

ECE 445
Senior Design Laboratory
Final Report

CfA Flying Area Accuracy Determination

Team No. 78

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Abstract

This document describes the overall project design and results from throughout the semester, including the parts needed, description of the test environment, outline of testing processes, and the conclusions based on quantitative data. Ethics, cost, and tolerances will also be discussed and an estimation of the total workload will be given at the end as well as how this project can be continued.

Contents:

1. Introduction	1
1.1 Purpose.....	1
1.2 Functionality.....	1
1.3 Subsystem Overview.....	2
1.3.1 Calibration Object.....	2
1.3.2 Motion Tracking Configuration.....	2
1.3.3 Software.....	2
2. Design	3
2.1 Equations & Simulations.....	3
2.1.1 Equations.....	3
2.1.2 Simulations.....	3
2.2 Design Alternatives.....	5
2.3 Design Description & Justification.....	5
2.4 Subsystem Diagrams & Schematics.....	6
3. Cost and schedule	8
3.1 Cost.....	8
3.2 Schedule.....	9
4. Requirements & Verification	10
4.1 Completeness of requirements.....	10
4.2 Verification Procedures.....	14
4.3 Quantitative Results.....	15
5. Conclusion	16
5.1 Accomplishments and Data Analysis.....	16
5.1.1 Data Analysis.....	16
5.1.2 Accomplishments.....	17
5.2 Uncertainties.....	17
5.3 Future Work.....	17
5.4 Ethics.....	18
References	19
Appendix	21

1. Introduction

1.1 Purpose

The challenge we faced over the course of this semester was in regard to the Intelligent Robotics Lab Facility wanting to design a software that will analyze how consistently the position of a drone is able to be tracked throughout the Flying Arena based on the configuration of the motion tracking setup. This project idea was proposed by Principal Research Engineer, John Hart. The current motion tracker system used in the Flying Arena is the Vicon Tracker 3 which gathers up to one mm position accuracy. However, in areas where the motion tracking camera's configuration does not allow for optimal observation, the accuracy has proven to decrease. The purpose of this project is to see how the accuracy changes when the drone would move higher, lower, and further away into the arena and away from the cameras throughout the entire volume of the arena. Additionally minimizing the error in the tracking device as much as possible to get very accurate data for their flying devices. Ideally after testing, the camera locations can be recalibrated to get the best observation angle and data will be taken to notice any patterns in the data based on location of board in the arena.

1.2 Functionality

The goal is to see how the accuracy changes when the drone would move higher, lower, and further away into the arena and away from the cameras throughout the entire volume of the arena. Ideally after testing, the camera's locations and angles can be recalibrated to get the best observation angle.

Since reflective balls are normally used in the Flying Arena to reflect the infrared flashes from the cameras, these acted as the "observed" location. Due to the balls reflecting instead of emitting, they are considered passive markers and are susceptible to unwanted interference from other light. The LEDs acted as the "true" location. From a performance perspective, since LEDs emit infrared light they are active markers and can be measured at a further distance and more consistently than passive markers, making them more accurate overall [1]. By comparing the motion-captured location of the reflective balls and infrared LEDs at the same time, we were able to calculate the percent error between the centerpoints of each configuration. Based on the results, we will reconfigure the camera setup until both the reflective balls and LEDs have similar position measurements on the x,y, and z axes throughout the entire volume of the arena.

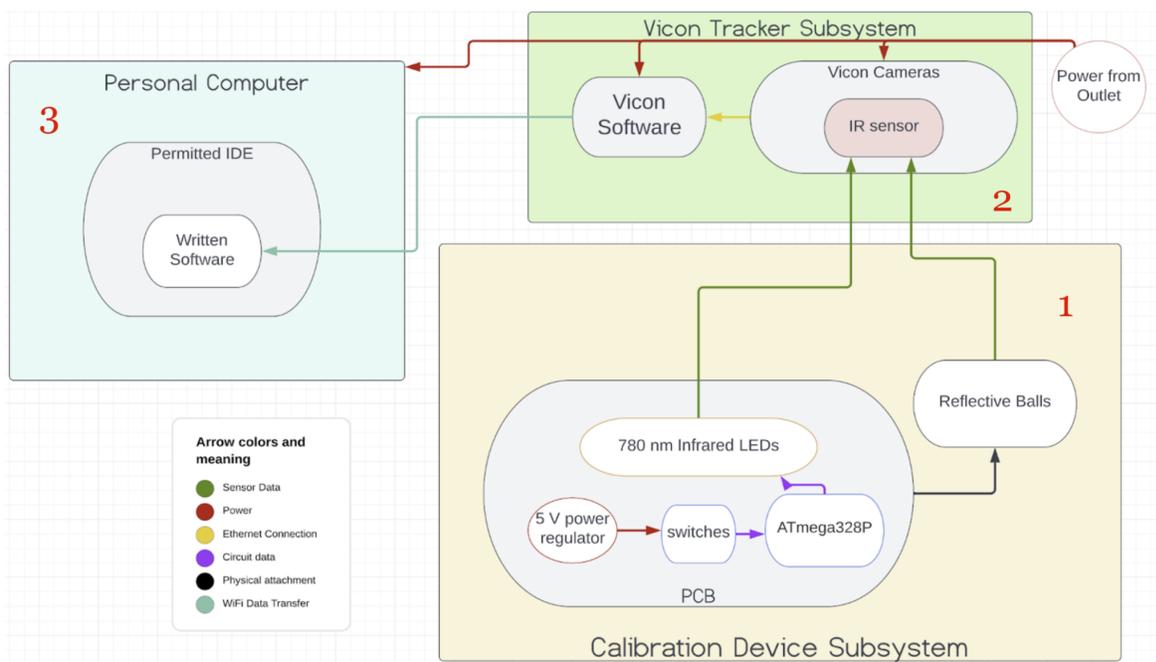


Figure 1. This image shows the numbered block diagram of the three main subsystems and the subcomponents of each.

1.3 Subsystem overview

1.3.1 Calibration Object: The calibration object will mostly consist of the PCB with LEDs and reflective balls mounted onto it. Instead of connecting the PCB to the drone battery, a voltage regulator was used to step down a 9 V battery to a 5 V power source that leads into both the switches and the Atmega328P, which is the microcontroller of our choice. Two I/O pins were designated for the switches, while another eight I/O pins lead to individual LEDs. The two switches each controlled four LEDs as shown in Figure 7. There will also be several resistors so as to not overload the Infrared LEDs, which are now shown in the block diagram in Figure 1.

1.3.2 Motion Tracking Configuration: The Motion Tracking Configuration consists of nine near-cameras and the Vicon Tracker software. Both were powered by the wall outlets, but the data collected by the multiple camera system is sent to the software over an ethernet connection. The cameras record 370 frames per second, meaning that there will be 370 data points per second. The camera flashes a near-infrared light of about 780 nm, which will be reflected by the reflective balls, and which is why the LEDs need to have a bandwidth of 780 nm [2]. Using the Vicon Tracker 3 software, one entire LED configuration and one reflective ball configuration were each grouped into their own objects and their center points were automatically calculated [3].

1.3.3 Software: The software was designed to read data from a .csv file that is sent from the Vicon Tracker 3 Motion Capture System to the personal computer we were working on via the local Illininet Wifi. Using a compatible system such as MATLAB, the two main groups of data that we had to analyze are the 3-dimensional measured location of the reflective balls and

the near-infrared LEDs. At each parallel recorded set of (x,y,z) points, the percent error was calculated and used to determine the accuracy of the current Motion Tracking Camera configuration.

2. Design

2.1 Equations & Simulations

2.1.1 Equations

$$\left| \frac{\text{observed} - \text{expected}}{\text{expected}} \right| * 100 = \text{percent error \%} \quad \text{Equation 1. Percent Error Calculation}$$

$$\Delta T = kQ \quad \text{Equation 2. Newton's Law of Cooling}$$

$$I_{\text{in}} = I_{\text{out}} \quad \text{Equation 3. Kirchoff's Current Law}$$

$$P_{i_{\text{in}}} > P_{o_{\text{out}}} \quad \text{Equation 4. Power relation due to heat loss}$$

$$I(A) \rightarrow Q(w) \quad \text{Equation 5. Thermal Relation to Current}$$

$$V(v) \rightarrow \Delta T (^{\circ}C) \quad \text{Equation 6. Thermal Relation to Voltage}$$

$$R(\Omega) \rightarrow \theta_r (^{\circ}C/w) \quad \text{Equation 7. Thermal Relation to Resistance}$$

$$V = IR \quad \text{Equation 8. Ohm's Law}$$

2.1.2 Simulations

The largest percent error that we will allow recording location between the reflective balls and the infrared LEDs is $\pm 0.01\%$, which would reflect the claim made by the Vicon System, being accurate within 1 mm. Since 1 mm is 0.1% of 1 m, the tolerance for the percent error is as follows. Ideally, once fully configured, the cameras should measure the locations within this difference throughout the entire arena.

$$\left| \frac{\text{observed} - \text{expected}}{\text{expected}} \right| * 100 = 0.1$$

Providing that the expected value is at location 1 m in the x-direction:

$$\left| \frac{\text{observed} - 1}{1} \right| * 100 = 0.1$$

$$\text{Observed} - 1 = 0.001$$

As a result the observed center can be at maximum 0.001 m, or 1 mm, away from the center of the expected location.

Similarly to what was explained above, the LEDs should be as close to the “true” location as possible, as they are representing the ground location. Therefore, the LEDs should also be within 1 mm of the ground location.

By this logic, the reflective balls should be only within a maximum of 2 mm from the ground location, or a 0.2% error.

$$\left| \frac{\text{observed} - \text{expected}}{\text{expected}} \right| * 100 = 0.2$$

Providing that the expected value is at location 1 m in the x-direction:

$$\left| \frac{\text{observed} - 1}{1} \right| * 100 = 0.2$$

$$\text{Observed} - 1 = 0.002$$

An additional tolerance that we calculated out was the thermal circuit analysis in the voltage regulator on the PCB. Looking at a regulator we know that output current is approximately equal to the input current since the other path goes straight to ground. According to kirchhoff's law $V=IR$ and Newton's law of cooling $\Delta T= kQ$ there exists a relationship between the following variables.

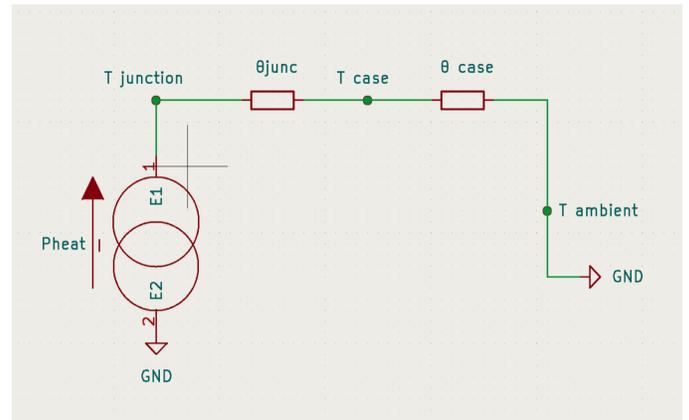
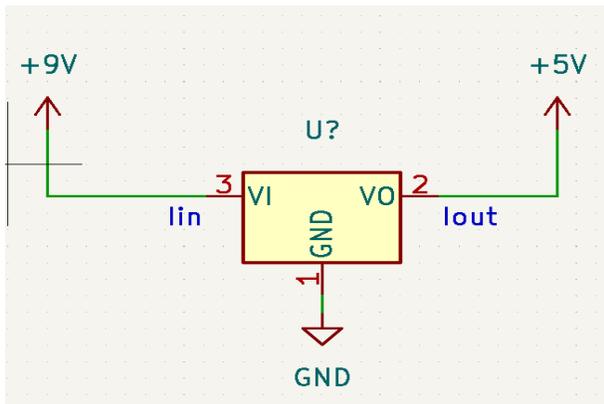
$$I_{in} = I_{out}$$

$$P_{in} > P_{out}$$

$$I(A) \rightarrow Q(w)$$

$$V(v) \rightarrow \Delta T (^{\circ}C)$$

$$R(\Omega) \rightarrow \theta_r (^{\circ}C/w)$$



Figures 2 and 3. These images show the Voltage Regulator (left) as expected, as well as a thermal analysis case (right).

$$P_{heat} = P_{out} - P_{in} = I_{out}(V_{in} - V_{out})$$

$$T_{junc} - T_{amb} = P_{in}(\theta_{ja})$$

Seeing this we must ensure that the temperature at the junction (T_{junc}) will be lower than the working temperature of the component found in the datasheet $125^{\circ}C$ [5].

Another addition is to ensure that each LED is not being overloaded with current. According to the ATmega328P datasheet, the DC current per I/O pin is about 20 mA and 5 V [4].

According to the datasheet of the LEDs, the 2.0 V forward Voltage. This means that the resistors connecting to the LEDs must be around 150-220 ohms [6].

$$5 = (150 * 0.02) + 2$$

$$5 = 3 + 2$$

2.2 Design Alternatives

An issue we ran into was determining the actual location of the dead zones in the arena which would help us determine if the error percentage spikes were caused due to camera angles in that area or some other factor. This was solved during the final week thanks to a new algorithm designed that would show error percentage moments matched up with the location in the actual 3D space.

Another issue we ran into with the PCB design was how the LEDs interfered with the reflective balls. Since the LEDs emitted the same wavelength of light as the Vicon Cameras, the reflective balls would reflect light from the LEDs and skew the object visibility in the Vicon Software. It was impossible to create two consistent separate objects. Opting for a time-efficient solution, we chose to breadboard the circuit using an Arduino to illuminate four different LEDs that could be manually moved into different configurations. This was the optimal solution as it saved time for proper data collection and testing of the written program, and Arduino includes an ATmega328-P.

2.3 Design Description & Justification

● 1: Calibration Device

- **PCB.** The PCB resembled the shape of the drone, as shown in Figures 5 and 7 and it included eight mounting holes for the reflective balls to be attached. The required materials, including the ATmega328-P, the LEDs, the voltage regulator, and various other elements were soldered onto it. The design in KiCAD can be seen in Figure 5. The final product is shown in Figure 7.
- **LEDs.** There were eight near-infrared LEDs in total, four of which will be closer to the center and the other four will be on the outer arms of the PCB as shown in Figures 5 and 7. They needed to have a bandwidth of exactly 780 nm to emit light of the same wavelength as the flash of the Vicon Cameras. Ideally, various configurations were to be tested to analyze the effect of LEDs being closer to the midpoint of the PCB versus further out on the PCB [3].
- **Switches.** There were two switches connected between power from the voltage regulator and the ATmega328P microcontroller. One controlled the innermost LEDs and the other controlled the outermost LEDs. When both switches are closed all eight of the LEDs will be illuminated. This is shown in Figure 7.
- **Atmega328P.** The Atmega328P is the microcontroller of our choice, as it has 23 I/O pins that can easily address the eight different LEDs. It was programmed to turn on LEDs based on which switch is currently flipped. This was intended to allow for different configurations to be tested on top of just the base ones stated previously.
- **AVR-ISP-6.** This was the programmer, and it allowed the ATmega328-P to be programmed through SPI Protocol. The MISO, MOSI, and SCK pins were connected.

- **Reflective Balls.** The reflective balls are styrofoam balls that are used in the robotics lab to mark drones for flight tracking. The reflective paint allows them to reflect the flashes of the camera, making them passive markers [2]. Ideally, similarly to the three configurations of LEDs, there will also be a matching three configurations of reflective balls to keep measurements fair.
- **2: Vicon Tracker 3:**
 - **Vicon Tracker 3 Software.** The system processed the data collected from the cameras to determine a 3D image of the calibration objects and determine the location of each's center. Both the reflective balls and the infrared LEDs were tracked as separate objects, each of which was manually grouped together for the following trials. The x, y, and z coordinates of each object's center are recorded 370 times per second and the data can be exported as a .csv file and sent over WiFi to the designed software to further analyze for accuracy [2]. A view of Vicon can be seen in Figures 6, 9, and 10.
 - **Vicon Tracker 3 Cameras.** There were eight Vicon cameras in total that each strobe a “near infrared” wavelength of 780 nm. The strobes act as flashes that will be reflected by the reflective balls. Providing that the LEDs are 780 nm, they will be registered by the cameras when illuminated [3]. The LEDs will stay illuminated throughout the entirety of the trial, instead of responding to the strobes like the reflective balls will, which makes their optical output more consistent throughout the arena, and thus more accurate. About 370 points of data were collected per second, all of which were transferred to the Tracker 3 software over an ethernet connection. The cameras can be calibrated after sufficient data is collected to reset the origin of the arena.
 - **Routing Over WiFi.** The local Illininet WiFi was the routing method when sending the .csv file from the computer running the Tracker 3 software to the personal computer used for data analysis.
- **3: Software:**
 - **Continuous Recording of Both Object Locations.** In order to properly analyze the data collected, it must be streamed from the desktops with the Vicon System to the designed software on our personal laptop. This occurred at the end of the given trial in the form of a .csv file which can be immediately read and analyzed.
 - **Calculate Percent Error Between Objects and Produce 1D and 3D Graphs.** The percent error is calculated using Equation 1. The LEDs are the expected value, and the reflective balls are the observed value. This was done for each x, y, and z coordinate over all the data. Various graphs were created as a result, which can be seen in Figures 12, 13, 14, and 15.

2.4 Subsystem Diagrams & schematics (All subsystem diagrams and schematics included. All elements are clean and coherent)

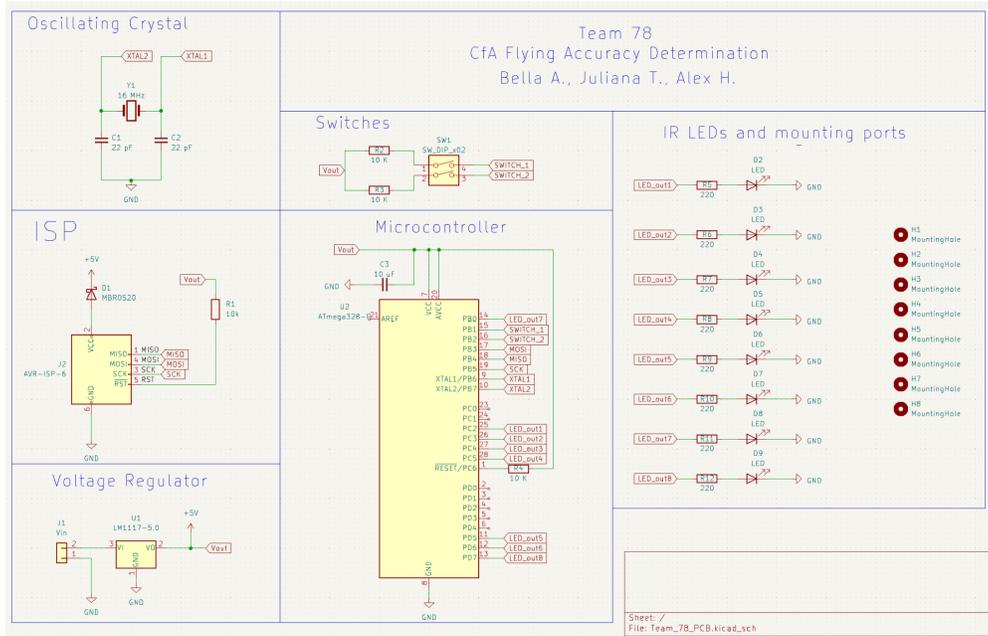


Figure 4. This image displays the schematic layout in KiCAD (Subsystem 1)

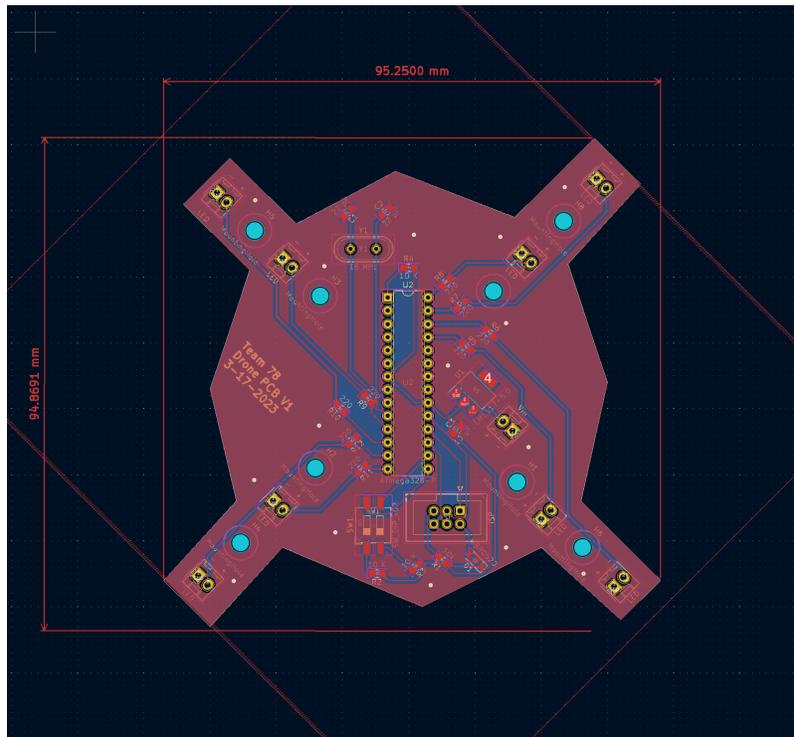


Figure 5. This image displays the PCB layout in KiCAD (Subsystem 1)



Figure 6. This image displays Vicon Tracker Software and the Flying Arena (Subsystem 2) [7]

3. Cost & Schedule

3.1 Cost

Description	Part number	Unit price	# bought	Total cost
780 nm IR LED [6]	LED750L	\$10.40	8	\$83.2
22 pF capacitor [8]	CL21C220JBANNNC	\$0.10	4	\$0.40
10 uF capacitor [8]	TMK212BBJ106MG-T	\$0.18	4	\$0.72
Diode [8]	MBR0520	\$0.16	2	\$0.32
Connector [8]	0022232021	\$0.21	2	\$0.42
ISP [8]	61200621621	\$0.48	2	\$0.96
Switches [8]	219-2MSTR	\$0.63	2	\$1.26
Voltage Regulator	LM1117MPX-50NOPB	\$0.61	2	\$1.22
16 MHz Crystal	LFXTAL003240BULK	\$0.50	2	\$1.00
Microprocessor [8]	ATMEGA328P	\$2.89	1	\$2.89
150 ohm resistor [8]	CFR-25JB-52-100R	\$0.068	8	\$.55
4-pack 9 V battery	Duracell CopperTop 9-volt Batteries	\$14.79	1	\$14.79
Battery Snap Connector	s20120200wm0184	\$3.43	1	\$3.43
PCB (4.5" x 4.5")	N/A	N/A	1	N/A
Total	////////////////////////////////////	////////////////////////////////////	41	\$111.16

According to the UIUC Salary Averages for the years 2020-21 [9][10], the starting Computer Engineering salary is \$105,352 and the starting Electrical Engineering salary is \$80,296. Assuming 40 hour work weeks, the hourly salaries for Computer Engineers and Electrical Engineers are \$50.65/hr and \$38.60/hr respectively. We each worked 8 hours a week on average, thus we can compute the estimated labor cost to be:

$$(\$50.65/hr + 2 \times (\$38.60/hr)) \times 88 hrs \times 2.5 = \$11,250.80$$

Adding up the total cost for the parts and the labor, our total cost is \$11,361.96

3.2 Schedule

Every member should contribute to the project approximately three days a week until the design of the pcb and understanding of the software for our purpose is complete. We will need to work on the board design one or two days a week and get into the lab two days a week to set up optimal camera positioning and become accustomed with software in the flying arena. Once the pcb design is complete our group will spend two days a week in the UIUC Robotics Lab in order to run sufficient amounts of tests and collect data as we fit our custom pcb board and discover the best way to compare accuracy.

Week	Objective
2/21	Check Design Document, Start building PCB All members
2/28	PCB Review, Finish up PCB design PCB Design: Bella PCB Review: Juliana
3/7	Order parts and PCB, Complete teamwork evaluation All members
3/14	Spring Break
3/21	Finish ordering parts, Start assembly, Start software development Software development: Alex Start assembly: Juliana, Bella
3/28	Finish assembling parts to be fit onto drone, Finish software, Begin testing in Flight Lab Finish Assembly: Juliana, Bella Finish software: Alex
4/4	Continue testing in Flight Lab Bella, Alex, Juliana
4/11	Work on hardware and software verification Hardware: Bella, Juliana Software: Alex

4/18	Present mock demo to TA, Work on final presentation and paper All members
4/25	Work on any issues that occurred, Continue working on final presentation and paper All members
5/2	Work on Final Paper All members

4. Requirements & Verifications

4.1 Completeness of requirements

Our main requirements included the following:

1. Design and create a PCB board with an ATmega328P as a microcontroller, eight programmable LEDs, two switches, and mounting holes to attach the reflective balls. The ATmega328P must be programmed to light up the LEDs in three different configurations.
2. Design an algorithm in the software to compare the locations of the reflective balls and the Infrared LEDs simultaneously.
3. Simultaneously track two objects, one being the 4 reflective balls and the other being any of the three configurations of LEDs, and stream the data over Illininet WiFi to MATLAB on a personal computer.

To accomplish this, three necessary subsystems were identified based on the three different high level requirements: a calibration device, Vicon Tracker 3, and a written algorithm. These three, labeled in order by number, are shown in the block diagram in Figure 1.

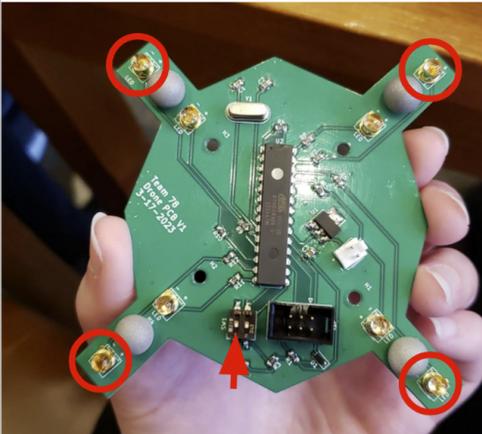
The calibration device consisted of a PCB connecting the ATmega328-P, switches, a power source, various resistors and capacitors, near-infrared LEDs of 780 nm, and reflective balls. This essentially summarizes the first high level requirement as well. The microcontroller we chose to use is the ATmega328P as it has 23 programmable I/O ports to connect to eight near-infrared LEDs individually and three buttons that will control three main configurations of the LEDs which are shown in Figure 7. Also as shown in Figures 5 and 7 the PCB board was shaped similar to the top-view of a drone, in which there are four different “wings”. On each wing in between the two LEDs, there will be a hole that allows for mounting a reflective ball. Two switches will control three different LED configurations, being that the outer four emit light (one switch), the inner four emit light (second switch), and all eight LEDs emit light (both switches at once). There were some changes made to this subsystem throughout the semester due to optical interference between the reflective balls and the 780 nm LEDs, leading us to breadboard the design instead of utilizing the PCB so that the two markers would have adequate separation. Specifically, the reflective balls were only a few millimeters away from the LEDs on the PCB causing Vicon to have difficulty in differentiating the two markers. We chose to use an Arduino as it uses the ATmega328-P. While the breadboarded design did accomplish the main

goals, we were not able to desolder all eight LEDs and make different configurations based on the switches. Therefore, this high level requirement is mostly complete.

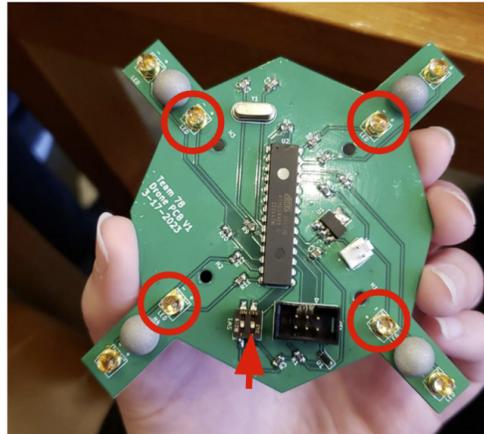
The second subsystem was the motion capture setup itself, which was provided to us by the Intelligent Robotics Lab. This consisted of the Vicon Tracker 3 software and the nine Vicon Cameras which recorded the (x,y,z) position. Two objects were successfully created in the software at once, as shown in Figures 9 and 10, one being an object of the LEDs in red and the other being the object of reflective balls in gray. Their centerpoints were automatically calculated by the software and 370 points of data were recorded per second. Since the cameras only emit and receive near-infrared light at a wavelength of 780 nm, specialized LEDs were ordered. Ultimately, the third high level requirement was satisfied and no changes were made throughout the semester.

The last subsystem was the software written to calculate the percent error between the centerpoint of each object. Data recorded by the motion tracking sensors was successfully streamed over illininet WiFi in the form of a .csv file, as shown in Figure 11, and parsed to create various graphs that show the trajectory of the calibration device throughout the Flying Arena which are shown in Figures 14 and 15. Hence, the second high level requirement was satisfied and no changes were made throughout the semester.

Configuration 1



Configuration 2



Configuration 3

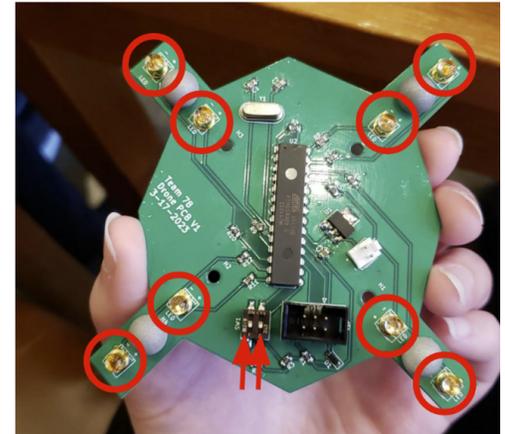


Figure 7. This image displays the three configurations of the fabricated PCB.

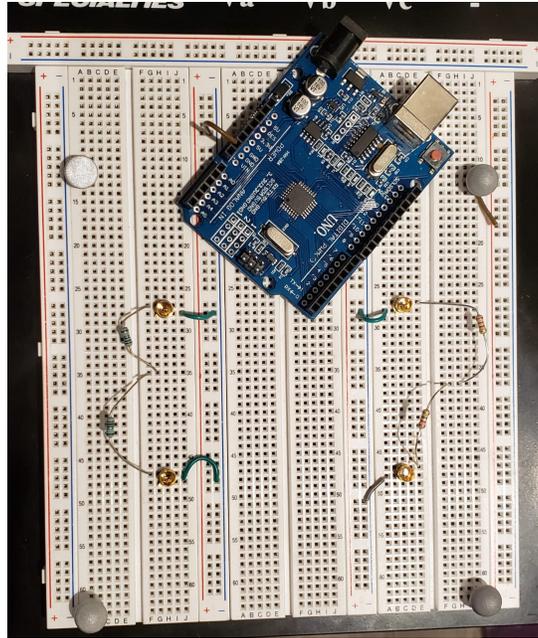


Figure 8. This image displays the alternative design approach done through breadboarding..

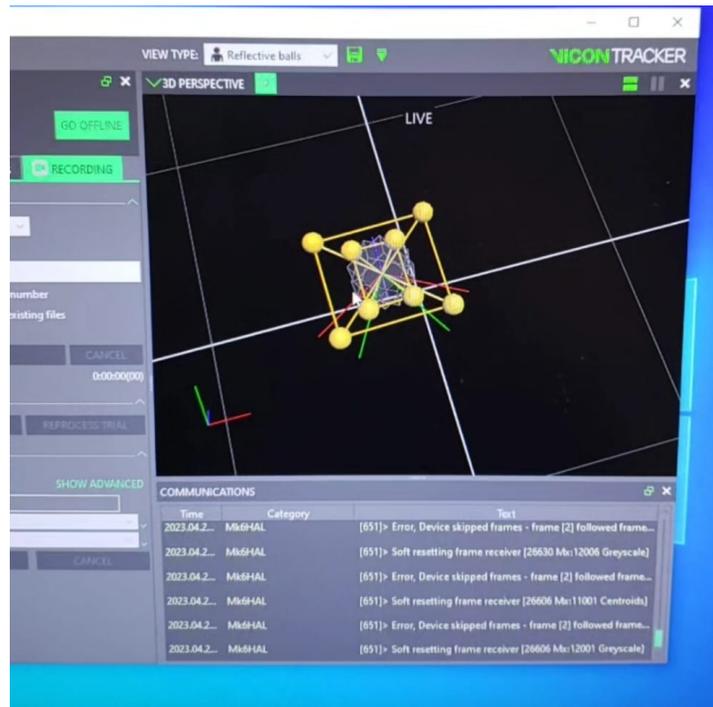


Figure 9. This image displays the view of the different objects in Vicon Tracker 3.

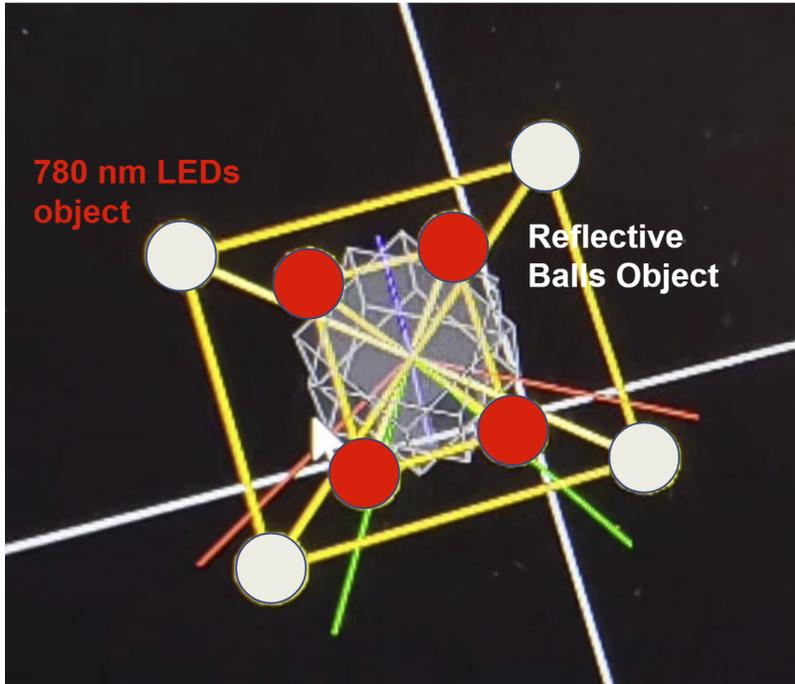


Figure 10. This image displays the three configurations of the fabricated PCB.

Data we use for analysis →

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Objects													
2	100													
3			Global Angle	LEDS:LEDS					Global Angle	Reflective Balls:Reflective Balls				
4	Frame	Sub Frame	RX	RY	RZ	IX	IY	IZ	RX	RY	RZ	IX	IY	IZ
5			rad	rad	rad	mm	mm	mm	rad	rad	rad	mm	mm	mm
6	1	0	3.027719	-1.017682	0.05367	191.907227	247.597076	1654.53259	-0.108786	-0.062824	3.536918	192.645081	247.622284	1654.09595
7	2	0	3.033782	-1.015975	0.064685	192.000198	247.922836	1654.36475	-0.109912	-0.062525	3.537122	192.532394	247.756973	1654.10608
8	3	0	3.030057	-1.01714	0.080283	191.816467	247.495972	1654.63953	-0.107552	-0.064631	3.536967	192.359589	247.974289	1654.25745
9	4	0	-0.991183	-2.956265	-0.090621	191.631439	247.382858	1654.98755	-0.109746	-0.0609	3.536908	192.343292	248.025223	1654.19421
10	5	0	-0.996951	-2.948482	-0.084276	191.687805	247.204529	1654.83057	-0.110046	-0.063324	3.537362	192.194031	248.205673	1654.31152
11	6	0	-0.990713	-2.954476	-0.092363	191.444717	247.368027	1654.99219	-0.110205	-0.062334	3.537306	192.137177	248.266739	1654.33252
12	7	0	-0.991825	-2.949461	-0.081181	191.498779	247.395111	1654.81043	-0.111232	-0.061512	3.53743	192.079102	248.369263	1654.39661
13	8	0	-0.986058	-2.954105	-0.088416	191.367188	247.547836	1654.94592	-0.11132	-0.06068	3.537071	192.029495	248.427155	1654.39514
14	9	0	-0.981905	-2.950778	-0.092593	191.467392	247.669754	1654.78845	-0.112188	-0.059796	3.536799	192.004578	248.509567	1654.41589
15	10	0	-0.981687	-2.960009	-0.088541	191.495239	248.149231	1654.5144	-0.112029	-0.0595	3.536462	191.989578	248.564377	1654.40442
16	11	0	-0.978291	-2.949156	-0.094594	191.574112	248.159027	1654.71838	-0.112054	-0.05857	3.53622	191.975143	248.562134	1654.39343
17	12	0	-0.984327	-2.959721	-0.087383	191.425995	247.754715	1654.60632	-0.111452	-0.058397	3.535951	192.033493	248.611877	1654.36694
18	13	0	-0.983129	-2.959624	-0.086545	191.619263	248.239182	1654.47131	-0.111167	-0.057593	3.535595	192.109802	248.676071	1654.33887
19	14	0	-0.985096	-2.959266	-0.084578	191.666641	248.244934	1654.45203	-0.109311	-0.05778	3.535571	192.200851	248.727875	1654.30469
20	15	0	-0.990393	-2.954531	-0.081841	191.723969	248.256134	1654.73718	-0.108064	-0.0574	3.535356	192.288635	248.745361	1654.22888
21	16	0	-0.986907	-2.949596	-0.086762	191.879089	248.488968	1654.42419	-0.106241	-0.057845	3.535183	192.37941	248.76355	1654.12793
22	17	0	-0.986935	-2.95034	-0.086922	192.056412	248.592224	1654.25891	-0.104124	-0.058698	3.534758	192.529587	248.779968	1654.0144
23	18	0	-0.985734	-2.941518	-0.08921	192.265259	248.784882	1654.3031	-0.102055	-0.05952	3.534628	192.694702	248.807068	1653.89148
24	19	0	-0.988112	-2.939967	-0.089605	192.359238	248.415512	1654.20801	-0.100243	-0.060386	3.534604	192.832809	248.810104	1653.82568
25	20	0	-0.987817	-2.938857	-0.089326	192.651581	248.576675	1654.14258	-0.09893	-0.061331	3.534212	193.036072	248.850952	1653.75635
26	21	0	-0.982706	-2.940616	-0.090034	192.858749	248.469437	1653.82434	-0.097144	-0.061754	3.534096	193.219452	248.893768	1653.68298
27	22	0	-0.98187	-2.938578	-0.089131	193.047287	248.469437	1653.78784	-0.092168	-0.068637	3.530925	193.610214	249.297073	1653.797
28	23	0	-0.992681	-2.961078	-0.078071	193.088867	248.603455	1653.82593	-0.093412	-0.063307	3.533742	193.622665	248.993271	1653.474
29	24	0	-0.994194	-2.956578	-0.075003	193.300491	248.507401	1653.64722	-0.091703	-0.064254	3.53325	193.798325	248.984924	1653.36218
30	25	0	0.088797	0.048081	-2.751455	193.512253	248.55162	1653.55762	-0.08926	-0.065726	3.533099	194.032455	248.993912	1653.23291
31	26	0	0.086035	0.049884	-2.751896	193.729095	248.584732	1653.45496	-0.086703	-0.067054	3.532823	194.199188	248.990631	1653.09106
32	27	0	0.064039	0.062274	-2.75105	193.974045	248.058746	1653.36206	-0.084278	-0.069569	3.53265	194.34021	248.960663	1652.99817
33	28	0	0.080383	0.067954	-2.750417	193.793137	247.954758	1653.6864	-0.083871	-0.071917	3.532647	194.50087	248.859238	1652.84985
34	29	0	0.079896	0.067491	-2.750936	193.891883	247.919632	1653.71252	-0.07863	-0.072569	3.531779	194.551087	248.808026	1653.82472

Figure 11. This image displays the output CSV file with a very small snippet of data. Circled in red is the relevant x,y, and z information of each object.

4.2 Verification Procedures

Requirement	Verification
<p>Continuous Recording of Both Object Locations.</p>	<ul style="list-style-type: none"> ● Check the output file to ensure that all 370 frames captured each second have independent positional data for each LED/reflective ball and there are no gaps in data. ● Check that there is a stable connection to Illininet Wifi.
<p>Constantly Compare the Two Data Sets using Vicon Tracker 3 System</p>	<ul style="list-style-type: none"> ● Construct a graph picturing the locations of each of the 4 or 8 LEDs (depending on the configuration) and reflective balls over the flight duration in Vicon Tracker 3. ● Ensure that the LEDs and reflective balls are grouped as two different objects. ● Verify that the centerpoints of each object are approximately the same.
<p>PCB</p>	<ul style="list-style-type: none"> ● The PCB functionality was tested in both the senior design lab as well as the Robotics Lab, as there is a soldering station there. It was soldered in the Robotics Lab. ● The PCB must be flipped diagonally in order to fit the 100 mm x 100 mm requirement. ● All components were hand soldered, and thus easier to work with and test.
<p>Atmega328P</p>	<ul style="list-style-type: none"> ● This microcontroller is easily programmable for the purposes of keeping different configurations of IR LEDs illuminated [4]. ● It will be tested by programming the code onto an Arduino first, to remove errors, then onto the ATmega used in our design. ● SPI Protocol was used on the PCB. If using the arduino, such as in the breadboarded design, digital input and output commands can be used.

LEDs	<ul style="list-style-type: none"> • The LEDs were first tested alone, separate from the PCB, on a breadboard to ensure that the Vicon Cameras can register them. They must be 780 nm exactly, and could only be found from Thorlabs. • On the PCB, the LEDs must successfully turn on when the switches are flipped. This was tested in the senior design lab after the ATmega is correctly working.
Reflective Balls	<ul style="list-style-type: none"> • Reflective balls must successfully be picked up by the Vicon cameras simultaneously as the leds are on. • The ability to properly fit into the mounting holes was examined.

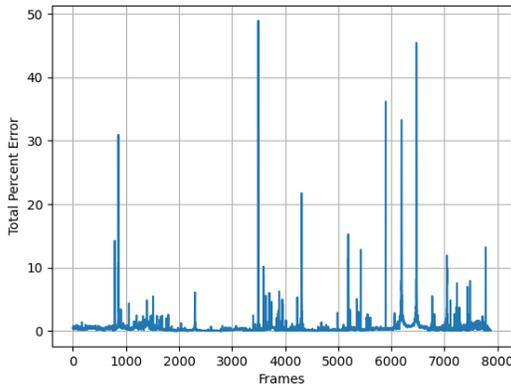
4.3 Quantitative Results

After analyzing the percent errors between the median positions of the LEDs and the reflective balls in the 3D coordinate plane, we determined that the median total percent error was slightly higher than ideal, but still very minimal. Specifically, the percent errors we reviewed were 1.5141, 0.5050, 0.5052, 0.6054, and 0.3411, with a median total percent error of 0.5052. However, we noticed that the percent error in the Z dimension was exceptionally low compared to the X and Y dimensions, as indicated by the graphs below. This low Z percent error suggests that our measurements in the Z dimension are accurate, and we will focus on improving the accuracy of our X and Y measurements to reduce the overall median percent error further in the future if this project continues. We will also continue to analyze our data and take appropriate corrective measures to ensure the highest level of precision in our results.

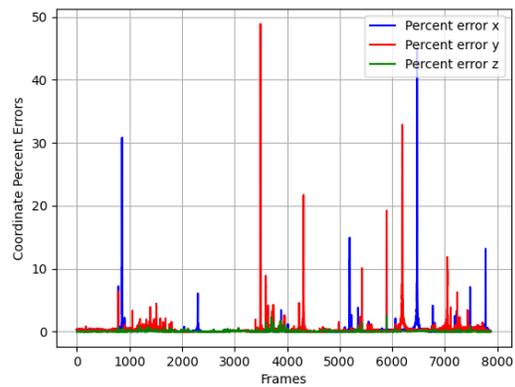
Trial #	Median Total Percent Error
1	1.5141
2	0.5050
3	0.5052
4	0.6054
5	0.3411

Table 1. This table describes the median percent error per trial as we carried the PCB throughout the arena.

Total % Error between Reflective Balls and 780 nm LEDs for Trial 5

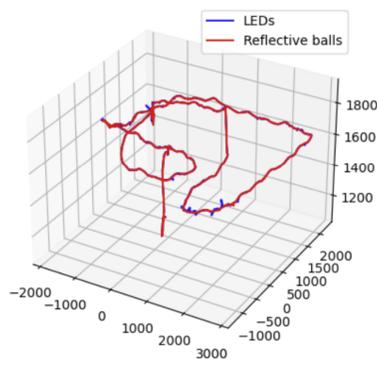


Coordinate % Error between Reflective Balls and 780 nm LEDs for Trial 5

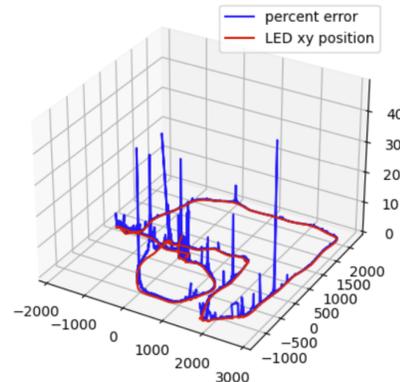


Figures 12 and 13. These graphs display the percent error per frame on the left (Figure 12), and the percent error per axis on the right (Figure 13).

Coordinate Values (mm) for Reflective Balls and 780 nm LEDs for Trial 5



Percent error between Reflective Balls and 780 nm LEDs for Trial 5



Figures 14 and 15. These graphs display the 3-dimensional differences throughout the arena for trial 5, which had the lowest median percent error. The difference in mm between each centerpoint is shown on the left (Figure 14) and the percent error between the centerpoints during the flight path is shown on the right (Figure 15).

5. Conclusion

5.1 Accomplishments and Data Analysis

5.1.1 Data Analysis. Since trial 5 had the lowest median percent error across the five trials, we decided to analyze the 3D trajectory of that path. As shown in Figure 14, there are barely any visible differences between the centerpoint of the reflective balls and the LEDs. However, since the Vicon Tracker 3 is so sensitive to tiny movements, even the smallest differences lead to a large percent error, as shown in Figure 15. If a user is standing outside of the arena but looking in, the x-axis of Figure 15 represents the direction perpendicular to the user, or left-right. The y-axis represents the direction parallel to the user, which is going in or out of the

arena. It can be concluded from Figure 15 that the highest percent error occurs in the deeper-set left corner of the flying arena, which is closer to the windows.

Since the reflective balls were causing the majority of the error, it is clear that something was interfering with the way they reflected the camera flashes. This could be the sunlight coming in from the nearby windows, which can be seen in Figure 6. It could also be due to human error and improperly tilting the breadboard, as we did not get to place the PCB or the breadboard on the drone. We did not complete flight training and were therefore not allowed to fly the drones.

From here, the next steps would be to recalibrate the cameras in order to place the origin of focus further back and to the left. This would ideally reduce the percent error in the back corner and make data collection more even throughout the entire arena.

5.1.2 Accomplishments. In the first subsystem, which was designing the PCB, there were a few main accomplishments, one being that the correct LEDs were able to be found. As only 780 nm LEDs would be registered by the cameras, it was crucial to do the research and find a reliable vendor. Another accomplishment was getting the first version of the PCB to function properly, despite the difficulties arising later on from the interference between the LEDs and the reflective balls.

In the second subsystem, the biggest accomplishment was quickly learning how to work with the software and being able to create multiple objects.

Lastly, in the third subsystem the biggest accomplishment was being able to read a massive amount of data. Each trial conducted lasted at least several minutes, leading to thousands of points of data to be analyzed. As shown in Figure 12, 8,000 individual points of data needed to be analyzed altogether. Furthermore, in the last week of design and testing we were able to successfully create the 3D graphs shown in Figures 14 and 15.

5.2 Uncertainties

An issue we ran into was determining the location of the dead zones in the arena which would help us determine if the error percentage spikes were caused due to dead zones or some other factor. This was solved during the final week thanks to a new algorithm designed that would show error percentage moments matched up with the location in the actual 3D space. Our main issue that was not fixed during the allotted time is in regard to the LED and reflective ball interference. This result was unsatisfactory and unforeseen, it occurred due to overlooking the distance between the LEDs and reflective balls. From our original design we saw incorrect data and big error percentages because the LEDs themselves were reflecting off the balls causing the cameras to record very skewed locations.

5.3 Future Work

Moving forward a lot of the research and trial and error has been done so far and a clear path exists. The first step to continue is calculating the minimum distance needed between near-IR LEDs and reflective balls in order to not have interference in the data. Once this distance is calculated a new PCB design must be created using the new dimensions, but the same

components used in this project can still be implemented. The only challenge from this new design would be the size constraints both for the 100 mm x 100 mm issued by the course, and the weight of a larger PCB being placed on a bigger drone. Following the reconstructed PCB a new stress tolerance calculation would have to be made to account for the extended wings as well as make sure the PCB is within the weight limits for a flying device.

An additional concept to entertain in the future is utilizing the actual flying devices source of voltage to connect straight to the tracking PCB. This would be done to eliminate the need for an external battery and be more mass efficient. The drawback we foresaw would be the dangers of overloading the power source as well as the use of lithium batteries since they are the main source for the drones. Doing this could result in a fire. Therefore this design alternative would have to be looked into to ensure user safety and follow IEEE code of ethics [10].

5.4 Ethics

The main ethical concern of this project is if we irresponsibly were to fly the drone. According to rule number II.9 in the IEEE code of ethics, we must “avoid injuring others, their property, reputation, or employment by false or malicious actions, rumors or any other verbal or physical abuses” [10]. If we irresponsibly fly the drone, it may cause damage to others or the lab environment/equipment. Regarding safety we must take the proper precautions and training when entering the robotics lab. Mechanically we run the risk of damaging lab equipment (drone), if it were to be operated improperly. Electrically we must design a PCB board that will have fully functioning connections, short circuits can damage the PCB board as well as the frame depending on the level of issue.

Furthermore, it is important to not overload the circuit, as if overheating occurs it could cause a fire in the robotics lab. This issue deals with lithium batteries being combustible and leading to dangerous electric fires. Due to this reason, we performed the thermal calculations in the tolerance analysis to make sure that specifically the linear voltage regulator is not overloaded when reducing a 9 V supply down to 5 V.

Regarding the lab space, it is important to keep the drone at a safe level within the arena and always announce when takeoff will occur no persons are allowed in the arena when the device is used. Otherwise, people may get harmed by the quickly moving propellers. This could also cause property damage, such as to windows or lightbulbs, if the drone were to be flown outside of the protective cage.

The robotics lab has expensive equipment, and it is important to only go into the lab with your team and not hold the door for anybody else, even if they try to verify that they have access.

References

- [1] K. Richardsson, “The active marker deck,” *Bitcraze*, 02-Sep-2019. [Online]. Available: <https://www.bitcraze.io/2019/09/the-active-marker-deck/>. [Accessed: 09-Feb-2023].
- [2] Chris Joslin, “Motion capture,” *Optical Motion Capture*. [Online]. Available: <https://mocap.csit.carleton.ca/index.php?Section=System&Item=Cameras&Page=Default>. [Accessed: 23-Feb-2023].
- [3] *Vicon Tracker User Guide*, 1st ed. Vicon Motion Systems., Kidlington, U.K., 2020
- [4] 8-bit AVR Microcontroller with 32K Bytes In-System Programmable Flash, 7810D–AVR–01/15 [Online]; Atmel: San Jose, CA, 2015, https://ww1.microchip.com/downloads/en/DeviceDoc/Atmel-7810-Automotive-Microcontrollers-ATmega328P_Datasheet.pdf. [Accessed: 23-Feb-2023].
- [5] 800 mA Low-Dropout Linear Regulator [Online]; ON Semiconductor: 2021, LM1117 - 800 mA Low-Dropout Linear Regulator (onsemi.com) [Accessed: 24-Mar-2023].
- [6] Ultrabright Near Infrared LED [Online]; ThorLabs: 2014, Microsoft Word - 16385-S01 rev D.docx (thorlabs.com) [Accessed: 17-Mar-2023].
- [7] Intelligent Robotics Lab [Online]; University of Illinois at Urbana-Champaign: 2022, (<https://robotics.illinois.edu/lab/>) [Accessed: 1-May-2023].
- [8] “Switches: Toggle switches: Digi-key electronics,” *Digi*. [Online]. Available: <https://www.digikey.com/en/products/filter/toggle-switches/201?s=N4IgtTCBcDaIM4HcCWAXAxcwKZxAXQF8g>. [Accessed: 23-Feb-2023].
- [9] T. G. C. of Engineering. “”The Grainger College of Engineering - Computer Engineering”.” (2022), [Online]. Available: <https://grainger.illinois.edu/academics/undergraduate/majors-and-minors/electrical-engineering#:~:text=Post%5C%2DGraduation%5C%20Success&text=The%5C%20average%5C%20salary%5C%20between%5C%202020,median%5C%20signing%5C%20bonus%5C%20of%5C%20%5C%2415%5C%2C000>. [Accessed: 14-April-2023].
- [10] T. G. C. of Engineering. “”The Grainger College of Engineering - Computer Engineering”.” (2022), [Online]. Available: <https://grainger.illinois.edu/academics/undergraduate/majors-and-minors/computer-engineering#:~:text=Post%5C%2DGraduation%5C%20Success&text=The%5C%20average%5C%20salary%5C%20between%5C%202020,median%5C%20signing%5C%20bonus%5C%20of%5C%20%5C%2415%5C%2C000>. [Accessed: 14-April-2023].

[11] “IEEE code of Ethics,” *IEEE*. [Online]. Available: <https://www.ieee.org/about/corporate/governance/p7-8.html>. [Accessed: 09-Feb-2023].