Design of an Unmanned Aerial Vehicle Using Commercial Off-The-Shelf Components

Capstone Project for ME5643: Mechatronics

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1 Project Description and Technical Objectives

Unmanned Aerial Vehicles (UAV) find many real world applications and have become a cost effective and efficient test platform for aircraft control research. This design project aims at providing a low-cost, easily deployable test platform for future research in the area of aircraft controls at the Polytechnic Institute of NYU. Low-cost UAV platforms have previously been used at institutions such as the NASA Ames Research Center. These were used as platforms for the testing and validation of various prototype inner and outer loop controllers. These Plug-and-Play UAV's have successfully been used to test Prototype designs such as adaptive neural network controllers for damaged airplanes and for various trajectory and path planning algorithms.The use of Commercial Off-the-Shelf (COTS) parts and avionics/sensors reduced the price of the UAV, compared to systems with equivalent functionality and also simplifies construction,integration and testing. This also allows for various payload modules to be added rapidly and with minimal customization. This results in the UAV having Plug-and-Play capabilities.

This UAV, designed as part of the Mechatronics course, demonstrates the deployment of a simple heading and attitude hold controller. The control system on the airplane maintains a commanded course, pitch or roll angle. Although a fairly simple controller, this system finds tremendous applications for small scale autonomous aircraft. The procedures documented in this report highlight the Plug-n-Play nature of the describe autonomous system.

2 Cost/Budget Details

The project is partly supported by the Exploration Aerial Vehicle (EAV) Lab of NASA Ames Research Center[1]. Components such as the Engine, Safety switch, software resources and technical support are provided by the EAV lab. Table 1 provides a brief description of the component costs. Components that do not have a price listed in the table were already procured by Department of Mechanical Engineering at Polytechnic.

Component	**Description**	**Poly**	**NASA**
Airframe	Hangar 9 1/4 Scale J3 Piper Cub	$630	
Engine	Fuji Imvac BT43		$512
Hardware	Servos, Props,connecters etc.	$800	
Aircraft Radio	JR XP662		
Flight Computer	Fit PC2	$315	
GPS Sensor	Garmin 18x USB		$90
IMU	Microstrain 3DM-GX3	$2000	
Servo Controller	Propeller Servo Control Unit	$40	
Safety Switch	NASA Custom UAV safety switch		
Airspeed Sensor	MPXV500 Diff. Pressure Sensor	$20	
Telemetry Radio	MaxStream OEM 900 Mhz		
Control Software	Reflection		
Operating System	Microsoft Windows XP Embedded SDK		$1000
	Approximate Total	$3805	$1602

Table 1: Cost Description

3 System Description

3.1 Airframe and Power Plant

A COTS Radio controlled model airplane kit is used as the airframe/test platform. The airframe chosen for this a Hangar 9, 1/4th scale Piper J3 Cub. See Figure 1(a). The kit is available in Almost Ready-To-Fly condition, an hence minimized assembly time. The scaled down model of a popularly studied general aviation aircraft, such as the Piper Cub, also simplifies dynamic modeling of the platform [1]. The Hangar 9 Piper Cub is equipped with individually actuated control surfaces that are used to simulate situations such as aircraft damage and unmodeled dynamics such as a change in the moment coefficient, C_{m_0}, due to lowering of both ailerons simultaneously, thus acting as flaps. These capabilities make the UAV a good test platform for adaptive control research.
The power plant chosen for this project is a Fuji Imvac BT43EI gasoline/oil engine(Figure 2(b)).

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This engine provides sufficient power for the airframe with the added weight of the avionics system and batteries.

(a) Hangar 9 25% Piper J3 Cub

(b) Fuji Imvac BT43-EI

Figure 1: Airframe and Power Plant

3.2 Flight Computer

The flight computer used is a FitPC2 mini computer. The FitPC2 is fanless Intel Atom based single board computer. This computer was chosen due to its light and small form factor and rugged construction. The Intel based architecture enables the use of commercially used operating systems such as Windows Embedded and VX Works.The computer has six external USB ports, an HDMI display port and uses a solid state memory (CF card) for data storage. This makes the flight computer less susceptible to damage due to vibration. Power to the flight computer is provided Lithium Polymer batteries, capable of delivering a charge of upto 2450 mAh at 14.8 volts.A power board comprising of two voltage regulators, to step down the voltage from 14.8 volts to 12 volts was built. Since all the sensors and avionics are powered through the flight computers USB ports, the battery was chosen so as to reliably deliver the power needed to run the computer and avionics.

3.3 Avionics/Sensor Suite

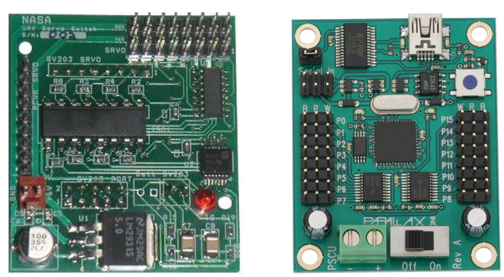
The UAV will uses a Microstrain 3DM-GX3 Attitude Heading Reference System for orientation, angular and linear inertial force measurements. The Microstrain 3DM-GX3 combines a triaxial accelerometer, triaxial gyro, triaxial magnetometer, temperature sensors, and an on-board processor running a sophisticated sensor fusion algorithm to provide static and dynamic orientation and inertial measurements [2]. The 3DM-GX3 has a USB 2.0 interface. The small form factor makes optimal sensor placement easy.
The Garmin 18x OEM GPS will be used for position sensing. The 18x GPS sensor is a Wide Area Augmentation System (WAAS) enabled GPS sensor that provides an accuracy of three meters. This GPS sensor has a USB 2.0 interface.
The current configuration of the aircraft uses only inertial measurements for 3 Degree of Freedom control, Euler angle control.

A UAV safety switch to enable switching between manual pilot and autopilot control of the airplane is used. This is a custom circuit board with eight servo channels, provided by the EAV lab (NASA Ames). The Safety switch (Figure 3(a)) is essentially a multiplexer that optically isolates

the signals coming from the servo control board and the safety pilot/Radio control system. Thus in case of control system malfunction, the "safety" or manual pilot can take control of the plane quickly.
Interfacing to the servos and actuators is provided by the Propeller Servo Controller Unit (PSCU). The PSCU (Figure 3(b)) can control upto 16 servos by sending serial commands using a propeller microcontroller. The commands are be sent to the PSCU at a rate of 38.4 kbps, over USB.

(a) Fit-PC2 (b) Microstrain 3DM-GX3 (c) Garmin 18x OEM

Figure 2: Flight Computer and Avionics/Sensors



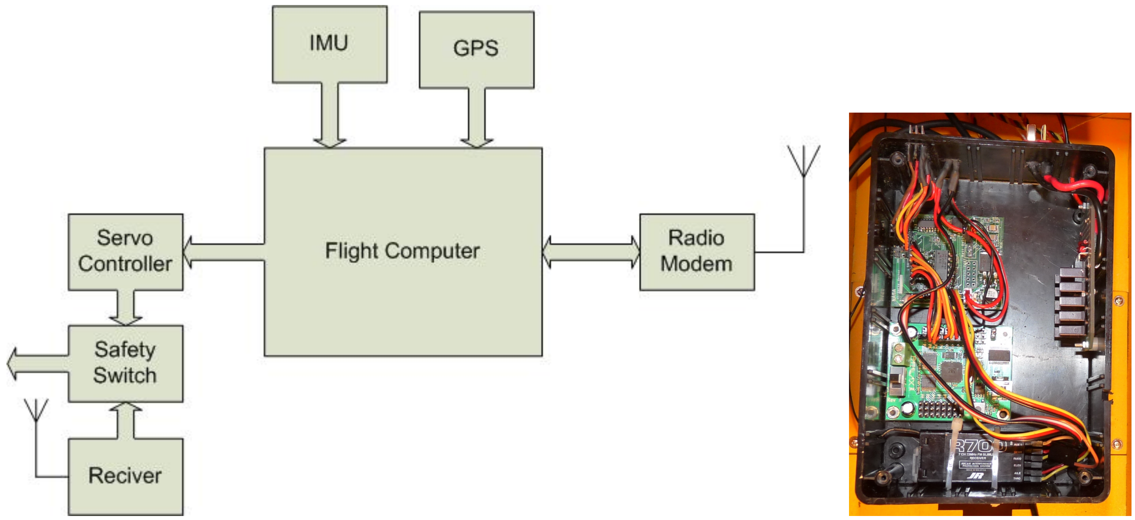
(a) Safety Switch (b) Propeller Servo Controller

Figure 3: Flight Computer and Avionics/Sensors

The assembled avionics box (Figure 4(a))consists of the Flight Radio, the Radio Modem, the safety switch and servo controller. The voltage regulator for the flight computer is also housed in the avionics box. The flight computer is secured on top of the avionics box. This whole setup is soft mounted on the cabin floor of the aircraft using "bumper beans", to reduce vibrations. Figure 4(b) shows an overall component schematic.

3.4 Software

Microsoft Windows XP Embedded will be used as the onboard operating system. The Embedded version of Windows provides realtime operating system capabilities, ensuring stable running of the control system programs. The current configuration of the UAV is running Windows XP Professional, for ease of development.
The UAV is developed around a central Plug-and-Play software infrastructure, the Reflection Architecture [3], that provides an end-to-end platform for rapid development, integrated simulation and Hardware-In-Loop Simulation testing, and flight testing of experimental sensors and control system algorithms. Reflection is a realtime component-based plug-and-play architecture. It is used as a



(a) Hardware Schematic (b) Avionics box

Figure 4: Hardware Schematic and Avionics box

development environment for embedded control systems and simulations. The Reflection architecture features a wide variety of existing modules, displays, and interfaces to build upon. See Figure 5(a). The unique feature of reflection is that it is also flown as the control/telemetry/interface system on the physical Unmanned System platform. The modular architecture of Reflection allows rigorous testing of components in a mixed environment of real hardware and simulated data in multiple configurations (Figure 5(b)). This also allows extremely rapid reconfigurability, since the hardware components can easily and quickly be replaced with simulation components.

4 Modeling and Simulation

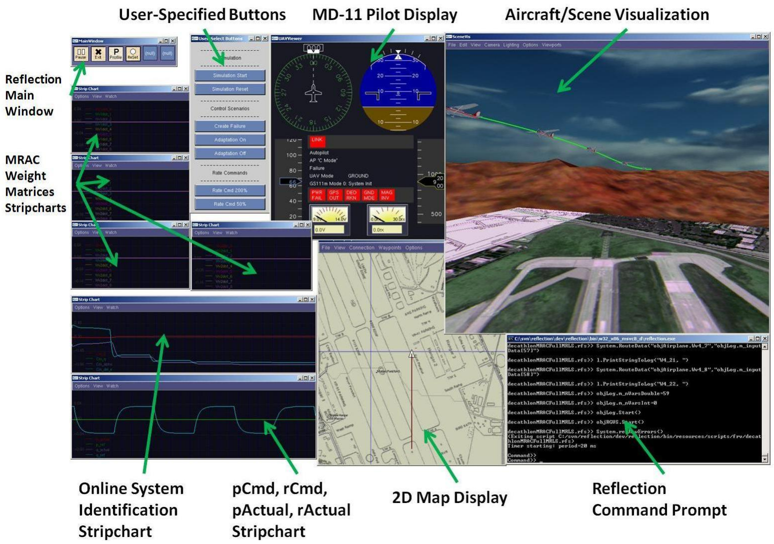
The first phase of the control design process was to create modules for each hardware component in Reflection. All modules were created using the libraries and templates provided in Reflection architecture.

4.1 Microstrain module

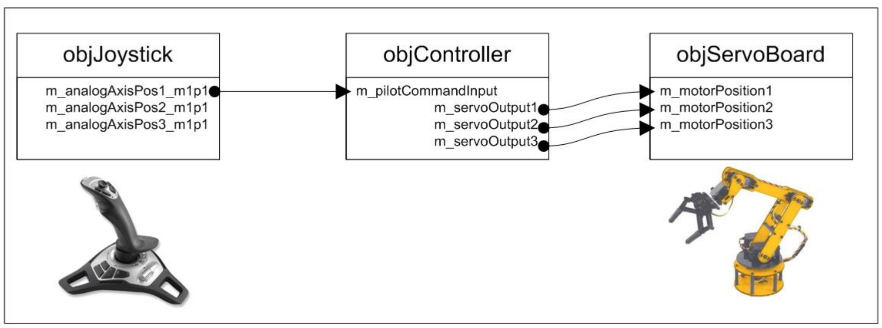
The 3D Microstrain 3DM-GX3 IMU communicates with the main flight computer over USB at a Baud Rate of 115.2 kbps, using asynchronous serial communication protocols. The module sends simple single byte binary commands to the sensor. The sensor then replies with fixed length binary data records. The Microstrain IMU provides an acceleration vector, with 3 acceleration components, an angular rate vector, with 3 angular rate components for each axis and a 9 element rotation matrix. The rotation matrix [4] is given in equation 1

$$M = \begin{bmatrix} \cos\psi\cos\theta & \sin\psi\cos\theta & -\sin\theta \\ \cos\psi\sin\theta\sin\phi - \sin\psi\cos\phi & \sin\psi\sin\theta\sin\phi + \cos\psi\cos\phi & \cos\theta\sin\phi \\ \cos\psi\sin\theta\cos\phi + \sin\psi\sin\theta & \sin\psi\sin\theta\cos\phi - \cos\psi\sin\theta & \cos\theta\cos\phi \end{bmatrix} \quad (1)$$

where the euler angles or roll, pitch and yaw are given by ϕ, θ and ψ respectively. The euler angles are then calculated from the rotation matrix in refrotation, using equations(2- 4)



(a) Reflection Architecture Showing Different modules



(b) Reflection modules: Hardware interface

Figure 5: Reflection Archtitecture

$$\phi = \tan^{-1}(\cos\theta\sin\phi/\cos\theta\cos\phi) \tag{2}$$

$$\theta = \sin^{-1}(-\sin\theta) \tag{3}$$

$$\psi = \tan -1(\sin\psi\cos\theta/\cos\psi\cos\theta) \tag{4}$$

The calculated Euler angles (in radians) are passes as output parameters.

4.2 Controller module

The controller module computes the control surface commands based on the its input parameters i.e: Euler angles provided by the IMU modula and commanded Euler angles, provided by the user. The elevator, rudder and aileron commands are produced using three separate feedback loops, with proportional controllers. Figure 6 shows an example of a feedback control loop.

4.3 Servo Controller module

The servo controller module provides commands to the Propeller Servo Control unit, which is an interface between the actuators and the controller module. The inputs to this module are control

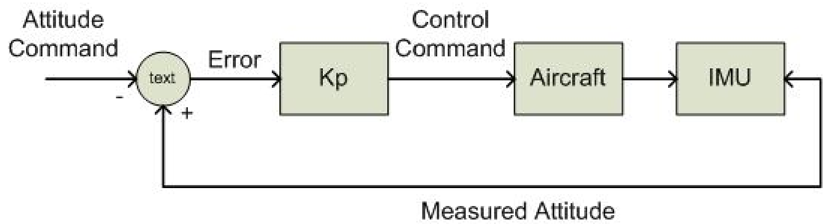


Figure 6: Controller Feedback loop

surface commands, scaled between -1.0 and 1.0, with 0.0 being the center position and -1.0 and 1.0 being the extreme left and right positions. The commands sent to the PSCU consist of 8 bytes packets. These packets contain the servo set position command, the channel number, the ramp slope and the servo position. The ramp slope is the slope for the ramp function with which the servo responds. This prevents the servo from overloading, in case of sharp or sudden inputs. The servo position is a number between 1250 and 250, where 1250 and 250 are the extreme positions and 750 is the center position.

4.4 Autopilot system

The autopilot system consists of the aforementioned modules, running in a continuous loop at 20 Hz. The arguments passed to the system are the port numbers for the IMU and PSCU and commanded euler angles. Figure 7 shows a flowchart of the autopilot system.

5 Applications and Future Work

The current attitude and heading hold system has many real world applications. One such application is an oscillation reducer for small scale UAV's. Small aircraft, such as this one, often enter the Phugoid mode. The Phugoid is a dynamic mode of an aircraft excited by a single sharp or step elevator input. This causes the aircraft to begin oscillations in the pitch axis. Often, pilots tend to try and correct this behavior extreme elevator input responses, sometimes leading to pilot induced oscillations. The attitude heading hold system can be deployed on small trainer aircraft to avoid situations such as this.
Future work on the autopilot system would be to include the GPS module for better position data. The IMU and GPS could be fused together using an estimator based approach, to get accurate position data. Future versions of the autopilot will also have the ability to transmit flight data to a ground based computer for monitoring and analysis. This will be done by including the 900 MHz radio modem, in the autopilot loop.

6 Acknowledgements

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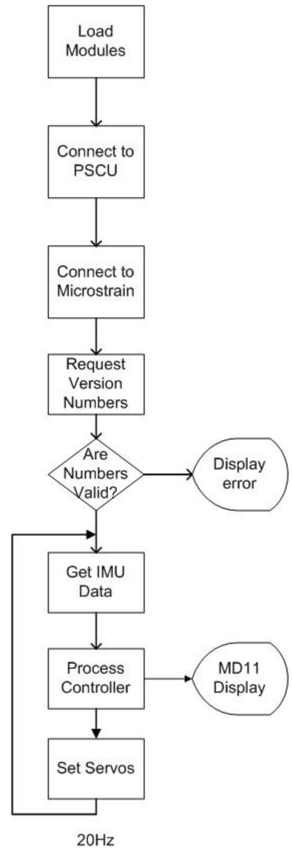

Figure 7: Controller Feedback loop

References

[1] Dongwon Jung. *Hierarchical Path Planning and Control of a Small Fixed-Wing UAV: Theory and Experimental Validation.* PhD thesis, December, 2007.

[2] http://www.microstrain.com/3dm-gx3-25.aspx.

[3] Corey Ippolito. Reflection User Manual.

[4] Brian L. Stevens and Frank L. Lewis. *Aircraft Control and Simulation.* Wiley-Interscience, 2003.