SMARTPHONE-FPGA BASED BALLOON PAYLOAD USING COTS COMPONENTS

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Abstract
This paper describes a low cost architecture of multi sensor remote sensing balloon payload design for prototyping student's micro-satellite payload project. Commercial off the Shelf (COTS) components are being used to implement the payload instrumentation. COTS components provide high processing performance, low power consumption, high reliability, low cost and are easily available. The main architecture of the system consists of commercially available Smartphone, FPGA (field-programmable gate-array) and microcontroller connected together along with sensors and telemetry systems.

Presently available smart phones are combination of multiple advanced sensors, different communication channels, powerful operating system and multi-core processors with large non-volatile memory. This also supports high resolution imaging devices for remote sensing application. The smart phone is interfaced to a microcontroller to expand its I/O to interface sensors and FPGA. FPGA supported high speed onboard parallel processing needs and complex controls. Flexible configurations for data acquisition system is provided using built-in A/D converters, counters and timers available in FPGA and microcontroller. The proposed system is an experimental balloon payload for monitoring atmospheric parameters like temperature, humidity, air pollution etc. This can also monitor city traffic, agricultural field and city landscape for security and surveillance.

Keywords: Tethered Balloon, Sensors, Payload, Smartphone, FPGA, Microcontroller

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1. INTRODUCTION

Commercial electronic components are increasingly being used for the space instrumentation. On-board systems in future satellite missions are likely to use increased complex functionalities demanding higher processing power. To cope-up with the demands of miniaturized space qualified versions of such subsystems in limited development period are difficult and expensive. Commercial off the shelf (COTS) electronics are becoming popular technology for future satellite missions [1][2]. Compared to the expensive low availability space qualified radiation tolerant components, COTS electronic devices and sensors provide higher performance, less power dissipation, higher integration and lower costs. These devices need to be insulated for higher radiation doses or designed for redundant fail safe operation so that they could be used in space instrumentation. COTS devices are excellent choice for microsatellites in that they perform highly complex tasks while allowing developers to achieve considerably lower cost and short development cycles when compared to traditional space missions. However these devices may not withstand prolonged radiation doses. Hence, these are suitable for the payloads of short life cycles like sounding rockets, balloon payloads and transition period experiments of planetary missions.

This paper describes a hybrid architecture using proven subsystems to implement an experimental balloon payload for monitoring atmospheric parameters like temperature, humidity, air pollution etc. This may also monitor city traffic, agricultural field and city landscape for security and

surveillance. The proposed architecture makes extensive use of COTS components, like smartphone, commercial FGPA (Field Programmable Gate Array) boards, off-the-shelf microcontrollers and solar cells. Smartphone that runs Google's Linux-based Android open source mobile operating system offer a wide range of capabilities needed for satellite payload systems. It supports multi-core processors, large non-volatile memory, powerful multitasking operating system and advanced sensors like high-resolution cameras, GPS receiver, accelerometer, gyroscope etc.

Android phones are designed as dedicated smart personnel communication device and its interfaces are not suitable for data acquisition and instrumentation. There are limited hardware input/output interfaces like USB and audio jack. It also does not support parallel processing for high speed distributed sensor interfaces which are required in scientific payloads. Most space mission today uses FPGA based payload design for reliable and high speed parallel interfaces. However FPGA based systems need special skill of VHDL (VHSIC Hardware Description Language) programming and hardware design. It is difficult and time consuming to design complex sequential tasks as general purpose language like C/C++ is not well supported. Development time is high due to slow compilers and complex syntaxes. Microcontrollers on other hand supports efficient optimizing C/C++ compilers and produces assembly listing which could be further optimized and quality assure. However, the operating speeds of microcontrollers are serious bottleneck for interfacing high speed sensors and actuators.

This paper describes design of an educational space payload which is deployed using tethered helium balloon. The main architecture of the system consists of commercially available smartphone, FPGA and microcontroller connected together along with sensors and telemetry systems with easily available hardware software systems. The experimental setup is simplified using COTS components and high level language compilers like Eclipse ADT with core JAVA, VHDL and Arduino C. The tasks like ground communication, navigation, orientation, imaging and on-board storage functions are supported by smartphone. The ground communication with the tethered balloon is established using GSM. The system could be ported to microsatellite version by interfacing a standard satellite transponder [5] replacing GSM through Bluetooth or Wi-Fi Direct. Table-1 shows the performance summary of Smartphone, FPGA and microcontroller.

Table -1: Performance Summary of Subsystems

No	Features	Smart phone	FPGA	Micro-controller
1	Name	Lenovo P780	Papilio Pro	Arduino Mega ADK
2	Processor	Cortex-A7	Spartan 6	ATMEGA 2560
3	Clock Speed	1.2GHz	32MHz	16MHz
4	Memory	32GB	72KByte	8KByte
5	Operation	Serial	Parallel	Serial
6	Architecture	32Bit	Parallel	8Bit
7	Executable	PC Pro-grammable	Repro-grammable	Repro-grammable
8	Approx. Power	500mW	Low	250mW
9	Language	Java	VHDL	Arduino C/C++
10	Approx. Cost	Rs.17,000	Rs.6,500	Rs.4,000

Considering the advantage and disadvantage of different technologies as shown in table I, it is essential to combine them as a hybrid unit which takes advantage from each technology. Proposed architecture is shown in Fig-1 and is described in the next section.

2. SYSTEM DESCRIPTION

The proposed system is intended to monitor atmospheric parameters and land images using low cost tethered helium balloon. The data acquired by the system is to be transmitted to a mobile ground station using standard GSM connectivity. This tethered setup is initially to be used for testing the functioning and reliability of the instrumentation for final launching of navigation controlled balloon flight. Fig-1 shows the block diagram of the complete system. It consists of three processing units as mentioned in table I. Actual components used are shown in photograph of Fig-2. Microcontroller works as a communication bridge between smartphone and FPGA. The smartphone is connected to the microcontroller through USB Host shield connection. Microcontroller is connected to FPGA via 8 bit bidirectional parallel communication using three handshake lines. This supports a high speed gateway for image transfer between smartphone and FPGA for data compression or image processing type applications. Microcontroller also transmits sensor data through the same parallel 8 bit data path to telemetry. The power supply system for these processors is described in subsection-C. We described here the different subsystems of the proposed experiment.

2.1 Data Acquisition System (DAS)

The essential components of DAS are:
- Signal Conditioning and Sampling
- Analog-to-Digital Conversion and Calibration
- Data Validation and Storage

Smartphone hosts the DAS for external and internal sensors. The analog signals from external sensors like temperature, humidity and air pollution as shown in Fig-1 are sampled and converted to 10 bit digital data using built-in A/D converter of microcontroller and forwarded with timestamp to smartphone for further processing. The internal sensors of smartphone are sampled at appropriate interval using android app and integrated with the telemetry buffer for transmission. The image data from camera is handled separately and stored in SDRAM buffer for offline use. The low resolution versions of the acquired images are added to telemetry buffer for quick look at ground station. Any high resolution image can be dumped online to internet cloud storage using ground command.
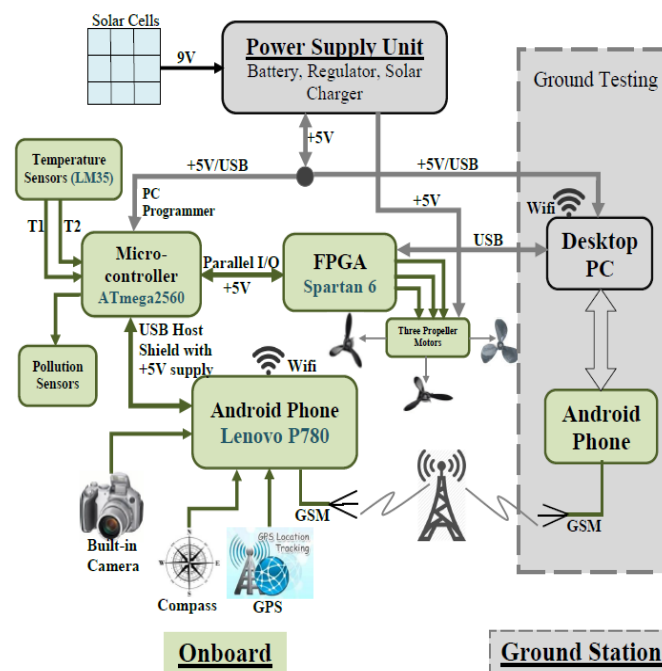
Fig -1: Block Diagram of the proposed instrumentation framework with data acquisition and command ground station. Photograph of actual components used are shown in Fig-2
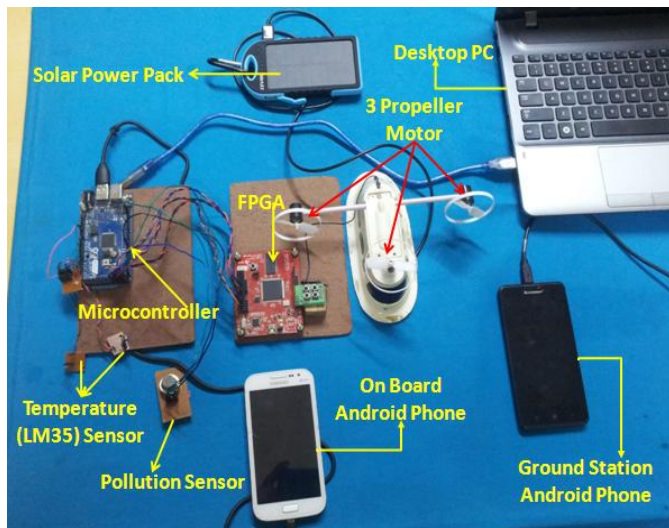
Fig -2: Photograph of different subsystems of experimental balloon payload with Laptop based Ground Monitoring Station. High performance low cost COTS components are used for implementation of payload.

2.2 Data Storage

It is desirable to reduce the storage requirement by transmitting the raw or processed data through telemetry system to ground station. However in certain applications, it is essential to buffer the data for different reasons like band compression, validation, re-transmission, transmission on demand or redundancy. The data storage needs to confirm sampling speed of parameters to be stored and accessing rate for telemetry. This is achieved using multitasking double buffered memory blocks independently handling read and write operations. Each processing module as mentioned in table I has its read/write memory. We use smart phone's 32GB memory as a redundant storage for data recovery at the end of flight. This is useful when online communication fails. It is proposed to dump the data automatically to cloud storage servers through internet, if balloon is not recoverable.

2.3 Solar Cell and Power System

The system consists of two power sources, one integrated with solar panel and the other built into smart phone as shown in Fig-3. The solar power pack delivers regulated +5V, 0.5-2A through two USB ports. Both the batteries can be charged either from solar panel when in flight or through USB power when docked to ground station. Microcontroller is powered from solar panel power pack which is connected in parallel to the ground station USB port. Microcontroller delivers +5V power to FPGA and smartphone. Smartphone internal battery is charged from this power.

In case of failure of solar power, smartphone provides power to rest of the system through OTG connected USB port. This allows redundant and uninterrupted operation power system and is capable of continuing at night with reserved power of smartphone and solar panel battery. All voltages other than +5V are generated using DC-DC converter IC.

Fig -3: Payload Power Source: a 1.2 ampere-hour solar panel with built-in 10 amp-hour battery having dimensioned same as most Smartphone's

2.4 Telemetry System

Telemetry is data link between space craft and ground station. It consists of radio frequency, trans-receivers to establish secure and reliable link to transfer the data from space craft to ground station and send control signals from ground station to space craft. Important parameters of a telemetry system are power, bandwidth, signal strength and directivity. In this experiment, we use a static tethered balloon in state of a space craft. The telemetry data link for this experiment is implemented using 3G data plan of mobile phone which connects to a similar smart phone using dedicated android communication app. Both these apps communicate to a common server website for online data transfer.

2.5 Sensors

Three independent smart sensors are used to measure temperature, humidity and air pollution. Apart from these, the built-in sensors of smartphone are used to measure geographical location using GPS, orientation using gyroscope and gravity sensor, acceleration using accelerometer, magnetic field direction using magnetic field sensor, ambient light sensor for solar cell and camera support, front and back imaging using 8MP primary and 1.2MP secondary cameras respectively. Temperature is measured with two LM35 devices which is a precision IC for analog temperature sensor. Its output voltage is linearly proportional to the temperature from -55° to 150° Celsius. An accelerometer is a sensor that measures the acceleration forces. It provides the total force applied on the device due to internal or external forces like propeller motor and wind blow. Roll, pitch, and yaw of payload are detected by the gyroscope sensor. It can measure the rate of rotation around a particular axis. Gyroscope measurement is not affected by gravity. The magnetic field sensor is used as magnetic compass for x, y and z direction. Light Sensor located at front of smartphone gives useful control information for solar sensor and camera operation. GPS sensor is interfaced to track the balloon in case of thread break or free flying balloon navigation.

2.6 FPGA

In proposed block diagram of Fig-1, Spartan 6 processor can be located in FPGA block. Xilinx Spartan-6 FPGA consists of 48 I/O lines, an efficient switching power supply, dual channel USB, 64Mb SDRAM, 18 Kb (2 x 9 Kb) block RAMs, 64KByte of internal SRAM, integrated JTAG programmer, 32 MHz crystal oscillator clock source.
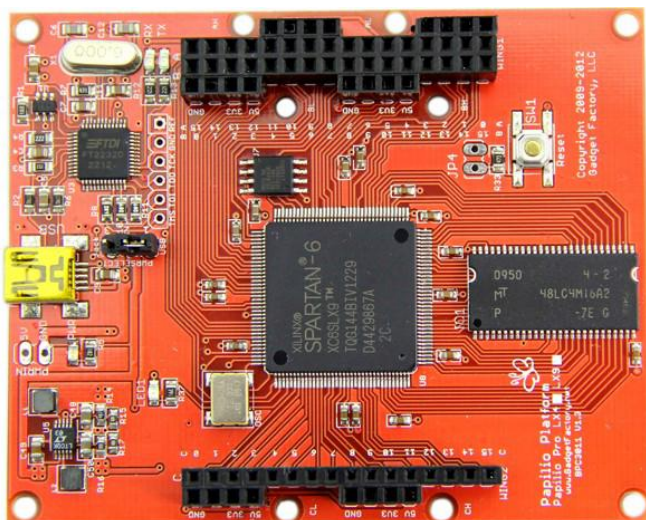

Fig -4: Papilio Pro Spartan 6 FPGA development Board

2.7 Microcontroller (ATMega 2560)

The Arduino Mega 2560 as shown in proposed block diagram of Fig-1 is a microcontroller board which has 54 digital input/output pins (of which 14 can be used as PWM analog outputs), 16 analog inputs, 16 MHz crystal oscillator, an USB connection, an ICSP header, 4 UARTs serial ports, a power jack, and a reset button. The ATmega2560 has 256 KB of flash memory for storing code (of which 8 KB is used for the bootloader), 8 KB of SRAM and 4 KB of EEPROM. The microcontroller on the board is programmed using the Arduino programming language. Arduino senses the environment by receiving inputs from many sensors and affects its surroundings by controlling lights, motors, and other actuators. The Arduino MEGA ADK can be programmed with the Arduino software.
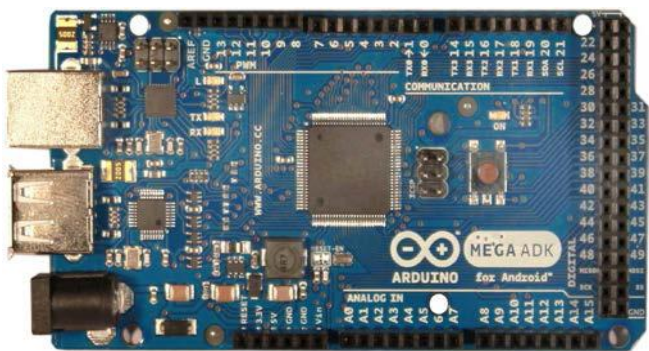

Fig -5: Arduino Mega ADK Microcontroller Board

2.8 Android Based Smartphone

Android based Smartphone is used as an onboard high level processor with 32 GB storage space. It supports stable android operating system variant of LINUX which is open source and tested for software reliability. It consists of enormous variety of advanced functionalities with terribly low weight, energy, volume and price.

Fig -6: Lenovo P780 Smartphone

We have selected Lenovo P780 as shown in Fig-6. It supports Quad-core 1.2 GHz processor, internal storage 4 GB, external storage up to 32 GB, RAM 1 GB, battery capacity 4000mAH, OS version Android v4.2, built-in rear 8MP camera and front 1.2MP camera, etc. It also supports multithreading and multitasking program environment.

It has many built-in sensors essential for navigation and control of the space vehicle and supports powerful communication modules with full driver and application support. These are GSM, Bluetooth and Wi-Fi which could be used to reduce internal wiring between different space modules, hence by reducing a total weight of the payload. GSM is specifically useful for communication to the ground station in balloon based experiments which can be supported by mobile towers or satellite phones.

3. ARCHITECTURE AND SYSTEM IMPLEMENTATION

Several experiments were conducted before optimizing the desired configuration. Total system weight was the most important consideration like in any space mission. Different types of gas filled balloons are used during development. Table-2 shows the weight lifting capacities of different type of balloons. Weight of smart phone and additional battery was constraint for low cost safe balloons. A simplified configuration is tried as shown in block diagram of Fig-9.

Table -2: Parameters of different types of gas filled balloons

| No	Gas Filled	Volume (m^3)	Lifting Capacity (kg)	Approx. Cost (Rs)
1	Hydrogen	0.26	0.28	850
2	Helium	0.26	0.26	4500
3	Hot Air	0.26	N/A	-

The setup consists of three miniature monolithic sensors MQ135, DHT11 and LM35 for air quality, humidity cum temperature and temperature sensing respectively. A 433MHz Transceiver pair with 2Km range is used for telemetry payload data as shown in Fig-7. Three smaller tethered balloons of total volume of approximately 600ml are used to lift the payload as described in block diagram of Fig-9[3].

Fig -7: 433MHz lightweight, low power telemetry system is used for ground communication

Fig -8: a handheld ground telemetry system is shown with a 433MHz transceiver powered by android phone
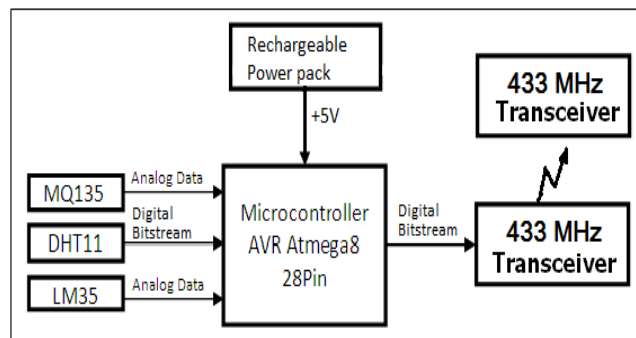
Fig -9: Block Diagram of the test setup with different sensors: MQ135 air quality sensor, DHT11 humidity cum temperature digital sensor and LM35 temperature analog sensor

Fig-13 shows the actual integrated version with sensors and +5V regulated power system. The sensors used in this experiment are shown in Fig-10. Some sample data received during the flight is shown in screenshot of Fig-14. Tethered balloon [4] is deployed in a university campus for trial run as shown in Fig-11.
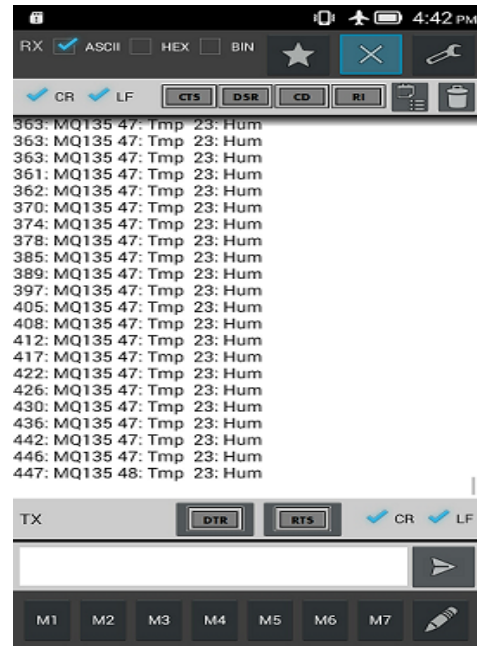

Fig -10: Photograph of LM35 analog temperature sensor, MQ135 air quality sensor, and DHT11 digital humidity cum temperature sensor

Fig -11: Tethered balloon is being deployed in a university campus for trial run

Fig -12: The payload shown in Fig-13 is launched using three hydrogen filled rubber balloons. The ground telemetry system is shown in Fig-8


Fig -13: Photograph of integrated balloon payload with sensors, microcontroller, telemetry, 433MHz antenna and power system

**Table -3**: Data acquired during the balloon flight using mobile ground telemetry system shown in Fig-8

No	MQ135 Air Quality Sensor (ppm)	DHT11 Temperature (°C)	DHT11 Humidity (%)
1	363	47	23
2	363	47	23
3	363	47	23
4	361	47	23
5	362	47	23
6	370	47	23
7	374	47	23
8	378	47	23
9	385	47	23
10	389	47	23

Fig -14: Screenshot of some sample data received during the flight

The test setup for calibration of temperature sensor LM35 with GSM based telemetry and telecommand is shown in Fig-15. A Peltier cooler cum heater device is used to generate temperature cycle.
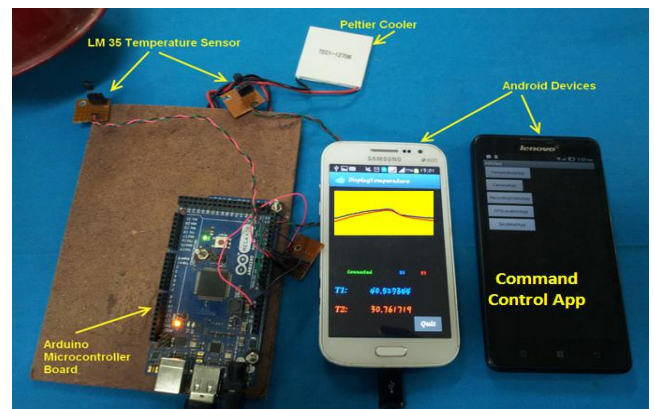
Fig -15: Photograph of the test setup of LM35 temperature sensors with remote command and data acquisition using Android phones. A Peltier cooler/heater device is used to generate temperature cycle.
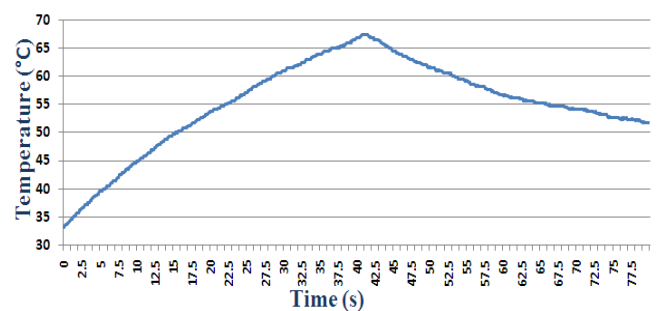
Fig -16: Data collected from analog LM35 temperature sensor with 10 bit ADC using experimental setup of Fig-15.

6. CONCLUSION

We have carried out balloon instrumentation experiment using COTS components as proto type of designing a students' microsatellite experiment. Commercial android phone is used for onboard imaging and data acquisition. Similar phone is used for telemetry and telecommand through GSM. A microcontroller and FPGA board is integrated with the android phone. This combination supports wide variety of sensors like temperature, humidity, air pollution, gyroscope, GPS, accelerometer, magnetic field direction, ambient light and high resolution color camera. A low cost balloon and payload versioned is tested with 433 MHz transmitter, ATmega8 microcontroller and three different sensors for air pollution, humidity and temperature measurement.

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BIOGRAPHIES

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