CHARMSat: High Level Design

Isaac Brej, Sarah Kopfer, Peter Gibbons, Aidan Oblepias

University of Notre Dame – EE Senior Design

Professor Mike Schafer

December 16th, 2024

Table of Contents

1 Introduction

Satellites are a cornerstone of modern communication, navigation, and Earth observation, yet their utility is constrained by an immediate problem after deployment: uncontrolled angular momentum on all three axes. This spin renders precise orientation and stabilization—a requirement for effective communication, imaging, and sensing—impossible without an attitude determination and control system. For small satellites, which are becoming increasingly prevalent, traditional detumbling and attitude control systems pose significant challenges. Current systems use a combination of reaction wheels and magnetorquers to stop the satellite from spinning and to change its orientation. Systems that use only magnetorquers require additional information from GPS and magnetometers to utilize Earth's magnetic field at that point in their orbit to facilitate detumbling and pointing. These systems are often too bulky, power-hungry, or complex to integrate into the constrained form factors of small satellite designs, or systems that fit the requirements are highly expensive.

CHARMSat, the Compact High-Accuracy, Reduced-power Magnetorquer Satellite, is an innovative response to this challenge. The project aims to design and implement a low-power, magnetorquer-only Attitude Determination and Control System (ADCS) tailored for satellites as small as 0.5U (10cm × 10cm × 5cm). This novel ADCS will simplify satellite development by providing a fully autonomous, plug-and-play solution that requires only power input from the satellite bus with no required system-external inputs – like GPS data. With a reduced sensor suite, CHARMSat delivers a modular, scalable, practical, cost-effective solution to both detumbling and nadir/sun pointing attitude control for small satellites. This mission represents a critical step in democratizing space by enabling the next generation of compact satellites to achieve high-performance attitude control without compromising power, cost, or volume.

2 Problem Statement and Proposed Solution

2.1 Problem Statement

When low Earth orbit (LEO) satellites are deployed from their launch vehicles, they inherit significant angular momentum on all three axes. This uncontrolled rotation makes crucial operations such as communication, imaging, or data collection impossible. To stabilize their orientation relative to Earth, satellites undergo a process called detumbling, which creates counteracting forces to slow their rotation. Detumbling is a critical initial step. However, for small satellites, this process introduces a unique set of challenges.

Small satellites, constrained by limited power, volume, and mass, often struggle to accommodate traditional detumbling systems. These systems are typically bulky, power-intensive, and complex, rendering them impractical for smaller form factors like 0.5U satellites. Furthermore, even after successful detumbling, satellites must maintain precise attitude control to align sensors with Earth for data acquisition or point towards the Sun to recharge their batteries. This functionality, provided by an Attitude Determination and Control System (ADCS), is vital for mission success.

The problem is particularly severe during the earliest stages of a satellite's mission. A significant proportion of small satellite mission failures occur during or shortly after deployment due to power exhaustion, inability to detumble, or complications arising during detumbling. These failures highlight the necessity for lightweight, low-power, and efficient ADCS solutions, especially during these vulnerable early phases of mission execution.

Current ADCS solutions for small satellites are often infeasible due to their reliance on power-hungry components like reaction wheels, thrusters, or extensive sensor arrays, including GPS. For small satellites, these systems not only exceed power and volume budgets but also introduce additional failure modes. There is a clear need for an ADCS that prioritizes simplicity, autonomy, and power efficiency without compromising on performance.

The challenge lies in designing a system that can detumble and control satellite orientation effectively while minimizing the number of sensors and devices required. This ultimately reduces complexity and power consumption. Such a system would not only enhance mission reliability but also open doors for smaller, more cost-effective satellites to perform complex operations in orbit.

2.2 Proposed Solution

To address the challenges of low Earth orbit (LEO) satellite stabilization, the IrishSat team proposes the development of a GPS-free, magnetorquer-only Attitude Determination and Control System (ADCS). This system is specifically designed for satellites as small as 0.5U (10cm × 10cm × 5cm) and will provide a fully autonomous, self-contained solution that requires only power input from the satellite's main bus. Unlike existing systems, which are either too bulky, power-intensive, or incompatible with such small satellites, this ADCS offers a compact, low-power, and effective alternative. The solution is divided into five key subsystems:

PCB, Sensor Suite, and Circuit Subsystem

CHARMSat's PCB employs a suite of sensors that work together through sensor fusion to determine the satellite's orientation. These include:

- **Infrared imaging cameras**: Two cameras positioned in orthogonal directions perform horizon sensing and sun sensing through image processing, providing data on the satellite's relative orientation to Earth.
- **Inertial measurement unit (IMU)**: Measures the satellite's rotational rates and orientation to provide dynamic feedback during motion.
- **Magnetometer**: Measures the Earth's magnetic field to assist in detumbling and attitude control by providing key data for the magnetorquer algorithms.

This sensor configuration is carefully chosen to minimize power consumption and volume while ensuring accurate attitude determination. By omitting GPS, the system achieves further savings in power and complexity.

Additional hardware is required on the PCB to allow for successful operation. To enable effective attitude control, the system requires efficient processing of sensor data and precise control of the magnetorquers. This is achieved through:

- A **radiation-tolerant microcontroller (MCU)** that processes sensor input and executes the control algorithms.
- **Custom digital and analog circuitry**, including H-bridge circuits, to regulate bidirectional currents through the magnetorquers.
- A **robust UART bus connection** between the ADCS and the satellite's main processor ensures seamless communication of status updates and operation completion signals.

This subsystem not only ensures proper functioning of the magnetorquers but also maintains the system's autonomy, minimizing the need for external intervention.

Magnetorquer Subsystem

Detumbling and attitude control in satellites can be achieved using several methods. However, many of these, such as reaction wheels or thrusters, are unsuitable for small satellites due to their size, weight, and power demands. CHARMSat's ADCS exclusively uses **magnetorquers**, which:

- Generate a magnetic field that interacts with Earth's magnetic field to produce a reactionary torque to change the orientation of the satellite.
- Are lightweight and low-power making them ideal for small satellite applications.

The system incorporates one magnetorquer per axis, enabling full control over the satellite's orientation. This design ensures precise orientation adjustments for both detumbling and attitude control, without overburdening the satellite's power resources.

Controls Software Subsystem

The software architecture for CHARMSat's ADCS is designed to achieve precise, efficient, and autonomous control of the satellite's attitude while maintaining low power consumption and system reliability. The key components of the software include control algorithms, sensor data processing, error handling, and real-time task management. Each element is specifically tailored to address the mission's requirements for stability, responsiveness, and autonomy.

Control Algorithms:

- **B-dot Algorithm**: This is used for detumbling the satellite. The algorithm computes the change in the magnetic field over time and drives the magnetorquers to counteract angular momentum, effectively reducing rotation rates across all three axes.
- **"Search" Algorithm**: This implements a systematic process to locate and lock onto the horizon for attitude alignment. This algorithm leverages data from infrared imaging cameras and IMU for accurate targeting.
- **PID Controller**: A proportional-integral-derivative (PID) control loop will be developed and tuned to achieve precise and stable orientation control. The specific parameters of the PID controller will be determined during the testing and refinement phases.

- **Filtering**: A Kalman filter or another suitable filtering technique may be implemented to refine sensor data and improve control accuracy by reducing noise and accounting for uncertainties.

Sensor Data Processing and Handling:

- **Data Collection**: Code to interface with the sensors (infrared imaging cameras, sun sensor, IMU, and magnetometer) ensures accurate and synchronized acquisition of input data for real-time processing.
- **Data Storage**: Persistent data storage routines will manage mission-critical data, such as sensor readings and system states, ensuring availability for post-mission analysis or telemetry downlink.
- **Error Handling and Flagging**: A robust error detection framework includes watchdog timers to monitor system performance and prevent deadlocks. Redundant checks and voting mechanisms ensure data integrity and safeguard against hardware or software malfunctions.

Real-Time Task Management:

- The software architecture is built on a **real-time operating system (RTOS)** to enable deterministic task scheduling and resource allocation.
- The RTOS ensures that high-priority tasks, such as magnetorquer actuation and error handling, are executed promptly while maintaining seamless operation of lower-priority tasks like data logging and telemetry.

System Reliability:

- **Watchdogs**: Monitor critical software components to reset or reinitialize processes in case of failures or unresponsiveness.
- **Voting Mechanisms**: Simulated voting techniques are implemented to resolve conflicting data inputs, ensuring reliable decision-making even in the presence of faulty sensors or degraded system performance.

Firmware Subsystem

The proposed solution requires the ability to interface with unique communications protocols and packet structure which will be transferred over serial connections between the payload and the bus processor. This software includes these functionalities to work properly:

- The ability to **construct data packets** in a way that is detectable and understandable to the NSL bus processor.
- The ability to **send requests** to the bus when information like health and safety information, battery levels, or data downlinks through Iridium comms networks are needed.
- The ability to **receive and interpret responses** from the bus and extract useful information from the packets sent to us over the serial connection.

This is an essential capability of the software architecture and enables the payload to be operational in orbit.

Structures and Thermal Subsystem

The payload must be able to physically interface with the NSL bus frame and be structurally stable during launch and operation. Additionally, the temperature within the payload space must be monitored and controlled to ensure that all electronics parts of the proposed solution stay within their operational temperature ranges. This will be controlled through adaptive resistive heating. Most of this work will be completed by the IrishSat team.

3 System Requirements

In April, the team will begin integrating the satellite payload into an 0.5U "ThinSat" satellite designed by Near Space Launch, Inc (NSL), a CubeSat manufacturer and launch opportunity provider based in Upland, IN. After conducting environmental and functional testing, the system will be launched on Falcon 9 and operate in space, specifically Low Earth Orbit.

3.1 Features and Objectives of the Product

This section is meant to describe the different functionalities and mission objectives of CHARMSat which will drive many of the flow down requirements of the full system and subsystems. The high-level objectives for the team are:

Data Objectives –

- effective torque, pointing accuracy, Current through magnetometers, correlated magnetometer reading, gyro reading over time (are we slowing down the rotation)

Learning Goals –

- Learn how to make a low power ADCS solution
- Discern the best material and magnetorquer design for optimal torque
- Learn the most efficient, autonomous software design for the system

Scientific Conclusions –

- Optimized magnetorquer design with new materials
- Low-power, low-cost magnetorquer-only solution with reduced sensor suite

High-level features which realize these objectives of the CHARMSat mission are as follows:

1. **CHARMSat's ability to "detumble"** or reduce angular velocity along an axis, slowing velocity to under 0.5 deg/s on all axes.
2. **Precise actuation of the magnetorquers** to produce an expected B-field, completing detumble and orienting to any specified attitude using **less than 7 Wh.**

3. **Control algorithm's ability to calculate the appropriate PWM signal** to send to the magnetorquer at any point during operation/testing based on sensor input (control of effective power given to magnetorquers for detumble and pointing).
4. **Interface with NSL's novel packet structure and serial communication protocol** to request data from the bus and send information to Iridium comms (this is done through an emulator given to us by NSL).
5. **Proper sensor data processing**, including the ability to do sun or horizon tracking with an IR sensor. This again requires an algorithm to do image processing.

Beyond these specific features that the system will have, the team has developed performance goals for the project which also assist in setting requirements. These are preliminary values that are adjustable as we learn more about the system through testing. They are as follows:

Precision for measurements	**Base Tier**	**Middle Tier**	**Stretch Tier**
Dipole moments of mu-metal rod	5 Am^2	10 Am^2	20 Am^2
Dipole moments of air core rod (Cm)	0.1 Am^2	0.2 Am^2	0.3 Am^2
Pointing accuracy (degs)	+/- 15 degrees	+/- 10 degrees	+/- 5 degrees

Table 1. Measurement Performance Goals, Tiered

Measurements of Success	**Base Tier**	**Middle Tier**	**Stretch Tier**
Earth pointing time (min)	45 mins	30 mins	15 mins
Detumble time (min)	1 hr 15 mins	45 mins	30 mins

Table 2. Operational Performance Goals, Tiered

3.2 Installation and Integration Requirements

As discussed, the CHARMSat payload must interface with a 0.5U "ThinSat" satellite designed by NSL. With this interface comes significant amounts of system requirements to make sure the satellite as a whole remains operational. NSL shared with the CHARMSat team an Interface

Control Document (ICD) outlining all system requirements that we must meet [1]. They are as follows:

ID	Payload Requirement	Verification Criteria	Verification Method			
			I	A	D	T
R1.1	Payload shall be clean and free from dust, contaminants, deposits, and any material which could impact outgassing or operation	Visually inspect payload with magnifying glass or microscope and blacklight	X			
R1.2	Payload shall be composed solely of materials which have a TML of less than 1% and CVCM of less than 0.1% per the NASA outgassing database or other reputable source, with deviations agreed to by NSL	Inspect BOM for nonconformance	X			
R1.3	Payload shall contain no prohibited materials: cadmium parts or cadmium plating; titanium; zinc plating; mercury or compounds containing mercury; pure tin or tin electroplate (except when alloyed with lead, antimony, or bismuth); silicone rubber or RTV silicones; magnets; other materials as identified by NSL	Inspect BOM for prohibited materials	X			
R1.4	Payload shall contain no pyrotechnics, propulsion, radio frequency transmitters or receivers, externally-facing cameras, or anything else that requires explicit approval from FCC, ITU, NOAA, FAA, or other governing agency, except where agreed to by NSL and included in appropriate licensing application documents	Inspect system block diagram, BOM, and delivered Payload for prohibited systems	X			
R1.5	Payload shall contain no energy storage devices including pressure vessels, batteries, springs, etc., except where approved by NSL	Inspect system block diagram, BOM, and delivered Payload	X			
R1.6	Payload shall be designed such that no space debris, intentional or unintentional, are generated during launch, separation, commissioning, or operation, and to survive high-vibration launch environment	Inspect Payload for weak or mechanical connections, thin structural members, etc. Optional: perform vibe test	X			
R1.7	Payload shall be designed to operate in temperatures ranging from -30 to +60 Celsius and survive temperatures ranging from -40 to +80 Celsius	Analyze manufacturer specs for materials and parts Optional: perform TVAC test		X		
R1.8	Payload shall comply with the volumetric constraints presented in Section 3	Inspect outside w/ calipers Demonstrate fit check into ThinSat (top and bottom)	X		X	
R1.9	Payload shall be rigidly mounted to the four primary connections points identified in Section 3 via #2-56 stainless steel machine screws with thread depth into the Bus of no less than 3 mm and no greater than 5 mm	Inspect thread depth with calipers Demonstrate bolting into ThinSat with clean alignment	X		X	
R1.10	Payload shall have primary electrical connector placed as specified in Section 3.2	Demonstrate fit check with ThinSat Visually inspect pins during insertion for deflecting or misalignment	X		X	
R1.11	Payload may not exceed 250g	Analyze the payload CAD model and verify. Demonstrate that the Payload is 250g or less.		X	X	

Table 3. Mechanical/Workmanship Requirements from NSL ICD [1]

ID	Payload Requirement	Verification Criteria	Verification Method			
			I	A	D	T
R2.1	Payload shall be powered solely by the Bus 3.3v, 5v, and 6-9v BUSS+ rails	Demonstrate near-zero potential with voltmeter on various Payload PCB test points with Bus powered but all Payload switches off			X	
R2.2	Payload shall be tolerant to +-5% deviations from nominal voltage on both the 3.3v and 5v rails, and the full 6v to 9v range on the BUSS+ rail	Analyze BOM components for sensitivity to input voltage Demonstrate payload operation at min (3.1v, 4.7v, 6v), max (3.5v, 5.3v, 9v), and any other specifically concerning combinations based on intended Payload design and operation		X	X	
R2.3	Payload shall draw inrush current of no greater than 5 amps per rail for no longer than 50ms	Test inrush current for each rail and switch by measuring supply voltage and current through a shunt resistor with two oscilloscope channels triggered by the voltage increase and sampling for at least 100ms				X
R2.4	Payload shall draw no more than 1 amp peak on the 3.3v rail (across both switches), after inrush	Demonstrate the current draw from a power supply in the highest-draw state is less than 1 amp			X	
R2.5	Payload shall draw no more than 1 amp peak on the 5v rail (across both switches), after inrush	Demonstrate the current draw from a power supply in the highest-draw state is less than 1 amp			X	
R2.6	Payload shall draw no more than 2 amps peak on the 6-9v BUSS+ rail, after inrush	Demonstrate the current draw from a power supply in the highest-draw state is less than 2 amps			X	
R2.7	Payload shall include clearly labeled electrical test points for all nets of the Primary Connector used by the Payload that can be accessed from the top or sides after integration with the ThinSat base	Inspect labels for readability Demonstrate probe access to each test point with the payload installed in the ThinSat base	X		X	
R2.8	Payload shall comply with the Primary Connector pinouts specified in Section 4.1	Inspect schematic Demonstrate electrical continuity with a multimeter between each connector pin and the labeled test point	X		X	
R2.9	Payload shall be designed such that the voltage from all Payload outputs (analog, RTS, and TX pins) cannot exceed the voltage of the 5v rail, ignoring minor transient effects	Inspect schematic for nonconformance Analyze using simulation tools if basic inspection cannot deterministically provide verification	X	X		
R2.10	Payload shall have primary processor be powered solely by Switch 1 (3.3v and 5v)	Demonstrate Payload can turn on Switch 2/3/4 (if used) via Bus request when starting with just Switch 1 on			X	
R2.11	Payload shall be tolerant to abrupt power loss on all rails at any time	Analyze worst-case effect based on known code procedures, mutex locks, triplication, etc. Demonstrate abrupt removal of power from all rails at arbitrary time and successful power-up afterwards with no adverse effects		X	X	
R2.12	Payload shall be designed to draw no more than 0.5 watts (nadir) or 3 watts (sun-pointing) OAP	Analyze OAP of all operational modes based on measured power draw, pointing configuration, and duty cycling		X		
R2.13	Payload shall not produce EMI or RF radiation at levels that interfere with bus operations	Analyze possible noise sources and verify through similarity and/or discussions with NSL Demonstrate nominal Bus operations with Payload powered during day-in-the-life test Optional, or if required by NSL: perform RE102		X	X	

Table 4. Electrical Requirements from NSL ICD [1]

ID	Payload Requirement	Verification Criteria	Verification Method			
			I	A	D	T
R3.1	Payload shall be able to send downlinks, fetch uplinks from buffer, and request self-reboots	Demonstrate successful downlink, uplink, and self-reboot commands to the Bus			X	
R3.2	Payload shall be designed to have useful and relevant data even in limited throughput scenarios of less than ten 200-byte packets daily	Test Payload against the NSL emulator for a 24-hour continuous DITL with the emulator in limited-throughput mode, and document usefulness/relevance of collected data				X

Table 5. Firmware/Protocol Requirements from NSL ICD [1]

3.3 Testing Requirements

In addition to payload specifications and requirements given to us from NSL, they also have given us testing requirements with which to create a testing plan for the finished payload before integration. They are given below:

ID	Payload Requirement	Verification Criteria	Verification Method			
			I	A	D	T
R4.1	Payload shall pass pre-environmental functional testing	Test payload functionality in all operational modes and document thoroughly				X
R4.2	Payload shall undergo thermal vacuum bakeout at no less than 60° Celcius and no greater than 1E-4 Torr, for no less than 6 hours	Test and document temperature and pressure throughout full test				X
R4.3	Payload shall pass post-environmental functional testing	Test using same as R4.1				X

Table 6. Testing Requirements from NSL ICD [1]

Beyond the required testing, NSL also had recommended testing that the teams should pursue but are not necessary [1]:

- Perform random vibration testing at NASA GEVS Qualification levels (14.1 GRMS) on an EM unit or Acceptance levels (10.0 GRMS) on the FM unit (the integrated FM ThinSat with Payload will undergo vibe at the system level, but it will be too late in the schedule to allow for changes post-vibe).
- Perform TVAC cycling between -30 and +60 C or beyond; 1 hour dwell at each extreme; at least 4 hot/cold cycles.
- Perform MIL-STD-461 RE102 radiated emissions test.

From these requirements, the CHARMSat team was able to construct a comprehensive test plan for the payload:

Potential pre-testing:

- design a balloon demo/testing platform using the IrishSat IRIS system.
    - Image processing demo with IR cameras, Test in-flight emulator communication

Helium MEMS Technology Testing:
- According to NSL, MEMS technology including gyros are sometimes disabled by helium exposure during a rocket launch.
    - Perform a test where we expose the IMU and other technology to significant amounts of helium for 2 hours while operating. Observe sensor behavior and potential degradation.

Pre-environmental testing:
- Test all operational modes of the satellite
    - Sun-pointing control, Earth-pointing control, Detumble control, Induce Tumble, System off
- Interface with **emulator** and test data interface with bus in all modes

TVAC testing:
- Use **on-campus TVAC system**, run the payload through TVAC cycling meeting ICD testing requirements
    - 60 degrees celsius , 1E-4 Torr, 6 hours (Bake out)
- Run TVAC thermal cycling test
    - -30 degrees to 60 degrees celsius, 1 hour dwell at each extreme, 4 cycles

Vibration testing:
- Use NASA GEVS Qual levels (14.1 GRMS) on EM units and Acceptance levels (10.0 GRMS) on FM units
- Utilize Near Space Launch vibration table or GOAT Lab vibration tabl**e** for testing

Radiation testing (if possible):
- [Plan TBD, need to find facility with these capabilities, MIL-STD-461 RE102]

Post-environmental testing:
- After all other testing, make sure the system still functions. Repeat pre-environmental testing.

This test plan was found to be sufficient, covering all testing requirements, in a Critical Design Review with NSL.

3.4 Risk Mitigation Requirements

In order to be proactive in the design phase of the system, the CHARMSat team performed a comprehensive risk analysis and developed different mitigation measures to assist the mission in meeting its requirements and mission objectives.

Risk	Potential Effect	Mitigation Measure
MEMS Sensor Helium Effect	Sensor performance drift or failure due to helium permeation	Use helium-resistant packaging options or select alternative sensors less susceptible to helium exposure. Test and monitor sensor performance during environmental testing.
3 Sensors with No Redundancy	Each sensor could be a single point of failure	Implement watchdog timers for resetting faulty sensors, using software-based fault detection and safe mode reinitialization for recovery from sensor failures.
Structural Integrity	Physical damage to board, connections, or magnetorquers during launch or operation	Conduct extensive FEA, vibration, thermal, and shock testing to aerospace standards. Use robust design and secure mounting techniques to avoid physical breakage.
Circuitry Incorrectness	Non-functional or suboptimal performance limiting mission success	Validate circuits through SPICE modeling, breadboarding, logic analyzers, and in-depth testing with test pads before final assembly to ensure performance.
Over-consuming Power	Exceeding power budget leading to mission failure	Perform detailed power budgeting, implement low-power modes, power cycling, and optimize component usage to stay within power constraints.
Cosmic Radiation	Hardware damage or bit flips in data	Use radiation-tolerant or rad-hardened components, apply error-correction coding (ECC), and implement redundant systems such as Triple Modular Redundancy (TMR) for reliability.
Thermal Management Failure	Overheating or undercooling of critical components	Incorporate thermal modeling and design thermal dissipation systems (heatsinks, radiators). Use temperature monitoring to enable active thermal management.
Sensor Data Inaccuracy	Inaccurate sensor readings affecting ADCS performance	Apply sensor calibration before flight, and implement filtering algorithms (e.g., Kalman filters) to validate sensor data in real-time.
Software Bugs	Unexpected software behavior leading to mission degradation	Thorough testing of software in simulation and HIL environments.
Communication Failure	Loss of data link between payload and bus	Redundant communication channels and periodic communication checks. Include software-based reconnection protocols for link recovery.

Table 7. CHARMSat Risk Analysis and Corresponding Mitigation Strategy

4 System Block Diagram

4.1 Overall System

As seen in **Figure 1**, the CHARMSat system has been broken down into three physical subsystems: the sensor suite, the control and data handling PCB, and the magnetorquers. Additionally, the block diagram also shows integration points with the NSL power and data bus which allow us to interface with the whole satellite system.

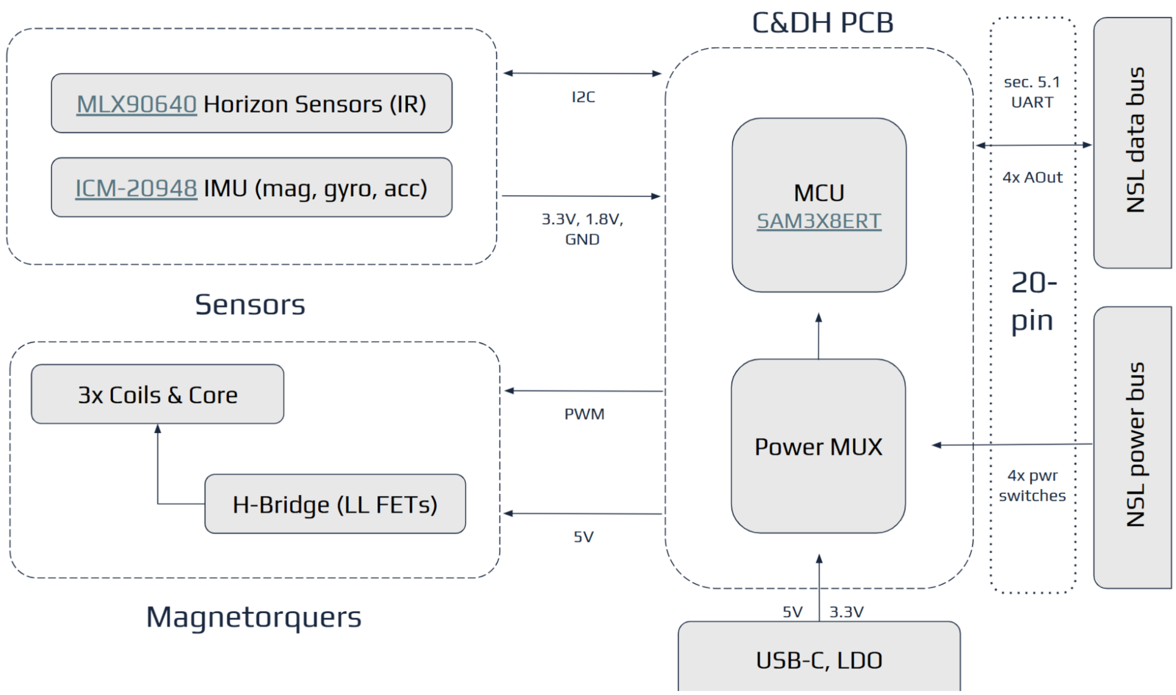

Figure 1. Overall System Block Diagram

From a project management perspective, the team was broken down into 5 subsystem teams:

1. PCB and Sensor Design
2. Magnetorquer Design
3. Controls Software Design
4. Firmware and Operations Design
5. Structures and Thermal Design

The physical subsystems including the sensor suite and PCB have been combined into one subsystem. The magnetorquers, a critical subsystem, remains on its own. The required software was broken into a controls team and a firmware and operations team. Finally, in order to meet all NSL requirements listed above, the structural and thermal design team helps CHARMSat meet all integration requirements for our system.

This division of 5 subsystems was done so that the team could effectively and efficiently create a working system. This strategic division of labor allowed us to spread out engineering tasks amongst all engineers involved, assign appropriate leadership to each team, and maximize the use of specific expertise on the CHARMSat team.

4.2 Sensor Requirements

For the entire system, there are several requirements that are non negotiable. These include low power consumption (7 Wh total detumble power available), small volume and mass (10cm x 10cm x 5cm and 250g), and relatively low cost (low 4 figure budget). These requirements will be taken into consideration in addition to the per-system requirements, detailed below:

4.2.1 Horizon Sensor Requirements

Our control algorithms will work on a variety of different camera data inputs, but one of the most effective algorithms relies on the infrared energy emitted by the Earth (higher values) and the infrared energy emitted by the vacuum of space (very low values). We will pick cameras that can operate in this spectrum of wavelengths so we can capture this energy. The field of view of these cameras is also important, since we want to capture both the horizon and the Earth in any images. Other controls considerations are the resolution of the image and the refresh rate of the camera, which are important to ensure that we can collect enough data to reliably determine our orientation. In addition, the small PCB means that any analog transmission will be in close proximity to our digital signals (PWM, I2C, etc.), which could cause significant interference on the return path. This means we would prefer a separate board to do all the analog processing and rely on digital communication standards to relay the information to the MCU.

4.2.2 Gyro/Accelerometer Requirements

The requirements for the gyro and accelerometer are less restrictive compared to the strict camera guidelines. Since we expect to see a maximum spin rate of 15 deg/s on each axis, we want to be able to read this spin on all axes simultaneously. This is not a restrictive requirement, as nearly every mobile phone IMU has this capability. A more important requirement would be the technology behind the IMU: MEMS-based IMUs rely on an internal vacuum to properly operate, and exposure to helium and other gases in the payload integration stage can ruin the calibration of the sensor. We’ve done separate research and determined that hermetically sealed IMUs should be able to withstand the indirect exposure, but this is an important note that could jeopardize our control algorithm if not accounted for.

4.2.3 Magnetometer Requirements

The magnetometer is perhaps the most important sensor in the suite. This measures the magnetic field experienced on each axis relative to the body frame of the satellite and is crucial for calculating the proper reactionary torque to cancel out the spin detected by the MCU. The most important requirement for this sensor (apart from the obvious 3-axis measurement) is the upper and lower magnetic field detectable. The magnetic field outside of the planet is much different from measurements on the ground, so by using COTS sensors we run a risk of experiencing a magnetic field and environment not tested or planned for by the manufacturer. To address the concerns regarding this mission-critical sensor, we will add a redundant standalone magnetometer and implement an alternate (slower) control algorithm that can operate on strictly magnetometer data.

4.3 Magnetorquer Requirements

The magnetorquers are the only actuator that reacts with the environment of space on CHARMSat, so their construction is important. While considering power, mass, and volume requirements, these devices (which can be simplified down to a high relative permeability core and wrapped wire) must operate to produce the most torque possible. This means choosing a material with a very high relative permittivity so the most torque can be induced for the least current. This means choosing mu-metal, a material with a relative permeability of 80-100000. The tradeoff with a high mu-metal means a high inductance and a slow “charging speed”, meaning that a voltage applied to the terminals of the magnetorquer will take some finite time to reach the desired current. With this slow charging speed comes additional control problems and additional requirements for the H-bridge, shown below.

4.3.1 H-Bridge Requirements

An H-bridge will be utilized to ensure that current can flow through the magnetometer in both directions. Besides the transistors being able to handle the max current flow (<0.5A), the max Vds (5V), and the proper control voltage (3.3V), the transistors should have a very low “Rds on” to minimize power consumption and to reduce charging speed. These transistors will be controlled with a PWM signal, meaning that the high inductance magnetorquers will experience a frequent and large dI/dt. This will lead to large, potentially harmful voltage spikes across the transistors. One way to mitigate this problem is to rely on the built-in body diodes of the FETs, but the speed of response of these transistors is not fast enough to handle the kHz-range PWM oscillations. Instead, we plan on protecting the transistors and the rest of the circuit using Schottky diodes due to their low voltage drop and fast response time.

4.4 PCB Requirements

4.4.1 MCU requirements

The main MCU requirement is radiation tolerance, since the very dense layout of transistors can easily be affected by the increased radiation in space. Beyond this, we want a lower logic level of 3.3V rather than 5V for power consumption purposes as well as the capability to interface with I2C, UART, and potentially SPI depending on our flash storage needs. We don’t need multiple cores due to our relatively simple control algorithms and we don’t need a very high clock speed. Another requirement would be a low-power/shutdown mode when the system is not actively controlling attitude. We want the MCU to be programmable over USB to allow quick debugging and come in a package size that can reasonably be integrated onto our board.

4.4.2 Power Multiplexor requirements

This subsystem is not mission critical but provides a lot of nice-to-haves for the debugging process. We want this system to be able to replicate the power provided by the NSL bus but be provided strictly through the USB port. In a testing scenario where the PCB might already be integrated into the chassis, we don’t want to have to simulate the entire NSL bus when testing simple systems like the magnetorquers. Having an alternative power source is important to ensure rapid iterations of our software design.

4.5 NSL Bus Requirements

These requirements are provided directly by NSL and mostly entail the communication structure of the packets sent between CHARMSat and the bus. These are very specific, but once implemented can easily be replicated. The bus communicates on 5V TTL logic, meaning that a level shifter will be required to properly indicate ‘high’ logic levels if we use a 3.3V MCU. All of these requirements are listed in **Section 3.2 Installation and Integration Requirements.**

4.6 Future Enhancement Requirements

Future iterations of CHARMSat will focus on lower power consumption and low volume. We are currently optimizing for quickest time-to-detumble, but we could easily reduce the maximum current to optimize for lowest power consumption (at the cost of lower torque and lower speed). Future improvements can always optimize for lower mass, leaving more room for other payloads. The first version of CHARMSat will focus on achieving all the operational goals acting as a proof of concept for IrishSat, and future versions will perfect the design with orbital data collected.

5 High Level Design Decisions

At a high level, CHARMSat relies on inputs to the system, processing and manipulation of those inputs, and outputs based on the results. The NSL bus initiates any action from CHARMSat by sending an input in the form of a serial command. This is then parsed and interpreted by the MCU and the system responds accordingly. This involves triggering the necessary inputs (the cameras and IMU) to gather information for the system. This data, including infrared images, velocity and acceleration, and magnetic field data, is then transmitted from the sensors to the MCU. The MCU performs a calculation in the form of B-dot or any of the necessary control algorithms. This algorithm will produce a particular torque number and axis that needs to be achieved in order to induce a rotation of the satellite. To achieve this number, CHARMSat must create an output. This involves sending variable power to the necessary magnetorquer(s), which will then fire as necessary until the number is achieved (determined by a PWM signal and a time-since-applied calculation). This output then affects the inputs to the system, and the cycle continues.

Each component used by CHARMSat was selected based on its weight, volume, power, cost, and overall performance. The most rigid requirement is volume and power, so these were considered first before any other decisions were made. All devices must fit within a <10cm x 10cm x 5cm payload area with designated cutouts, so devices larger than this cannot be used. To assist in the volume and mass calculations, we created a full CAD model of CHARMSat so that the magnetorquers, cameras and other position-critical components could be placed first and more flexible components (IMU and MCU) could be placed later. This was a great assistance in the placement and routing of the PCB, since no-zones were already marked.

All devices must be powered by the NSL 7 usable-Wh battery through 3.3V and 5V rails. This is a restrictive number, especially for a first iteration of the system, so power consumption was taken very seriously and components with significant power draw (even at the cost of a larger feature set) were not considered. Using components designed for mobile phones was one strategy we took to avoid high power consumption. It's important to note that a lot of devices use a 3.3V nominal VDD but also use a 1.8V VDD_IO, so finding a device with the proper internal regulator would be a nice efficiency boost and save some cost and time.

Communication between subsystems is a critical part of the mission goals of CHARMSat. If components cannot quickly and accurately transfer data, then no part of the system will operate as expected. Due to the low power requirements, camera and IMU data is not incredibly high resolution, so high throughput communication protocols are not necessary, but robust and reliable standards are critical, especially in a harsh environment like space. We chose components compatible with common serial protocols like I2C and SPI due to their relatively high speeds (in the hundreds of kHz is plenty for our purposes) and data validation built in (ACKs and parity bits). Implementing a custom protocol might be more robust, but short transmission paths and lower data rates meant that this was not necessary.

These details, along with the individual requirements per subsystem detailed in **Section 4 System Block Diagram**, were enough to get a system-level design for CHARMSat.

6 Known Unknowns

One major challenge we expect to face will be interfacing with the rad-tolerant MCU, since we have never worked with that exact model before. To help mitigate this risk, we designed an alternative system using an ESP32 in parallel, a microcontroller that we are comfortable with using.

Another unknown will be implementing the control algorithm, a notoriously computationally demanding program, on a power-limited system. We are in the process of converting B-dot to C so its performance impact and power requirements can be measured, but this should present some challenges with implementation and remains unknown.

Designing and assembling any sort of PCB can also be difficult. We expect to have a lengthy troubleshooting process to correct any mistakes in routing, but are also verifying schematics as we go along to ensure proper operation.

Other major roadblocks we expect to face are outlined in **Section 3.3 Testing Requirements** and **Section 3.4 Risk Mitigation Requirements**, where we review testing requirements and associated risks with the CHARMSat design that need to be designed for. Testing has not begun yet and represents a significant area of unknown findings on the effectiveness of our mitigation strategies and system design. We expect to have to make adjustments to the system in January and February when we begin system integration and testing based on these known unknowns.

7 Major Component Costs

Major costs of the CHARMSat project are outlined below in **Table 8** and **Table 9**, with each line item broken into one of two groups: Full Fabrication Costs and Testing Equipment Costs.

Part Type	**Part Number/Material**	**Cost**
High-permeability Ferromagnetic Material	Mu-Metal	\$200.00
Medium-permeability Ferromagnetic Material	Ferrite	\$75.00
Structural Material	Aluminum Stock	\$50.00
MCU	SAM3X8ERT	\$300.00
IR Camera (x2)	MLX90640	\$75.00 ea, \$150.00
Crystal Oscillators (x2)	N/A	\$10.00 ea, \$20.00
IMU	ICM-20948	\$9.00
PCB Fabrication	N/A	\$30.00
Copper Wire	30 gauge	\$15.00
Non-Critical Components	N/A	\$15.00
	Total:	\$864.00

Table 8. Payload Full Fabrication Costs

Part Type	**Cost**
Helmholtz Cage	Provided by IrishSat, \$0.00
Thermal Vacuum Chamber	Provided by ND Research Partner, \$0.00
Helium	Provided by IrishSat, \$0.00
Vibration Table	Provided by NSL, \$0.00
High-altitude Balloon (HAB)	Provided by IrishSat, \$0.00
Arduino Mega Emulators (x2)	\$50.00 ea, \$100.00
Total:	\$100.00

Table 9. Testing Equipment Costs

8 Conclusions

With significant restraints and requirements, CHARMSat will begin testing in January to prove that it meets its requirements and also the CHARMSat mission objectives and performance goals in LEO. Most major components have been purchased and comprehensive fabrication and testing plans have been made to meet all requirements listed in this HLD document. In doing this, the CHARMSat team is ready to take the proper steps towards mission success, creating a foundation for many more small satellite missions to improve our world.

Attitude Determination and Control Systems (ADCS) are essential for enabling effective communication, imaging, charging, and sensing between satellites and Earth. While many ADCS solutions exist, none are designed to provide a fully autonomous, "plug-and-play" system for small satellites that require only power input from the satellite bus. CHARMSat addresses this gap by delivering a compact, low-power ADCS specifically tailored for satellites as small as 0.5U. With its innovative use of magnetorquers and a carefully selected suite of sensors, CHARMSat provides precise attitude control and detumbling capabilities without the complexity, bulk, or power demands of traditional systems. This design not only simplifies integration for satellite developers but also makes advanced ADCS functionality accessible to even the smallest and most resource-constrained satellite missions. CHARMSat represents a critical step toward democratizing space by enabling small satellite developers to achieve reliable, high-performance stabilization and control.

References

[1] NearSpace Launch, “0.5U ThinSat Interface Control Document (ICD)”, Dream Big Program satellite ICD, Sept. 2024 [Revised Nov. 2024].