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Attitude Determination and Control, On Board Computing & Communication Subsystem Design for a CubeSat Mission

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CubeSat Introduction

This is WPI's first foray into CubeSat development; these reports are a baseline for a CubeSat mission designed to measure Greenhouse Gasses, similar to the CanX-2 mission launched in 2008. The purpose of this baseline is to build a basic knowledge base of CubeSat missions, and practices. Throughout the reports illusions to two simultaneous systems are developed, a lab option, and a flight option. Depending on the subsystem the two systems greatly vary, for example with ADCS there is a single sensor as opposed to the six or more components that are slated for the flight. The lab option in some cases is being developed in order to test novel concepts in nano-satellite development, such as in the propulsion system.

Orbit Specification:

Element	Value
semimajor axis a (km)	7051
eccentricity e	0.0
inclination i (deg)	98.0
RAAN Ω (deg)	0.0
argument of latitude u (deg)	0.0

Note: The above elements correspond to a circular orbit with altitude of 680 km and period of 98.2 min. For a circular orbit, the argument of perigee ω and true anomaly ν are replaced by the argument of latitude u defined as $u \equiv \omega + \nu$. The argument of latitude given corresponds to the value at time of orbit insertion.

Scientific Payload:

The primary scientific payload for this MQP is an infrared spectrometer which will be used to investigate greenhouse gases in the atmosphere. The Argus 1000 IR Spectrometer was selected for flight on the Canadian Advanced Nanospace eXperiment 2 (CanX-2). The CanX-2 mission was originally designed to use a 3U CubeSat with a launch in 2008.

Payload Operational Requirements:

A science "data set" consists of three observations, made along three distinct viewing angles as described below.

<u>1. 1 Instrument Orientation</u>: Once per orbit, the instrument shall be oriented to collect data in three directions: Nadir and +/- 64.6 degrees from nadir in a

direction normal to the orbital plane. The latter two angles have been selected to allow limb observations from a nominal altitude of 680 km.

<u>1. 2 Pointing Precision and Duration</u>: The instrument will maintain each of the three pointing orientations within a band of +/- 0.573 degrees (+/- 10 milliradians) for a duration no less than 5 minutes.

<u>1. 3 Pointing Sequence and Rate</u>: For a single data set, the instrument can be pointed along its three required directions in any order, but the time period between any two orientations shall not exceed 2 minutes.

Reports:

“Attitude Determination and Control, On Board Computing and Communication Subsystem Design for a CubeSat Mission,” MAD-CUBE, Andrew Bigelow, Cyle Hawkins

"Mechanical, Power, and Propulsion Subsystem Design for a CubeSat Mission,” JB3-CBS1, Keith Cote, Jason Gabriel, Brijen Patel, Nicholas Ridley, Stephen Tetreault, Zachary Taillefer

“Design and Analysis of Subsystems for a CubeSat Mission,” NAG-1002, Andrew Olvia, Greg Schaalman, Simone Staley

Abstract

This project describes the development of the attitude determination and control, on board computing, and communications subsystems for an Earth orbiting nano-satellite. The goal of each subsystem is to enable the infrared spectrometer to collect data that can be used in tracking greenhouse gas concentrations. Gyroscopes, sun sensors, a magnetometer, magnetorquers, and orbital environment models are employed to meet the pointing requirements of the scientific instrument. The on board computer operates in conjunction will all other satellite subsystems as the main link between the software and hardware. This system consists of a real time operating system and several MSP430 microcontrollers to fulfill computational requirements and acceptable redundancies. Communication between the ground and the satellite is paramount for the transmission of scientific data back to Earth and simple commands to the spacecraft. Two dipole UHF antennas and an S-band antenna serve the communication system's transceivers.

Transcript Abstract

This project describes the development of the attitude determination and control, on board computing, and communications subsystems for an Earth orbiting nano-satellite. The goal of each subsystem is to enable the infrared spectrometer to collect data that can be used in tracking greenhouse gas concentrations. Gyroscopes, sun sensors, a magnetometer, magnetorquers, and orbital environment models are employed to meet the pointing requirements of the scientific instrument. The on board computer operates in conjunction will all other satellite subsystems as the main link between the software and hardware. Communication between the ground and the satellite is paramount for the transmission of scientific data back to Earth and simple commands to the spacecraft.

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Table of Contents

CubeSat Introduction 1
Abstract 3
Transcript Abstract 3
Acknowledgements 4
Table of Tables 7
Table of Figures 8
Table of Acronyms 9
1 Attitude Determination and Control System 11
1.1 Introduction 11
1.2 Background 12
1.2.1 Attitude Sensors 12
1.2.2 Actuators 14
1.2.3 Disturbances 15
1.3 Hardware Selection and Design 16
1.3.1 Lab Option IMU 16
1.3.2 Lab Option Magnetorquers 17
1.3.3 Flight Option Gyroscope 18
1.3.4 Flight Option Sun Sensors 19
1.3.5 Flight Option Magnetorquers 20
1.4 ADCS Design 20
1.4.1 Attitude Dynamics Model 20
1.4.2 Attitude Determination 22
1.4.3 Attitude Control 24
1.5 ADCS Testing 25
1.5.1 Attitude Determination 25
1.5.2 Attitude Control 27
2 On Board Computer 29
2.1 Introduction 29
2.1.1 On Board Computer Design Methodology 29
2.2 Literature Review 30
2.2.1 Command and Data Handling in CubeSats 30
2.2.2 CubeSat Hardware Overview 31
2.2.3 Real Time Operating System Overview 35
2.3 Design Considerations 37
2.3.1 Operating Environment 37
2.3.2 Power Consumption 38
2.4 Hardware and Software Selection 39
2.4.1 Component Selection 39
2.4.2 Lab OBC – Flight OBC Hardware Comparison 40

2.5 Software 41
2.5.1 MSP430 Development Environment 41
2.5.2 Printed Circuit Board Layout Software 41
2.6 Flight Software 42
2.6.1 High Level Functions 42
2.7 System Integration 45
2.7.1 Power Subsystem 45
2.7.2 Attitude Determination and Control Subsystem 45
2.7.3 Payload 45
2.7.4 Propulsion 45
2.7.5 Communication 45
3 Communications 47
3.1 Introduction 47
3.2 Design Considerations 47
3.3 Literature Review 48
3.4 Communications Architecture 49
3.5 Frequency Selection 49
3.5.1 Optical Communication Alternative 50
3.6 Hardware Selection 50
3.6.1 Antenna Selection 51
3.6.2 Lab Communication System 51
3.7 Ground Station 52
4 Bibliography 53
5 Appendices 56
5.1 Disturbance Calculations 56
5.2 Past CubeSat ADCS Design Review 58
5.3 On Board Computer Datasheets 59

Table of Tables

Table 1: IMU Sensors 16
Table 2: Magnet wire properties 17
Table 3: Symbols for lab option magnetorquer 17
Table 4: Gyroscopes 18
Table 5: Sun Sensors 19
Table 6: Clyde Space magnetorquer 20
Table 7: Symbols for quaternion attitude dynamics model 20
Table 8: Symbols for TRIAD method 22
Table 9: Symbols for the EKF 23
Table 10: Symbols for stability controller 24
Table 11 AAUSat-I OBC Specs 31
Table 12 AAUSat-II OBC Specs 31
Table 13 CanX-I OBC Specs 31
Table 14 CanX-2 OBC Specs 32
Table 15 CP1 and CP2 OBC Specs 32
Table 16 CubeSat Kit OBC Specs 32
Table 17 CubeSat XI-IV OBC Specs 32
Table 18 CUTE-I OBC Specs 32
Table 19 DTUSat OBC Specs 33
Table 20 HAUSAT-1 OBC Specs 33
Table 21 KUTEsat OBC Specs 33
Table 22 Mea Huaka'i OBC Specs 33
Table 23 MEROPE OBC Specs 34
Table 24 NCUBE OBC Specs 34
Table 25 Sacred and Rincon OBC Specs 34
Table 26 SwissCube OBC Specs 34
Table 27 FreeRTOS (Real Time Engineers Ltd., 2010) 36
Table 28 Salvo Professional RTOS (Pumpkin Inc., 2010) 36
Table 29 MSP430 Integrated Development Environment Comparison 41
Table 30 Layout Software Comparison 42
Table 31 ADCS High Level Commands 43
Table 32 Payload High Level Commands 43
Table 33 Propulsion High Level Commands 44
Table 34 CubeSat Communication Systems (Klofas, Anderson, & Leveque, 2008) 48
Table 35 Communications Subsystem Hardware Selection 51
Table 36: Symbols for gravity gradient disturbance calculations 56
Table 37: Symbols for solar radiation disturbance calculations 57
Table 38: Symbols for Atmospheric drag disturbance calculations 57
Table 39: AAU CubeSat Specifications 58
Table 40: ION CubeSat Specifications 58
Table 41: Swiss Cube Specifications 58

Table of Figures

Figure 1: TRIAD Determination Test 25
Figure 2: Extended Kalman Filter Test 26
Figure 3: Stabilizing Controller Test 27
Figure 4 MSP430F5438 Datasheet 59
Figure 5 MSP430F5438 User Guide 60
Figure 6 MSP430F2012 Datasheet 61
Figure 7MSP430F2012 User Guide 62
Figure 8 TUSB3410 Application Report 63
Figure 9 Salvo User Manual 64

Table of Acronyms

ADC .... Analog Digital Converter

ADCS .... Attitude Determinations and Control System

AWG .... American Wire Gage

BPS .... Bits per second

CCStudio .... Code Composer Studio

COTS .... Commercially Available Off The Shelf

DAC .... Digital to Analog Converter

DMA .... Direct Memory Access

DSP .... Digital Signal Processor

EKF .... Extended Kalman Filter

FOV .... Field of View

GPS .... Global Positioning System

GUI .... Graphical User Interface

HEP .... Highly Energized Particles

I^2C .... Inter-Integrated Circuit

IAR EW .... IAR Embedded Workbench

IDE .... Integrated Development Environment

IGRF .... International Geomagnetic Reference Field

IMU .... Inertial Measurement Unit

IR .... Infrared

JTAG .... Joint Test Action Group

KBPS .... Kilobits per Second

LASER .... Light Amplification by Stimulated Emission of Radiation

LEO .... Low Earth Orbit

MBPS .... Megabits per Second

MEO .... Medium Earth Orbit

MSP .... Mixed Signal Processor

OBC .... Onboard Computer

PCB .... Printed Circuit Board

PMAD .... Power Management and Distribution

RTC.. Real Time Clock
RTOS .... Real Time Operating System
SA ....Situational Awareness
SBW... SPI-Bi-Wire
SD Card... Secure Digital Card
SPI...Serial Peripheral Interface
STK.. Satellite Tool Kit
TT&C...Tracking, Telemetry & Command
UART..Universal Asynchronous Receiver/Transmitter
USB.. Universal Serial Bus
UTC.. Unified Clock System
UHF... Ultra High Frequency
VHF... Very High Frequency

1 Attitude Determination and Control System

1.1 Introduction

The goal of the Attitude Determination and Control System (ADCS) is to orient the satellite in a desired direction during a specified time period for the optimal operation of the scientific instruments. This goal will be accomplished through the combined and coordinated use of sensors and actuators. The following is an excerpt describing the required attitude (instrument pointing) performance from the mission requirements document:

> *<u>1. 1 Instrument Orientation</u>: Once per orbit, the instrument shall be oriented to collect data in three directions: Nadir and +/- 64.6 degrees from nadir in a direction normal to the orbital plane. The latter two angles have been selected to allow limb observations from a nominal altitude of 680 km.*
>
> *<u>1. 2 Pointing Precision and Duration</u>: The instrument will maintain each of the three pointing orientations within a band of +/- 0.573 degrees (+/- 10 milliradians) for a duration no less than 5 minutes.*
>
> *<u>1. 3 Pointing Sequence and Rate</u>: For a single data set, the instrument can be pointed along its three required directions in any order, but the time period between any two orientations shall not exceed 2 minutes.*

Various sensors that could be used were studied and the desired sensors chosen based on required performance and the satellite's limited resources. Similar considerations were used for analyzing and choosing the appropriate attitude actuators. Specific devices were chosen for both a lab and flight option. The lab option CubeSat will be constructed using low cost materials and components to demonstrate and evaluate the satellite system design. The flight option will be designed using high performance and mostly space qualified elements. The goal of this design is to provide a self-consistent platform for accomplishing the science objectives.

A simulation model for the attitude dynamics was created using a quaternion formulation. Torques applied from the chosen actuators were included into the model. Utilizing the dynamics model and the Satellite Tool Kit (STK) software package, the chosen sensor types were modeled in the simulation. These tools were used in the development of the attitude determination and control software for both the lab and flight option.

1.2 Background

1.2.1 Attitude Sensors

There are many different sensor types that can be used in conjunction with the ADCS and the most commonly used in spacecraft applications were studied in detail. A database of hardware flown on past CubeSats was compiled for system design reference. A portion of this database is presented above. From this database six potential sensor types were identified: magnetometer, sun sensor, gyro, accelerometer, Earth sensor, and star tracker.

A magnetometer measures the magnetic field strength along an axis. When multiple magnetometers or multi-axis sensors are used the complete magnetic field vector can be measured (Acuna, 2001). Solid state magnetometers can be very small and use very low amounts of power making them feasible for the nano-satellite (PNI Corporation, 2005). The sensor reading can be compiled with the position of the satellite and a model of Earth's magnetic field to find a portion of the attitude of the spacecraft (NOAA, Geomagnetism, 2010). Many magnetometers are also inexpensive and can easily be purchased for satellite testing. These sensors are very important to the ADCS when using magnetorquers as control actuators. Magnetorquers rely on the Earth's magnetic field to orient the satellite and will be discussed in detail later.

Sun sensors detect the sunlight shining on the spacecraft and more importantly the angle at which angle the sunlight is illuminating the surface. A variety of electronic components can be used as a sun sensor such as photoresistors, cameras, or even the solar cells already on the spacecraft that allows for flexibility in there design and the possibility of being self-powered. By using multiple sun sensors on different surfaces, the direction vector of the sun relative to the satellite can be determined. Using this vector a portion of the attitude can be determined. Although sun sensors can provide information about the attitude they only work when the craft has a line of sight with the sun (Winetraub, Bitan, Heller, & dd, 2005). The orbit being considered for the satellite only allows for the line of sight to the sun during half of the orbit. If sun sensors are to be used other data may be required in determining the attitude while the satellite is in the Earth's eclipse.

Gyro sensors and accelerometers measure angular velocity and translational acceleration respectively. Small and low powered models of both sensor types can be purchased and can be inexpensive (Eterno, 1999) pp 375. A benefit to using a gyro is that the spin rates around axes are known which can take the place of time derivatives of noise corrupted data from other sensors. Measurements of the acceleration in three dimensions can be useful during orbit changes with the propulsion system, but the attitude information gathered would be redundant when paired with gyro sensors. The accelerometer readings are coupled with its position onboard complicating the calculation for angular acceleration.

Earth sensors are often comprised of infrared cameras used to detect the radiation from Earth. One way Earth orbiting satellites use these sensors for attitude is detecting Earth's horizon to fix the orientation along an axis (Eterno, 1999) pp 374. These sensors can be less accurate when used in Low Earth Orbit (LEO) because the Earth can encompass much of the sensor's range of vision.

Star trackers use optical sensors to track multiple celestial bodies in determining the spacecraft's orientation. The bodies tracked are relatively fixed in space and therefore act as precise references enabling these sensors to be highly accurate. They can however experience interference by larger and much close bodies such as the moon. Star trackers require sensitive equipment for tracking the small appearing bodies and sufficient computational resources for processing the high resolution images rapidly. These high requirements often cause accurate star trackers to be expensive, large in size and power consumption (Eterno, 1999) pp 373-4.

The magnetometer and sun sensor types were found to be used on many past CubeSat missions and are feasible for inclusion onboard the nano-satellite. The magnetometer will be used for controlling the magnetourquer actuator that was chosen and calculating a portion of the spacecraft's attitude. Gyros will also be used because of their low space and power requirements and the valuable data that can be provided about the dynamic motion of the satellite. Accelerometers will not be used because of their redundant measurements when paired with gyros. Earth sensors will not be used because of the image processing requirements and the need to be pointed towards Earth to function. Star trackers will also not be used because of the required highly sensitive image capture and processing equipment that will be complex and difficult to integrate into the nano-satellite.

1.2.2 Actuators

Actuators are used to control the attitude of the satellite and can either be passive or active. Passive actuators have no power or fuel requirements but can restrict control over the spacecraft's attitude. Conversely, active devices require energy but allow for greater control. Researching past CubeSat missions and available actuator technologies five potential actuators were identified: reaction wheels, magnetorquers, permanent magnets, hysteresis rods, and gravity gradient booms.

Reaction wheels are an active actuator and are comprised of radial weights that are spun using electric motors. Changing the weight's angular velocity changes the satellite's proportionally but in the opposite direction. To ensure complete attitude control in three dimensions three reaction wheels aligned orthogonally must be used (Rayman, 2010). Benefits of this actuator include internal torques that don't rely on interactions with external fields and they can be fast acting if sized well. Through the use of the actuators and counteracting disturbance torques the wheels can become saturated, requiring a momentum dumping maneuver to decrease the stored momentum and required energy. This maneuver will then require a second actuator system (Weisstein, 2007).

Magnetorquers are active electromagnets that create torques as they interact with the Earth's magnetic field. The applied torques act to align the electromagnet with the external field. Magnetorquers are solid state devices having no moving parts which increase their reliability (Eterno, 1999) pp 369. This type of actuator is generally slower acting than reaction wheels and the applied torques vary with magnetic field strength and attitude.

Permanent magnets are similar to magnetorquers except are passive and can only align an axis of the satellite in one orientation relative to the external magnetic field. They are passive so no power is required and the actual device is simply a magnet. Because the actuator is always present the satellite will oscillate about the magnetic field direction without any other system to dampen the motion. Because of this permanent magnets are generally paired with another passive actuator, hysteresis rods.

Hysteresis rods act to passively dampen satellite spin. They accomplish this from the hysteresis effect. The Earth's magnetic field partially magnetizes the rods and when the satellite spins the magnetic field in the rods tries to align itself acting against the spinning motion. As he spacecraft spins the rods are in a state of being magnetized that lags behind the current magnetic field vector. It therefore will always counteract spin and act towards stabilizing the craft. The actuator itself is very simple, just ferrous rods.

Gravity gradient booms use gravity to align towards the Earth. The boom consists of a support rod with a mass at the end. The gravitational force will be greater on the main satellite body than the mass at the end of the boom and will orient the boom axis with the center of the Earth. This passive system, like the permanent magnet, requires a damping system to stabilize the spacecraft from oscillations.

The chosen actuators are magnetorquers for their ability to control the attitude of the spacecraft, low mass, and reliability. One issue that exists for magnetorquers is that only control torques perpendicular to the magnetic field can be generated. This complication has been studied in detail and a number of control laws have been developed for the specific use of magnetorquers. These findings will be examined later. Three magnetorquers must be used to ensure the highest possible controllability. Using the compiled database of CubeSat missions, magnetorquers were found to be the most commonly used actuators and shows flight heritage.

1.2.3 Disturbances

The satellite's objectives require certain attitudes during its mission to be successful. In the environment of Low Earth Orbit (LEO) there exist sources of external forces that can provide torques and perturb the satellite's attitude. Identifying these potential disturbances is important because the attitude actuators must be able to counteract them and meet the pointing requirements. Three probable disturbance sources are gravity gradients, solar radiation, and atmospheric drag.

The satellite's configuration is a 3U CubeSat and the mass distribution isn't completely symmetric. This asymmetry close to the Earth causes gravity gradient torques trying to align the long axis of the spacecraft with the Earth's center of mass. While facing the sun any spacecraft will experience a slight pressure from the solar radiation. If the center of pressure is offset with the center of mass then the pressure will cause a torque. The final disturbance source is atmospheric drag. Because the satellite is in a LEO the density of the atmosphere is high enough to cause some forces on the craft. This source is similar to the solar radiation where a pressure is applied to the surface area facing in the direction of the velocity vector. A torque is likely to be produced by the offset of the center of pressure and the center of mass.

1.3 Hardware Selection and Design

The design of the ADCS requires components for both the sensors for attitude determination and actuators for attitude control. There will also be two distinct sets of hardware components because a lab option is to be developed for ground testing before the flight model will be constructed. The lab option will contain less expensive parts and have limited capabilities. The testing environment will allow for a single degree of freedom for satellite rotation inside a vacuum chamber.

1.3.1 Lab Option IMU

An Inertial Measuring Unit (IMU) with nine degrees of freedom was selected as the sensor package for the lab option. This unit measures angular velocity, the local magnetic field vector, and acceleration all in three dimensions. The IMU was mainly chosen based on cost, size, utility, and ease of use. At $124.95 it is affordable for providing three axis measurements of three inertial states. There is limited space in the CubeSat and therefore the sensors chosen must be small and able to easily fit inside. The IMU's board size is 4.953 x 2.794 cm and will be able to fit comfortably inside the test satellite.

One of the good features of the IMU is that is contains all the sensors that are to be used on the lab option on one board. It also communicates using a single serial connection. Other sensor options include obtaining individual sensors that each need their own digital connection, power source, and structure mounting. This also allows the IMU to be easily connected to a computer to record and analyze the sensor data directly in addition to test the board without the use of the On Board Computer (OBC). This will allow initial board testing to progress quicker and enable the communications with the OBC to be verified.

Included on the IMU board are four individual sensors and a microprocessor to collect the data and send it over a single serial communication interface. The following is table containing the sensors and basic specifications.

Table 1: IMU Sensors

Sensor Name	Sensor Type	Specifications
LY530ALH	Gyroscope	Single axis measurement with limit of ±300°/s
LPR530ALH	Gyroscope	Dual axis measurement with limits of ±300°/s
ADXL345	Accelerometer	Triple axis measurement with limits of ±16g
HMC5843	Magnetometer	Triple axis measurement with limits of ±4 gauss

1.3.2 Lab Option Magnetorquers

Many previous CubeSats that have used magnetorquers in their designs constructed custom devices by wrapping thin magnet wire into a rectangular frame. Two such satellites include the SwissCube and AAU CubeSat. These magnetorquers are often light, simple, and low cost. There are few commercially available magnetorquers and are expensive. For these reasons a custom magnetorquer will be used for the lab option.

The simple design will be magnet wire wrapped around a square frame. It was decided to use the same voltage as the flight option (5V) to reduce the change in power requirements. To easily fit within the satellite, the average side length of the wire coil will be 8cm. The next selection was the wire gauge. SwissCube and AAU CubeSat used wire with diameters .15mm and 0.13mm respectively. A wire diameter of 0.16mm (34 AWG) was chosen because the magnetorquer will be similar and the slightly larger diameter is to increase the allowable current through the wire. Below is a table with properties for a 34AWG magnet wire from Belden.

Table 2: Magnet wire properties

Product Number	Resistance	Max. Recommended Current	Density	Overall Diameter
8057	857.325 Ohm/km	0.057 A	0.179 Kg/km	0.18288 mm

From this data the magnetorquer specifications can be designed. For safety, the maximum current will be 70% of the recommended, or about 40mA. The following are calculations for the performance and physical properties of the magnetorquer.

Table 3: Symbols for lab option magnetorquer

Symbol	Description	Symbol	Description
V	Voltage across coil	**R**	Total coil resistance
r	Wire resistance density	**I**	Maximum current
s	Length of a side of the coil	**n**	Number of wire turns in the coil
μ	Magnetic moment	$\mathbf{d_w}$	Wire diameter
$\mathbf{d_c}$	Coil diameter	$\boldsymbol{\rho_w}$	Linear wire density
A	Area of coil	**L**	Total wire length
m	Mass of the coil		

$$\mu = nIA$$

$$R = Lr = \frac{V}{I} = 125\ \Omega$$

$$L = \frac{R}{r} = 145.8\ m$$

$$m = L\,\rho_w = 26.1\ g$$

$$A = s^2 = 64\ cm^2$$

$$n = \left\lceil \frac{L}{4s} \right\rceil = 456$$

$$\mu = nIA = \frac{LVs}{4R} = \frac{Vs}{4r} = 0.1166\ Am^2$$

$$d_c = 2d_w\sqrt{\frac{n}{\pi}} = 4.407\ mm$$

1.3.3 Flight Option Gyroscope

The selection process for the flight option gyroscope was primarily based on performance but also considered flight heritage and power consumption. Gyroscope research resulted in companies that could potentially provide adequate devices for the satellite. Three such companies are Memsense, Analog Devices, and InvenSense and each produces small, low power gyroscopes. The products offered are reviewed below and one is selected to be implemented in the CubeSat.

Specific gyroscope selections for many flown CubeSats are not available making locating sensors with flight heritage difficult. The data that was collected indicated that past CubeSats have used Commercial off the shelf (COTS) low cost sensors. The Cute 1.7 CubeSat by the Tokyo Institute of Technology utilized the ADXRS150 gyro from Analog Devices and was also considered in gyro selection of the SwissCube satellite. Swiss Cube used the IDG300 by InvenSense and considered the TR0150S050 from Memsense. The following is a table listing a number of gyroscopes and their specifications.

Table 4: Gyroscopes

Sensor Name	# of Axes	Power Req.	Range	Typical Bandwidth	Noise Density
ADXRS150	1	5V, 6mA	±150 °/s	40Hz	0.05 °/s/√Hz
ADXRS450	1	3.3V or 5V, 6mA	±300 °/s	80Hz	0.015 °/s/√Hz
ADIS16265	1	5V,41mA	±80,160,or 320 °/s	50 or 330 Hz	0.044 °/s/√Hz
ADIS16135	1	5V,88mA	±300 °/s	335Hz	0.0122°/s/√Hz
TR0150S050	3	4.75-5.25V, 18mA	±150 °/s	50Hz	0.04 °/s/√Hz
IDG-300B	2	2.7-3.3V,7-9.5mA	±500 °/s	140Hz	0.017 °/s/√Hz
ITG-3200	3	2.1-3.6V, 6.5mA	±2000 °/s	100Hz	0.03 °/s/√Hz

From this selection of gyroscopes the ADXRS450 was chosen for the satellite. It has very low power requirements, moderate sensor range and bandwidth, and low noise density. The ADIS16135 has various selectable ranges, higher bandwidth, but consumes much more power which is a concern for the resource limited CubeSat. The IDG-300B is a similar sensor with two measured axes but a lower range is preferred because the satellite will be rotating slowly throughout its mission.

1.3.4 Flight Option Sun Sensors

Similar to the review of the available gyroscopes, sun sensors, preferably with flight heritage, from reputable companies were reviewed. Because sun sensors are more frequently employed on CubeSats and spacecraft in general is more information and flight proven products available. Three companies that sell such sun sensors are Comtech AeroAstro, Optical Energy Technologies, and ISIS.

Many previously developed CubeSats have used the attached solar panels and in-house developed devices to measure the sun vector. An alternate option used by the Cute 1.7 CubeSat previously mentioned and the Chasqui I CubeSat by the Universidad Nacional de Ingenieria, Peru is a light angle sensor. This sensor, the S6560 from Hamamatsu, detects the light angle over only one axis with a ±50^o range and has relatively low accuracy. The sun sensors considered for use in this report likely have higher accuracies and measure the sun angle in two axes.

California Polytechnic State University's CP1 CubeSat used a sun sensor donated from Optical Energy Technologies. Sun sensors from Comtech AeroAstro flew on multiple spacecraft including ALEXIS, HETE, and MOST. The developers of the product from ISIS have flown hardware on PROBA-2 and the International Space Station. The following is a table of the possible sun sensors for the satellite.

Table 5: Sun Sensors

Sensor Name	Mass	Size	Power	Field of View	Accuracy
Model 0.5	40g	N/A	<50mW	100^o	0.5^o
Miniaturized Analog Fin Sun Sensor	50g	46x45x14mm	N/A	Nominal:128x128^o Unobstructed: 160x160^o	0.5^o over 120^o FoV
Coarse Sun Sensor	20g	12.7mm dia x 9mm	N/A	120^o	5^o
Medium Sun Sensor	36g	24.3mm dia x 34.9mm	N/A	60^o	1^o

The coarse and medium sun sensors from Comtech AeroAstro are both small and light making them good candidates, however they have lower accuracy and field of view respectively than the others. From the images available on Optical Energy Technologies's website Model 0.5

is comparable in size to the miniaturized sun sensor from ISIS. The miniaturized sun sensor was chosen for its accuracy, large field of view, and no power consumption.

1.3.5 Flight Option Magnetorquers

Two magnetorquers were considered for the flight option. Only one viable COTS product was considered because of the limited availability of such devices. This is likely the result of most satellites using custom developed magnetorquers. They are simple to produce as described for the lab option and are therefore considered for the flight option. A heavier grade magnet wire would be used in a custom magnetorquer because of its higher durability. This would cause the actuator to be heavier than the lab option. Clyde Space sells a magnetorquer rod (with specification listed below) specifically for CubeSats and is also considered.

Table 6: Clyde Space magnetorquer

Magnetic Moment	Power	Mass	Size	Lifetime
0.2 Am^2	5V, 40mA	27g	Length: 7cm Diameter: <9mm	>10 years

This rod has the same power requirements and similar mass to the lab option coil. One advantage is that it has a significantly higher magnetic moment and therefore can provide more torque. Based on this and the fact that it is space qualified, it was selected for use in the satellite.

1.4 ADCS Design

1.4.1 Attitude Dynamics Model

A simulation of the attitude dynamics was created to research the optimal ADCS algorithms. A quaternion based description of the dynamics was used to avoid singularities present with Euler rotation angles. The current model assumes torque free rotational motion. The table below gives the set of symbols used in the model's equations.

Table 7: Symbols for quaternion attitude dynamics model

Symbol	Description	Symbol	Description
$\mathbf{i}$	One of the three magnetorquers (1,2,3)	$\boldsymbol{\tau}_i$	Applied torque from the magnetorquers
$\mathbf{B}$	The Earth's magnetic field	$\boldsymbol{\mu}_i$	The magnetic moment of a magnetorquer
$\boldsymbol{\Omega}$	Angular velocity of the body frame about its axes	$\boldsymbol{\alpha}$	The angular acceleration of the body frame about its axes
$\boldsymbol{\alpha}_i$	Angular acceleration due to a magnetorquer	$\mathbf{q}$	The inertial quaternion for describing the body frame attitude
$\mathbf{I}_i$	The inertia tensor about a magnetorquer	$\mathbf{I}$	The inertia tensor about the center of mass

The following equations show the basic relationship between torque and angular acceleration (time derivative of angular velocity) and the applied torque from a magnetorquer.

$$\boldsymbol{\tau}_i = \boldsymbol{I}_i \boldsymbol{\alpha}_i$$

Equation 1[1]

$$\boldsymbol{\tau}_i = \boldsymbol{\mu}_i \; x \; \boldsymbol{B}$$

Equation 2[2]

Using these two equations the total angular acceleration for the satellite can be solved for.

$$\boldsymbol{\alpha}_i = \boldsymbol{I}_i^{-1}\boldsymbol{\tau}_i = \boldsymbol{I}_i^{-1}(\boldsymbol{\mu}_i \; x \; \boldsymbol{B})$$

Equation 3

$$\boldsymbol{\alpha} = \sum_{i=1}^{3} \boldsymbol{I}_i^{-1}(\boldsymbol{\mu}_i \; x \; \boldsymbol{B})$$

Equation 4

By integrating this equation the angular velocity of the satellite can be determined. The torques that arise from a rotating spacecraft described in Euler's equation needs to be added to the dynamics. The following equation results from this addition.

$$\boldsymbol{\alpha} = \sum_{i=1}^{3} \boldsymbol{I}_i^{-1}(\boldsymbol{\mu}_i \; x \; \boldsymbol{B}) + \boldsymbol{I}^{-1}(\boldsymbol{\omega} \; x \; \boldsymbol{I}\boldsymbol{\omega})$$

Equation 5

Similarly for the angular velocity, differential equations for the quaternion describing the satellite's attitude are needed to model the dynamics completely. The following equations describe the quaternion and its derivative.

$$\boldsymbol{q} = \begin{bmatrix} \widehat{\boldsymbol{q}} \\ q_4 \end{bmatrix}$$

Equation 6

Where $\widehat{\boldsymbol{q}}$ is the vector part of the quaternion and q_4 is the scalar part.

$$\frac{d}{dt}\boldsymbol{q} = \frac{1}{2}[\boldsymbol{\Omega}]\boldsymbol{q}$$

Equation 7[3]

$$[\boldsymbol{\Omega}] = \begin{bmatrix} 0 & \omega_z & -\omega_y & \omega_x \\ -\omega_z & 0 & \omega_x & \omega_y \\ \omega_y & -\omega_x & 0 & \omega_z \\ -\omega_x & -\omega_y & -\omega_z & 0 \end{bmatrix}$$

Equation 8[4]

The time derivatives of the angular velocity and quaternion need to be integrate simultaneously. This is done using the software package MATLAB. The magnetic field **B** is

[1] Formulated using equations 10.28-29 (Young & Freedman, 2008) p.332

[2] Equation 27.26 (Young & Freedman, 2008) p.937

[3] Equation 9.151a (Curtis, 2010) p.556

[4] Equation 9.151b (Curtis, 2010) p.556

time variant because the spacecraft orbits around Earth. To include this into the model a table containing the magnetic field vector with a time interval of ten seconds along the satellite's orbit was generated. The Satellite Tool Kit software was used to generate this table with the International Geomagnetic Reference Field (IGRF) model. The table is then interpolated by MATLAB to obtain the magnetic field vector during the simulation.

The simulation also includes models of the sensors. Gaussian noise was optionally added to all sensors to increase the simulation's accuracy. The magnetometer readings are interpolated from the IGRF table. Similar tables were also generated using STK for the center of mass position and the sunlight vector to simulate the GPS and sun sensors respectively. Data for the gyro sensors is taken from the dynamics model.

1.4.2 Attitude Determination

Measurements collected with the spacecraft's onboard sensors are used to determine the attitude of the satellite. There are a number ways of accomplishing this such as direct and recursive methods. Direct methods use the instantaneous readings from the sensors in combination with other known data to calculate the attitude. This method is often computationally simple but may contain significant sensor error. Recursive methods are more complex and use current sensor measurements to modify the previously calculated attitude. This method often consists of filters to reduce noise generated by the sensors.

1.4.2.1 TRIAD Method

The TRIAD method is very simple and well used algorithm. Two vector pairs are used as inputs with each pair measuring similar values in separate coordinate systems. A pair of composite vector sets is generated and a coordinate transformation (direction cosine matrix) is calculated. In this case the first vector pair will be the measured magnetic field and sun vector in the body axis frame. The second pair is the calculated values from the position of the satellite provided by the GPS and software models of the sun's position relative to earth and the geomagnetic field. The following are equations for calculating the DCM (Benet, 2007) pp 10-11.

Table 8: Symbols for TRIAD method

Symbol	Description	Symbol	Description
$\mathbf{B_s}$	Magnetic field vector from sensor	$\mathbf{S_s}$	Sun vector from sensors
$\mathbf{B_m}$	Magnetic field vector from model	$\mathbf{S_m}$	Sun vector from model
$\boldsymbol{\alpha}_{1,2,3}$	First set of composite vectors	$\boldsymbol{\beta}_{1,2,3}$	Second set of composite vectors

$$\alpha_1 = \frac{B_s}{|B_s|}$$

$$\alpha_2 = \frac{B_s\ x\ S_s}{|B_s\ x\ S_s|}$$

$$\alpha_3 = \alpha_1\ x\ \alpha_2$$

$$\beta_1 = \frac{B_m}{|B_m|}$$

$$\beta_2 = \frac{B_m\ x\ S_m}{|B_m\ x\ S_m|}$$

$$\beta_3 = \beta_1\ x\ \beta_2$$

$$A = [\alpha_1 \quad \alpha_2 \quad \alpha_3][\beta_1 \quad \beta_2 \quad \beta_3]^T$$

1.4.2.2 Extended Kalman Filter

The Extended Kalman Filter (EKF) is a recursive algorithm used to filter out sensor noise with Gaussian distributions. This algorithm has two distinct cycles, predict and update (or filtered) cycles. The purpose of the predict cycle is to use the nonlinear dynamics equations with the previous estimated state to predict the current state. The filtered cycle then uses the sensor data to modify the output from the predict cycle. The following are the equations in the EKF algorithm (Ribeiro, 2004) pp 31-33.

Table 9: Symbols for the EKF

Symbol	Description	Symbol	Description
x	System state	**f**	Nonlinear dynamics equations
u	Control input	**w**	Process noise
y	Output from sensor measurements	**h**	Output state
v	Output noise	**Q**	Process noise covariance matrix
R	Output noise covariance matrix	**F**	Jacobian matrix of **f**
H	Jacobiam matrix of **h**	**P**	Estimate covariance matrix
K	Kalman gain	**k, k+1**	Indicates the discrete index of iteration
I	Identity matrix		

Input and Output Equations

$$x_{k+1} = f_k(x_k, u_k) + w_k$$

$$y_k = h_k(x_k) + v_k$$

Jacobian Matricies

$$F(k) = \nabla f_k|_{\hat{x}(k|k)}$$

$$H(k+1) = \nabla h|_{\hat{x}(k+1|k)}$$

Predict Cycle

$$\hat{x}(k+1|k) = f_k(\hat{x}(k|k))$$

$$P(k+1|k) = F(k)P(k|k)F^T(k) + Q(k)$$

Filtered Cycle

$$\hat{x}(k+1|k+1) = \hat{x}(k+1|k) + K(k+1)\left[y_{k+1} - h_{k+1}(\hat{x}(k+1|k))\right]$$

$$K(k+1) = P(k+1|k)H^T(k+1)[H(k+1)P(k+1|k)H^T(k+1) + R(k+1)]^{-1}$$

$$P(k+1|k+1) = [I - K(k+1)H(k+1)]P(k+1|k)$$

1.4.3 Attitude Control

1.4.3.1 Stabilizing Controller

The purpose of this control is to stabilize the spacecraft when tumbling is an issue. This can occur when the spacecraft separates from the P-POD. To find the control law a Lyapunov stability analysis is performed.

Table 10: Symbols for stability controller

Symbol	Description	Symbol	Description
V	Lyapunov function	**μ**	Combined magnetic moment of the magnetorquers
ω	Angular velocity	**B**	Magnetic field
I	Inertia tensor	**τ**	Applied torque
C	Controller gain		

$$V = \frac{1}{2}\omega^T I \omega$$

$$\dot{V} = \omega^T I \dot{\omega}$$

$$\dot{\omega} = I^{-1}T - I^{-1}(\omega\ x\ I\omega)$$

$$\dot{V} = \omega^T T - \omega^T(\omega\ x\ I\omega) = \omega^T T < 0$$

$$T = \mu\ x\ B$$

$$\dot{V} = \omega^T(\mu\ x\ B) = \mu^T(B\ x\ \omega)$$

$$\mu = -C(B\ x\ \omega)$$

$$\dot{V} = -C(B\ x\ \omega)^T(B\ x\ \omega) < 0\ for\ C > 0$$

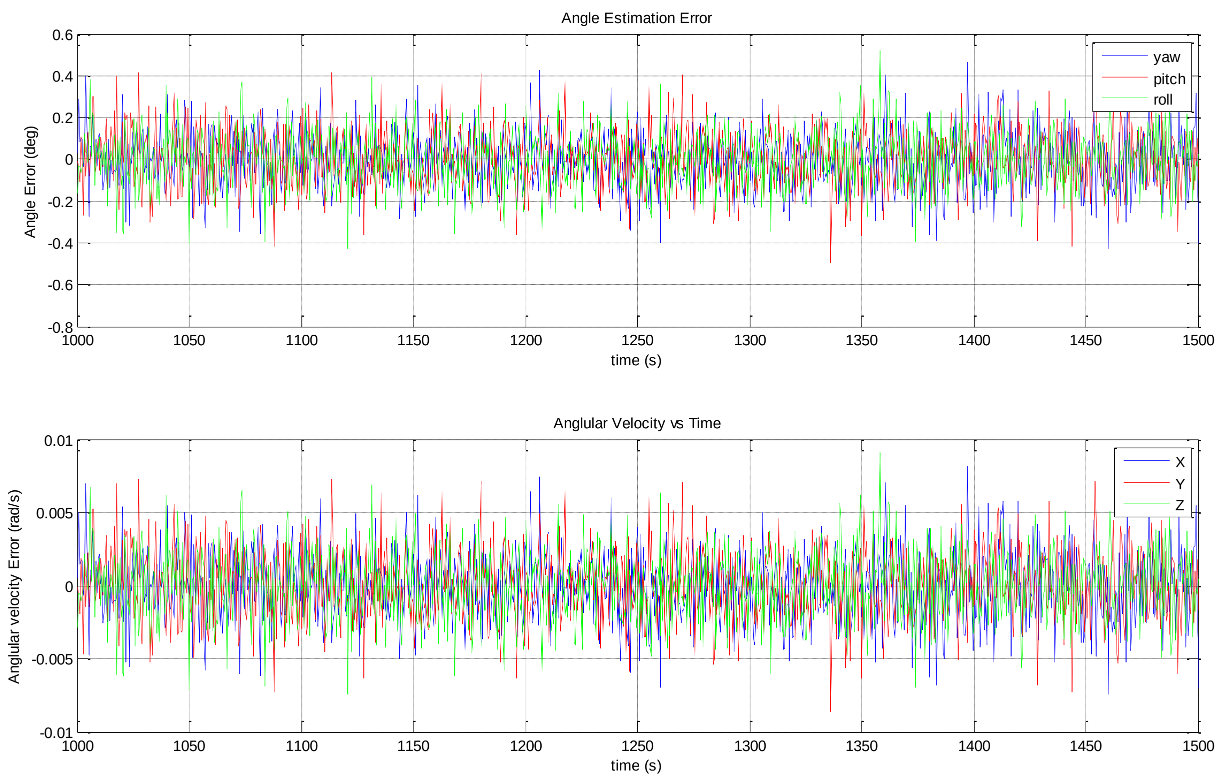
1.5 ADCS Testing

1.5.1 Attitude Determination

1.5.1.1 TRIAD Method

The TRIAD method described in the previous section is tested by the MATLAB simulation program that was developed. Predicted Gaussian noise is added to the simulated sensors based on the components chosen for the flight option. The angular velocity values are directly from the simulated gyroscopes and the angles are determined from the direction cosine matrix produced from the TRIAD algorithm. Below is a plot of the estimation error for the yaw, pitch, and roll angles and the angular velocity components. For this simulation the initial conditions of the satellite state are the body frame coincides with the inertial frame and the angular velocities in the x, y, and z directions in radians per second are 0.5, 3, and 1 respectively.

Figure 1: TRIAD Determination Test

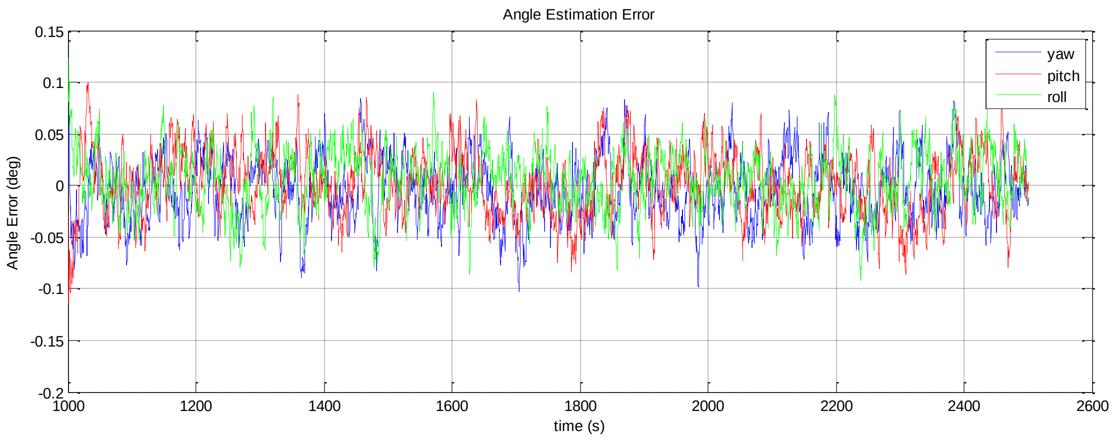


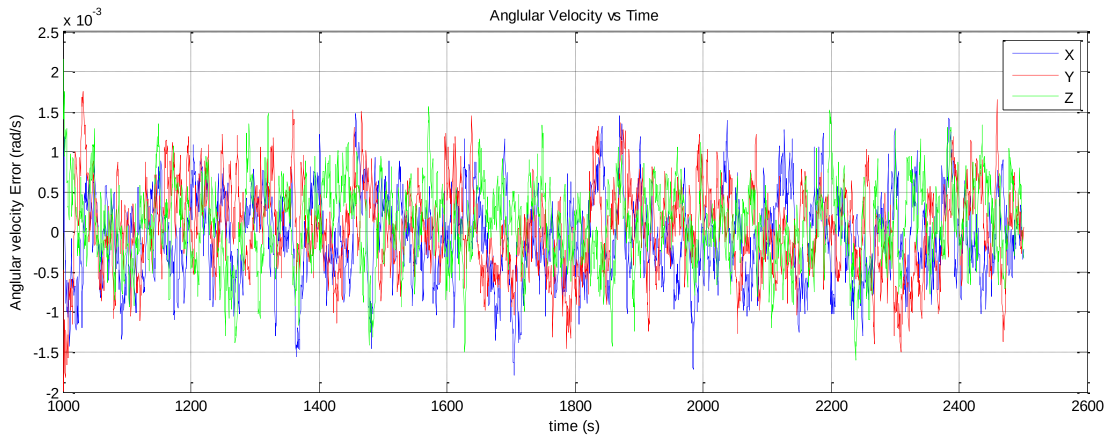
From the graph it can be seen that the angle error is mostly better than 0.3 degrees and the angular velocity error is mostly better than 5 miliradians per second. The standard deviation of the yaw, pitch, and roll angles are 0.1359, 0.1381, and 0.1352 respectively. The standard deviation of the x, y, and z angular velocities are approximately the same as the chosen gyroscope deviation at 2.36 miliradians per second. This test provides a baseline to use during other tests for attitude determination.

1.5.1.2 Extended Kalman Filter

Similarly to the test of the TRIAD algorithm the extended Kalman filter is tested using the same initial conditions. The expected sensor noise is calculated from the TRIAD test because this will provide the Kalman filter with the raw data. Below is a plot of the estimation error in the Euler angles and angular rates of the satellite.

Figure 2: Extended Kalman Filter Test





The results for the extended Kalman filter are much better than only using the TRIAD method. The standard deviations for the yaw, pitch, and roll errors are 0.0309, 0.0309, and

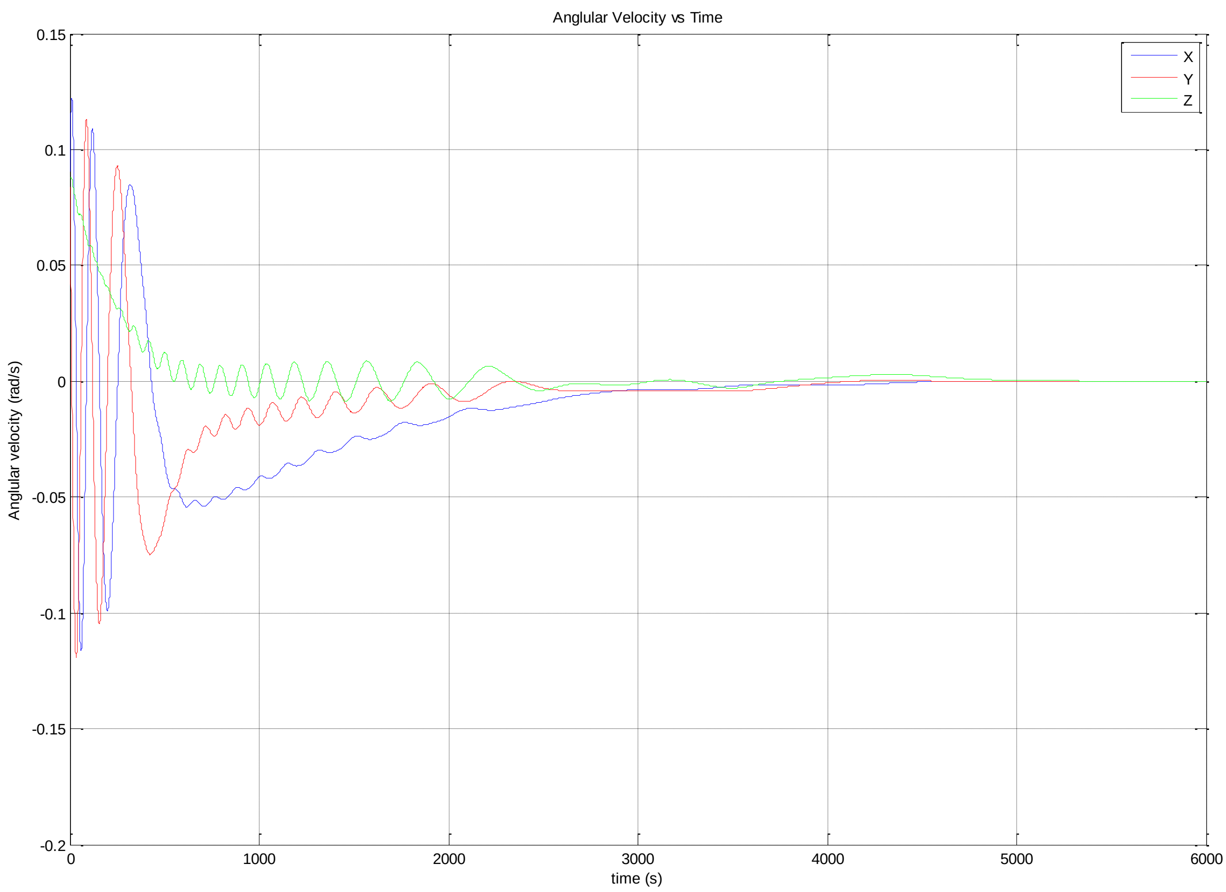
0.0285 degrees respectively. For the x, y, and z components of the angular velocity the standard deviations are 0.540, 0.539, and 0.497 miliradians per second respectively.

1.5.2 Attitude Control

1.5.2.1 Stabilizing Controller

The stabilizing controller slows the rate or angular rotation using the control law that was developed. To evaluate the performance of the controller a test was completed. The simulation's initial conditions are given as the satellite's body frame coincides with the inertial frame and each component of the angular velocity is 5 degrees per second. These initial conditions are to simulate the possible situation when ejected from the launch vehicle. Below is a plot of the angular velocity components vs. time.

Figure 3: Stabilizing Controller Test



The graph above shows that the within the first 2000 seconds the angular velocities drop significantly and after 5000 seconds the satellite has almost stopped. At that point all components are less than 0.4 miliradians per second (or 0.023 degrees per second). This amount of time is less than the orbital period of 98.2 minutes (or 5892 seconds) and therefore shows the satellite has the ability to stabilize itself within one orbit with these initial conditions. Power is a premium on the CubeSat and knowing the power consumption of each subsystem is important. For this reason calculations for the power required for a maneuver were added to the simulation. The estimated power cost for this stabilization maneuver is 323.75 Joules.

2 On Board Computer

2.1 Introduction

The onboard computer in any spacecraft is responsible for a multitude of tasks and is the principle means of controlling the craft from the ground. The onboard computer is closely tied to all subsystems and thus requires a level of system integration much unlike many others. In a CubeSat where space, power and processing are all at a premium, the onboard computer maintains a vast majority of all computing responsibilities for the craft, albeit propulsion calculations, communications, or data storage and management in situ. Coupled with the various sensors throughout the craft, measuring anything from propulsion tank temperature to Euler angles, the onboard computer's primary purpose is to use all that data and calculate the necessary corrections to maximize the possibility for mission success.

The onboard computer is being designed in a top-down approach, where major system functions dictate the need and design of the embedded system. Due to the overwhelming lack of power and other resources, it is clear that a minimalist design in terms of power consumption is necessary, this further dictates early design choices with respect to the choice of processor and thus a potential operating system. Note that many of the calculations that need to take place are continual and in real-time which also means that all calculations made on the fly are time dependent and have short lifespan, due to ever-changing deadlines.

2.1.1 On Board Computer Design Methodology

Using a top-down approach to the design of the onboard computer is desired in this situation. Very specific functions are needed in order to control the craft, (i.e. "turn on thruster for xx seconds"), these functions can be written in such a way that the skeleton of the code is modular and easier to debug/ adapt to the future needs of a subsystem. The top-down approach also temporary resolves problems with the design of the hardware components of the board as well. Instead of designing hardware and hoping for the best, designing the software then knowing exactly the needs and adding a safety buffer allows for better engineering practices and allows for additional research to be done on hardware components space heritage.

The bottom-up design approach is slowing become more of a relic as systems become ever complex, where the seed if you will doesn't know where the ground is let alone how to connect with other seeds and create layout that is quick and efficient. The bottom-up design controls application sizes and other memory concerns due to strictly knowing exactly the limitations, however this does not always mean the best hardware/ software combination is created. An example choosing a microcontroller for the CubeSat that will satisfy the requirements, from looking into many other CubeSats and options commercially of the self it is clear that the Texas Instruments MSP 430 is a solid choice. However there are over two hundred choices within the MSP 430 platform, with options including the number of bits in the analog to digital converter, clock speeds, the amount of flash memory, etc. The soundest decision is to first assess the needs of the mission the fidelity of the measurements and from there make a selection.

2.1.1.1 General On-board Computer Design Requirements

Using the top-down approach, a hard set of design requirements are necessary to propagate through the project and steer toward an end goal. The design requirements for the onboard computer of the CubeSat are to:

- Store data collected from the science mission and ensure transmission to ground station
- Contain a majority of the processing power for all subsystems
- Be the median between the subsystems and the ground station
- Provide telemetry to the ground station

Noting each of the requirements scope, there are still quite a few necessities that are required in order to begin designing a system. The beauty of a top-down design through is that by knowing the end goal skeletons are able to be created. For example a mission requirement is pointing the aperture of the infrared camera toward both the limbs and nadir during each pass. There are additional requirements such as the pointing accuracy, but a block like this gives the Attitude Control and Determination subsystem access to the computational resources necessary as well as a connection to the power management and distribution system that actuates the magnetorquers.

2.2 Literature Review

2.2.1 Command and Data Handling in CubeSats

There are many typical considerations taken into account for CubeSat on-board computers a subset of all satellite computers. With power consumption and mass being a major driver of the CubeSat design there is continual check of allocations for everything being done. For embedded applications there is routinely the power consumption issue, thus multiple lines of low-power microcontrollers and high power density batteries. Another critical issue is the environment, ground based systems do not have to deal with high-energy particles that can cause bit-flops, latch-ups and burn-outs. For larger satellites it is routine for the processor be developed for the mission with redundant processors that are radiation hardened, and designed to meet the needs of the mission. However with a principle of CubeSats being an affordable methods for states and educational institutions (where space was once out of reach) to create space worthy craft; we must consider a commercial-of-the-shelf (COTS) microcontroller that meets all of our requirements.

2.2.2 CubeSat Hardware Overview

With over sixty CubeSats that were launched or are currently developing many solutions to the on-board computer exist. Currently there are commercially available CubeSat on-board computer kits that are pre-assembled and use either PICs or MSP430s for their primary microcontroller. Below is a breakdown of existing CubeSats and their processor selections.

Table 11 AAUSat-I OBC Specs

Specification	Data
Operating Voltage	5 Volts
Processor	Siemans C161-R1
Clock Frequency	10 MHz
Memory	RAM: 512 kB ROM: 512 kB Flash: 256 kB
Bus	DMA and I2C
Operating System	RTX166
Programming Language	C

Table 12 AAUSat-II OBC Specs

Specification	Data
Operating Voltage	3.3Volts (<300 mW @ 40 MHz; <80 mW @ 8 MHz)
Processor	Atmel AT915AM7A1
Clock Frequency	8 and 40 MHz
Memory	RAM: 2 MB SRAM Flash: 2+4 MB
Bus	CAN
Operating System	
Programming Language	

Table 13 CanX-I OBC Specs

Specification	Data
Operating Voltage	3.3 Volts (0.4 W)
Processor	Atmel ARM7
Clock Frequency	40 MHz
Memory	RAM: 128 kB ROM: 32 MB
Bus	One-wire; serial RS232

Operating System	None
Programming Language	C

Table 14 CanX-2 OBC Specs

Specification	**Data**
Operating Voltage	3.3 Volts
Processor	ARM7
Clock Frequency	15 MHz
Memory	RAM: 2 MB Flash: 16 MB
Bus	I2C
Operating System	CANOE Canadian Advanced Nanospace Operating Environment
Programming Language	C

Table 15 CP1 and CP2 OBC Specs

Specification	**Data**
Operating Voltage	3 Volts
Processor	PIC18LF6720
Clock Frequency	4 MHz
Memory	RAM: 4kB ROM: at least 1kB Flash: 128 kB
Bus	I2C
Operating System	
Programming Language	

Table 16 CubeSat Kit OBC Specs

Specification	**Data**
Operating Voltage	3.3 and 5 Volts (<100 mW)
Processor	TI MSP430
Clock Frequency	
Memory	SD/MMC external memory
Bus	I2C, SPI, UART
Operating System	Salvo Pro RTOS
Programming Language	MSP430 C Compiler

Table 17 CubeSat XI-IV OBC Specs

Specification	**Data**
Operating Voltage	2.0 and 5.5 Volts
Processor	PIC16F877
Clock Frequency	4 MHz
Memory	RAM: 368 bytes ROM: 32 kB
Bus	I2C
Operating System	
Programming Language	

Table 18 CUTE-I OBC Specs

Specification	**Data**

Operating Voltage	
Processor	H8/300
Clock Frequency	
Memory	RAM: 1 kB internal, 512 kB external SRAM ROM: 256 kB EEPROM Flash: 4MB AT45DB321B
Bus	
Operating System	
Programming Language	

Table 19 DTUSat OBC Specs

Specification	Data
Operating Voltage	3.3 Volts (3 mW/MHz)
Processor	Atmel AT91M40800
Clock Frequency	16 MHz
Memory	RAM: 1 MB ROM: 16 kB Flash: 2 MB
Bus	SPI
Operating System	
Programming Language	

Table 20 HAUSAT-1 OBC Specs

Specification	Data
Operating Voltage	3.3 and 5Volts (60 mW)
Processor	AT91LS8535
Clock Frequency	4 MHz
Memory	RAM: 512 bytes internal SRAM ROM: 512 bytes EEPROM Flash: 4 MB AT45DB321B
Bus	SPI
Operating System	
Programming Language	IAR C Compiler

Table 21 KUTEsat OBC Specs

Specification	Data
Operating Voltage	3.3 Volts
Processor	PIC18F4220
Clock Frequency	
Memory	SDRAM: 8 MB Flash: 4 MB
Bus	
Operating System	
Programming Language	

Table 22 Mea Huaka'i OBC Specs

Specification	Data
Operating Voltage	5 ± 0.25 Volts RCM2000: High 0.65 W; Med 0.3 W; Sleep 1.4 mW

	EEPROM: Write 165 mW; Read 2.2 mW; Standby 0.55 µW
Processor	Z-World RabbitCore RCM2000 and 23000 (x2 for redundancy)
Clock Frequency	1.8 – 30 MHz; 32 kHz in sleep mode
Memory	
Bus	I2C
Operating System	
Programming Language	Dynamic C

Table 23 MEROPE OBC Specs

Specification	**Data**
Operating Voltage	
Processor	Motorola MC68HC812A4
Clock Frequency	
Memory	128 kB Supersync FIFO IDT72291
Bus	
Operating System	
Programming Language	

Table 24 NCUBE OBC Specs

Specification	**Data**
Operating Voltage	3.6 Volts
Processor	Atmel AVR ARmega32L and PIC microcontrollers
Clock Frequency	
Memory	ROM: 4 kB
Bus	I2C
Operating System	
Programming Language	

Table 25 Sacred and Rincon OBC Specs

Specification	**Data**
Operating Voltage	
Processor	PIC16C77
Clock Frequency	4 MHz
Memory	RAM: 368 on chip; 64 kB FRAM
Bus	I2C
Operating System	
Programming Language	C

Table 26 SwissCube OBC Specs

Specification	**Data**
Operating Voltage	3.3 Volts (Stand-by: 1mW; Nominal: 150 mW; Peak: 250 mW)
Processor	AT91M55800A and MSP430F1611
Clock Frequency	32 MHz
Memory	RAM: 512 kB SRAM ROM: 512 kB EPROM Flash: 2 MB
Bus	I2C
Operating System	

Programming Language	C

Although the above is not an all-inclusive list of CubeSat processors and missions it does show the wide range of options for processors, memory, programming language or anything else. The hardware selection process is strictly driven by the payload and the communication ability of the satellite.

2.2.2.1 On-board Computer Functional Overview

Many CubeSats have broken the processing down into separate microcontrollers for individual subsystems and left the command and principle on-board computer tasked with command and data management; a primary focus of the software is housekeeping.

Housekeeping allows the satellite to minimize the storage resources necessary as well as reduce the fragmented data held in the memory bank. Housekeeping runs diagnostics on all the key systems in the CubeSat to improve survival, this is also reduces the duty load on the microcontroller and collects the status of each subsystem. The CubeSat on-board computer has another responsibility to manage as much of the daily survival tasks as possible, albeit subsystem reset, or complete isolation.

The requirements of this CubeSat require a different approach. A vast majority of logic is being handled at the onboard computer via software. The design of an all-inclusive on-board computer simplifies several concerns, including communication issues through between subsystems and also a reduction of physical connections to other boards. A detractor of the single motherboard design is that all software at a central location which has a potential for high energy particle radiation bit flops. One consideration that needs to be addressed in design though is the lack of redundancy, failure of the microcontroller would render the CubeSat useless. The possibility exists to have several microcontrollers on a single board; however more research needs to be done into the feasibility of that design.

2.2.3 Real Time Operating System Overview

All operating systems serve a common purpose, control hardware and provide a set of services for applications to use. A Real Time Operating System (RTOS) is optimized to yield results in real time; real time being a length of time that allows the information to still be pertinent and accurate. A simple time sensitive problem conceptually is attitude determination. It is time critical to know the orientation of the spacecraft during a positioning maneuver nearly instantaneously in order to meet the pointing requirements of the science payload.

Options for the RTOS vary greatly in expense, size, and complexity. An overview of previous CubeSat RTOS shows the variety of choices.

Table 27 FreeRTOS (Real Time Engineers Ltd., 2010)

Characteristics	Memory Requirements	MSP430 Support
FreeRTOS is a scale-able real time kernel designed specifically for small embedded systems. • **No software restriction on the number of priorities that can be used.** • **No restrictions imposed on priority assignment - more than one task can be assigned the same priority.** • **Free Development Tools** • **Free embedded software source code** • **Free**	Typically a kernel binary image will be in the region of 4K to 9K bytes.	YES

Table 28 Salvo Professional RTOS (Pumpkin Inc., 2010)

Characteristics	Memory Requirements	MSP430 Support
Salvo™ is the first Real-Time Operating System (RTOS) designed expressly for very-low-cost embedded systems with severely limited program and data memory. With Salvo, you can quickly create low-cost, smart and sophisticated embedded products. • **Three versions (Free – Limited number of tasks(3); LE – Unlimited number of tasks; Pro – Unlimited number of tasks** • **Free version limited to number of events (5)** • **Cost (Free- Free; LE - $900; Pro- $1500)** • **Restricted to IAR Embedded Workbench Integrate Development Environment** • **Only Pro version allows advanced configuration, and the source code** • **Developed to work with CubeSat kit**	Varies with functions used, up to 500 kB.	YES

The two RTOS above are the two possibilities for the CubeSat design, this will be determined in the coming weeks to finalize flight software structure, and capabilities. Upon examination of several other CubeSats it is a common for the CubeSat to have a custom operating system written completely in house. Due to limited resources and experience the CubeSat will use a COTS RTOS.

2.3 Design Considerations

2.3.1 Operating Environment

The operating environment of the CubeSat is typically considered a hostile at best, temperatures varying from lower than -40 degrees Celsius in eclipse to upwards of 45 degrees Celsius in full solar exposure which is within industrial standard temperature range. Along with these greatly varying temperatures within estimated 90 minute orbital period, the fear of highly energized particles (HEP) is also a constant fear of electronic components and specifically logic gates and microcontrollers/ processors. When designing the on board computer, there were many considerations that were explored; the issue of HEPs was deemed a non-issue partially due to the particle density in low Earth orbit, and more importantly the ability to account for any software issues of particle based bit flips through routine validation software. The greater fear occurs when there are HEPs that embed themselves in the logic gate, thus either shorting the gate and thereby reducing functionality or potentially draining power.

In order to accommodate the issues above, we determined that any it is necessary that any hardware used needs to have a very extensive power management module that allows either the peripheral chain to be switched off or that there is method of detecting a short and attempting to clear the error. Another possibility would be a radiation hardened package that would reduce the HEP penetration. Rarely is there the availability of powerful package that enables the use of many new and upcoming technologies at the microcontroller level and that have space heritage that commits corporations in developing this line of products. Texas Instruments® has a line that does fit many of the other design requirements, however there costs far outweighs the gains obtained with the hardened shell. This line would also reduce the available peripherals and increase the power requirement, in a system where mass and power are the principle drivers. However all MSP430s are considered low power microcontrollers that allow for the peripherals to be independently controlled and correct any issue. In speaking with the environmental teams only during a solar storm conditions are these even HEPs a consideration, and the potential/

warning available for a solar storm would allow the on-board computer to be powered down with enough time that everything would be safe and in a protected state.

The final environmental concern is spacecraft charging where there is the potential for the bus to short to the internal structure/ electronics. In order to design for this issue we consulted with biomedical engineers that have to conquer a similar issue on a daily basis. By using shunts that were commonly used to reduce high frequency noise, we are also able to deal with spikes in power coming from any external peripherals, and also act a decoupling capacitors for those braches coming into the system.

2.3.2 Power Consumption

To combat the problem of severe lack of power and the ability to complete all the tasks necessary, including communication, low power solutions were solely explored. Based on previous research and the need for a simple and redundant system, the focus immediately began on microcontrollers. Although the benefits of a microprocessor based system such as improved computation and full 32-bit software, the need to power the processor, as well as the memory and finally the layout of 32-bit busses connecting the memory processor and all other peripherals reduced the allure of a microprocessor, similarly with 16-bit processors. Next, looking into Digital Signal Processors (DSP), the arithmetic workhorses they are, it was clear that the need for so many peripherals, and the power to clock cycle ratio was not as good as Mixed Signal Processor (MSP). MSPs have very similar traits to both a DSP and a microcontroller, although normally considered a microcontroller.

All MSP430 lines manufactured by Texas Instruments are capable of extremely low power states in the standby modes, and just microseconds to go from the lowest power states all the way to full power, and back again. When properly implemented, then the MSP will be in a low power state for a majority of the time. Specifically the primary MSP selected for the CubeSat lab option has four timers that are able to run independently of one another, and thereby can initialize separate interrupts a that will force the an application to begin the next command, whether it be opening a propulsion valve, or beginning communications with the ground station. This ability reduces the power consumed by the microcontroller significantly, and this is compounded with the multi MSP design in the lab option OBC. By using multiple smaller MSPs that each draw less power, and using the primary MSP to interrupt the low power state, in order to run a specialized task allows the primary MSP to stay at lower state. Just as important though it allows for a multi-tiered priority configuration where the primary MSP would essentially continuously run if this did not exist.

2.4 Hardware and Software Selection

2.4.1 Component Selection

2.4.1.1 Primary MSP430F5438

Many hours went into pouring over datasheets, ensuring all the necessary peripherals are available to all the subsystems in the CubeSat, specifically necessary were sixteen analogue-to-digital converters (ADC), four-timers, communications (including I^2C and SPI), as well as the ability to program it with JTAG. The MSP430F5438 granted the team with a high enough frequency that it could debug the system using USB through a UART/SPI-USB bridge. The MSP430F5438 offers a 25 MHz core, and a 32-bit hardware multiplier that is especially needed in Attitude Determination and Control. The F5438 also offers the utility of having a Unified Clock System (UTS) including a Real-Time Clock (RTC) which can also trip interrupts, even if the MSP is in a lower power state.

2.4.1.2 Secondary MSP430F2012

The need for the secondary MSP430 was not evident until the need for multiple thruster control and so many ADC channels were fixed due to other subsystems. For example the power subsystem needed independent channels for each battery to system determine health and further to determine the illumination levels on each face. This coupled with independent control of every subsystem from the on board computer, quickly meant that there was a need for a less powerful but similar microcontroller, similar to what the SwissCube determined.

This MSP430 needs only to have I^2C and multiple ADC, this is a very easy task, however finding another MSP430 that will be able to reduce the load and the power consumption is difficult. During the initial development stages using the MSP430F2012 allowed the teams to identify many of the features that are necessary for the final product. Using this experience and determining that it was a suitable match, the MSP430F2012 was selected for the secondary MSP430.

2.4.1.3 UART/SPI-USB Bridge TUSB3410

While this component only has purpose in the developmental stages of the onboard computer, the value of having it far exceeds the resources that it takes, during the flight configuration, this component will be unpowered. The power for this component as well as the rest of the OBC during ground operations is supplied through the USB port. This allows multiple things to occur; the OBC can be debugged independently of the power subsystem, as well as saving power if the lab option board was to be used as the flight option board, and during simulations we are able to feed information into the on-board computer for sensor readings, that are more similar to flight conditions.

2.4.2 Lab OBC – Flight OBC Hardware Comparison

We selected a commercial OBC option for the flight option over continuing the development of the lab option OBC, for a few reasons, including continuing development costs. The TI MSP430 based OBC designed for the lab has many features that are not present on the commercial OBC, such as redundant microcontrollers for key watchdog features and survival. This is important where if a specific branch of the system failed due to a software error the board would be able to reload the initial flight software, or even be able to receive software updates while in flight. This functionality was explored and although it would increase the survivability of the satellite, it may be considered unnecessary in a short term mission, as well as the proposed scientific payload. However if an additional payload, or a payload that requires computation on board were to be added to the mission, a multi-MSP design would be much more efficient and allow for additional functionality, as well as greater flexibility and customization.

The flight option on board computer (OBC) is at commercially available CubeSat motherboard with an MSP430 processing unit. This product has a 3 week lead time that will is readily available from Clyde Space a UK based company, also the retailer of many other flight option components, such as PMAD, batteries, solar panels, and both communication transceivers. Features of the Clyde Space OBC include a USB ground tether, as well as a separate power supply, this along with the CubeSat Kit standard PC 104 connector. The commercial OBC has an extensive flight history with several microcontrollers, including many TI MSP 430s. The commercial OBC provides a fixed pathway for software as well where the RTOS, which may be purchased, is a higher version of the test software being used for the lab option.

2.5 Software

2.5.1 MSP430 Development Environment

There are many options for developing software for the MSP430 microcontroller. Texas Instruments supplies two options, Code Composer Studio (CCStudio) and IAR Embedded Workbench (IAR EW). The both of the software included have constraints for the free versions, however CCStudio does allow greater flexibility, additionally the CCStudio connects with all Texas Instrument development tools. Further the CCStudio has a familiar layout for anyone who has used any Eclipse based IDE. However these are all the advantages of CCStudio, IAR EW is the industry standard for MSP430 software development. Salvo the planned flight and lab RTOS, comes with instructions to compile and flash MSP430s via IAR EW. Therefore all flight software will be written in IAR EW. One point that needs to be emphasized, despite IAR being used for the RTOS, and primary MSP430, in the lab option, the CCStudio is more than adequate to develop a subsystem, and because all the code is written in C then there already is a high level of interoperability. Furthermore, there is third option that has no such limitation, however lacks any company backed support, using a base Eclipse IDE, and installing mspgcc. Both Eclipse and gcc are free, open sources alternatives, however the set-up of the system is much more difficult than CCStudio or IAR.

Table 29 MSP430 Integrated Development Environment Comparison

MSP430 IDE	Pro	Cons
Code Composer Studio v4 Microcontroller Edition	Simplest to implement Eclipse Based GUI Code Optimizer	1-Locked User: $495 1-Floating User: $795
IAR Embedded Workbench MSP430	Salvo RTOS Technical Support Code Optimizer	1-Locked User starts at $795 No Educational Pricing Lowest price: limited code size
Eclipse + mspgcc	Free Updated Frequently Eclipse GUI No Code limits	Difficult to setup No Technical Support

2.5.2 Printed Circuit Board Layout Software

Similarly there are hundreds of options for the development of the motherboard in the case of the lab option. The key to selecting the software for the motherboard development boils down to knowing the requirements for the components and the ability of the board manufacture. In the CubeSat there are very stringent dimensions for printed circuit boards (PCB), and thus is a driver for the selection of the software. Other drivers include minimal cost, the ability to have four-layers, meeting the 6mil spacing of the MSP430 component leads, and lastly easy to learn and use. Researching this lead to many hobby shop applications that lacked a professional quality in many regards, such as an inability to export the files to industry standard Gerber files, or other issues such as the inability to import stencils for key components, such as the 100-pin MSP430F5438. After consulting with Electrical and Computer Engineering students, the focus shifted to three primary software packages: ExpressPCB, EAGLE Layout Software, and DesignSpark. All of the software packages listed were free or had a "freemium" that allows students to design freely as long as there is not a commercial application.

Table 30 Layout Software Comparison

Layout Software	Comments
ExpressPCB	Simple Unable to import components Unable to export Gerber Files
EAGLE Layout Software	Convoluted to use "Freemium" license De facto industry standard Component importation Meets all requirements
Design Spark	EAGLE Compatible 2 Free licenses per person Meets all requirements Easy to learn

2.6 Flight Software

Every subsystem is responsible for developing the primary algorithm for their operations, ranging from ADCS, where there is a constant reading from the sensors, and continual adjustments in order to maintain the point requirement, or in order to maximize solar recharging. The algorithms are first derived from a set of high level commands that are being determined as more of the mission is frozen. The sooner these are frozen the higher likeliness of a successful mission because there is additional time to develop the software algorithms and time to optimize the sequencing of these to optimize power consumption in both lab options and flight option.

2.6.1 High Level Functions

As this is a baseline for the CubeSat mission, there many holes with regards to specific details, such as the exact schedule of communications, and the number of sensors available to a given subsystem. However, below is the first batch of high level commands submitted by the subsystems.

Table 31 ADCS High Level Commands

Command	Action
Read IMU	1. Initialize IMU
	2. Wait 100ns
	3. Read data
Turn IMU On	1. Turn IMU Power Circuit On
	2. Send Initialization Data
Turn IMU Off	1. Turn IMU Power Circuit Off
Rotate XX degrees about XX axis	1. Determine magnetic field vector
	2. Determine sun vector
	3. Initialize IMU
	4. Calculate time of power on for magentorquer XX
	5. Turn on magnetorquer XX for XX seconds
	6. Evaluate Change
	7. Repeat Steps 4-6 until proper orientation
Read Magnetometer	1. Open Magnetometer Port
	2. Read Data

Table 32 Payload High Level Commands

Command	Action
Initialize Payload	1. Turn on Payload (Send PMAD on signal)
	2. Initiate DMA to SD card
	3. Read data
Turn Off Payload	1. Wait for last data packet
	2. Close DMA to SD Card
	3. Turn off Payload (Send PMAD off signal)

Table 33 Propulsion High Level Commands

Maneuver	Inputs	Operations	Outputs
CCW Rotation	1. Propellant tank temperature [K]	1. Valve Open time [sec]: ZZ	1. Open solenoid valves 1 and 3 for ZZ seconds (initiates).
	2.Target rotation [deg]	2. System standby time [sec]: YY	2. System standby for YY seconds.
		3. Valve open time [sec]: AA	3. Open solenoid valves 2 and 4 for AA seconds (rotation).
CW Rotation	1. Propellant tank temperature [K]	1. Valve Open time [sec]: ZZ	1. Open solenoid valves 1 and 3 for ZZ seconds (rotation).
	2.Target rotation [deg]	2. System standby time [sec]: YY	2. System standby for YY seconds.
		3. Valve open time [sec]: AA	3. Open solenoid valves 2 and 4 for AA seconds (rotation).
Drag compensation (DC)	1. Propellant tank temperature [K]	1. Valve Open time [sec]: ZZ	1. Open solenoid valves 1/2 and 4/3 for ZZ seconds (translation).
	2. Target compensation [m]	2. System standby time [sec]: YY	2. System standby for YY seconds.
		3. Valve open time [sec]: AA	3. Open solenoid valves 2/1 and 3/4 for AA seconds (translation).
Orbit raising/shaping	1. Propellant tank temperature [K]	1. Valve Open time [sec]: ZZ	1. Open solenoid valves 1/2 and 4/3 for ZZ seconds (translation).
	2. Target raise/shape [m]	2. System standby time [sec]: YY	2. System standby for YY seconds.
		3. Valve open time [sec]: AA	3. Open solenoid valves 2/1 and 3/4 for AA seconds (translation).
Notes:			
	1. This command list assumes a propulsion system with two thruster couples. 2. Commands assume $\omega_o = 0$ and $\omega_f = 0$. 3. DC and orbit raising/shaping may need to be performed in conjunction with a CCW or CW rotation maneuver.		

2.7 System Integration

2.7.1 Power Subsystem

The power subsystem and the OBC need to work hand in hand in order to control the satellite. The OBC is useless without power, however the power subsystem is lacks the logic to dictate which components are supposed to stay on during eclipse. Furthermore the power subsystem sends more signals back to the OBC than any other subsystem, because it handles all power amplification for analog signals, in addition to all the telemetry information being passed. Lastly, the power subsystem is the only system that can completely reset the OBC in case of a latch up error.

2.7.2 Attitude Determination and Control Subsystem

The ADCS subsystem is a mathematical workhorse, without the logic all of the calculations that are necessary to control the CubeSat, would be impossible. Many of the processing capabilities were driven with active ADCS in mind; an example is the hardware 32-bit multiplier that reduces the clock cycles used to work with high precision numbers. ADCS is also a principle reason for the investigation of the lab option board versus the existing COTS flight option motherboard.

2.7.3 Payload

The payload is the driver of the mission, and thus knowing that there is a high data output, it drove the OBC to integrate a larger amount of storage, via onboard Secure Digital (SD) card, and making sure that the primary MSP430 was capable of Direct Memory Access (DMA).

2.7.4 Propulsion

Propulsion has a larger part of the OBC design than many realize. The propulsion system is responsible for the need of a RTC on the microcontroller. All of the propulsion equations are based on time, whether they are derivatives of time or otherwise.

2.7.5 Communication

Communication allows the CubeSat to serve a purpose, the interoperability of the OBC and Communications subsystems need to demonstrate this, the Communications subsystem is the only system that can reset the CubeSat remotely, or more importantly receive commands from the ground station, and lastly potentially update malfunctioning software. The other DMA channel belongs to the communication system, where it is able to place files in to the storage, as well as downlink them to the ground. This is addition to the telemetry that it is constantly sending out and the last watchdog for the OBC.

3 Communications

3.1 Introduction

The communications subsystem in a CubeSat can mean a lot of things; in some cases the Communications system is the primary payload, where the mission is to test a new method of communication. Most commonly the communications system is used to relay data, telemetry and commands from the craft to the ground. The ability for satellite to communicate is nothing new and dates as far back as Sputnik. The advancement of communications to the point of transmitting many gigabits per second of data at ranges of over 10,000 km, has managed to make these communications systems smaller and more capable. Currently the accepted norm for communication subsystems on a CubeSat is to have two independent transceivers, one to accommodate the Tracking, Telemetry and Command (TT&C) data, and a second transmitter for the payload data, as well as other high data rate operations, such as a software update. The CubeSat will mimic this two transceiver communications scheme, and have a single command ground station. However, continually transmitted data from the CubeSat and global amateur radio operators there is a highly likelihood of continual beacon reception, if we supplied a method to retrieve the data. In order to meet federal regulations on amateur radio frequencies, the CubeSat is limited to unencrypted transmission due to the prohibitive cost of other frequency ranges. Furthermore if the CubeSat were to use a global network of amateur radio operators the need for easily accessible frequencies is a key to success.

3.2 Design Considerations

In order to develop a communication subsystem for a satellite, primary considerations of power, utility, mass, and volume must be considered. Keep in mind this is in addition to the ongoing environmental concerns that are present in space such as the greatly varying temperature range and spacecraft charging. Continuing with the sample payload of the Argus spectrometer, the need for a high bandwidth communications system is necessary as well as a lower power beacon, for telemetry, command reception and tracking.

The absolute maximum amount of data that is generated by the Argus spectrometer in an orbital period is approximately 22.4 megabytes as provided by the Payload subsystem, this amount of data needs to be combined with continuous global positioning satellite tracking data, and potentially any software updates coming from the ground. With an estimated maximum data transmission of 36 Megabytes per orbit, there is a need for higher bandwidth technologies, and frequencies.

3.3 Literature Review

The need for a communications system for a CubeSat let alone all other satellites dictates that our CubeSat is not the first to have a system. Below is a table of several CubeSats and their respective communication systems.

Table 34 CubeSat Communication Systems (Klofas, Anderson, & Leveque, 2008)

Satellite	Size	Frequency	License	Power	Antenna
AAU1 CubeSat	1U	437.475 MHz	Amateur	500 mW	Dipole
DTUsat-1	1U	437.475 MHz	Amateur	400 mW	Canted Turnstile
CanX-1	1U	437.880 MHz	Amateur	500 mW	Canted Turnstile
Cute-1	1U	436.8375 MHz 437.470 MHz	Amateur Amateur	100 mW 350 mW	Monopole Monopole
QuakeSat-1	3U	436.675 MHz	Amateur	2W	Turnstile
XI-VI	1U	437.8475 MHz 437.490 MHz	Amateur Amateur	80 mW 1 W	Dipole Dipole
XI-V	1U	437.465 MHz 437.345 MHz	Amateur Amateur	80 mW 1W	Dipole Dipole
NCUBE-2	1U	437.505 MHz	Amateur		Monopole
UWE-1	1U	437.505 MHz	Amateur	1 W	End-Fed Dipole
Cute-1.7+APD	2U	437.385 MHz 437.505 MHz	Amateur Amateur	100 mW 300 mW	Dipole Dipole
GeneSat-1	3U+	437.067 MHz 2.4 GHz	Amateur ISM	500 mW 1 W	Monopole Patch
CSTB1	1U	400.0375 MHz	Experimental	<1 W	Dipole
AeroCube-2	1U	902-928 MHz	ISM	2 W	Patch
CP4	1U	437.405 MHz	Amateur	1 W	Dipole
Libertad-1	1U	437.405 MHz	Amateur	400 mW	Monopole
CAPE1	1U	435.345 MHz	Amateur	1 W	Dipole
CP3	1U	436.845 MHz	Experimental	1 W	Dipole
MAST	3U	2.4 GHz	ISM	1 W	Monopole
Delfi-C3	3U	145.870 MHz 143.9-435.55 MHz	Amateur Amateur	400 mW 200 mW	Turnstile Turnstile
Seeds-2	1U	437.485 MHz 437.485 MHz	Amateur Amateur	90 mW 450 mW	Monopole Monopole
CanX-2	3U	2.2 GHz	Space Research	500 mW	Patch
AAUSAT-II	1U	437.425 MHz	Amateur	610 mW	Dipole
Cute 1.7+APD II	3U+	437.275 MHz 437.475 MHz	Amateur Amateur	100 mW 300 mW	Monopole Monopole
Compass-1	1U	437.275 MHz 437.405 MHz	Amateur Amateur	200 mW 300 mW	Dipole Dipole

In addition to this Klofas, Anderson, and Leveque identify *Communications Subsystem Recommendations* in there paper. Key factors in a good communications design are:

- Include a long beacon
- Use common amateur modes
- Include a simple reset in case the satellite stops responding
- Verify your ground station
- Maintain your own ground station
- Get an AMSAT mentor

3.4 Communications Architecture

The communications architecture for the CubeSat follows a sensor satellite model for the both types of communication. TT&C will be transmitted continuously, over UHF band transceiver through the usage of two dipole antennae at one end of the CubeSat. The data will be transmitted only during the day when in view of the ground station and will be controlled automatically upon the reception of the TT&C signal, the reason for this is the much higher power consumption of the S-Band transceiver. If the mission involved a constellation of a dozen or more CubeSat then there would be a great potential to use satellite crosslinking, thereby a increasing the amount of time data would be able to reach the ground station. Despite this, beacon data would still be available globally because of its continual broadcasting status. Furthermore it is feasible to write software that would allow amateur radio enthusiast, to decode the data stream and forward it to the ground station thereby improving the situational awareness (SA) that the ground station has available to them. This architecture is very simple and easy to implement, the largest hurdles are signal acquisition, and error checking.

3.5 Frequency Selection

The selection of S-Band and UHF frequencies are tied to a number of factors. Both of these bands have portions that are within amateur radio bands, thereby allowing for minimal licensing cost, and maximum coverage in terms of receive-ability. The selection of these bands is also directly tied to the extensive flight heritage for both bands. A frequency above 100 MHz is required in order to escape Earth's ionosphere. The channel capacity referred throughout the report as bandwidth is dictated by Shannon–Hartley theorem, where a bit rate is proportionate to the pass band bandwidth, and the signal to noise ratio. $C = B\log_2(1 + S/N)$ [5] Where C is the channel capacity in bits per second; B is the pass band bandwidth; S is the total received signal power measured in watts; and N is the total noise measured in watts. Based on this theorem and

[5] (Wertz & Larson, 1999) pp 563

the design requirements there were only two choices for the beacon and a single choice for primary data downlink. The beacon is able to use either VHF or UHF, both are available via COTS for a CubeSat, thus either one is permissible. However based on Hartley's law, the UHF transmitter has higher data rates because the bandwidth channel is greater in UHF. Secondly the wave length and therefore antenna is much shorter (nearly half) in a UHF band as opposed to the VHF band. Lastly S-Band for the primary data downlink, and software uplink, is based on several logical assertions. Alternative transmitters are much larger, and thus would no longer meet the mass or volume budget, as well as a COTS S-Band transceiver, dictates that the CubeSat will use S-Band.

3.5.1 Optical Communication Alternative

A more novel alternative is using optic based communications as discussed by Alluru, and McNair in there paper titled *An Optical Payload for CubeSats.* The paper analysis the concept of multi-hop high speed optical links as opposed to RF based communications. The utility of the technology in CubeSat applications is astonishing, with the reduction of component mass and volume, it is possible for CubeSats to implement optical crosslinks. These links would allow the CubeSat to switch to a relay based communications architecture which improves the robustness of the system, though reducing the possibility of RF interference, and reduce the power requirement of the communication subsystem. Another benefit of the laser based optic system is that, the information would be transmitted in a digital signal, thus a reduction in the need for digital to analog converters and multiplexers. Although this CubeSat will not be implementing this technology, it should be kept in mind.

3.6 Hardware Selection

For the baseline design all components for the communications subsystems are from Clyde Space Ltd. Specifically chosen are an S-Band transceiver, a UHF/VHF transceiver, and the two antennas. These components meet all the existing requirements, and are very modular in case a new driver changes the need for a part of the communications system. A custom S-Band patch antenna is necessary, in order to fit the dimensions of the CubeSat. The baseline components are:

Table 35 Communications Subsystem Hardware Selection

Component	Important Specification
S-Band Transmitter Part number: TXS Cost:£7,759.34 ($12,468.4834 USD) ISIS 38400bps S-band Transmitter	Data rates: Up to 384 kbps Mass: < 125 grams Form Factor: 90x96x40 mm (PC/104 compatible) Power Consumption: 2W Data: I2C PCB: PC/104 (CubeSat kit compatible) Thermal Range: -40° to +85° C
UHF/VHF Transceiver Part number: TRXVUVARA Cost:£8,215.77($13,201.9208 USD) ISIS variable data rate UHF downlink / VHF uplink transceiver with AFSK uplink	<u>UHF transmitter</u> Frequency range: 400-450MHz (Crystal controlled) Transmit power: 300mW PEP, 150mW average Data rate selectable: 1200, 2400, 4800, 9600 bit/s CW (Morse) beacon mode <u>VHF Receiver</u> Frequency range: 130-160MHz (Crystal controlled) Data rate: 300-1200 bit/s Mass: 85g Form factor: 90x96mm (PC/104 compatible) Power: <2.1W (transmit on), <0.2W (receiver only) PCB: PC/104 (CubeSat kit compatible) Data: I2C bus interface -20- +60 degrees Celsius
Deployable Antenna System Part number: ANTSCDUV Cost:£3,651.45 ($5,867.515 USD)	ISIS Deployable CubeSat Antenna System for 1 UHF dipole antenna and 1VHF dipole antenna

3.6.1 Antenna Selection

Although there needs extensive research to be done on the mounting and location of the antennas, the baseline design calls for 2 dipole antennas for the UHF/VHF transmission, and a patch antenna for the S-Band system. Both Antenna systems are COTS, though Clyde Space, Ltd.

3.6.2 Lab Communication System

The need for a diagnostic communications system became apparent as the first MSP430 began to be coded. In order to perform any simulation that activate a subsystem such as propulsion or ADCS then we would need to provide a command signal. Similarly with the need to test the ADCS subsystem there is a need to initialize the simulation with variables and data from statistical models from MATLAB. In order to accomplish all of this there is a USB port that has direct access to the SD card, as well as receives diagnostics from the software.

3.7 Ground Station

The ground station will need to be able to receive all the data as well as process the data. This will need to be researched further to determine the specifications for all antennas, and transceivers within the ground operations component of the CubeSat mission.

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5 Appendices

5.1 Disturbance Calculations

While in orbit a spacecraft will experience disturbance forces and torques from a variety of potential sources. Probable disturbances will come from gravity gradients, solar pressure, and atmospheric drag. The following are calculations for the worst case disturbances. The attitude actuators must be able to adequately counteract these disturbances and therefore must be determined and considered in their design.

The first calculation is for the worst case gravity gradient. In this case because the mass distribution of the satellite is not determined a uniform distribution for a 3U CubeSat is used.

Table 36: Symbols for gravity gradient disturbance calculations

Symbol	Description	Symbol	Description
m	Mass of the satellite	**x,y,z**	Satellite side length along the x, y, and z axes
I_k	The moment of inertia along the k axis	**μ**	The Earth's gravity constant
θ	Deviation angle of the Z-axis to the local vertical	**τ_g**	The gravity gradient torque
R	Distance from the mass center of the satellite to the center of the Earth		

$$m = 4kg;\ x = 10cm; y = 10cm;\ z = 32.7cm$$

$$\mu = 3.986 \cdot 10^{14}\, m^3/s^2\, ; R = 7058.137\ km$$

Equation 9: Satellite Parameters and Constants

$$I_y = \frac{1}{12} m(z^2 + x^2) = 0.03898\ kg \cdot m^2$$

$$I_z = \frac{1}{12} m(x^2 + y^2) = 0.00667\ kg \cdot m^2$$

Equation 10: Moments of Inertia[6]

$$max(\sin(2\theta)) = 1\ @\ \theta = \frac{\pi}{4}$$

$$\boldsymbol{\tau}_g = \frac{3\mu}{2R^3} \left| I_z - I_y \right| \sin(2\theta) = 5.494 \cdot 10^{-8}\ Nm$$

Equation 11: Worst-Case Gravity Gradient Torque[7]

[6] Equations in Figure 9.1c (Curtis, 2010) p. 504
[7] First formula in Table 11-9A (Eterno, 1999) p.366

The second disturbance calculation is for solar radiation. For the worst case a 3U CubeSat with a mass center offset of 2cm and perfect reflecting surface is used. The mass center offset was chosen from the published CubeSat launch requirements.

Table 37: Symbols for solar radiation disturbance calculations

Symbol	Description	Symbol	Description
Fs	Solar constant	**As**	Surface area exposed to solar radiation
$\mathbf{c_{ps}}$	Location of the center of pressure	**Cg**	Center of gravity
q	Reflectance factor	**I**	Angle of incidence of the solar radiation
c	Speed of light	$\boldsymbol{\tau_{sp}}$	Solar radiation torque
x, y, z	Satellite side length along the x, y, and z axes		

$$F_s = 1367\ W/m^2; c = 3 \cdot 10^8\ m/s^2; q = 1; x = 10cm$$

$$y = 10cm; z = 32.7cm;\ \left(c_{ps} - cg\right) = 2cm; i = 0$$

Equation 12: Satellite Parameters and Constants

$$max(A_s) = z\sqrt{x^2 + y^2} = 0.04625\ m^2$$

Equation 13: Maximum Illuminated Area

$$\tau_{sp} = \frac{F_s}{c} A_s (1 + q)\left(c_{ps} - cg\right) \cos(i) = 8.4289 \cdot 10^{-9} Nm$$

Equation 14: Worst Case Solar Radiation Torque[8]

The next disturbance comes from atmospheric drag. For the worst case scenario a 3U CubeSat with a mass center offset of 2cm and high drag coefficient is used. The maximum surface area in this case is the same as for solar radiation.

Table 38: Symbols for Atmospheric drag disturbance calculations

Symbol	Description	Symbol	Description
$\boldsymbol{\rho}$	Atmospheric density	**As**	Surface area
$\mathbf{c_{ps}}$	Location of the center of pressure	**cg**	Center of gravity
$\mathbf{C_D}$	Coefficient of drag	**V**	Satellite's orbital velocity
$\boldsymbol{\tau_a}$	Atmospheric torque		

$$\rho(alt = 680km) = 3.9 \cdot 10^{-9}\ kg/m^3$$

Equation 15: Atmospheric Density[9]

$$\left(c_{ps} - cg\right) = 2cm;\ C_D = 2.5; V = 7514.9\ m/s$$

Equation 16: Satellite Parameters

[8] Second formula in Table 11-9A (Eterno, 1999) p. 366
[9] Found in Table I (NOAA, NASA, & USAF, U.S. Standard Atmosphere 1976, 1976) p. 72

$$\tau_a = \frac{1}{2}\rho C_D A_s V^2 (c_{ps} - cg) = 1.546 \cdot 10^{-9} Nm$$

Equation 17: Worst Case Atmospheric Torque[10]

5.2 Past CubeSat ADCS Design Review

Many CubeSats that have already been fully developed were reviewed to provide a starting point for the design of this project. A few of these past missions with available materials detailing the satellites' ADCS hardware and software are outlined below. Many CubeSats have basic hardware descriptions published but the ADCS algorithms used are not readily available.

Table 39: AAU CubeSat Specifications

Specification	Data
Sensors	Magnetometer, Sun Sensors
Actuators	Magnetorquers
Determination Method	Optimal two observation quaternion estimation method
Control Method	Constant gain controller with integral action

Table 40: ION CubeSat Specifications

Specification	Data
Sensors	Magnetometer
Actuators	Magnetorquers
Determination Method	Extended Kalman filter
Control Method	Linear quadratic regulator

Table 41: Swiss Cube Specifications

Specification	Data
Sensors	Magnetometer, Sun Sensors, and Gyro
Actuators	Magnetorquers
Determination Method	Optimal REQUEST algorithm
Control Method	PD control law for positioning and a separate de-spin algorithm

[10] Last formula in Table 11-9A (Eterno, 1999) p. 366

5.3 On Board Computer Datasheets

Figure 4 MSP430F5438 Datasheet

TEXAS INSTRUMENTS

MSP430F543x, MSP430F541x

www.ti.com

SLAS612C – AUGUST 2009 – REVISED MARCH 2010

MIXED SIGNAL MICROCONTROLLER

FEATURES

- Low Supply Voltage Range: 2.2 V to 3.6 V
- Ultralow Power Consumption
  - Active Mode (AM):
    All System Clocks Active
    312 µA/MHz at 8 MHz, 3.0 V, Flash Program Execution (Typical)
    140 µA/MHz at 8 MHz, 3.0 V, RAM Program Execution (Typical)
  - Standby Mode (LPM3):
    Real-Time Clock With Crystal , Watchdog, and Supply Supervisor Operational, Full RAM Retention, Fast Wake-Up:
    2.6 µA at 3.0 V (Typical)
    Low-Power Oscillator (VLO), General-Purpose Counter, Watchdog, and Supply Supervisor Operational, Full RAM Retention, Fast Wake-Up:
    1.8 µA at 3.0 V (Typical)
  - Off Mode (LPM4):
    Full RAM Retention, Supply Supervisor Operational, Fast Wake-Up:
    1.69 µA at 3.0 V (Typical)
- Wake-Up From Standby Mode in Less Than 5 µs
- 16-Bit RISC Architecture
  - Extended Memory
  - Up to 18-MHz System Clock
- Flexible Power Management System
  - Fully Integrated LDO With Programmable Regulated Core Supply Voltage
  - Supply Voltage Supervision, Monitoring, and Brownout
- Unified Clock System
  - FLL Control Loop for Frequency Stabilization
  - Low-Power/Low-Frequency Internal Clock Source (VLO)
  - Low-Frequency Trimmed Internal Reference Source (REFO)
  - 32-kHz Crystals
  - High-Frequency Crystals up to 32 MHz
- 16-Bit Timer TA0, Timer_A With Five Capture/Compare Registers
- 16-Bit Timer TA1, Timer_A With Three Capture/Compare Registers
- 16-Bit Timer TB0, Timer_B With Seven Capture/Compare Shadow Registers
- Up to Four Universal Serial Communication Interfaces
  - USCI_A0, USCI_A1, USCI_A2, and USCI_A3 Each Supporting
    - Enhanced UART supporting Auto-Baudrate Detection
    - IrDA Encoder and Decoder
    - Synchronous SPI
  - USCI_B0, USCI_B1, USCI_B2, and USCI_B3 Each Supporting
    - I^2C^{TM}
    - Synchronous SPI
- 12-Bit Analog-to-Digital (A/D) Converter
  - Internal Reference
  - Sample-and-Hold
  - Autoscan Feature
  - 14 External Channels, 2 Internal Channels
- Hardware Multiplier Supporting 32-Bit Operations
- Serial Onboard Programming, No External Programming Voltage Needed
- Three Channel Internal DMA
- Basic Timer With Real-Time Clock Feature
- Family Members are Summarized in Table 1
- For Complete Module Descriptions, See the *MSP430x5xx Family User's Guide* (SLAU208)

Figure 5 MSP430F5438 User Guide

MSP430x5xx/MSP430x6xx Family

User's Guide

Texas Instruments

Literature Number: SLAU208H

June 2008–Revised December 2010

Figure 6 MSP430F2012 Datasheet

MSP430x20x1, MSP430x20x2, MSP430x20x3
MIXED SIGNAL MICROCONTROLLER

SLAS491E – AUGUST 2005 – REVISED APRIL 2010

- Low Supply Voltage Range 1.8 V to 3.6 V
- Ultralow Power Consumption
  – Active Mode: 220 µA at 1 MHz, 2.2 V
  – Standby Mode: 0.5 µA
  – Off Mode (RAM Retention): 0.1 µA
- Five Power-Saving Modes
- Ultrafast Wake-Up From Standby Mode in Less Than 1 µs
- 16-Bit RISC Architecture, 62.5 ns Instruction Cycle Time
- Basic Clock Module Configurations:
  – Internal Frequencies up to 16 MHz With Four Calibrated Frequencies to ±1%
  – Internal Very Low Power LF Oscillator
  – 32-kHz Crystal
  – External Digital Clock Source
- 16-Bit Timer_A With Two Capture/Compare Registers
- On-Chip Comparator for Analog Signal Compare Function or Slope A/D (MSP430x20x1 only)
- 10-Bit 200-ksps A/D Converter With Internal Reference, Sample-and-Hold, and Autoscan (MSP430x20x2 only)
- 16-Bit Sigma-Delta A/D Converter With Differential PGA Inputs and Internal Reference (MSP430x20x3 only)
- Universal Serial Interface (USI) Supporting SPI and I2C (MSP430x20x2 and MSP430x20x3 only)
- Brownout Detector
- Serial Onboard Programming, No External Programming Voltage Needed Programmable Code Protection by Security Fuse
- On-Chip Emulation Logic With Spy-Bi-Wire Interface
- Family Members Include:
  MSP430F2001: 1KB + 256B Flash Memory 128B RAM
  MSP430F2011: 2KB + 256B Flash Memory 128B RAM
  MSP430F2002: 1KB + 256B Flash Memory 128B RAM
  MSP430F2012: 2KB + 256B Flash Memory 128B RAM
  MSP430F2003: 1KB + 256B Flash Memory 128B RAM
  MSP430F2013: 2KB + 256B Flash Memory 128B RAM
- Available in a 14-Pin Plastic Small-Outline Thin Package (TSSOP), 14-Pin Plastic Dual Inline Package (PDIP), and 16-Pin QFN
- For Complete Module Descriptions, See the *MSP430x2xx Family User's Guide*

description

The Texas Instruments MSP430 family of ultralow-power microcontrollers consist of several devices featuring different sets of peripherals targeted for various applications. The architecture, combined with five low-power modes is optimized to achieve extended battery life in portable measurement applications. The device features a powerful 16-bit RISC CPU, 16-bit registers, and constant generators that contribute to maximum code efficiency. The digitally controlled oscillator (DCO) allows wake-up from low-power modes to active mode in less than 1µs.

The MSP430x20xx series is an ultralow-power mixed signal microcontroller with a built-in 16-bit timer, and ten I/O pins. In addition the MSP430x20x1 has a versatile analog comparator. The MSP430x20x2 and MSP430x20x3 have built-in communication capability using synchronous protocols (SPI or I2C), and a 10-bit A/D converter (MSP430x20x2) or a 16-bit sigma-delta A/D converter (MSP430x20x3).

Typical applications include sensor systems that capture analog signals, convert them to digital values, and then process the data for display or for transmission to a host system. Stand alone RF sensor front end is another area of application.

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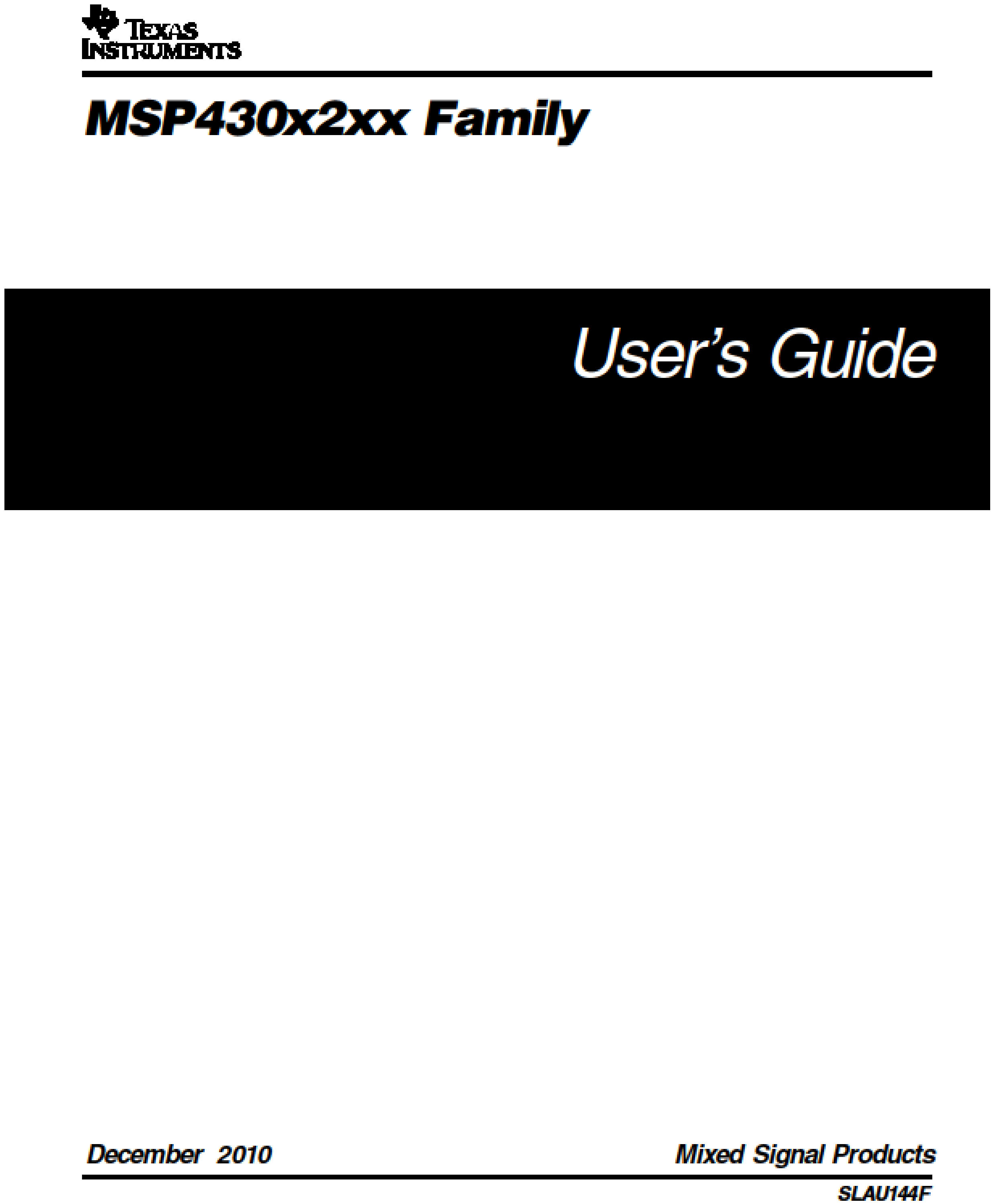
1

Figure 7MSP430F2012 User Guide


TEXAS INSTRUMENTS

MSP430x2xx Family

User's Guide

December 2010

Mixed Signal Products

SLAU144F

Figure 8 TUSB3410 Application Report

TEXAS INSTRUMENTS

Application Report
SLAA276A – October 2006

MSP430 USB Connectivity Using TUSB3410

Andreas Dannenberg
MSP430

ABSTRACT

This application report presents a ready-to-use USB connectivity reference design for MSP430 microcontrollers using the Texas Instruments TUSB3410 USB-to-serial bridge controller. The provided solution enables high-speed data transfers with speeds of up to 921,600 bit/s as well as MSP430 Flash code download through the USB port. The reference design includes MSP430 and PC software, drivers, schematics, layout, and BOM information.

Contents

1 Introduction 3
2 Design Decisions and USB Configuration....4
3 Reference Design Hardware 6
3.1 Standard Solution Using MSP430F1612....6
3.2 Lower-Cost Solution Using MSP430F2274....7
4 Reference Design Software....9
4.1 Overview 9
4.2 MSP430F16x Demo Firmware 9
4.3 MSP430F22xx Demo Firmware 12
4.4 PC Demo Application 15
4.5 Customized Bootstrap Loader Tool....17
5 Reference Design USB Drivers 19
5.1 Overview 19
5.2 Manual Driver Installation....19
5.3 Standard TUSB3410 Driver....20
5.4 Custom MSP430-TUSB3410 Reference Design Driver 21
5.5 Automated Driver Installer....21
6 Other Lower-Cost Options 21
6.1 No External EEPROM 21
6.2 No External MSP430 Crystal....22
7 Summary....22
8 References....23
Appendix A. F16x Solution Hardware Description 24
A.1 Schematics....24
A.2 Board Layout 26
A.3 Bill of Material....28

1

Figure 9 Salvo User Manual