transmitted from the computer to a PIC16F84 microcontroller using the SPORT232 acquisition card. The microcontroller, converts that information into a three-channel RC signal, and sends it to the airplane using another Hitec RC transmitter/receiver pair. In the airplane, the three-channel signal directly controls the airplane servos, closing the control loop.

As presented before, two independent communication systems require two antennas on the airplane: one for transmitting sensors data and another one for receiving manipulated variables. To avoid electromagnetic interference between the antennas, both were located as far as possible: the transmitting antenna in the airplane fin, and the receiving antenna in the right wing (figure 1), subtending a right angle with the first antenna. This configuration was safely tested in ground proving to work properly for sending the information in both directions, at distances of 500 m or more. If this issue were not properly addressed, the airplane could easily fly out of the communications system range, and the possibility of controlling it would be lost.

After testing the airplane communications system in ground, some test flights were programmed. During those flights, the airplane was fully controlled under Simulink environment using the joystick manual controller for the three manipulated variables, while the ground computer recorded the measured variables every 0.1 sec. Some of those records are shown in figures 5 and 6.

6. AIRPLANE TESTS

Before the airplane was finished, several PID, fuzzy and other control systems for controlling its altitude and speed were developed and tested in the simulator; when the airplane was ready to fly, all of these controllers were tested. The airplane was also used in an undergraduate automatic control course as a demonstrator and experimental platform. This section presents the results for some of these tests.

6.1 PID Controller

The first control strategy tested in the airplane for controlling its altitude and speed was based on three PID controllers. One PID controller was used to control the airplane speed, and two cascade PID controllers were used to control its altitude (figure 8).

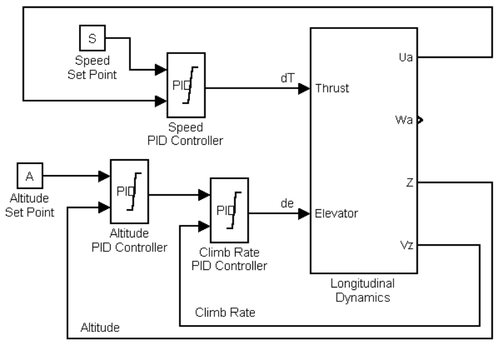

Fig. 8. Altitude and Speed PID Control System Block Diagram.

The speed controller inputs the speed set point and the airplane current speed, and outputs the airplane thrust δ_T (manipulated variable). This simple control loop, tuned by trial and error, was tested in simulations and proved to work properly for controlling the airplane speed at a fixed altitude; however if the altitude changes, the airplane speed control becomes difficult.

Before controlling the airplane altitude, it is necessary to control the airplane climb rate. The climb rate controller has two functions: to keep the climb rate in a safe range, reducing the risk of stalling or diving; and to prevent the airplane pitch angle from exceeding the limits for a normal flight. Some simulations and real tests showed that the controller accomplishes both objectives when the airplane climb rate is limited within the range of -3 m/s to 3 m/s. When this controller works properly, the outer PID controller (altitude controller) commands the airplane either to climb or to dive or to keep its altitude.

After fine tuning the three PID controllers in the simulator, some real tests were executed. During the tests, the airplane was manually taken off and landed, and automatic altitude and speed control was used only for high altitudes. During all the flights, the rudder deflection was always controlled manually.

First results were poor and discouraging, therefore it was decided to test one controller at a time. In individual tests, the speed controller performed reasonably good, keeping the airplane speed near to the set point even after climbing or diving. Having this controller tuned, the altitude controller was analyzed. The inner control loop showed some problems due to the difference between the airplane mathematical model and its real behavior. The model was corrected (as explained in section 3), then the controller was tuned again, and the whole control system was tested in the real airplane. Figure 9 compares altitude and speed records to their set point values for this test. It can be appreciated that the airplane altitude is forced to reach the set point value. However, the control performance is not as good as expected, showing some oscillations around the set point value. This behavior is due to the lack of inertial sensors and slow sampling rate. Despite the previous reason, the controller was able to keep the airplane in safe conditions during the entire flight, making the use of manual control unnecessary.

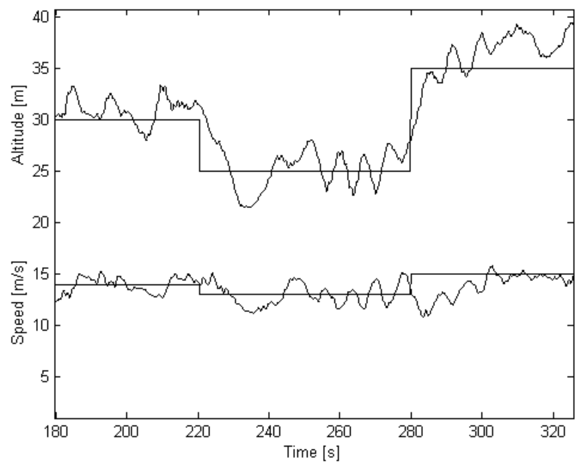

Fig. 9. Airplane Altitude and Speed Control Using PID Controllers.

6.2 Automatic Control Education

This system was successfully used in the undergraduate course IEE2612 Automatic Control at Pontificia Universidad Católica de Chile as an experimental platform for students. During one of the first classes, the complete project was presented to students as an example of an automatic control development. During that presentation, students showed interest and motivation for the project. They also asked some questions about the implementation details and the project stages.

During the last part of the course, students received an assignment concerning the airplane control. The assignment was divided in three parts: open-loop simulations, controller design and closed-loop simulations.

In the first part of the assignment, students were asked to simulate the airplane behavior using the airplane model, and to explain its behavior according to the basic aerodynamic forces. The model given to them, developed in Simulink environment, includes a 3D animation of the airplane over the airstrip. In the second part, they were asked to tune a PID controller for the airplane climb rate using the Ziegler-Nichols tuning method for the simulated airplane. In the third part of the assignment, they applied their controller in combination with a given altitude PID controller to control the airplane altitude in simulations. For these simulations, they were asked to determine the RMS error of their controller in order to evaluate their performances. They worked hard to reduce the RMS error of their controllers, knowing that the best controllers of the class would have the opportunity to control the real airplane.

Once finished the assignment, the RMS errors of all of the controllers were compared and the best three controllers were chosen to control the real airplane. Despite the final demonstration was a public activity, some students were not able to attend because of other exams. Those who attended were pleased to know that what they had learned in the course was useful to control a real system. They also encouraged the lecturers to design more assignments like this, because of the motivating topic, the competition for the best controller and the possibility to use it in a real, high-impact system. Figure 10 shows a record of the altitude during the flight of the airplane using the best controller of the class.

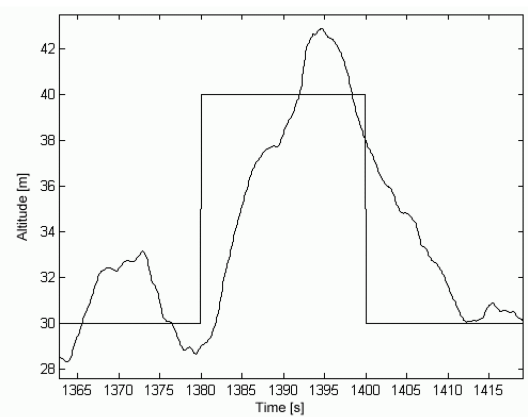

Fig. 10. Airplane Altitude Control Using PID Climb Rate Controller Tuned by a Student.

During the development of the assignment, students were surveyed about their opinion on it. Most of them declared to be satisfied with the assignment, considering it as a real contribution to the course, highly motivating and applicable.

7. CONCLUSION

In this paper, the design, development and test of an experimental platform for controlling the longitudinal dynamics of a RC airplane have been presented.

The system, designed and built using low-cost components, lets students to test different control systems in a nonlinear, dynamic, motivating, high impact platform. The testbed (including sensors and communications system) has been proved for different controllers, showing its functionality. It was also useful in improving the education of automatic control for undergraduate students, motivating them with a high-impact, impressive demonstrator.

In future, the platform will be used in advanced Automatic Control courses to test more complex and advanced control systems, such as GPC and neural networks (Camacho, 1999; Palm and Driankov, 1997).

8. ACKNOWLEDGMENTS

The authors wish to thank FONDECYT for the financial support given to project 1990101.

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