Design of Unmanned Aerial Vehicle Autopilot based on Freescale Qorivva 32-bit Microcontroller

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Abstract: Unmanned Arial Vehicle (UAV) is typically a low-cost aircraft designed to execute missions that are expensive or dangerous to be executed using its contrary .i.e. manned aircraft. Autopilot acts as the brain of the UAV along with the eyes and ears (sensors). Autopilot has two major components, system software and hardware. Freescale's MPC5644A is selected as the main embedded controller. Qorivva MPC564xA family is a 32-bit Power Architecture® microcontroller solution designed primarily for engines and advanced transmissions. The selected microcontroller is highly suitable for Autopilot application because of high performance and on-chip integrated resources. Design and development started from a bare board, initialization, configuration and peripheral interface development is followed. A Ground Control Station (GCS) is also developed using National Instrument's Lab Windows CVI (Integrated Development Environment) for constant monitoring of UAV health and mission plan upload. Testing of the Autopilot software is accomplished by Hardware-in-loop simulation. Design of the Guidance and Control Algorithm is not included in this research, open-source Algorithm is currently used and can be replaced by customized algorithms in future research.
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1. Introduction

The basic definition of a UAV is that, it is an aerial vehicle without human pilot. There are two broad categories; Unmanned Aerial System (UAS) and UAV. If the aerial vehicle has a pilot on ground which is controlling the vehicle through a remote link the system is called UAS. On the other hand a UAV is termed as a system which has the capability to autonomously perform different missions without human interference. It may support Manual/Override mode, but it must be capable of autonomous mission execution and flying back home.

UAVs are easier to handle, maintain and operate, and can even be expendable. There are different classes of UAVs starting from very small hand-launched and remote-controlled drones to large, fully autonomous combat UAVs. Similarly, the operating altitude and range also vary a lot; altitude between 1km and 10kms, and range starting from 1km (short-time) to thousands of kilometers (round-the-clock operation). The nature of the missions also varies a lot; target drones for munitions testing to surveillance/reconnaissance aircrafts to long-range combat operations. Lately, the UAVs are also operated to augment/substitute for the satellite and/or ground communication links. Natural disasters like earthquakes often affect the communication infrastructure; UAVs are lately being used to restore utilities such as phone and internet services (Reyes & Dogan, 2003). Currently, due to availability of long range radio equipments, cheaper airframes and powerful microcontrollers UAVs have found their application in the civilian circumstances like remote sensing, mapping traffic monitoring, research and rescue. The idea of unmanned aerial flight was first conceived in 1887, when the first aerial photograph was taken using a kite, a camera and a very long string attached to the shutter-release of the camera by a British meteorologist Douglas Archibald (Douglas, 1912).

This paper is organized as follows; Chapter 2 presents literature review on basics of Autopilot, history and the recent autopilots available today. Chapter 3 describes the Autopilot hardware system (On-board microcontroller and sensors), its configuration (start to main) and initialization of the resources like, timers and interrupts. Chapter 4 discusses Autopilot software, GCS and Hardware-in-loop Simulation (HILS). Chapter 5 discusses the system testing results for Hardware-in-loop simulation and conclusion.

2. Autopilot

In the early days of aviation industry the aircrafts were piloted by humans throughout the flight duration. Later on to avoid the human error and pilot fatigue, Autopilots were developed to assist the human pilots. In case of manned aircrafts (Passenger planes, Cargo Planes, Fighter Planes etc.) Autopilots are installed to assist the human pilot. Autopilots do not replace the human pilot but facilitate them in controlling the vehicle especially during the level flight (cruise), so that the human pilot can focus on the other broader aspects of the operation like weather, trajectory and systems (Federal Aviation Administration, 2014). On the other hand in case of UAVs, Autopilots are solely responsible for the complete operation of the aircraft starting from take off to landing.

An “Autopilot” is a complex control system which handles the aircraft either to assist or completely replace the pilot (including a remote pilot). It becomes even more important when it is a UAV operating beyond the visual range of the operator(s). Therefore, an autopilot is the most crucial component of a UAV. Generally, an autopilot is an embedded system that integrates the flight sensors and actuators for its stable control, guidance and navigation algorithms for execution of tasks and decoding the operator’s commands. In this sense, it is a complete Flight Control System (FCS). Moreover, it also integrates/communicates with the Ground Control Station (GCS) or, sometimes referred to as Mission Control.

Autopilot system has two major sections: State Observer and Controller. State Observer acts as the eyes and ears of the system and typically comprises of sensors and state estimation Algorithm. In real time readings from the sensors are passed to the state estimation Algorithm which determines the current state of the aircraft, states are passed to the Control law which calculates the corrections for the control surfaces to maintain the desired altitude and attitude of the aircraft. The block diagram of a typical Autopilot is shown in the Figure 1.

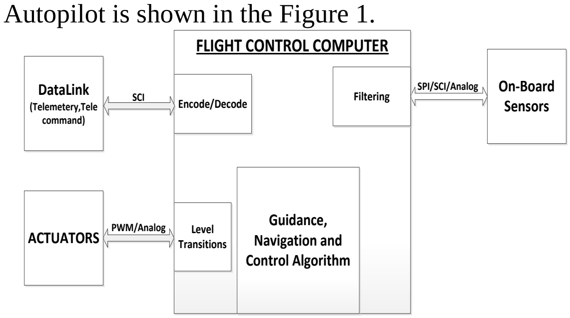

Figure 1. Typical Autopilot Block Diagram

2.1 History of Autopilots

Sperry Corporation designed the first Autopilot in 1912 (Stevens & Lewis, 2003). This autopilot used gyroscopic heading sensor, and altitude sensor connected to hydraulic elevators and rudder, enabling the aircraft to fly straight at a fixed altitude without pilot interaction (UAV at the centennial, 2005). In 1930 Sperry Jr., the son of Lawrence Sperry continued the work on the same autopilot and tested it in a US Army Corps aircraft that kept the aircraft on a fixed heading and altitude for three hours (“Now - The Automatic Pilot”, 1930). In the same year in 1930 British Royal Aircraft, designed an autopilot called “Pilot’s Assister” which also used a gyroscope to control the flight (“Robot Pilot”, 1930). During the 1950s, technological breakthroughs and innovations led to the development of reconnaissance UAVs equipped with advanced Autopilots. Further Research for development of more sophisticated and efficient autopilots continued in the next years and was highly facilitated by advancements especially in the area of computing (Microprocessors and Microcontrollers) and sensing (MEMS based Inertial Navigation Sensors).

2.2 Modern Autopilots available today

In this section some off-the-shelf autopilots are discussed. Most of the modern UAV Autopilots have similar features which include; airspeed hold, altitude hold, turn coordination, GPS navigation, vertical takeoff and landing (VTOL), autonomous operation from launch to recovery. Normally Single board, i.e. sensors, processor and peripheral drive circuits are all integrated on a single board to give the lower volume and weight (Chao, Cao & Chen, 2010).

2.2.1 MicroPilot MP Series

MicroPilot offers a series of Autopilots MP2x28 for fixed wing and rotary wing aircrafts. These Autopilots are full featured UAV autopilots capable of, airspeed hold, altitude hold, turn coordination, GPS navigation, vertical takeoff and landing (VTOL) and autonomous operation from launch to recovery.

2.2.2 Piccolo by Cloud-Cap Technology

Cloud-Cap Technology provides a series of Autopilots called piccolo for different applications, the most sophisticated till date is Piccolo II. It provides a complete Flight Control Solution with inertial and Air data sensors, GPS receiver, Datalink Radio and Microcontroller all in a shielded enclosure.

2.2.3 Kestrel Flight Systems Procerus

Kestrel has a 29MHz Rabbit 3000 onboard processor with 512KB RAM for onboard data logging. It has the built in ability for autonomous take-off and landing, waypoint navigation, speed and altitude hold. The flight control algorithm is based on the traditional PID control.

2.3 Open Source Autopilots

The researchers around the world have shown a lot of interest in the open source autopilots in the recent years because of flexibility in software and to some extent in hardware. Researcher can easily modify the autopilot based on their own special requirements. Autopilot software can be modified very easily to test and validate advanced guidance, navigation and control Algorithms.

Famous open-source Autopilots are listed as under (Jang & Liccardo, 2006);

- Paparazzi autopilot by researchers from ENAC University, France
- APM Multiplatform Autopilot
- Autopilot form University of Minnesota UAV Research group
- Crossbow MNAV and Stargate autopilot

3. Autopilot Hardware System

Most of the modern autopilots available today use GPS navigation integrated with inertial navigation to increase the navigation accuracy of the system. The on-board sensors are mostly MEMS to make the system light weight and small size.

3.1 Hardware Platform

Selection of the suitable Microcontroller is very important in view of the requirements. The selection is normally based on a number of factors like;

- Computation Speed normally measured in MIPS
- Volume and Weight
- Power Requirements
- System Integration Capability (On-Chip resources)
- Costs of development

Comparison of well known embedded processors reproduced from Tu & Du (2010) is shown in Table 1.

Table 1. Comparison of Microcontrollers

Attribute	Microcontroller/Microprocessor			
	PC-104	DSP -56xx	DSP-200x	MPC-5644A
Speed	Moderate	Fast	Fast	Fast
Volume	Large	Small	Small	Small
Integration	High	Moderate	High	High
Cost	High	High	Low	High

Based on these comparisons Freescale's 32-bit MCU MPC5644A is selected, although this series of devices is manufactured for transmission applications in automobiles but is highly suitable for Autopilot application due to the number of suitable features described below (Freescale Semiconductor, 2012);

- Size 23 x 23 mm (324 pins Chip)
- Speed up to 150 MHz e200z4 Power Architecture core
  - Superscalar architecture with 2 execution units
  - Up to 2 integer or floating point instructions per cycle
  - Up to 4 multiply and accumulate operations per cycle
- System Integration
  - 4 MB on-chip flash memory with Read While Write (RWW)
  - 192 KB on-chip SRAM
  - 3 enhanced Serial Communication Interface (eSCI) channels
  - 3 Serial Peripheral Interface (SPI) channels.
  - Forty 12-bit Analog input channels (multiplexed on 2 ADCs)
  - Up to 120 general purpose Input/output (GPIO) lines, including Enhanced Modular Input/output System (EMIOS).
- Power reduction mode: slow, stop and stand-by modes

3.2 Inertial Measurement Unit (IMU)

IMU is the main component of inertial navigation system used in aircrafts and spacecrafts. The data collected from the IMU's sensors allows a microcontroller to track an aircraft's position. An inertial measurement unit works by detecting the current rate of acceleration using one or more accelerometers, and detects changes in rotational attributes like pitch, roll and yaw using gyroscopes. And some also include a magnetometer, mostly to calibrate against orientation drift. The primary sensor selected for the Flight Control System (FCS) is Analog Device's ADIS-16488. It is a complete inertial measurement unit which includes a three axis gyroscope and gyroscope, a three axis accelerometer, a three axis magnetometer, and a pressure sensor all on a single chip. Each inertial sensor in the ADIS16488 combines signal conditioning with MEMS technology to optimize the performance (Analog Devices, 2012). IMU communicates with the microcontroller using a standard Serial Peripheral Interface in slave mode as shown in Figure 2.

3.3 GPS Data Receiver

GPS plays a pivotal role in the autonomous flight of the UAVs by providing the absolute position measurements .The GPS receiver module selected for the project is 3DR GPS LEA6 from 3D Robotics. The receiver provides a Navigation update rate of up to 5 Hz and a reasonable position accuracy of 2.5 meters. The GPS module communicates with the FCC over a standard SCI interface.

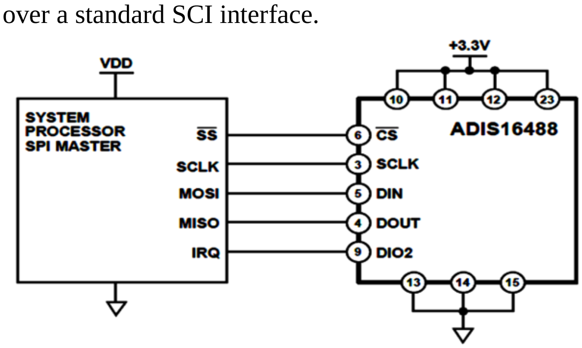

Figure 2. Inertial Measurement Unit (IMU) Interface

4. Autopilot Software

After the selection of the hardware components, system software is developed using Freescale CodeWarrior^{TM} Integrated Development Environment (IDE). In the first step initialization of the microcontroller functional modules like System clock, Timers, Interrupts and Peripheral interfaces is carried out using a graphical development tool called RAppID Init. A simple toggle LED application is first developed to understand the basic functionalities of the evaluation board and USB Multilink in circuit debugger. A front end of the Freescale CodeWarrior is shown in Figure 3.

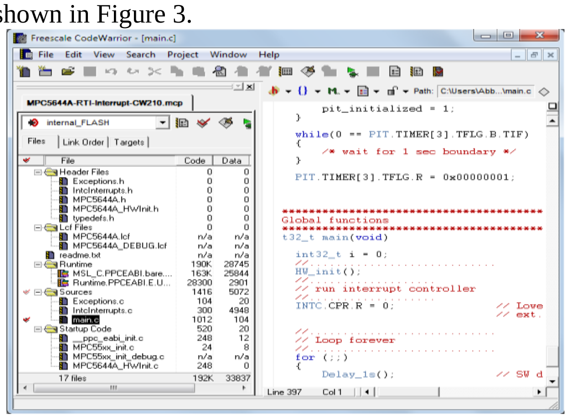

Figure 3. Freescale CodeWarrior (IDE)

Next step in the software development is to design the interfaces for on-board sensors, GCS, and actuators and Real Time Simulation computer for Hardware in-the-loop Simulations. Each Interface is first developed and tested individually to ensure reliable communication and is then added to the system software. Figure 4 below, shows the software debugging setup.

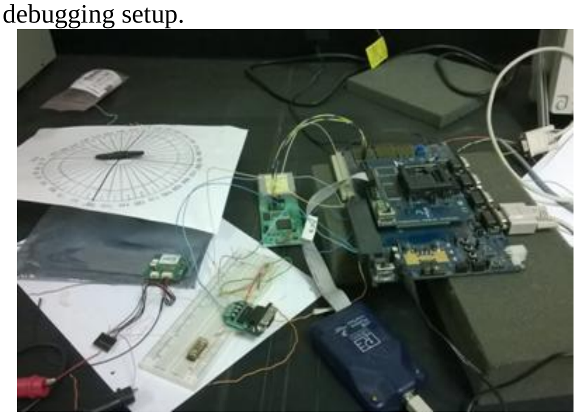

Figure 4. System Software Debugging Setup

Algorithm block used is an open source Guidance and Control Algorithm developed by university of Minnesota UAV Research group. Algorithm block is also implemented on the selected hardware. Figure 5 shows the overall system block diagram.

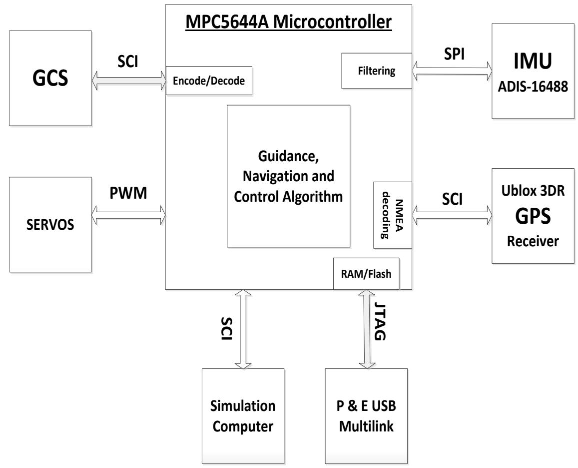

Figure 5. Final system Block Diagram

4.1 Ground Control Station

Ground Control Station developed for the system is a PC application and can be installed on any windows based platform (laptop, windows tablet) making it highly portable. National Instruments Lab Windows CVI is used, which is an ANSI C based IDE for Engineering User Interface (UI) design. Telemetry and Telecommand both features are implemented in the software, Telemetry data is displayed graphically during run time as well as logged for later analysis. There are two major components of the GCS software, Mission planning module, Telemetry/Telecommand module. Telemetry module receives Telemetry packet from FCC which primarily contains data of the on-board sensors data, system states and displays it on different tabs of the User Interface.

4.2 Hardware-in-loop simulation

Hardware-in-loop simulation (HILS) is an important component in the Design of the Flight Control software for UAV. HIL simulation emulates the sensors and passes this information to FCC which in reply outputs the control commands that are fed to system model in the simulation, resulting in new sensor data for next iteration. The process continues for complete simulation time. HILS is the most authenticated method for testing the Autopilot software except the actual flight of the UAV (Hao , Fang, Li & Liu, 2011).

University of Minnesota UAV simulation model is used for HILS (Minnesota UAV Research, 2012). Simulation is developed in Matlab/Simulink environment. System models for two airframes are incorporated in the simulation FASER and UltraStick. Guidance & Control (G&C) Algorithm is running on the embedded processor and communicates with the Simulink model in real time through SCI communication interface to receive the sensors data and transmit the control commands.

5. Results and Conclusion

For verification of the Autopilot software a mission plan comprising of six waypoints (home waypoint included) is uploaded to the flight control computer. The aircraft successfully achieves all the waypoints and returns back to the Home waypoint in the HIL simulation. Constant monitoring of the system state is done using the GCS and visually through the FlightGear Flight simulator. Figure 6 shows the HIL simulation results in-terms of waypoint tracking.

Selection of the appropriate hardware platform and MEMS based sensors enables the system to achieve not only miniaturization and low power requirements but also higher accuracy for special mission requirements. The on-board processor is capable of achieving as high as 200Hz update rate for control loops making the system more accurate and suitable for a broad category of UAVs. In the future Center of Excellence in Intelligent Engineering Systems (CEIES) aims to develop its own algorithms for Autopilot, so this research will provide the platform for testing and verification.

Modular nature of Autopilot software makes it flexible and reusable for different hardware platforms as well as different avionics sensors with little modifications. All the software modules like; system initialization (hardware, software), sensors data, GCS Telemetry/telecommd, and Flight control Algorithm are implemented in separate source files making the system flexible for hardware as well as software changes. With the successful implementation and testing of Hardware in-loop Simulation equipped us with a tool to easily design, develop and verify custom guidance, Navigation and control Algorithms in future work.

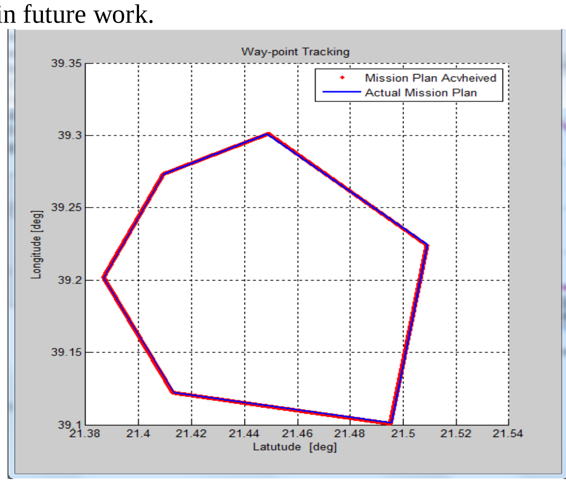

Figure 6. Way-Point Tracking result from HIL Simulation

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