Team 26: Computation, Localization, and Power Systems for Distributed Robotics
ECE445: Design Document

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1 Introduction

1.1 Objective

Drones and autonomous vehicles are becoming ever more popular in modern society. From enthusiast quadcopters to multimillion dollar military vehicles, there are autonomous vehicles of many shapes, sizes, and levels of sophistication. Considering the popularity of drones among enthusiasts and their prevalence in cutting edge research fields, it is surprising that no cross-platform hobbyist electrical system exists, i.e. almost every drone or robotics project needs its own power, localization, and control system. Developing such an integrated unit would greatly benefit enthusiasts and researchers across the world.

We plan to make this project open source and to use only easily obtainable consumer components to make the system as easily replicable as possible, and hopefully save anyone intending to build an autonomous vehicle of this scale both money and time. They will be able to reference schematics, parts lists, and diagrams, use our source code, and should be able to either copy or expand upon our system for their specific use case. Considering the number of enthusiasts and the sheer volume of robotics research, this project should have the potential to save hundreds of thousands of dollars and countless painstaking hours of labor.

1.2 Background

This project originated as a research project for Professor Geir Dullerud. He tasked us with updating an old project called HoTDeC, which was an autonomous hovercraft platform from 2004 [1]. Back in 2004, a cutting edge robotics initiative took several researchers many years to develop, and cost thousands of dollars per unit. Nowadays, with better consumer electronics products, developing electrical systems for an autonomous vehicle is easier, which has led to a booming hobbyist industry [2]. Interestingly, though, while consumer quadcopters and vehicles of the sort are easily available for consumer purchase, the industry still lacks an open source, all in one electrical/localization/power system that is both cost efficient and flexible for cross-platform use. This is something we noticed as we were brainstorming for professor Dullerud's project, and realized that such a system would be able to exponentially cut down development time. As such, we decided that we would make this system that the world currently lacks, taking the next step in improving the accessibility of distributed robotics electrical systems. Developing an affordable, open-source, all-in-one unit will drastically lighten development costs and times for researchers who would prefer to focus on control, vision, and path planning, rather than toiling over hardware. It will make drones and robotics accessible to kids of a younger age and allow them to cultivate a passion for engineering and problem solving earlier in life. Finally, it will make it cheaper and less burdensome for hobbyists to do what they love.

1.3 Physical Implementation

Since demonstrations and results are a crucial aspect of any project, we will be demonstrating a specific implementation of the electrical system, namely, the revamped HoTDeC hovercraft. The HoTDeC is a perfect example of an autonomous system developed for research that can hugely benefit from our system. The HoTDeC implements many key innovations that are rather unique to its specific mode, like custom bidirectionally-optimized propellers and a rubber air bearing levitation system. With that said, implementing the sophisticated electrical system that it calls for without making the system compatible with autonomous vehicles of other modes would be a shame. Therefore, we plan to make the system both physically contained in a discrete unit and to build in compatibility for other types of systems. As such, the system's capabilities will be demonstrated in the innovative HoTDeC platform, which showcases many innovations of its own. Shown in Figure 2.6.3 is a picture of the current chassis. Shown in Figure 1.3 is a side view of the propeller tubes. Shown in Figure 1.3 is a view of the air bearing.

Figure 1: HoTDeC Chassis

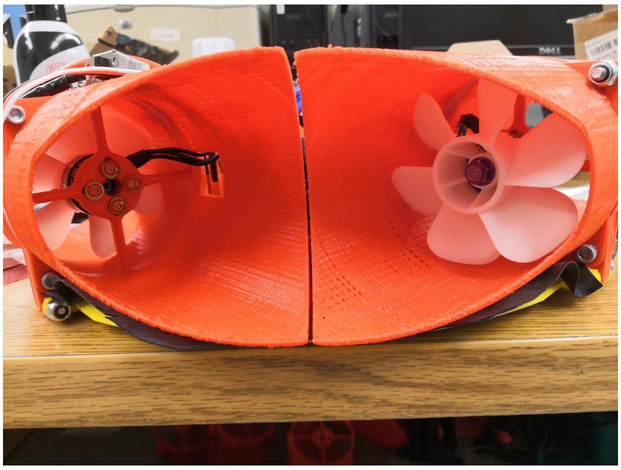

Figure 2: HoTDeC Propeller Tubes

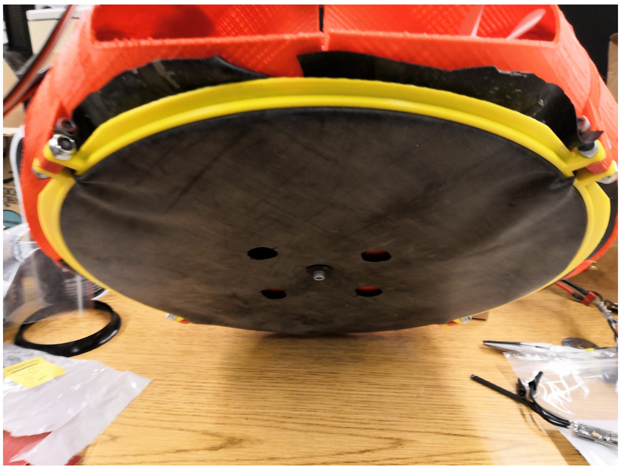

Figure 3: HoTDeC Air Bearing

1.4 High-Level Requirements

- System must be able to supply 1000 W combined peak power to up to 5 motors and actuators for 5 minutes and accommodate battery hot-swapping
- Positional localization must be accurate to 10 cm in absolute position and 10° in any orientation
- System must weigh less than 500 g without batteries and less than 1500 g with batteries and fits in a 3000 cm^3 space
- System must relay motion commands to physical outputs and relay signal data to localization system in under 30 ms and 20 ms respectively.

2 Design

The components of the system have been split into modules. There are 6 core modules of the project: The power module, computing module, communication module, electromechanical module, the sensor module, and the user switches module. The power, computing, and sensor modules are the core modules and will require the most development time and the other three are somewhat auxiliary and less technically complex. In all, the power system may be the most challenging because it has the most stringent demands, safety ramifications, and the greatest complexity of custom made components. A block diagram of the system is included in Figure 2

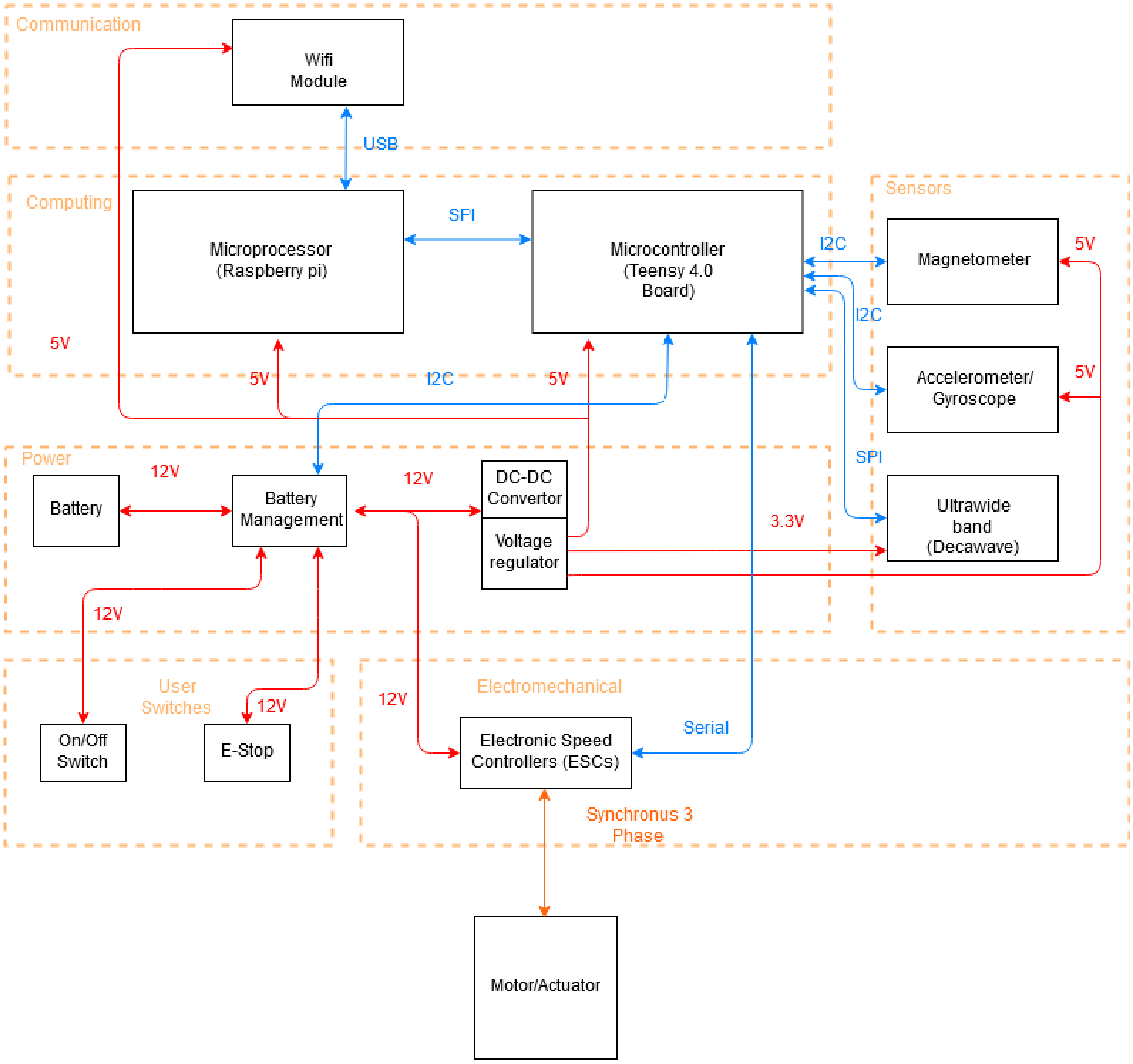

Figure 4: Overall System Block Diagram

2.1 Physical Layout

Since the physical layout of the electronics is very application specific, most of the users will be designing and building this on their own. Of course, since we are also implementing the system for our demo, we will be creating our own physical implementation of the various components for use on the HoTDeC craft. This physical layout is designed to fit within the body of the HoTDeC chassis and strategically positions batteries to be easily accessible and to balance the weight of the craft. Additionally, it positions sensors at the geometric center of the craft. Finally, since the chassis of the craft serves as shielding of the electrical system, the housing will not be fully to enclosed to save material and weight. Should this system ever be mounted externally in another application, the housing selected will need to be fully enclosed as a safety precaution. Several views of a CAD model of the electronic system are shown below. Please note that some components are mere placeholders and may be slightly different models than the actual components used. Regardless, the approximate dimensions of various components are accurate and the general layout is reflective of the intended design.

2.2 Power

2.2.1 Battery

The battery must be able to power a 'typical' craft for 10 minutes before a battery swap. Although power needs will be different depending on the craft, a typical autonomous vehicle of the targeted size will consume around 50 A power at around 67% throttle. This will be assumed to be 'average' use of a 'typical' craft. As such, with a small factor of safety, the battery needs to supply 6 Ah before dropping below 9.5 V. Additionally, the battery should supply 11.1 ± 1.0 V at full charge, and needs to be able to provide peak currents of 90 A for up to 5 minutes at a time, which corresponds to maximum throttle. Finally, the battery leads must be safe from shorts against a flat conductive surface.

Requirements	Verification
Battery pack leads cannot be shorted against any flat surface	• Press non-conductive surface against battery connector • Verify that neither lead is able to make contact with surface

Battery pack supplies $11.1 \pm 0.5V$ at full charge	• Discharge battery to between 9 V and 9.5 V • Charge battery to maximum capacity • Verify on voltmeter that battery voltage falls into this range
Battery pack stores provides 6 Ah before dropping below 9.5 Volts	• Charge battery to capacity • Discharge battery at 60 A for 10 minutes • Verify on voltmeter that battery voltage still exceeds 9.5 V
Battery pack can discharge 90 A for 5 minutes continuously	• Charge battery to capacity • Discharge battery at 100 A for 5 minutes • Ensure no overheating, inspect for 'burning' smell of any sort, visually inspect system

Table 1: Battery Requirements & Verification

2.2.2 Power isolator

In order to protect the electronics equipment form the back EMF of the motors, we will implement a pwm signal voltage isolator circuit which will prevent the voltage from spiking up over 10% of the target, in this case over 3.6 V for 3.3 V signal lines.

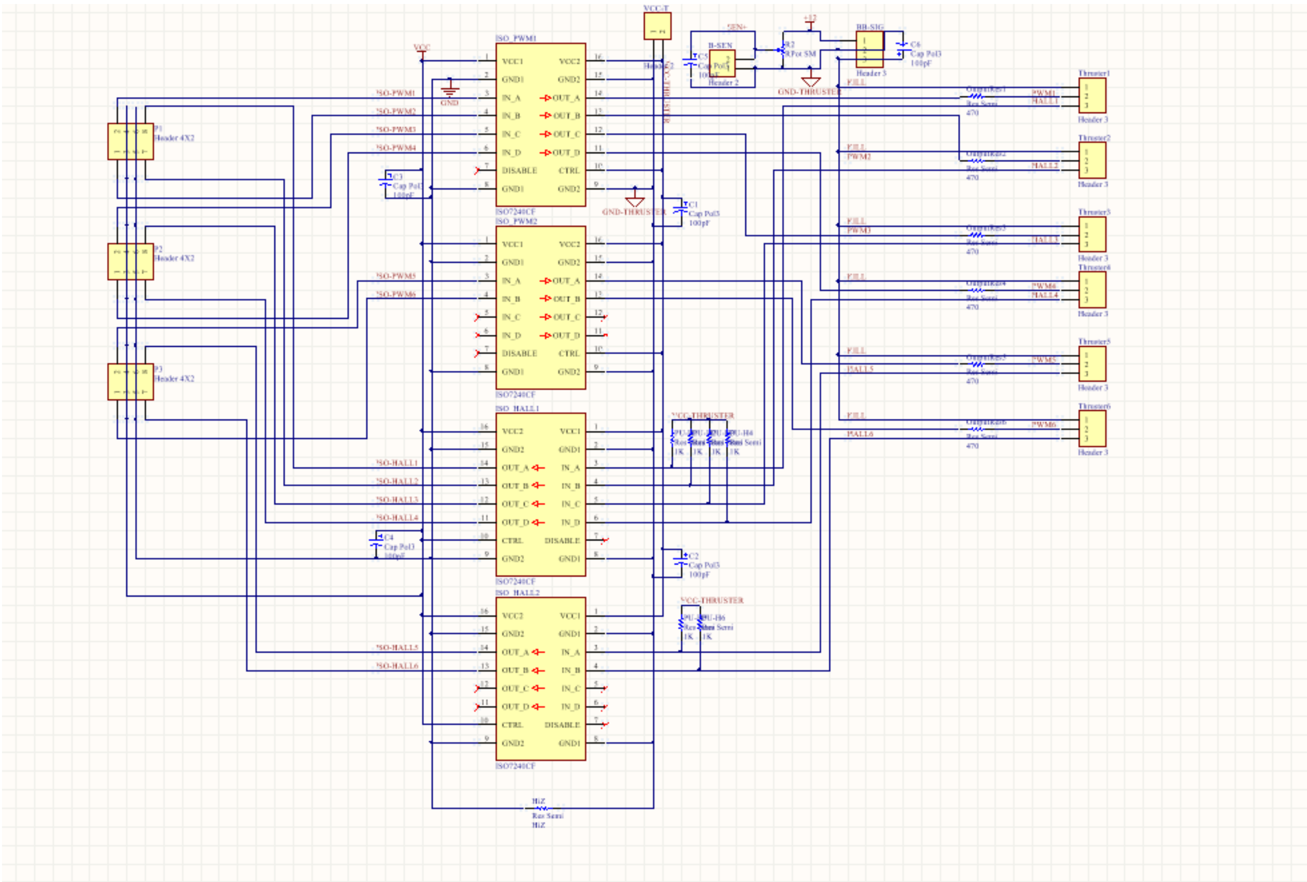

Figure 5: Power isolator schematics

Requirements	Verification
Verify voltage spikes do not exceed 3.6 V	• Connect oscilloscope to output of isolator • Set to trigger at 3.6 V • Run for a long time, verify that 3.6 V was not exceeeded at any point

Table 2: Power Isolator Requirements & Verification

2.2.3 Battery Management

The system should support hot-swappable battery, which means that there are two battery, main battery and backup battery. We plan to use LTC4417 for the management IC and a microcontroller to control the discharge and power transfer between battery. This will have the functionality of cutting power to the system when the battery voltage drops below a threshold in the 9.25 V - 9.5 V range. During normal operation condition, the power of the entire system will be fed by the current from the main battery. During the event of main battery swap, the system will rely on the backup battery and will operate on low power mode, i.e. the output power of the thrusters will be limited. The battery management system also has to correctly shut off the system when either the system is switched to off or when the e-stop is pressed. The requirements and verification for this will be included in the respective sections for each of these components, but they have ramifications in the battery management unit nonetheless. The backup battery unit needs to be able to supply between 9.5 V and 11.6 V at 30A for a total of 2 minutes and supplies 11.1 ± 0.5 V at full charge.

Requirements	Verification
System disconnected voltage threshold falls between 9.25 V and 9.5 V	• Run system until threshold is triggered • Measure battery voltage, confirm voltage falls between 9.25 V and 9.5 V
Backup battery supplies $11.1 \pm 0.5V$ at full charge	• Discharge backup battery to between 9 V and 9.5 V • Charge backup battery to maximum capacity • Verify on voltmeter that backup battery voltage falls into this range

Backup battery stores 1 Ah before dropping below 9.5 Volts	• Charge backup battery to capacity • Discharge backup battery at 60Amps for 10 minutes • Verify on voltmeter that backup battery voltage still exceeds 9.5 V

Table 3: Battery Management Requirements & Verification

2.2.4 DC-DC Converter & Voltage regulator

We need to have a buck converter to step down the 12 V main voltage from the battery to 5 V for the electronics systems. It should be able to provide enough current for the computing systems, which is around 5 A. Voltage stability is one of the main priorities of the power system, especially when providing the power to electronics systems. It should be able to regulate the voltage on the main electronics systems to 5 ± 0.25 V output.

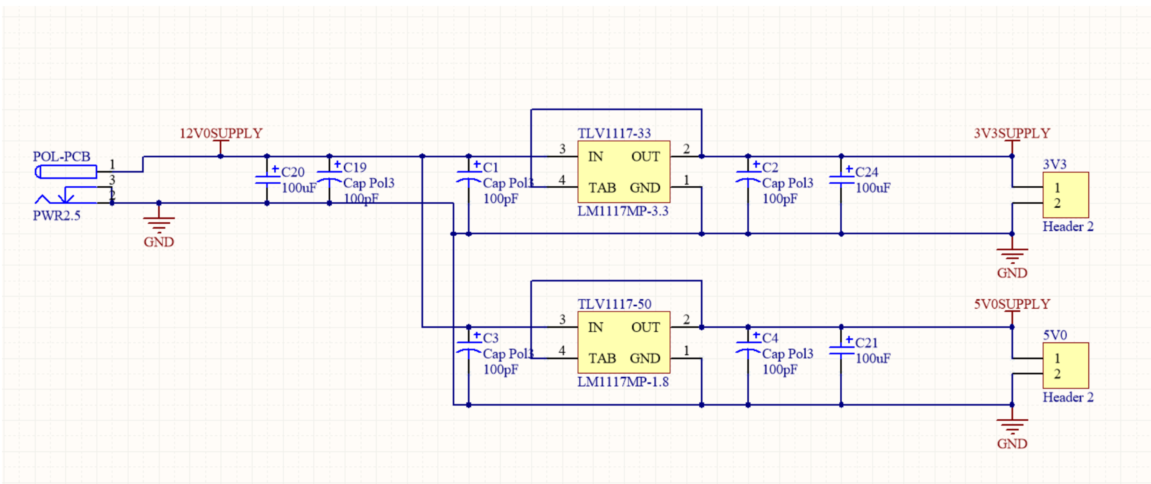

Figure 6: Power converter schematics

Requirements	Verification

Voltage of main electronics system is 5 ± 0.25 V output	• Hook up voltmeter to output of converter • Attach a battery at full 11.1 V charge • Hook up voltmeter to battery leads • Discharge it until it reaches 9.5 V • Verify that DC-DC converter output voltage remains between 4.75 and 5.25 V throughout
Main electronics system can supply 5A current	• Create a $0.8 \pm 0.1\Omega$ equivalent resistance by combining resistors • Verify equivalent resistance • Short equivalent resistance over DC-DC converter output leads • Verify that current draw falls above 5V and that voltage still falls within • Verify that DC-DC converter output voltage remains constrained to 5 ± 0.25 V throughout.

Table 4: DC-DC Converter Requirements & Verification

2.3 User Switches

There are two interactive components on the actual craft, which both take the form of power switches. One is the normal on/off switch and the other is an emergency stop button.

2.3.1 On/Off Switch

The On/off switch turns the system on and off. It feeds directly into the power distribution board and will be physically mounted at the top plate of the hovercraft near the power distribution module.

Requirements	Verification
On/off switch cuts power to at most 0.5V in under 10 ms	• connect power lines to oscilloscope • Set trigger to a threshold under normal power • Shut off power using On/off switch • Verify power coming out of the power management unit reached under 0.5V in 10ms.
On/off switch is easily accessible	• Press button • Verify that it was pressed easily and without strain or excessive force
On/off switch is at least 5cm absolute distance from unshielded actuated mechanical components or power transmitting areas	• Measure distance to nearby hazardous components • Verify that each distance is greater than 5cm

Table 5: Power Button Requirements & Verification

2.3.2 E-stop Button

Since this is a system for a mobile vehicle and may potentially cause bodily harm and physical damage to its surroundings if it loses control, an emergency stop button is a crucial safety feature. The E-stop button must cut power to the craft within 10 ms in order to immediately shut off the craft in the event of an emergency. Additionally, it must have all the characteristics of the On/off switch in terms of accessibility and distance from hazardous components.

Requirements	Verification

E-stop switch cuts power to at most 0.5V in under 10 ms	• connect power lines to oscilloscope • Set trigger to a threshold under normal power • Shut off power using E-stop • Verify power coming out of the power management unit reached under 0.5V in 10ms.
E-stop switch is easily accessible	• Press button • Verify that it was pressed easily and without strain or excessive force
E-stop button is at least 5cm absolute distance from unshielded actuated mechanical components or power transmitting areas	• Measure distance to nearby hazardous components • Verify that each distance is greater than 5cm

Table 6: E-stop Requirements & Verification

2.4 Communication

This is a small portion of the system. There is only one component in this system that allows the craft to communicate with the outside world or any centralized server

2.4.1 Wifi Module

To reduce complexity, we will use off the shelf wifi usb adapter for this, and it will communicate with the raspberry pi through a usb port mounted on the main processing board

Requirements	Verification

Be able to communicate with the server under 20 ms	• Time movement commands in software • Verify with different type of protocol, TCP, UDP, http, etc.
Provide at least 15 m of range with line of sight	• Test the percentage of dropped packet. • Test the maximum range in which the speed is above 10 Mbps and ping latency is under 20 ms

Table 7: Wifi Module Requirements & Verification

2.5 Computing

There are two main computing units on the craft: a Raspberry pi compute module and a mcu (micro controller unit). High level tasks will be performed on the Raspberry Pi. Low level real time tasks such as control will be performed on the mcu.

2.5.1 Microprocessor

Raspberry Pi Compute module (CM 3) is used as the main microprocessor to handle high level task and communications. It will run on soft real-time Linux kernel with prioritized process using POSIX convention. The raspberry pi is powered by a 5 $\pm$0.25 V input coming from the voltage regulator and interfaces with two other components of the system. The Raspberry Pi communicates via USB with Wifi Module via SPI with the mcu microcontroller. For example, the RPi will need to relay commands received through the Wifi module to the mcu. To make the craft responsive, the RPi will have to process a movement command such that the total time from receipt of the signal to command transmission to the Microcontroller is less than 20 ms. Similarly, it should read diagnostics and sensor feedback from the mcu and relay that back to the Wifi module to the user interface. This should also happen within 20 ms.

Requirements	Verification

Processing time of movement command takes under 20 ms	• Time movement commands in software • Verify that timing is consistently under 20 ms for all types of movement commands.
Processing time of diagnostic data takes under 20 ms	• Time diagnostic data processing in software • Verify that timing is consistently under 20 ms for all types of diagnostic data

Table 8: Microprocessor Requirements & Verification

2.5.2 Microcontroller

The microcontroller we will use is a Teensy board. The Teensy receives 5 ±0.25 V input from the voltage regulator. It connects via SPI as the slave of the Raspberry PI and we are setting a minimum criterion of 99% packet accuracy. It also connects to the ultrawide-band via SPI as the master and connects to the gyro, accelerometer, and magnetometer via I2C. The Teensy has speed requirements for receiving data from the sensors, which will be detailed in each of the sensor sections. These ramifications play into the Teensy's capabilities as well, but won't be discussed in the requirements here. For the minimal data delay, we have done some experimentation with the baud rate of the serial between Raspberry pi and teensy, and the result is as follows.

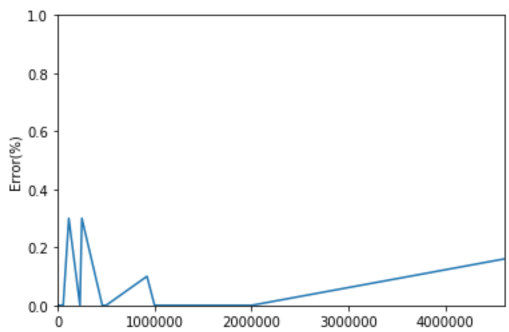

Figure 7: Error rate for each baud rate, in % [3]

The max baud rate that has virtually no error is 2000000 bits per second. The delay of passing the data from python to mcu unit, including software delay, is approximately 15ms [3].

Requirements	Verification
Have no more than 1% corrupted packets though serial communications	• Write code to count corrupted packets and correct packets • Send many packets of data • Verify that fewer than 1% of packets were corrupted

Table 9: Microcontroller Requirements & Verification

2.6 Sensors

There are 3 main sensor units on the craft. This first of these is an accelerometer/gyroscope unit. The gyroscope integrates angular acceleration twice to estimate orientation. The accelerometer integrates linear acceleration twise to estimate position. The accelerometer seves as a backup system for when the ultrawide-band fails or is unavailable. The second sensor unit is a magnetometer, which is used primarily for calibrating the gyroscope. The final unit is the ultrawide-band sensor, which is the primary position-determining unit, but requires preset surrounding units, requiring usage in a confined space and setup time. All of them will communicate directly to the microcontroller unit through I2C bus.

2.6.1 Magnetometer

The Magnetometer will primarily be used for calibration of the gyroscope. The magnetometer should be able to determine absolute angle accurate to 5° while the craft is stationary and 10° while the craft is in motion.

Requirements	Verification

Magnetometer accurate to 5° while craft is stationary	• Align craft to polar north • Find error in magnetometer orientation reading and confirm that it is under 5° • Repeat until a 99% confidence interval is achieved
Magnetometer accurate to 10° while craft is in motion	• Repeatedly rotate craft back and forth between two fixed known angle setpoints • Find error in magnetometer orientation reading between extreme readings and setpoints • Confirm that each error is under 10° • Repeat until a 99% confidence interval is achieved
Magnetometer can report values every 50 ms	• Sample values every 50ms • Confirm that no two read values are exactly the same unless craft is absolutely stationary

Table 10: Magnetometer Requirements & Verification

2.6.2 Gyroscope/Accelerometer Unit

The gyroscope will be the primary mechanism for orientation determination. Position and angles are determined by integrating the readings of the accelerometer and gyroscope, respectively. Gyroscopes are very accurate at measuring and recording sudden changes in orientation, but are prone to gradual drift of sensor calibration. The gyroscope to drift by less than 5 degrees per minute while the craft is stationary. Additionally, during 'normal' operation, which typically consists of angular accelerations of under $\frac{1\,rad}{s^2}$, the gyroscope should hold calibration accurate to 20 degrees per minute.

The accelerometer will be a backup system for determining position. Unfortunately, accelerometers are far less accurate than gyroscopes, and we will therefore be using ultrawide-band as the primary localization system for position. We do, however, want a backup system in case the user wants to run the craft in a location without preset ultrawide-band receivers. The accelerometer should drift by less than $\frac{5cm}{min}$ while the craft is stationary. Additonally, during 'normal' operation, which typically consists of angular accelerations of under $\frac{5\,m}{s^2}$, the accelerometer should be accurate to $\frac{1m}{min}$ absolute deviation from the starting point. Finally, the accelerometer and gyroscope will report data at a rate of 20 Hz

Requirements	Verification
Drift of less than $\frac{5°}{min}$ while stationary	• Calibrate gyroscope • Leave craft stationary for 1 minute • Measure reported change in angle and ensure it is less than 5° • Repeat until a 99% confidence interval is achieved
Drift of less than $\frac{20°}{min}$ while experiencing angular accelerations up to $\frac{1\,rad}{s^2}$	• Calibrate gyroscope • Apply a periodic angular acceleration control sequence to the craft for 1 minute • Measure reported change in angle and ensure it is less than 20° • Repeat until a 99% confidence interval is achieved

Drift of less than $\frac{5cm}{min}$ while stationary	• Calibrate accelerometer • Leave craft stationary for 1 minute • Measure reported change in absolute position and ensure it is less than 5 cm • Repeat until a 99% confidence interval is achieved
Drift of less than $\frac{1m}{min}$ while experiencing angular accelerations up to $\frac{5\,m}{s^2}$	• Calibrate gyroscope • Apply a periodic random acceleration control sequence to the craft for 1 minute • Measure reported change in angle and ensure it is less than 1 m • Repeat until a 99% confidence interval is achieved
Gyroscope and accelerometer can report values every 50 ms	• Sample values every 50ms • Confirm that no two read values are exactly the same unless craft is absolutely stationary

Table 11: Gyroscope/Accelerometer Requirements & Verification

2.6.3 Ultrawide-Band

The ultrawide-band unit measures absolute position using at least 3 or 4 stationary receiver units, depending on the number of degrees of freedom of the craft. We will be using 4 for some level of redundancy and to likely increase accuracy. These four receivers will be powered with simple USB wall plugs. The ultrawide-band system should accurately place the craft to within 10cm absolute position of its actual position. We will have a "tag" ultrawide-band chip on the main computing system, which will communicate to the microcontroller through SPI

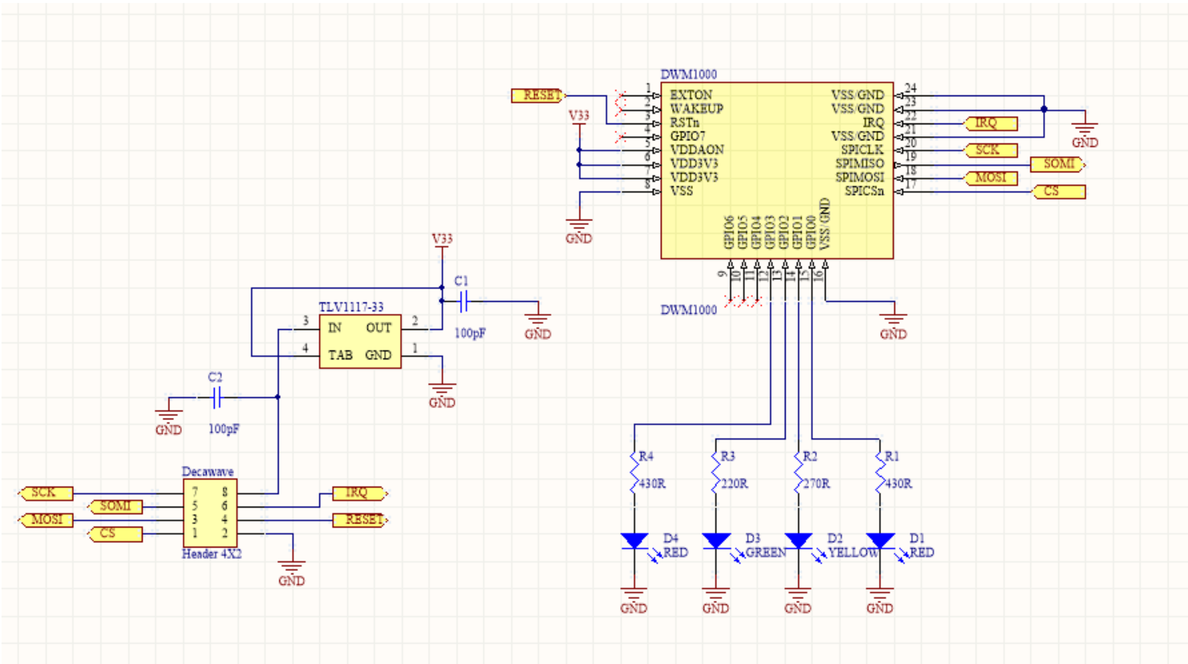

Figure 8: Ultrawideband support PCB schematics

Requirements	Verification
Ultrawide-band position accurate to 10cm absolute positional error	• Calibrate craft at a center point in the test space • Place craft at numerous places in the test space and record position. • Measure actual position relative to center point and find find error in reported position • Confirm that each error is under 10 cm • Repeat several times, changing ultrawide-band receiver locations each time

Ultrawide-Band can report values every 50 ms	• Sample values every 50ms • Confirm that no two read values are exactly the same unless craft is absolutely stationary

Table 12: Ultrawide-Band Requirements & Verification

2.7 Electromechanical

The electromechanical portions of the system are solely built to transmit a motion command into a physical motion in a motor or actuator. The components within the actual system are just the ESCs but some requirements for motors will also be discussed, even though these will be implementation specific.

2.7.1 Electronic Speed Controllers

Electronic speed controllers must be able to drive the motors and actuators at many different speeds and in both direction. This is important, because we need the system to support any imaginable configuration of mechanical components depending on what specific robotic implementation is desired. This means that the ESC needs to be able to drive a motor forward and backward at both high and low RPMS. The hard criterea we will set are at mist a 250 RPM minimum speed and at least a 3000 rpm maximum speed in either direction when driving a 3000kV at 28 mm stator brushless three phase motor, as this seems like a fairly 'average' motor that would be similar to most motors used in the projects needing the system. Additionally, the ESCs need to transmit commands to the motors with minimal delay. The maximum acceptable delay of a movement command will be 10 ms from the time it reaches the ESC to the time when it is trasmitted to the motor.

ESCs will communicate directly to the mcu using PWM analog signal, and will give feedback to the microcontroller using a digital protocol on serial communication.

Requirements	Verification

Capable of running forward and backward at 250 RPM	• Set ESC to drive motor at lowest speed possible such that it is still spinning • Monitor 3-phase motor voltage using oscilloscope prove • Verify that the frequency is less than 4.167 Hz. • Repeat for the opposite direction.
Capable of running forward and backward at 3000 RPM	• Set ESC to drive motor at maximum throttle supported by the ESC • Monitor 3-phase motor voltage using oscilloscope prove • Verify that the frequency is greater than 50 Hz. • Repeat for the opposite direction.
Transmits signals in less than 10 ms	• Initially send a neutral command to the ESC • Monitor input signal and output signal on oscilloscope • Set oscilloscope to trigger when input signal is received • Determine the signal delay and ensure it is less than 10 ms.

Table 13: ESC Requirements & Verification

2.7.2 Motors and Actuators

The motors and actuators are not explicitly part of the closed system, but nonetheless have governing requirements in order to be compatible. One critical component is that the motors are cooled sufficiently to run at full throttle for 5 minutes and at 67% throttle for 10 minutes. This means that they must be able to thermally dissipate around 300W of power at a temperature underneath the glass transition phase of PLA around $57^\circ C$ [4]. We will set a hard minimum of 320 W combined conductive and convective dissipation at a temperature of $55^\circ C$. A heat transfer analysis has been performed, but additional manual verification will be performed through temperature measurements.

Requirements	Verification
Combined thermal dissipation of over 320 W at $55^\circ C$	• Run motor on 100% throttle for 5 minutes • Measure temperature of motor surface, confirming that temperature is under $55^\circ C$.
All moving component's motion envelopes need to be shielded from obstacles and holding surfaces are 5 cm minimum away from motion arcs	• Ensure that no static obstacles can enter a motion envelope by horizontal translation of the craft. • Ensure that all gripping areas of the craft are at least 5 cm from any moving components at any configuration of the craft

Table 14: Motor and Actuator Requirements & Verification

2.8 Case

The case will protect electrical components from impact and will ensure will subsequently protect mechanical systems from stray wires. The case will not be electrically conductive in order to minimize potential for any accidental shorts and will be made of PLA, nylon, ABS, acrylic, or some polymeric solid of the sort. Nylon 6-6, for example, has a resistivity of $10^{15}\,\Omega - cm$ [5]. Additionally, the case must be able to withstand moderate distributed loads in the order of 10 lbs without greater than 5% deformation and without any fracture or noticeable fatigue. Finally, the case must hold the elements of the system

Requirements	Verification
Contains all wires and electronic components to interior of box	• Attempt to feed loose cables through any holes in box • Verify that cables were unable to be pulled through any holes.
All components must be fastened and withstand 2 g's of acceleration	• Manually subject system to at least 3.46 g's of acceleration in each principle direction, which ensures that a minimum of 2 g's can be withstood in any direction • This can be accomplished by weighing the craft, selecting an appropriate counterweight, and setting up a simple balance lever to accelerate the craft upwards at a precisely measured rate • Verify acceleration targets were reached through timing and distance travelled • Verify that all components are still properly situated.
Case must withstand 10 lbs distributed compressive or tensile load in each principle axis with less than 5% total strain and no fracture of any sort	• Subject case to compressive force in each primary axis • Determine strain and verify it is less than 5% • Perform fracture and fatigue inspection • Repeat with tensile load

Resistivity of case must be greater than $\frac{1G\Omega}{m}$	• Measure resistance over 10 cm distance on case • Verify that resistance is greater than $10^8\Omega$

Table 15: Case Requirements & Verification

2.9 Software

There are two main part of the software system: high level on raspberry pi and low level on micro controller unit.
High level python: As the system will serve as a test platform for control algorithm, an easy to program API is preferred. Therefore, python is selected to be used as a high level interface to calculate high level matrix multiplication and other control/planning algorithms. Provided with rich libraries for mathematical computation and matrix manipulation available on python, the user will be able to modify and use the software for any control experiment they wish to build. Low level C: Similar to the high level, we want the system to be easy to program by the user and make the code non-hardware specific as much as possible. We chose Arduino for programming the Teensy board, primarily due to the wealth of publicly available libraries. It will be used to handle low level task such as outputting PWM to control actuators/electronic speed controllers, and sample the data from sensors and implement some basic PID controller. We are planning to use some Real Time Operating System (RTOS) to implement concurrency and real-time scheduling as well, but that might be beyond the scope of this class.
The two will communicate through serial connection with MessagePack protocol, which is a json-like object protocol designed for data stream. Python will send commands such as desired motor torque to the microcontroller, and read back RPM feedback or motor temperature sensors from the microcontroller.

2.10 Tolerance Analysis

There are several key tolerances in the electrical system. One important tolerance is that the sensor data bits must align closely enough with the microcontroller clock. The key consideration is that the signal cannot travel through a wire faster than light, so some delay must be considered. The most important tolerances, however, are the tolerances for the power system. There are several critical tolerances within this system that need to be maintained.

One of these is the DC/DC converter output which needs to hold the 5 VDC signal accurate to 0.25 V at all times to avoid damaging any components.

Another important tolerance is the accuracy of the accelerometer and gyroscope sensors. There are methods to use data from these sensors to determine position and orientation through integration, but using integration for positioning compounds errors in sensor data. If our acceleration in the system is a and our sensor error is Δa, we can see that our positional error actually follows a quadratic relation with time, rather than a scalar error:

$$\int\int (a + \Delta a)\, dx = \int (v + t\Delta a) dt = p + \frac{t^2 \Delta a}{2} \tag{1}$$

A scalar error of even $1mm/s^2$, if left uncorrected, blows the positional error past our 10cm positional accuracy tolerance in just over 14 seconds:

$$(p + 100)mm = p + \frac{t^2 * (1)}{2} mm \Rightarrow 200 = t^2 \Rightarrow t = 14.14s \tag{2}$$

This error compounding speaks to the necessity of gyro and accelerometer error correction using decawave and magnetometer data, and gives valuable insight into the necessary timing of such operations.

Aside from the tolerances in the electrical system, there are tolerance considerations for the physical HoTDeC as well. The main physical tolerance that the electrical system casing must abide by is hole oversizing for additively manufacuctured components. Since the case will be additively manufactured, appropriate tolerancing will need to be selected for mounting hardware. In additive manufacturing, it is common that holes will come out smaller than intended [6]. This means oversizing holes by approximately 0.8 mm diameter for parts printed on TAZ/Ultimaker, and 0.2 mm diameter for Ford RP Lab parts. While there are a number of other mechanical tolerances that are important for the HoTDeC hardware, these begin to transcend the scope of the class, and won't be discussed here in detail.

3 Costs

Labor costs for the project are estimated using salaries of $40 per hour, 10 working hours per week per person, and 15 weeks for the semester.

$$2 * \frac{\$40}{hr} * \frac{10\, hr}{wk} * 15 * 2.5 = \$30,000 \tag{3}$$

Component costs are tabulated in the table below:

Part	Cost
Raspberry Pi + 8GB SD Card	\$42.99
Teensy 4.0	\$26.95
Assorted Wires & Connectors	\$12.85
15 in^2 of PCB	\$45.00
2x 4000 mAh Li-Po battery + 2 spares	\$123.96
Gyrosensor and Accelerometer unit	\$14.94
5 ESCs	\$50.64
Decawave x5	\$149.40
4x USB Charger (for decawave)	\$15.96
Mounting hardware (varied)	\$2.99
Total	\$458.64

Table 16: Parts List & Cost

All in all, development costs will amount to approximately \$30,000 and each unit will cost around \$459. If someone, perhaps for coordinated drone projects, wished to build several units at once, the cost per unit could probably be drastically cut to perhaps as low as \$150 or so, primarily because only one set of decawave receivers and their USB chargers would need to be purchased, and fewer batteries would probably be needed.

4 Schedule

Below is a weekly schedule with the intended deliverables for each week and the initials of which member is responsible for that deliverable

Week	Deliverables
October 7	Design Review, begin work on computing and sensor PCB (both)
October 14	Finish computing and sensor pcb (both), submit for early bird PCB deadline, Begin work on Power PCB (both)
October 21	Finish design and submit power pcb(both)
October 28	Test computing and sensor pcb (TL), begin on controls algorithms (LR), individual progress reports (each)
November 4	Finish controls (both), iterate on computing and sensor pcb if necessary (TL), test power pcb (LR)

November 11	Test full system (both), iterate and submit power pcb if needed (LR), submit revised computing and sensor pcb if necessary(TL)
November 18	Mock Demo (both), Complete final versions of all software (both), begin working on report and presentation (both)
November 25	Integrate all revised components (both), get system working (both), finish demo prep (both)
December 2	Final Demo (both), finish report and presentation (both)
December 9	Final presentation (both), submit final report (both), notebook check (each)

Table 17: Schedule

5 Ethics and Safety

First of all, the project itself does have the power system that pose safety concern over the use of lithium-polymer batteries. Lithium polymer batteries are highly flammable if used incorrectly and pose a safety hazard if not handled with care [7]. In the system, we do have a battery management system that will monitor the voltage and current draw from the battery, which will protect the battery from over-discharging. We will use a battery which its discharge rating is greater than our system max current draw by at least 10%. In addition, during the battery assembling and battery circuit testing we will work in the MEL 2204 lab, which has fire extinguisher and sand bucket in case of accidental fire. We will also plan to utilize Lithium polymer fire-proof bag during charging as well.
Autonomous systems have gained a notoriety for their use in warfare and espionage. Additionally, there have been growing concerns about drones' commercial availability and potential safety or privacy issues associated with this increased availability [8]. By making an all in one powerful localization, control, and power system, we are making custom autonomous vehicles more accessible to everyone, including, unfortunately, those who intend to use such a system for ill. Because we don't want our system being weaponized, we are building the system with strict limits of power delivery, which limits the scale of any potential craft developed using the system. In this way, we will not be enabling ill-doers beyond any capabilities that a conventional off the shelf drone would be able to provide. Certainly, this drastically limits the extent to which the system would be able to be weaponized.

Additionally, by making this system, we may be enabling inexperienced hobbyists or young children to pursue their own projects using the system. While this is great, it makes the safety of the system all the more important, because these consumers may be inexperienced with handling high power batteries and powerful mechanical actuators and motors. As such, the safety requirements must be met and tested with 100% certainty, with the intend to ”hold paramount the safety, health, and welfare of the public,” as is stated in the IEEE Code of Ethics [9]. This includes making sure batteries are properly positioned, that powered leads are not susceptible to shorts, and that the frame of the box is not electrically conductive. Additionally, protections need to be implemented to minimize the chance of fire in the possible, however unlikely event of a short. This will require thoughtful placement of surge protection throughout the system. Additionally, hazards of the craft will be noted, in compliance with IEEE's guideline to ”disclose promptly factors that might endanger the public or the environment” [9].

Because this is an autonomous moving system, there is a risk that the system will become out of control and may be a hazard to the health of nearby individuals and the integrity of the surroundings. To best mitigate that risk, the system will feature a prominent and easily accessible E-stop that immediately cuts power to the system. Additionally, to avoid damage and injury, all motorized or actuated components of the craft must have their motion envelopes within the interior of the craft frame and must be shielded.

Regardless of our effors, certain safety precautions must be taken by the end user. For safe operation, the craft should only be operated in the safe temperature operating range of the battery, or between $0^\circ C$ and $50^\circ C$ [10]. Additionally, batteries should not be discharged to lower than 9 V to avoid battery damage. Key considerations like this will be detailed in any finalized product as prominent warnings.

6 References

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