ECE 445 Project Proposal

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1 Introduction

1.1 Problem

The University of Illinois Aerospace Engineering department's Laboratory for Advanced Space Systems at Illinois (LASSI) develops nanosatellites for the University of Illinois. Their next-generation satellite architecture is currently in development, however the core bus does not contain an Attitude Determination and Control (ADCS) system.

An ADCS system is a spacecraft subsystem that is capable of performing controlled changes and determination of a spacecraft's attitude.

1.2 Solution

Design an IlliniSat-0 specification compliant ADCS module. This module shall be capable of sensing the Earth's magnetic field, sensing the body rotation rate of the module, executing algorithms to generate control solutions, and actuate those solutions using magnetorquer coils.

A magnetorquer coil is a solenoid coil that can be commanded to generate a field of a certain strength and direction. This field interacts with Earth's magnetic field and generates a body torque on the spacecraft. [4] This form of solid-state attitude control is very weak, and as such is only used on small spacecraft.

In order for an ADCS system to be useful to LASSI, the system must be compliant with their modular spacecraft bus architecture. This module shall be physically, electrically, and digitally compliant with LASSI specifications. One of the important factors in the design of magnetorquer devices is the shape and size of the driving coils. The coils must be simultaneously efficient at producing a magnetic field, and be small enough to fit inside, and not waste space in, a nanosatellite bus. To that end, we have analyzed contemporary solutions, as well as studies of the optimization of magnetorquers [1], to develop driving coil geometries that are both compact and make efficient use of the current being fed through them.

1.3 Visual Aid

Figure 1: A photograph of a commercial off-the-shelf (COTS) 2-axis ADCS module for cubesats. Roughly 10cm on a side, this is comparable to what we are building. Unlike this unit however, our module is compliant with LASSI hardware, making it far more useful to UIUC interdisciplinary endeavours.

1.4 High-Level Requirements

Requirement	Verification
1. The system shall be compliant with LASSI IlliniSat-0 specifications for spaceflight hardware.	**1A.** Design board with LASSI provided mechanical drawings and related pattern files. **1B.** Select external interface parts, such as serial transceivers and stack connectors, from LASSI specified part numbers. **1C.** Completed hardware shall draw no more than 2 amps of current from the 3.3 volt power supply rail at maximum load. **1D.** Completed hardware shall be capable of accepting commands from the CAN and RS-422 serial interfaces. **1E.** Completed hardware shall be capable of sending telemetry and attitude data over the CAN and RS-422 serial interfaces.
2. The system shall enter a fault state when abnormal performance is detected.	**2A.** Ensure the system transitions to a fault state when a strong permanent magnet is brought within 3 centimeters of the magnetometer. **2B.** Ensure the system transitions to a fault state when the board is rotated at greater than 100 degrees per second. **2C.** Ensure the system transitions to a fault state when the constant-current drivers are shorted by a 5cm copper wire bridging the coil solder connections. **2D.** Ensure the system transitions to a fault state when the actuator coils are disconnected, leaving an open circuit through the constant-current drive.
3. The system shall accurately read the local magnetic field vector and rotation rate.	**3A.** Using the STM32 under the control of a hardware debugger, read the magnetic field strength values from the magnetometer. Ensure they remain within 5% of values returned by external magnetometers. **3B.** Using the STM32 under the control of a hardware debugger, read the rotation rates from the gyroscope. Ensure they remain within 5% pf values returned by external gyroscopes.

A note on the requirements of this project. This project inherently requires us to interface and test with hardware that we did not create. This hardware is in development concurrently, however in the event that parts shortages or unforeseen schedule slip causes external test hardware to be unavailable, we do not want to be stuck. As such, we have been overly cautious regarding the use of such hardware, and we have deliberately under-promised certain performance and testing requirements out of caution. Should everything go according to plan, we should be able to exceed what we have laid out here.

2 Design

2.1 Block Diagram

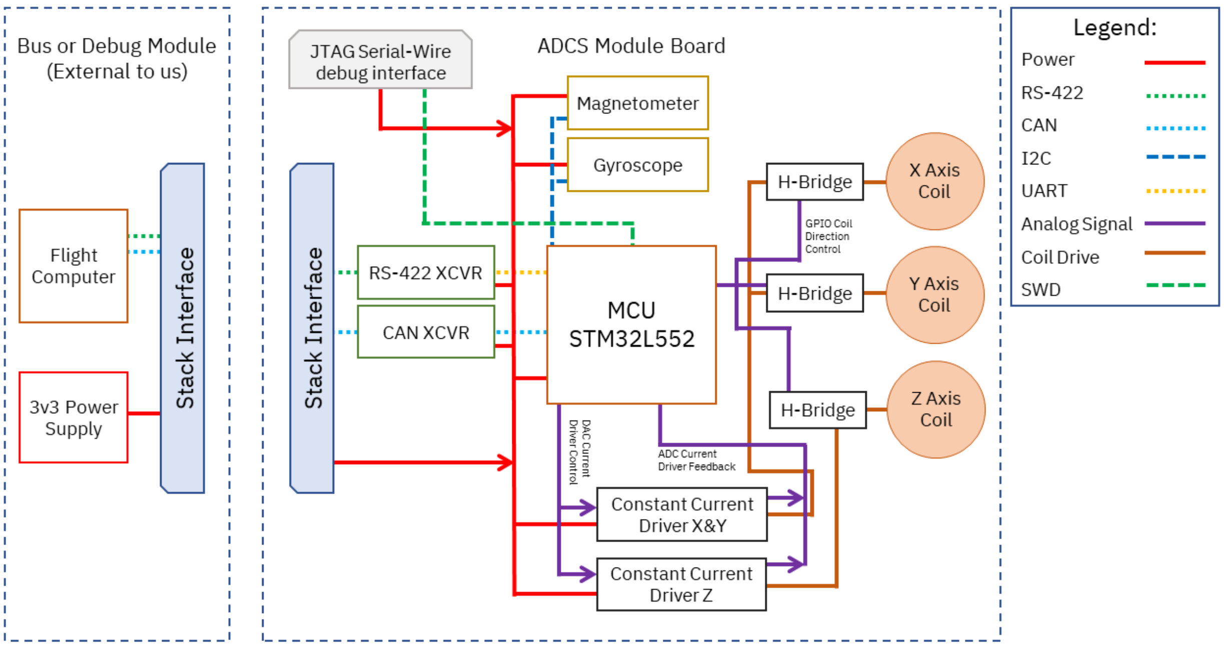

Figure 2: Block diagram of the ADCS module. All connections are of the legend-specified type unless otherwise noted.

2.2 Subsystem Overview

Constant-Current Drivers

The constant-current drivers are a critical part of this system. Without the ability to reliably and controllably draw current through the magnetorquer coils, a control solution cannot be implemented and the module will not meet its desired functionality. We performed an analysis on several different constant-current architectures and determined that an op-amp current-feedback architecture was the best option for our purposes. [3]

There are two independently-controlled constant-current drivers on the module, one which drives current through the X and Y axis coils, and one that drives current through the Z axis coil. This fragmentation is due to the fact that the X and Y axis coils are identical, but the Z axis coil is shaped differently and therefore has a different set of characteristics. Because the constant-current drivers are tuned for a certain amount of ohmic resistance in the coils, the Z axis driver must be tuned differently in order to present a high dynamic-range control regime to the microcontroller.

The drivers are given a set point by the DACs built into the MCU. The driver then automatically seeks that set current and holds there until a new set point is given by the MCU. The current feedback signal is tapped by an ADC channel on the MCU for firmware feedback capability.

Stack Interface and Serial Transceivers

In order for subsystems of the satellite to communicate with each other and share resources, a standard board stacking connector and pinout was determined and set by LASSI specifications. Due to formatting constraints, the specification diagram for the stack connector is not included in this document.

In order to accommodate differences in subsystem data volume and rate requirements, the LASSI specification calls for two different serial interfaces on each module. These are RS-422, a differential signalled form of UART, and CAN bus, a multi-drop packet protocol commonly used in industrial and automotive applications. Both RS-422 and CAN interfaces require dedicated transceiver ICs in order to operate correctly. The RS-422 transceiver will communicate to the MCU over a dedicated UART line and the CAN transceiver will communicate over the MCU dedicated CAN interface. The MCU has a CAN interface but requires the external transceiver to drive the lines correctly.

The higher-layer protocol that will be used over both of these interfaces is the same. It is a LASSI specification modification of the AX-25 protocol and MessagePack. This protocol is currently in development and will be completed and operational within the next several weeks. The implementation of this protocol is not considered a risk to project success at this time.

IMUs

In order to perform control operations, sensor input must be acquired. For the purposes of this device, those sensors consist of a 3-axis gyroscope, and a 3-axis magnetometer. Several important factors must be considered when selecting specific parts for this system; the devices must be extremely sensitive in order to detect the very weak magnetic field around the planet, and very low rotation rates, and that those fields and rates are very low-frequency signals.

Due to increased demand for small and high-accuracy inertial measurement capabilities, driven primarily by the wearable consumer technology market, modern IMUs are dramatically more capable than their contemporaries of even 5 years ago. Both of the selected devices contain configurable internal low-pass filters, which will reduce signal processing load on the microcontroller. Both devices also have configurable sampling rates and gain, allowing for improved accuracy.

Due to the ongoing component shortages, it was not possible to obtain a single-device all-in-one IMU with sufficient sensitivity for our application. As such, a discrete magnetometer and gyroscope have been selected. Both devices communicate over I^2C and will be sharing a bus to the MCU.

H-Bridges and Actuator Coils

The magnetorquer coils themselves are rather simple in their implementation. In order to perform magnetic rotations in orbit a spacecraft only needs to generate a magnetic field in the right orientation. [4] This breaks down into three simple solenoid coils, orthogonal to each other, rigidly mounted to the spacecraft body.

For our purposes, 32 AWG magnet wire will be wound around small 3d printed mandrels that will clip into spaces on the board. This will allow us to easily produce coils of reasonably precise dimensions. Due to the simple nature of the coil structure, we determined that it was best to wind each coil ourselves.

In order to be able to individually control each coil's direction, an H-bridge MOSFET structure is used to control each coil individually. This also allows the coils to be shorted closed, which is a useful emergency mode.

MCU and Firmware

Designing hardware for nanosatellites presents several unique environmental constraints that must be addressed in order for the module to be able to operate in a space environment. For the purposes of selecting an MCU, these constraints manifest themselves under the umbrella of power. Nanosatellites generally are low-power devices, operating at a maximum of only a few watts. This means that any module or subsystem inside that spacecraft must not consume too much power. Consuming large amounts of power in a small space results in localized heating. Due to the vacuum of space, this heat can only be released from the board through conduction through the board, and radiation to other parts of the spacecraft. Both of these processes are rather slow, and large thermal loads can damage the parts overtime.

Therefore, the MCU should operate in low-power constraints, support memory protection to prevent stray-writes and data corruption, support IO tamper detection since invalid data from defect sensors can render the ADCS system purposeless, and handle interrupts for handling requests from other sensors/hardware. Hence, we selected the STM32L5 series of 32 bit microcontrollers, given their extremely low-power performance, as well as our familiarity with their use in embedded systems for spaceflight.

The firmware running on the MCU does much of the heavy lifting of the module's capability. It must, at minimum, read data from the onboard sensors, communicate with external modules over the RS422/CAN, control and read currents from the constant-current drivers, perform self-test and calibration operations, and execute control algorithms using sensor data and current-driver actuators. We plan to use a Real Time Operating System (RTOS) to handle these tasks. This is a significant amount of tasks, however these tasks are all computationally low-impact and generally do not happen on-top of each other.

The firmware also has a state machine comprising of IDLE, FAULT, DETUMBLE, and TEST states, with optional SLEW, TARGET, DETERMINE states. These states are for performing necessary functions: help the satellite stay on course by adjusting its rotation (DETUMBLE), alert faulty behaviour of on-board hardware (FAULT), self-diagnosis and provide complete report of the ADCS system (TEST).

There is only one core on the MCU to execute these operations. This means that special care must be taken to ensure that the main firmware loop is highly stable and sufficient resources are given to each sub-function. Priority should be given to time-critical operations such as handling in-coming serial communications and the MCU must not be inhibited by other sub-functions running at the same time.

2.3 Subsystem Requirements

Constant-Current Drivers

Requirement	**Verification**
1. The drivers shall drive no more than 250 milliamps of current through the coils.	**1A.** Measure the resistance of the coil while it is isolated from the board. Using a multimeter, measure the voltage across the coil when the driver is set to maximum current. Use Ohm's law to calculate the current and ensure it is bellow 250 mA.
2. The MCU shall be able to read the current driven through the coils for a given set point.	**2A.** Measure the resistance of the coil while it is isolated from the board. Using a multimeter, measure the voltage across the coil when the driver is set to a known set point. Use Ohm's law to calculate the current and ensure it is within 5% of the targeted set point.
3. The MCU shall be able to perform a full-range sweep of each current driver and calibrate itself to the given coil's current response.	**3A.** Using the STM32 debugger, command the MCU to perform a calibration sweep of the driver. Measure the resistance of the coil while it is isolated from the board. Calculate the correct current of the coil at 4 arbitrary, but roughly evenly spaced out, set points. Compare the measured current of the coil to the targeted value before and after the test. Ensure the accuracy of the test currents improves. In the case of the 'before' test being already calibrated, ensure the accuracy of the results does not deteriorate.

Stack Interface and Serial Transceivers

Requirement	Verification
1. The stack interface shall physically and electrically conform to LASSI specifications.	**1A.** Use of standardized connectors, the Samtec ERM/F-8 series, and standardized footprint positioning will ensure the mechanical matching. **1B.** Compliance with pin matching and passthrough of unrelated pins will be enforced during board design.
2. The RS-422 interface shall be capable of bi-directional serial communication to the MCU at less than or equal to 1 MBaud.	**2A.** Connect an external RS-422 interface to the device, enter a serial test mode, and ensure that accurate data transfer occurs at the tested datarates.
3. The CAN bus interface shall be capable of bi-directional serial communication to the MCU at less than or equal to 1 MBaud.	**3A.** Connect an external CAN interface to the device, enter a serial test mode, and ensure that accurate data transfer occurs at the tested datarates.

IMUs

Requirement	Verification
1. Both IMU devices shall communicate over I^2C to the MCU at a datarate of 400kHz.	**1A.** Using the MCU in debug mode, ensure that both IMU devices respond to I^2C write and read commands appropriately. **1B.** The MCU firmware will enter a fault state in the event of IMU communications failure, ensure that the MCU does not enter this fault state when operating conditions are acceptable (low rotation rates, low field strength, etc.).
2. The magnetometer shall be able to accurately detect the orientation of a magnetic field of between 0.25 and 0.65 Gauss.	**2A.** Using LASSI magnetic test cage, simulate the magnetic field conditions of low Earth orbit. Using an external MCU debugger, ensure that the magnetometer-reported values match external magnetometer sensors to within 5% of read value.
3. The gyroscope shall be able to accurately detect body rotation rates around any axis of <50 degrees per second.	**3A.** Using an external MCU debugger, ensure that the gyroscope-reported values match external gyroscope sensors to within 5% of read value.

H-Bridges and Actuator Coils

Requirement	Verification
1. X and Y axis coils shall be constructed to have a resistance within 3% of each other.	**1A.** Measure the resistance of each coil after their construction, ensure that the resistance values are within 3%.
2. All three coils must be mechanically compatible with LASSI specifications and the ADCS board mounting points.	**2A.** Ensure that the coils, when mounted, do not protrude off of the sides of the board. **2B.** Ensure that the Z axis coil does not protrude more than 3 centimeters above the top surface of the board.
3. Each coil shall be capable of having its current direction controlled by the MCU.	**3A.** Using an external magnetometer placed within 1 centimeter of the end of each coil (in turn), and an external MCU debugger commanding a coil test mode, ensure that the generated field direction is controllable by the MCU.
4. Each coil shall be capable of being shorted closed individually by the MCU.	**4A.** Using an external multimeter in continuity mode, probe the ends of each coil while it is being commanded short. Ensure that a very low resistance path is seen across the coil by the multimeter.

MCU and Firmware

Requirement	Verification
1. The MCU shall be capable of communicating over RS-422, CAN bus, and I^2C serial protocols.	**1A.** This is validated through other subsystem requirements.
2. The MCU shall be capable of executing self-test functions to ensure subsystems are operational and behaving within expected performance.	**2A.** Using an external debugger, ensure that the test functions execute and return values within determined accepted levels.
3. The MCU shall be capable of controlling the current set point of the constant current drivers.	**3A.** Using an external multimeter, measure the voltage between the MCU control signal output and ground, ensure that this voltage is within 1% of the commanded voltage by the firmware.
4. The MCU shall be capable of controlling the configuration of each coil H-bridge.	**4A.** Using an external MCU debugger, command each H-bridge into the forward, backward, short, and open configurations. Using a multimeter in the continuity mode, ensure that the H-bridge exhibits the commanded configuration.

2.4 Risk Analysis

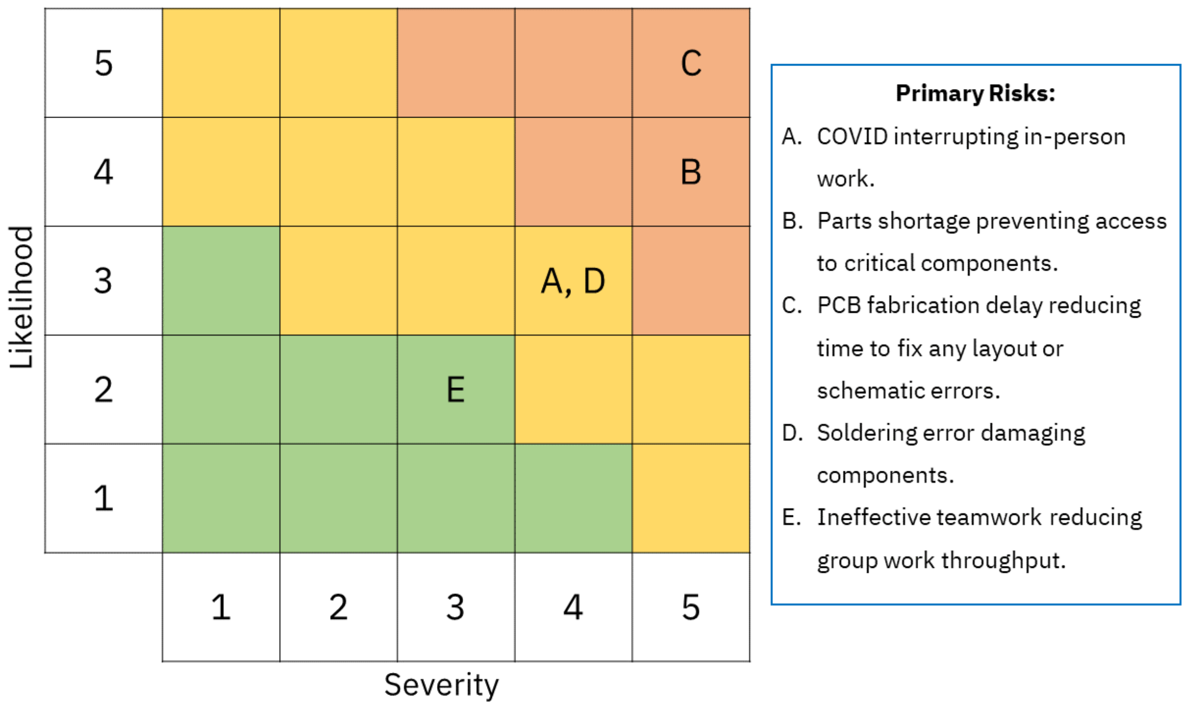

Figure 3: 5x5 Risk matrix and legend describing our 5 most significant risks to program success.

A short risk analysis was performed and the risk matrix in figure 3 was developed. While it is likely that the parts shortages will impact our ability to develop this system, much of that risk has already been retired through early parts acquisition.

Currently our most pressing risk is the likely delay in fabrication and shipping of the PCB that will reduce the amount of time we have to fix any mistakes and debug the device. There is little we can do to retire this risk other than to work diligently to not make any errors in schematic capture or layout.

Soldering errors are a significant risk for us as due to the parts shortage we are using a UFBGA-132 package. These packages are difficult to solder due to their extremely small ball pitch and our lack of an X-ray imaging device to verify that no solder bridges are present under the device. We are in possession of two of the devices in question, and should one be damaged due to bridged balls, one replacement can be made. One of our team members has significant micro-soldering experience and we believe that the likelihood of total failure in this manner is low.

COVID interrupting in-person work and reduced performance due to poor teamwork are similar in their end effect. Mitigation of COVID restriction hindrance is far outside of our control, however effective teamwork is something we can reasonably manage.

3 Ethics and Safety

3.1 Safety

This project presents some risks to student safety. These risks primarily involve standard risks when working with PCBs and electrical equipment. Risks such as burn hazards, chemical exposure hazards from solder, flux, and PCB manufacturing residues, and other minor lab-related risks are assumed. Mitigation of said risks is the job of each involved engineer and student, lab safety is everyone's job.

There are several unique safety risks involved in this project. They are related to the testing and validation of the hardware we will develop. Use of LASSI space environment test equipment is proposed (as available from LASSI, we do not take priority over their other missions) for this project. Primarily this will involve the use of the Helmholtz Cage, a 3d magnetic field simulator. This test equipment uses compressed air, posing injection and aural hazards, as well as high-current drivers, posing burn hazards. These hazards will be mitigated through careful operation of the equipment by trained personnel, hearing protection PPE, and clear understandings of what parts of the system are "no touch" zones.

If time and resources permits, we will attempt to test the functionality of the device in a thermal vacuum chamber. This system is capable of pulling vacuum on hardware to validate its performance in a space environment. Use of the TVAC chamber presents compressed air injection hazards, cryogenic exposure hazards, electrical exposure hazards, and burn hazards. As such, it will only be operated by trained personnel, and the requisite DRS safety trainings will be required of all involved students.

3.2 Ethics

This project does not pose any significant ethical concerns on its own. It is by its nature incapable of doing anything on its own. However, because this is designed for use on a spacecraft, there are some additional ethical constraints that require address.

Prior to 2013, the United States federal government classified technology such as this project as "munitions" and restricted export of it and access to materials pertaining to it to U.S. citizens and green card holders only. Since then the related laws, the International Traffic in Arms Restrictions (ITAR), have been adjusted to remove this form of satellite technology from the list of munitions technology. [2]

References

[1] Ivan Indir et al. "Design and Optimization of Air Core Magnetorquers for Attitude Control of LEO Nanosatellites". In: *2021 International Symposium ELMAR*. 2021, pp. 135–138. DOI: 10.1109/ELMAR52657.2021.9550888.

[2] Paul Marks. *US no longer lists satellites as weapons*. URL: https://www.newscientist.com/article/dn23058-us-no-longer-lists-satellites-as-weapons/.

[3] Randy Stephens. *White paper: Expanding the usability of current-feedback amplifiers*. Tech. rep. SLYT099. Dallas, Texas: Texas Instruments Incorporated, Q3 2003, p. 7. URL: https://www.ti.com/lit/an/slyt099/slyt099.pdf?ts=1644437138816.

[4] Ping Wang, Y.B. Shtessel, and Yong-Qian Wang. "Satellite attitude control using only magnetorquers". In: *Proceedings of Thirtieth Southeastern Symposium on System Theory*. 1998, pp. 500–504. DOI: 10.1109/SSST.1998.660124.