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ADVANCED FLIGHT CONTROLLER DESIGN FOR DEVELOPMENT OF UNMANNED AERIAL VEHICLE AUTOPILOTS

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ABSTRACT

This paper is about design, implementation and integration of an advanced flight controller autopilot system for comfortably designing and testing the autopilot controller and for agile development in a flexible way. The related work mainly concerns design of an advanced flight controller unit which is fast response, dual architecture, electronically protected, on-board emergency fail-saved, C/C++ compatible, MATLAB & SIMULINK compatible, embedded system, generic controller hardware and a flight power unit hardware design with embedded software realization for development of Unmanned Aerial Vehicle (UAV) autopilots. It is as a master thesis project academic research at Aerospace Engineering Department of Middle East Technical University. This flight controller is capable of reading data from various sensors of aerial vehicle and run autopilot algorithm through embedded software. This work also contains aerodynamic modeling, system modeling, controller design for integration the hardware and embedded system software to the air vehicle with peripheral avionics for testing the autopilot system.

INTRODUCTION

It is intended to design an autopilot controller hardware that is, generic, easy code development suited, robust, protected and improvable development kit. So, this work brings in an advanced flight controller hardware unit for aerospace engineers, control engineers and aerospace students who intent to apply a control algorithm for Unmanned Aerial Vehicles. Such a requirement arose from the situations during designing autopilot control algorithms that are not applicable practically to our air vehicle. In most of the situations we simulate them on MATLAB & SIMULINK type programs, but we cannot see the real applicable results as expected. By using some commercial hardware does not solve the problem because of integration, code restriction and software problems. Besides, they are not compatible with MATLAB & SIMULINK programs. They require good software knowledge like C/C++, assembly, etc. Therefore, this design project work addresses the autopilot controller integration dilemmas and offers a comfort path with a unique hardware solution to overcome development problems.

The purpose application of this controller hardware is for mini-UAVs. For this aim we chose Cessna 182 Scaled RC Trainer. The aerodynamic database of the airplane is generated mainly by using semi-empirical methods, by using Usaf Digital Datcom. Each component of the aerodynamic coefficients of the airplane is calculated individually. Datcom outputs stability and dynamic derivatives separately. As a result, total coefficients are found by

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adding these derivatives together. For each longitudinal and lateral force and moment coefficients, equations are defined in stability axes. Then, firstly a transformation from stability axes to body axes was performed, and the aerodynamic forces and moments of each component were carried to the center of the gravity.

The controller hardware is a microprocessor-based controller. Because of massive data flowing, the related processor should have high level computational processing capability. In addition, the designed system is portable and consumes minimum energy during operation.

The design started with the requirement analysis. After requirement analysis, the construction of the 6 Degree of Freedom (6DOF) dynamic model of the Cessna 182 scaled model was realized. Then the system matrices and control algorithms were designed in the light of system dynamics. State space modern controller design method preferred, since it is more convenient for our embedded flight controller design. Control structure was developed in MATLAB & SIMULINK environment. Then, hardware design carried out. The last step of the design is embedding the controller algorithm into the controller hardware. At the end, with the integration of all these hardware units, software and avionics peripherals to the air vehicle, the process has been finalized. The design procedure and the tools used for is shown in Figure 1.

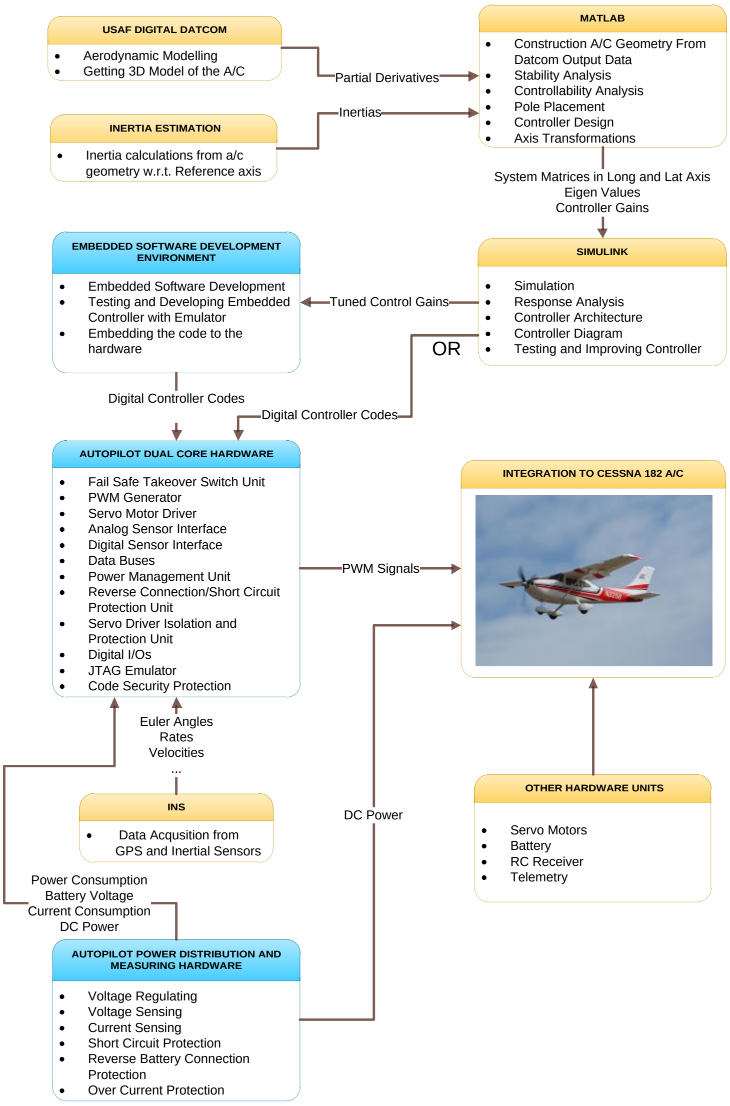

Figure 1: Workflow Diagram

AIRPLANE SYSTEM MODEL

Development of the Aerodynamic Model

Aerodynamic system model is prepared using the theoretical results obtained from the software Usaf Digital Datcom. Modeling of the air vehicle means constructing the system matrices mentioned before. In the system matrices, we need aerodynamic coefficients and inertias. Hence, the aerodynamic stability and control characteristics are required. The reason for using Datcom is to provide a systematic summary of methods for estimating stability and control characteristics rapid and economical in preliminary design applications [Division, and Missouri, 1979].

The Datcom+ is the improved version of Datcom for airplanes. In addition to these partial derivatives, Datcom+ gives the 3D modeled drawing which is shown in the Figure 2.

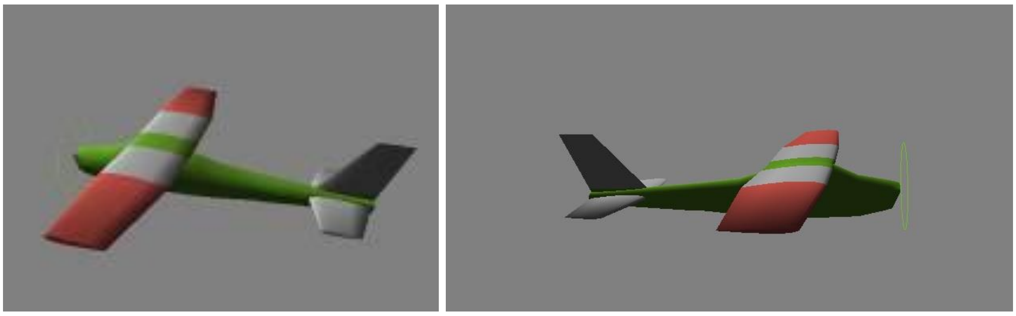

Figure 2: Datcom+ 3D Modeled Cessna 182 Scaled Airplane Drawing

The CESSNA 182 scaled airplane modeled in DATCOM was also validated in the MATLAB environment is shown in Figure 3.

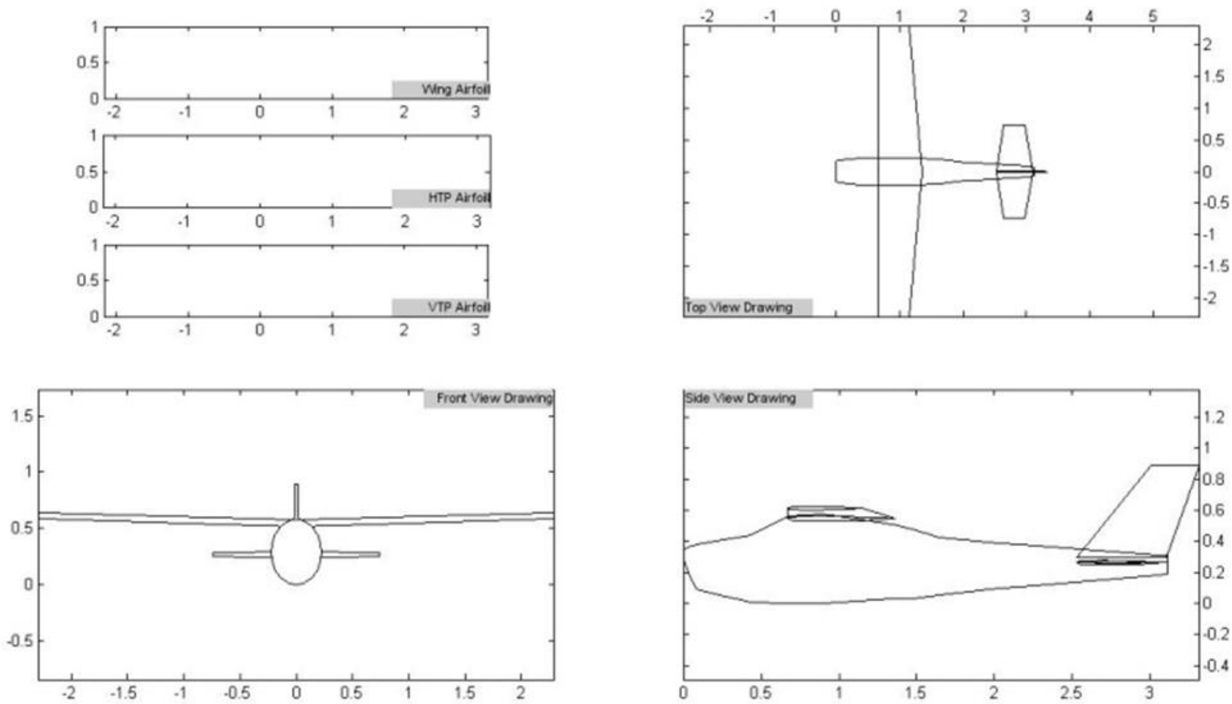

Figure 3: Datcom Modeled Cessna 182 Scaled Airplane Matlab Drawing

The regenerated drawing of the Cessna 182 scaled airplane are the same both for Datcom+ and Matlab.

Determining the Total Airplane Inertia in Pitch, Roll and Yaw about the Airplane Centroid

Inertias are necessary for calculating and analysis of the stability characteristics and linear modeling of the airplane.

The method used here to calculate the inertias is similar to Datcom method. In this method firstly calculations were made for the inertias of the sections. Then the inertias about the reference axis calculations were performed. Eventually the inertias of the airplane about the airplane centroids evaluated [Marsh, 1962].

Linear System Model

The translational equation of motion can be obtained using Newton's second law by the following equation.

$$\sum \overrightarrow{F}_B = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = m\overrightarrow{a_B^I} \tag{1}$$

$\overrightarrow{F}$ contains only the aerodynamic and propulsive forces. These aero propulsive forces are external forces that acting on the c.g. of the air vehicle.

The rotational equation of motion can be obtained using Euler Equation.

$$\overrightarrow{G_B} = \begin{pmatrix} L \\ M \\ N \end{pmatrix} = \frac{d\overrightarrow{H_B}}{dt}\Big| I = (\dot{I}_B\,\overrightarrow{\omega_B} + I_B\,\dot{\overrightarrow{\omega_B}}) + \overrightarrow{\omega_B} \times I_B\overrightarrow{\omega_B} \tag{2}$$

For trim point, net forces and net moments should be equal to zero, so accelerations, angular accelerations should be zero. There will be no change in p, q, r, u, v, w, θ and Ø.

After linearizing about the trim point, we have four linear equations for longitudinal dynamics. The input in the longitudinal system is δ_e, and the states are u, α, q, θ for a single input multi output (SIMO) system. The longitudinal system is in the form [Etkin, and Reid, 1996];

$$\begin{pmatrix} \Delta\dot{u} \\ \dot{w} \\ \dot{q} \\ \Delta\dot{\theta} \end{pmatrix} = \begin{pmatrix} \frac{X_u}{m} & \frac{X_w}{m} & 0 & -g\cos\theta_0 \\ \frac{Z_u}{m-Z_{\dot{w}}} & \frac{Z_w}{m-Z_{\dot{w}}} & \frac{Z_q+mu_0}{m-Z_{\dot{w}}} & \frac{-mg\sin\theta_0}{m-Z_{\dot{w}}} \\ \frac{1}{I_{yy}}\left(M_u+\frac{M_{\dot{w}}Z_u}{m-Z_{\dot{w}}}\right) & \frac{1}{I_{yy}}\left(M_w+\frac{M_{\dot{w}}Z_w}{m-Z_{\dot{w}}}\right) & \frac{1}{I_{yy}}\left(M_q+\frac{M_{\dot{w}}(Z_q+mu_0)}{m-Z_{\dot{w}}}\right) & -\frac{1}{I_{yy}}\frac{M_{\dot{w}}mg\sin\theta_0}{m-Z_{\dot{w}}} \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} \Delta u \\ w \\ q \\ \Delta\theta \end{pmatrix} + \begin{pmatrix} \frac{\Delta X_C}{m} \\ \frac{\Delta Z_C}{m-Z_{\dot{w}}} \\ \frac{\Delta M_C}{I_{yy}}+\frac{M_{\dot{w}}}{I_{yy}}+\frac{\Delta Z_C}{m-Z_{\dot{w}}} \\ 0 \end{pmatrix}\delta_e \tag{3}$$

CONTROLLER DESIGN

For a linear-time-invariant system [Ogata, 2002],

$$\dot{x} = Ax + Bu \tag{4}$$

$$y = Cx + Du \tag{5}$$

In most airplanes D=0;

$$y = Cx \tag{6}$$

The state space representation of the Cessna182 scaled airplane modeled in Simulink (Figure 4).

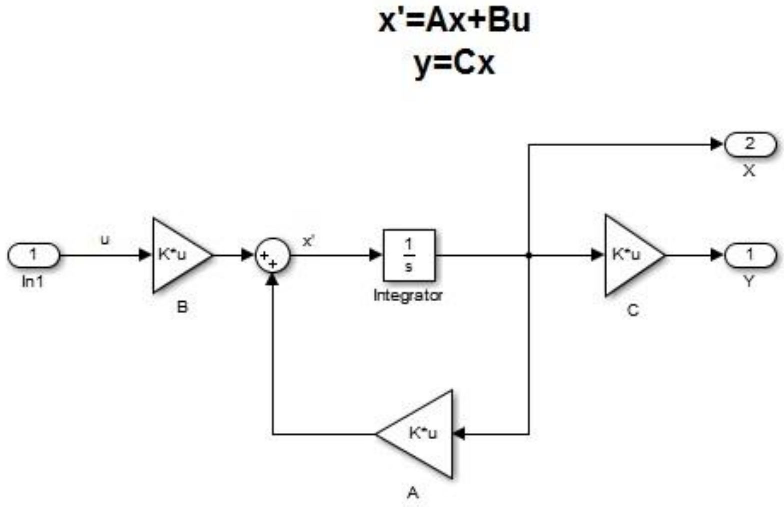

Figure 4: State Space Model of Cessna 182 Scaled Airplane

State space modern controller design method preferred, since it is more convenient for our embedded flight controller design. Flight control system designs are generally designed using classical techniques. However, as more loops are added, the design procedure may become more difficult [Stevens, 1992]. The generalized modern controller in longitudinal axis modeled in Simulink as shown in Figure .

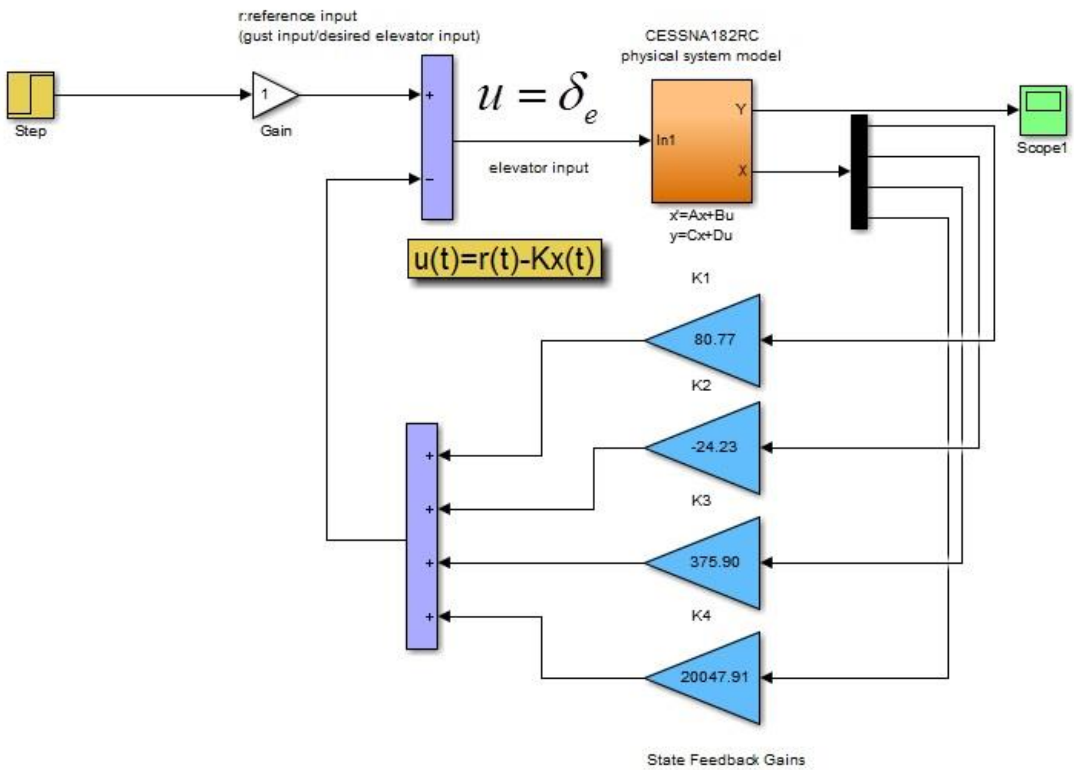

Figure 5: State Space Modern Controller Model for Steady Level Flight in Longitudinal Axis

AUTOPILOT HARDWARE DESIGN

The hardware consists of two electronic boards, flight controller board and flight power module board.

Flight Controller Hardware

Autopilot flight controller hardware (Figure) designed such that it processes sensor data collected from sensor units, operate control algorithms and produce Pulse Width Modulation Signals (PWM) to the appropriate control surface servo motors. Through the dual architecture design, it is possible process the control algorithm in one part and peripheral tasks in another part independently. Since, onboard sensors restrict to work with further technology sensors in the future or user may want a more advanced Inertial Navigation System (INS) or radio telemetry system with it, all the sensors are external peripheral units for this flight controllers. Furthermore, onboard sensor design with autopilot flight controller has magnetic interference disadvantages. So, it provides an interface on the flight controller that allows any type of sensor to be connected.

Flight controller equipped with six channels buffered advanced PWM (Pulse With Modulation) outputs up to 24 bit resolution. The device produces the PWM outputs in its own module. It does not produce PWMs with CPU (Central Processing Unit) timers. Hence, its PWM responses are very fast. Thanks to flight controller design, these PWM outputs are also buffered and protected against reverse servo actuator connections. This way the controller processor is isolated and protected.

Furthermore, flight controller has no jumpers for some configurations, because jumpers make confusion. It makes the necessary configurations automatically.

Full functional flight controller with its all peripherals has a weight of 78 gram (Figure).

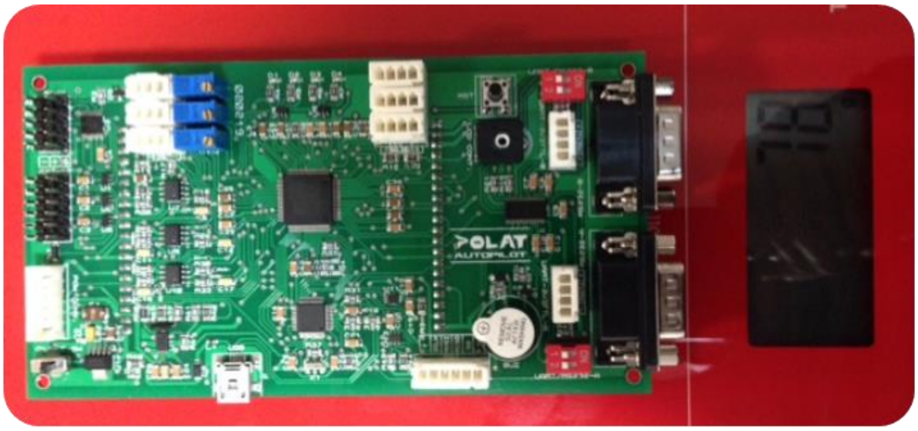

Figure 6: Autopilot Flight Controller Board

Hardware solutions have to be used to process signals that are too fast for processors to handle. In this case, programmable logic circuits like FPGA come to mind. But this type of hardware solutions is not easy programmable and cost effective. Time critical control is the majority of a closed loop system to collect data, process that data and update the system within a defined time period. If the system misses that critical time, its stability, precision and efficiency will degrade. So, the controller hardware should be very fast in time, easy programmable and cost effective. For these reasons, the hardware was designed to be a separate processing unit to handle the peripheral work, and separate to handle the control work. In this architecture design structure, while transactions are carried out independently, but communication and synchronization with each other are also provided. By this way, the independent control loop fully programmable processor that brings concurrent control loop execution to the advanced flight controller. The low interrupt latency of the control loop processing allows it to read peripheral samples time accuracy. This significantly reduces the samples to output delay to enable faster system response and higher speed control loops. By the dual architecture design provides to service time critical control loops, and the other processor is free to perform other system tasks such as communications and diagnostics.

The flight controller hardware equipped electronics fail safe multiplexer circuitry on it. Thanks to its analog circuitry design, the on board fail safe unit works very fast. The flight controller also has a six channel remote controller interface communicated with its fail safe unit.

Other features of the autopilot flight controller hardware board are listed in Table 1.

Analog Inputs	3 buffered 12 bit 3 MSPS Analog to Digital Converter (ADC) unit
Onboard Devices	Servo motor driver JTAG Emulator with on board USB Power management unit Software independent fail-safe unit
Data Busses	1 SPI channel, 3 I2C channels, 2 configurable UART channels
Digital I/O	18 configurable digital Input Output ports
Protection	Code security protection PWM reverse servo protection Advanced PWM outputs up to 24 bit resolution Analog / Digital Converter Protection Power protection Redundant power source management Fail safe MUX
Additional Features	Onboard buzzer and four LED indicators for developing and testing controller software PCB mounted ON/OFF power switch Smooth power on and off feature LCD screen and button unit connection compatibility
Weight	78g
Dimensions	16cm x 9cm.

Table 1: Autopilot Flight Controller Board Specifications

Flight Power Unit Hardware

This unit (Figure) provides the necessary voltage to the autopilot and the peripheral units. It also measures the voltage and the total current consumed from the battery. The extended features of the power unit are listed in the Table 2.

Battery Input Range	1S LiPo to 7S
Outputs	1 pc Flight controller power output 1 pc Battery voltage output for peripherals 3 pcs 5 VDC output for peripherals
Total Current 5 VDC Outputs	5 Amps
Total Current Battery Output	200 Amps
Voltage Measuring Range	0 VDC to +30 VDC
Current Measuring Range	Up to 200 Amps **without heating**
Protection	Short-circuit / over current protection Reverse connection protection Voltage fluctuation protection Anti-spark protection
Additional Features	Minimum power consumption for voltage and current measuring operation
Weight	20g
Dimensions	6.5cm x 4.5cm

Table 2: Flight Power Module Specifications

Figure 7: Flight Power Module Board

AUTOPILOT SIMULINK DESIGN

The design of the advanced flight controller is suitable for MATLAB SIMULINK. So, the design blocks of autopilot flight controller constructed in SIMULINK to design controller in an easy way. Digital inputs are most commonly used to connect switches to the autopilot flight controller. Digital outputs are used as the output of a process for turning a servo motor.

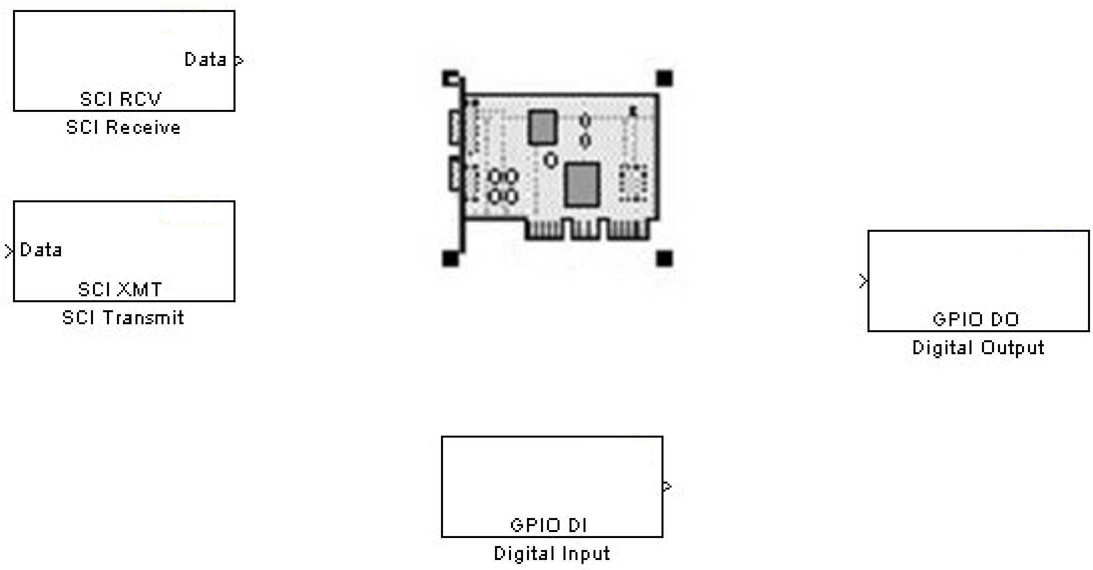

Figure 8: Autopilot Hardware Card Blocks in Simulink

Besides, it can be used the serial communication interface (SCI interface) to send data between the autopilot controller card and a personal computer using Windows Terminal.

An example model of the steady-level PID controller was created. The control loop model is shown in Figure .

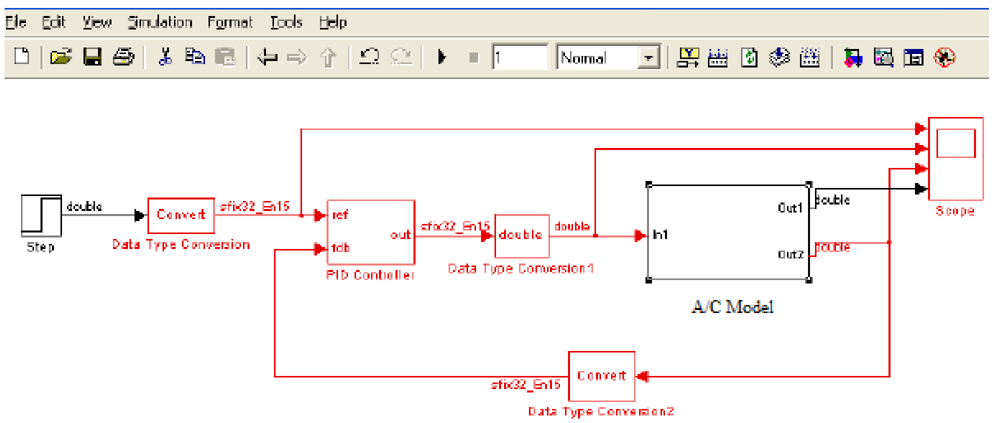

Figure 9: Flight Controller Loop Control in Simulink

CONCLUSION

Dual architecture flight controller hardware design has great benefits over standard embedded flight controller designs. One part of the hardware takes on peripheral issues while the other part takes the main function of autopilot controller algorithm. Besides, by accelerating the control loop on the second part, the hardware works nearly as real time. So, this way ensured there is nearly no delay. Thus, the most important problem for autopilot design engineers was solved. The second problem for autopilot design engineers is the emergency fail safe problem. In classic flight controller hardware designs, when autopilot engaged to take over the flight, in case of desiring to take over manual pilot, the hardware does not easily switch in. Because there may occur software crash or time response delay. Moreover, most of the fail-safe multiplexers are a separate hardware unit that plugging to the main board. In this embedded flight controller design, a real time on-board fail-safe multiplexer circuitry established. And the redundant channel of the receiver assigned. During tests observed in a case of emergency, the system immediately switches between autopilot to manual pilot without any delay. Moreover, the flight controller automatically switches from manual to autopilot in case of radio signal lose out of range.

In order to provide easily autopilot controller design, it is essential to observe the outputs and test results. Therefore, LCD screen and button units are compatible to be fitted on this controller hardware. Thus, the user easily sees some values (Euler's, attitudes, etc.) and even make gain tuning using buttons without making any modification on software.

To make the autopilot design easy and easy, a method of MATLAB & SIMULINK tool embedded to this controller hardware. By this way, an aerospace engineer does not have to know any embedded programing language like C/C++, etc.

If the designer wants a more elaborated software method, this flight controller is suitable C/C++ even with assembly language.

By designing this *advanced flight controller autopilot system,* it is aimed an optimized and efficient all in one controller development system so that facilitating aerospace engineers and students for designing autopilots. Through this integration work, aerospace engineering, electronics engineering and software engineering disciplines are combined, and the integration works in a harmony.

References

[1] Division, L., and Missouri, L. (1979), *The Usaf Stability and Control Datcom: Section 1*, Vol. 1., McDonnell Douglas Astronautics Company, 1979.

[2] Etkin, B., and Reid, L. D. (1996), *Dynamics of Flight: General Equations of Unsteady Motion*, 3rd ed., John Wiley & Sons, Inc., 1996.

[3] Marsh, D., (1992) *"Mass Moment of Inertia Estimation Methods", Society of Aeronautical Weight Engineers Technical Paper 313*, 1962

[4] Ogata, K., (2002) *Modern Control Engineering: Analysis of Control Systems in State Space*, 4rd ed., Prentice-Hall, Inc., 2002.

[5] Ogata, K., (2002) *Modern Control Engineering: Design of Control Systems in State Space*, 4rd ed., Prentice-Hall, Inc., 2002.

[6] Stevens, B. L., and Lewis, F. L., (1992) *Aircraft Control and Simulation*, John Wiley & Sons, 1992.