Heat Leakage Measurements Utilizing An Airborne Sensor Package

12/6/2019

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Table Of Contents:

Abstract

Temperature loss is a serious concern for the energy efficiency on building rooftops. We have developed an airborne sensor package that is able to track temperature changes through rooftops. These readings allow for insight into possible building improvements that can prevent energy leaks and lower heating costs for building owners. Our test results reveal that our device is capable of reliable IR measurements as functions of geospatial position. The building of interest is our very own Loomis Laboratory of physics. The data suggest that the Loomis rooftop displays heat differences up to 0.5 °C that are not attributed to external factors like light/shadow.

Introduction

The University of Illinois at Urbana-Champaign's campus has a multitude of older buildings, one such being the Loomis Laboratory of Physics. Our group has hypothesized that with buildings of this age, there will be a significant amount of heat loss through their rooftops. We intend for this report to raise awareness of these issues in infrastructure. Image 1 shows an IR image of an example building with bad roof insulation.

To quantify heat loss, we decided to measure temperature variations on rooftops using an airborne drone-mounted sensor package. This package will use both an IR sensor and a multipurpose sensor (BME-680) to measure temperature and collect data from campus rooftops. In addition, our instrument package will be collecting GPS data, acceleration, and elevation. This report will interpret these results and use a three-dimensional heat map that uses a color scale to display temperature variations. This IR and temperature data will be paired with GPS data in order to map the locations the data were acquired from.

We believe this is a valuable and efficient method for testing rooftop structures. By using a drone mounted package, we can access locations that may be hazardous to do so on foot. Another feasible method of acquiring this data to test this hypothesis involves manually walking the sensor package around the rooftop of interest. However, this method is significantly less efficient, in terms of measurement speed, than ours and comes with safety concerns, such as the stability of the roof being tested. Our drone-mounted method allows us to measure all types of roofs in an efficient manner when compared to a handheld approach.

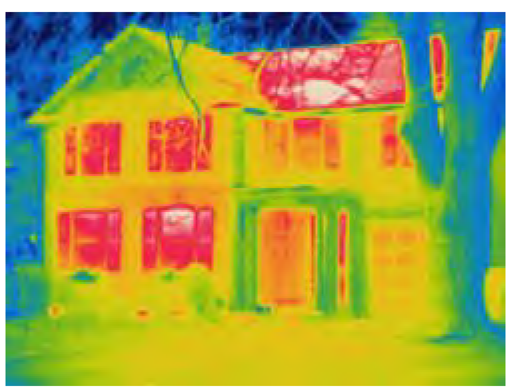


Image 1: House with poor roof insulation[1], red indicates warmer areas while blue shows cold areas.

[1] Image Credit (8)

Materials and Methods

Devices:

Our sensor package utilizes a variety of compact and lightweight circuit board sensors designed for airworthiness. The package is mounted onto a DJI Mavic 2 Pro drone that is flown close to a rooftop surface. The temperature is then mapped as a function of position via a GPS breakout board.

In designing a system capable of being attached to the drone, certain guidelines had to be followed. We would have liked to mount a processor to the bottom of the drone. However, this approach would have blocked the drone's sensors on its underside, which prevents the drone from flying and landing properly. To address this issue, we designed an apparatus that places devices on both the top and beneath the drone. This approach overall involves three components: a main package attached to the top of the drone which consists of the central processor and the other devices too large to place below the drone, a package containing our sensors designed to be held a distance away from and under the drone's own sensors, and a mount capable of supporting such a processor and a hanging set of sensors (Image 2).

Image 2: Sensors and processor 3-D Printed Apparatus on Drone

Sensors:

The array of sensors we used includes a three volt MLX90614 IR sensor for the temperature and an Ultimate GPS breakout board to track the position. The MLX utilizes a 90 degree field of vision to measure IR radiation emitted from the roof's surface and averages the values absorbed. Image 3 shows that the sensitivity of the sensor is at 50% at an angle of incident of 45°. By assuming a perfect blackbody surface, the MLX processes the incoming IR radiation as temperature measurements.The Ultimate GPS latitude and longitude outputs are then mapped to the temperature readings to assign the given temperature to a particular location.

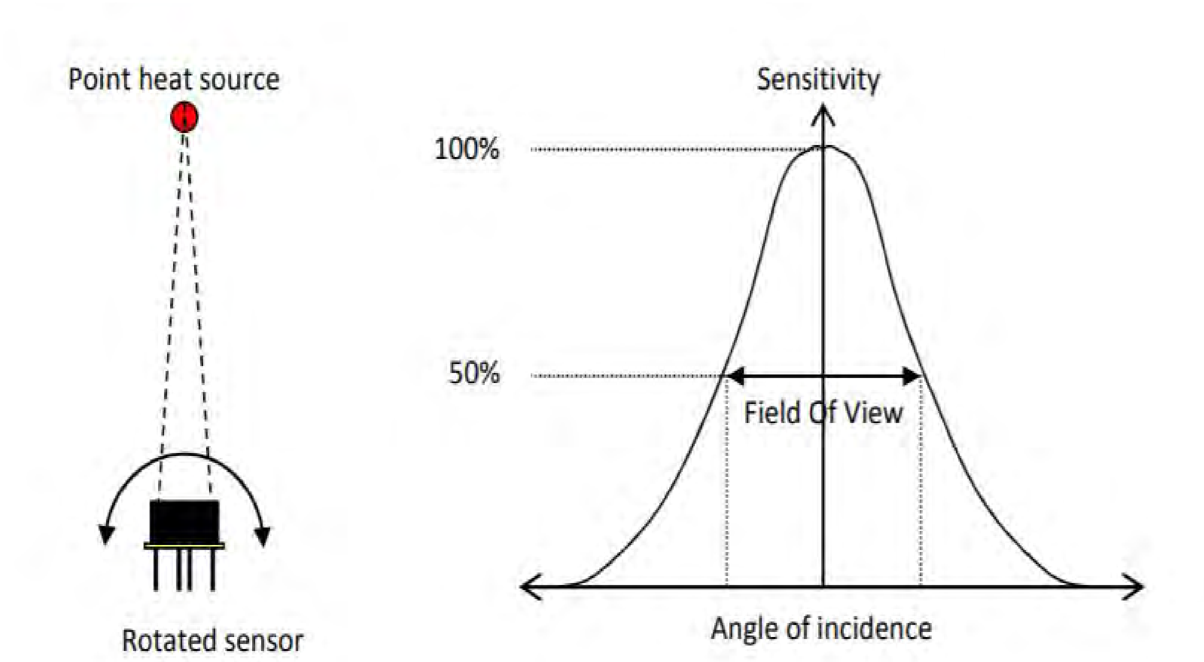


Image 3: Diagram of MLX angle of incidence from datasheet[2]

The LSM9S1 accelerometer provides utility data for any times the drone may not have been at a steady angle relative to the rooftop surface. Additional utility data was provided from the VL53L0X distance sensor to provide a comparative sense of the sensor's distance from the rooftop as compared to the drones altimeter, which measures height from the ground, during flight. This data also supports the validity of the temperature readings in relation to how far away the MLX cone is from the surface. The BME680 also provides auxiliary air temperature, pressure, humidity, and elevation data for environmental analysis.

The following is a table (Table 1) with a description of the various sensors. Note that accuracy refers to how close measurements are to expected values, whereas precision refers to how close measurements are between different devices.

[2] MLX Datasheet

Sensor	Functionality	Accuracy	Precision	Location
MLX 90614 	Measures Infrared Radiation as Temperature (-70 °C to +380 °C)	+/- 0.5 ℃	0.14 ℃	Sensor package
Ultimate GPS 	Measures Position	<3 meters	N/A	Central Package
LSM9DS1 	Measures acceleration (linear and angular) and orientation.	+/- 30dps for gyro +/-90 mg for acceleration	N/A	Sensor Package
VL53L0X 	Measures distance to surface (with narrow laser).	Depends on surface reflectivity.	Default mode: 50 mm to 1.2 meter	Sensor Package
BME 680	Measures air temperature, humidity, pressure, and elevation	±1.0 ℃ ±0.6 / ±0.12 hPa depending on (abs/local) humidity	0.01 ℃ 0.18 Pa	Sensor Package

Table 1. Device Accuracy and Precision[3]

[3] Device Datasheets (2-6)

Processor:

The central processor for the sensor package is a Feather M0 Addalogger (Image 4). The Adalogger allows for a compact and lightweight processing unit, weighing 5.3 grams. The processor serves as the source for I2C communication, a form of serial communication, used by all of our included sensors except for the Ultimate GPS, which uses a different form of serial communications. I2C serves as the protocol for our devices to communicate data with our Addalogger, and works by transferring data bit by bit from the sensor to the processors. The bits are synchronised between processor and sensor via a shared clock signal. The GPS uses a TX data line to transmit data to the Adalogger and a RX data line to receive data/instructions from the processor. Onboard the Adalogger is a microSD card reader/writer which saves space on the main board as well as giving us the means necessary to write the data gathered from our data collections. The complete package of processors plus sensors is shown in Image 5.

Image 4. Adafruit Feather M0 Adalogger

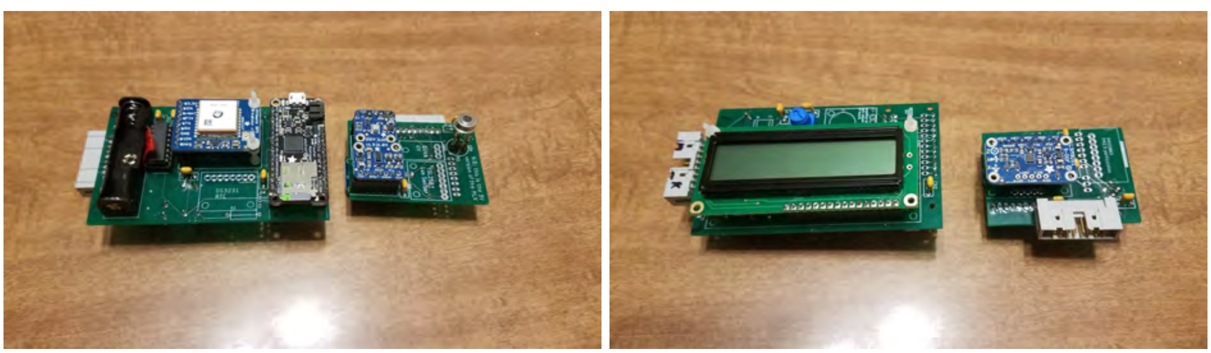


Image 5. Completed Processing and Sensor Packages

Package Transport:

The DJI Mavic 2 Pro (Image 6) is a maneuverable drone that weighs two pounds.[4] It offers a superlative 4k supported video feed with useful GPS and barometric/IR altimeter readings. These devices help provide comparative real time data for the sensor package measurements. Our package is mounted via a 3D-printed basket and cage system. The processing board is mounted atop the drone while the sensor package is suspended approximately 20cm from the underside of the aircraft. The sensor package is placed in a similar printed basket that is secured by wire to each arm of the drone. The sensor package hangs below the DJI MAVIC 2 Pro. The processing board sits above on the mount.

Image 6. Drone without Sensor Package

Data Acquisition:

The Data Acquisition (DAQ) is divided into three main sections: initialization, setup and the loop. In the initialization step, all the libraries are included for the different sensors. Next, all variables are initialized and assigned. Finally, during our initialization the DAQ looks for specific files; in our case FLIGHTXY.csv where X and Y represent digits between 0 and 9. If a file like this exists during the initialization of the program, XY is increased by 1 as long as there

[4] DJI Mavic 2 Pro Specifications (9)

is no name with the current file name which is then created. Therefore, we ensure that every measurement is saved in a distinct file and nothing is overwritten.

During the setup, all the sensors are checked and possible errors are printed on both the serial monitor (Arduino's display window) and the LCD screen of the sensor package. The DAQ program is uploaded via usb cable connection from the Arduino environment to the package. Then, the data file is opened and the first line is filed with the title for each column. The titles include the sensor names and the quantities that are measured.

In the last part of the DAQ, the loop, all the data from every sensor is collected and printed in the proper order into the data file. Some of the data are also printed to the serial monitor so there is a way to see whether or not the device is collecting meaningful data without terminating the program. The way the loop works is by collecting data from every sensor once and writing it to a new line of the file on the SD card. Then the loop returns to the top and reads from the sensors again. One cycle of the loop takes approximately half a second and therefore we get a sampling rate of about 2 Hz. Each flight averaged around 15 minutes and was flown in a counterclockwise circular pattern over the rooftop.

Offline Analysis:

The offline analysis was performed using Python. To read in the data, a data frame was created from the .csv files using the pandas library. As described above, the DAQ writes each data reading as a row in the data file and, by doing so repeatedly, creates columns for every measured quantity. With the pandas data frame, one can access every row individually and also apply computational operations to all the data points in that row. Table 2 shows a few lines of what the collected data looked like. In the beginning the measured GPS quantities show only zero because there was no GPS signal detected yet.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	latitude	longitude	GPS_altitu	GPS_hour	GPS_minu	GPS_seco	mlx_ambi	mlx_obje	vlx_distar	bme_tem	bme_altitude	bme_pressure	bme_humidity	bme_gas
2	0	0	0	0	0	7	22.41	22.19	667	21.77	142.85	996.21	32.24	54.47
3	0	0	0	0	0	7	22.37	23.23	160	22.02	142.51	996.25	32.29	100.25
4	0	0	0	0	0	8	22.39	22.13	388	22.33	142.51	996.25	32.25	135.8
5	0	0	0	0	0	8	22.39	22.57	395	22.57	142.51	996.25	32.16	160.58
6	0	0	0	0	0	9	22.39	22.93	246	22.74	142.34	996.27	32.04	179.43
7	0	0	0	0	0	9	22.39	21.77	671	22.85	142.51	996.25	31.9	193.48
8	0	0	0	0	0	10	22.39	21.67	660	22.94	142.34	996.27	31.79	207.06
9	0	0	0	0	0	10	22.37	22.75	179	23	142.34	996.27	31.67	217.98

1413	4006.648	8813.382	240.4	16	36	52	7.19	10.17	8190	8.84	148.08	995.59	68.2	808.78
1414	4006.648	8813.383	240.4	16	36	53	7.11	9.99	347	8.85	148.42	995.55	68.11	812.2
1415	4006.648	8813.383	240.4	16	36	53	7.11	9.61	8190	8.83	148.42	995.55	68.02	820.12
1416	4006.648	8813.383	240.3	16	36	54	7.03	9.43	8190	8.79	148.25	995.57	67.94	822.63
1417	4006.648	8813.384	240.2	16	36	58	7.01	9.43	8190	8.57	148.76	995.51	67.74	774.77
1418	4006.648	8813.384	240.2	16	36	58	6.97	9.53	8190	8.52	148.76	995.51	67.69	798.69
1419	4006.648	8813.384	240.3	16	36	59	6.91	9.67	8190	8.53	148.59	995.53	67.63	820.12
1420	4006.648	8813.384	240.3	16	36	59	6.91	9.61	8191	8.53	148.59	995.53	67.56	820.12
1421	4006.648	8813.385	240.3	16	37	0	6.87	9.67	8190	8.53	148.59	995.53	67.47	827.18
1422	4006.648	8813.385	240.3	16	37	0	6.87	10.61	8190	8.53	148.59	995.53	67.4	829.22
1423	4006.648	8813.385	240.4	16	37	1	6.87	11.37	729	8.53	148.59	995.53	67.33	836.44
1424	4006.648	8813.385	240.5	16	37	5	6.87	11.41	8190	8.36	148.92	995.49	67.22	785.17

Table 2. Snapshot of parts of the collected data

The first post-processing step was to remove all of the valid data points from the data that did not measure all quantities correctly. Therefore, all the data points with GPS data of zero latitude or longitude were removed. This data is collected when the breakout GPS sensor returns zeros because it does not connect to enough satellites. When the VL53L0X time of flight distance sensor was not able to collect a valid signal, it returns either the value 0 (mm) or 8190 (mm). So, only the rows with distances bigger than 10 (mm) and smaller than 2000 (mm) were counted as valid data and used for further analysis. During this step all of the invalid distance measurements were filtered out. Using that method for the post-processing, we were left with only rows in our frame that show valid and meaningful data for every measured quantity.

Figure 1 calibration measurement between measured temperature of a blackboard versus the measured distance to the blackboard. The orange line shows a linear fit that was fitted to the data. The black line shows the actual temperature of the blackboard measured via a thermocouple.

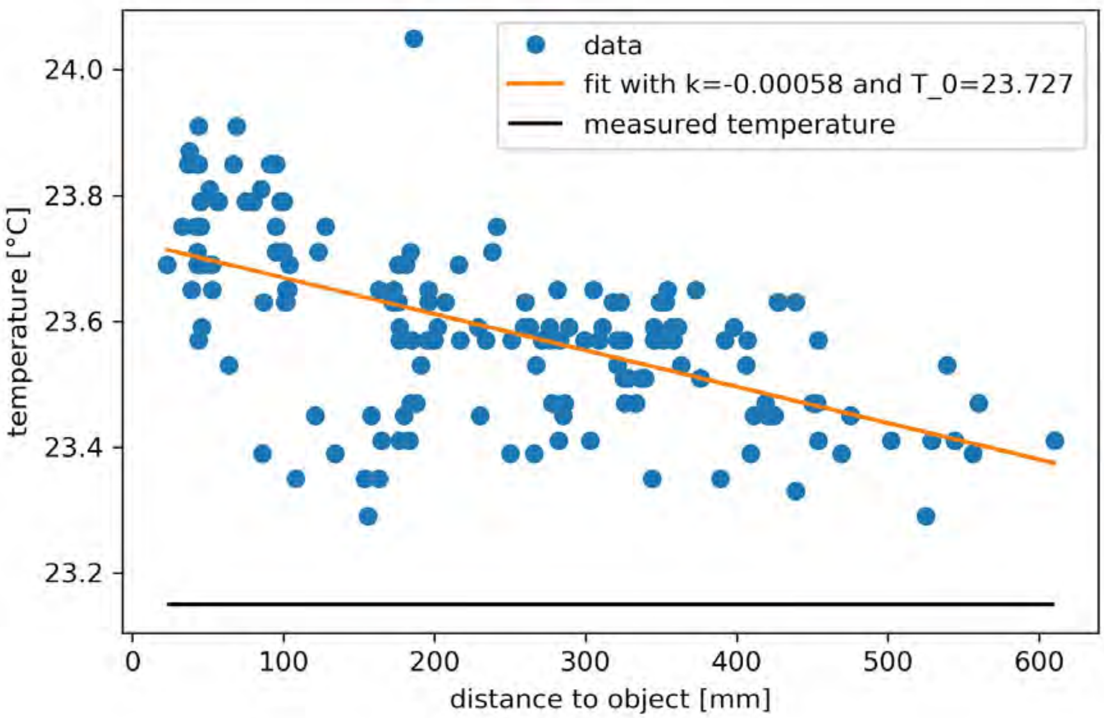


Figure 1. Blackboard Temperature Calibration

The next step was to calibrate the measured temperature. Therefore, a calibration measurement was conducted by using the device to measure the temperature of a blackboard with the distance to the object. Figure 1 shows the result of this calibration measurement. The data points are plotted in blue on a temperature versus distance graph. One can see that the measured temperature decreases with increasing distance. This data was fitted by a straight line:

$$(1)\quad T = k \times d + T_0 ,$$

where T is the measured temperature of the blackboard, d representing the distance of the sensor to the object, and k and T_0 are the fitting parameters. The black line in the figure shows the measured temperature of the blackboard according to a thermocouple which is known to be accurate. Using the determined parameters for k and T_0, it was possible to calibrate the measured temperatures of the following measurements by using:

$$(2)\quad T_C = T_{measured} + (T_{object} - (T_0 + k \times d)) ,$$

where T_C is the calibrated temperature, $T_{measured}$ measured temperature and T_{object} the actual temperature of the object.

Since the latitude and longitude are not as intuitive to handle, the two quantities were changed to distances in meters. The GPS data shown in table 2 is given in a ‘ddmm.mmmm’ format, where d stands for degrees and m for arc minutes. This was transferred to units of degrees. By using trigonometry it was possible to get the distance from the origin where the measurement was taken.

Finally, the data were plotted in two different ways. The 2D scatter plots show the distances calculated from the latitude and longitude on the y- and x-axes respectively, whereas the color indicates the calibrated temperature of each datapoint. The 3D scatter plots have an additional z-axis, which shows the measured distance of the sensor to the rooftop.

In addition, we tried to incorporate the BME 680 altitude measurements to the data to make up for the missing distance data. Therefore, we had to correlate the distance measurements of the VL53L0X and the altitude measurements from the BME680, but we found that there is no correlation between those two measurements (see Appendix B: Plot d.). This leads us to believe that the BME680 is not accurate enough to be a useful tool for our experiment.

Results

Omnifarious buildings were measured over the course of the experiment. We first flew over the Aerodynamics Research Building (ARB)[5]. We then traveled to a local farm where we measured the temperatures over the rooftops of a farmhouse and barn. We were able to successfully run two sensor packages for measurement comparability of the temperature readings. The main building of concern is Loomis Laboratory. We ran many trials and were able to successfully map the distance-calibrated temperature of the rooftop to the effective position of the sensor on the roof.[6] Figure 2 displays a satellite underlay displays our flight path and temperature measurements of the Loomis rooftop.

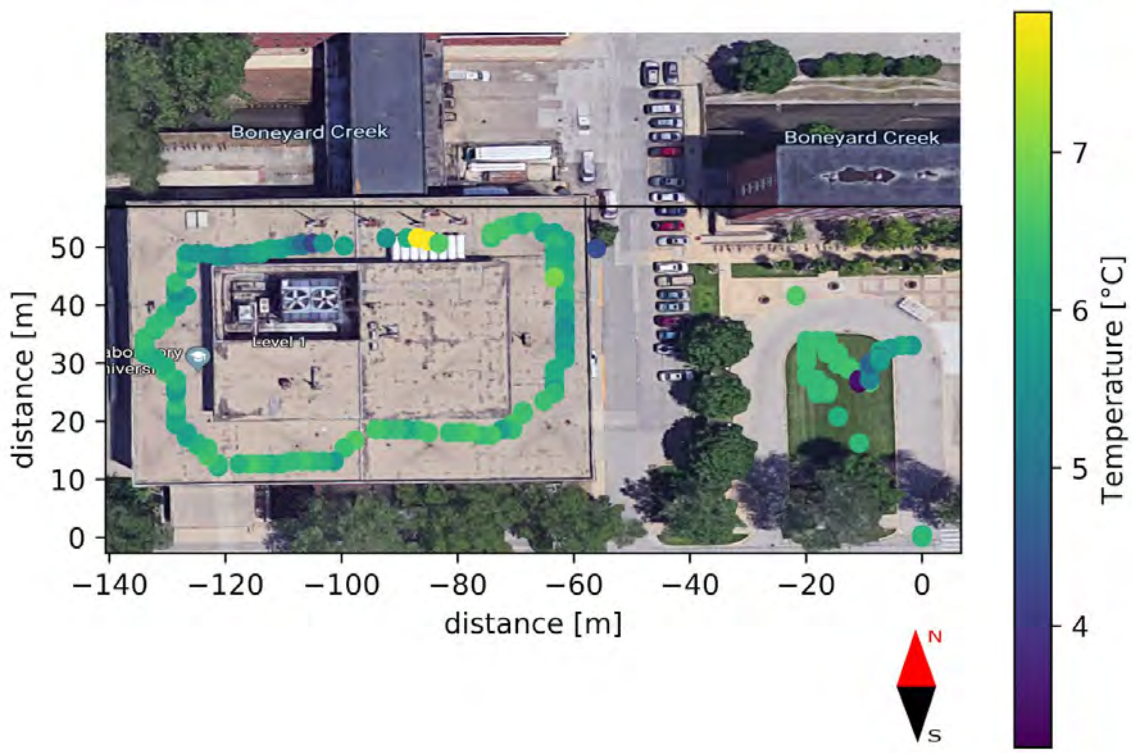


Figure 2. Satellite Flight GPS Overlay of Loomis Roof Temperature 18th Nov at 10 am

The values of the latitude and longitude are of no particular interest. They simply help define the flight path and the arbitrary starting point. The starting point is at the small patch of grass to the east of the building in the image. After conducting a short flight check the drone is flown up to the northeast corner of the building. Due to the removal of invalid data as described in the offline

[5] See Appendix A for images
[6] See Appendix B for plots

analysis section, only certain parts of the flight are represented in the figure. The flight path on the rooftop is separated into four branches, one segmented along each side of the building's rooftop perimeter. The line curves a bit at times to make an effort of avoiding obstacles such as antenna and vents. There is a central part of the roof that is raised and covered in obstacles. Thus we deemed it unfit for aircraft safety. The drone travels clockwise starting southward and completes its route upon returning to the northeast corner. The north segment has many antennae and tanks that were flown over in an attempt to avoid a flight accident.

Figure 3 displays the same flight from Figure 2 but without the satellite image background. We notice the building is particularly warmer on the south segment of flight. The eastern and northwestern corners have an average of 5.5 °C while the south side is approximately a half degree warmer. The strangely out of place hot point on the north side of the building is not to be taken with much interest. The north side has many gas tanks and antenna scattered about. The flight segment was approximately flown straight but altitude was increased to avoid the obstructions. This sensor height increase is evident in Figure 5 where the distance is mapped to the temperature around the roof. The ambient temperature outside was approximately 4 °C at 10 am on 19 Nov 19[7]. The weather was completely cloudy so there were no shadows, thus the roof is assumed to be approximately at equilibrium.

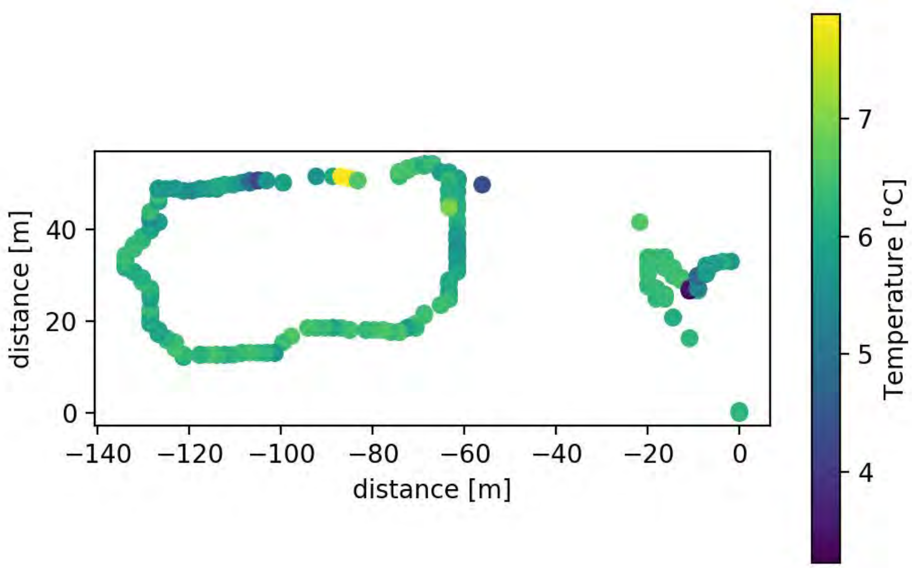


Figure 3. Loomis Roof Temperature 18th Nov (No Satellite Underlay)

[7] Williard (KCMI) weather station

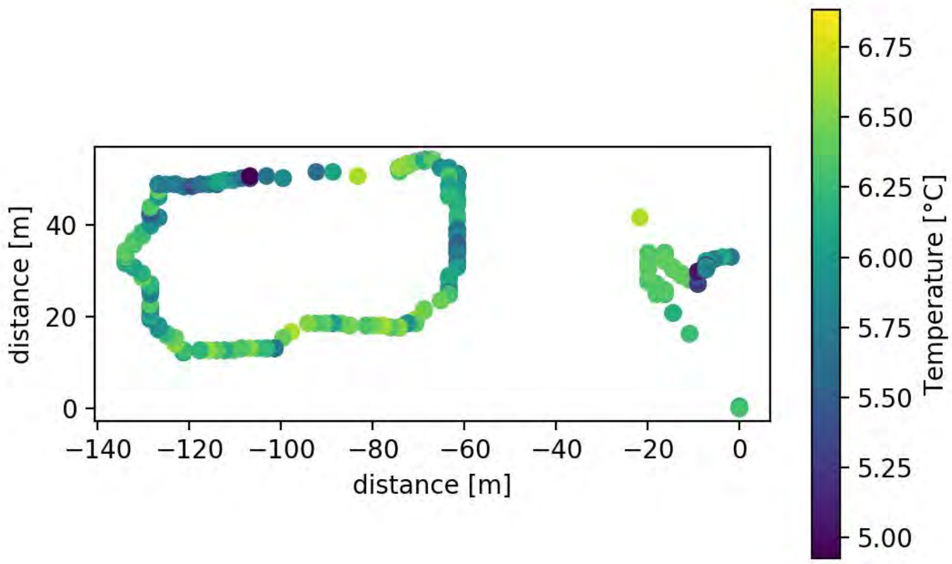


Figure 4. Loomis Roof Temperature restricted to 5°C to 7°C 18th Nov

	Temperature (℃)	Distance (mm)
Average	6.057	336.7
Median	6.195	368.0
Range	(3.223,7.888)	(12,1241)

Table 3. Temperature & Distance Statistics from Flight in Figure 3

We can see from Figure 3 that the northern and eastern sides of the roof are cooler and the southern region in particular is above average which may further support possible heat leakage in this region. Figure 4 restricts the temperature range for better observation of the temperature discrepancies previously described. We were able to reproduce these results similarly on November 20th as seen in figure 6 with an ambient temperature of 5 °C and sunny weather. In this 2nd run the north side is much cooler due to the central roof's shadow being cast over the north segment of the flight. Figure 4b displays the temperature as a function of time during the course of the November 18th flight. The sharply sloped line indicates the rapid air temperature drop as the drone flies from its launch pad up to the rooftop. Table 3 shows important statistical properties of Figure 3.

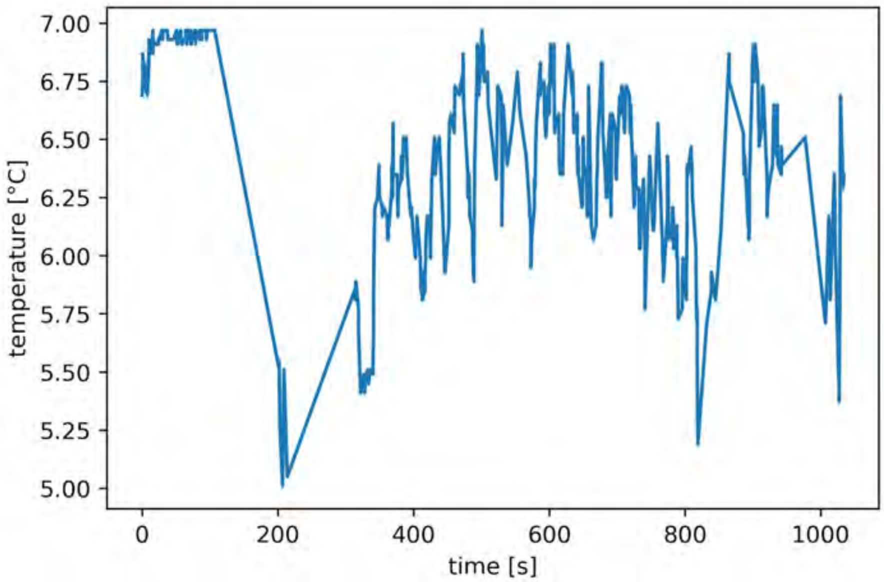


Figure 4b. Evolution of temperature shown in figure 4 over time 18th Nov

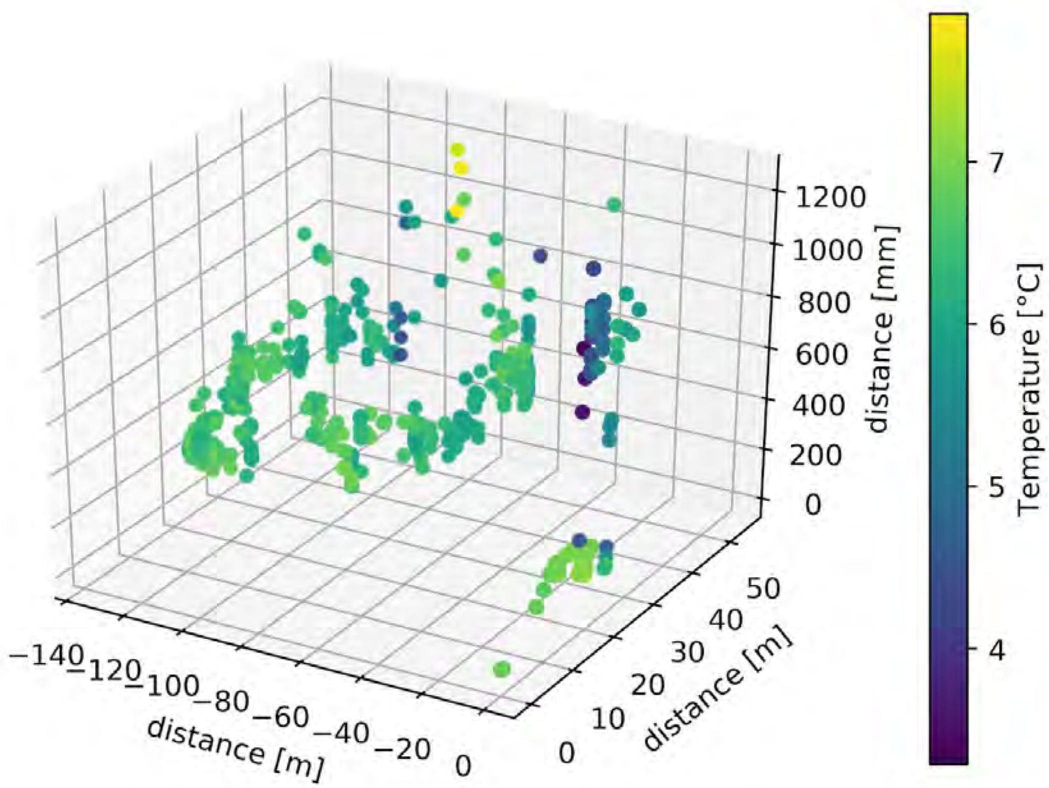


Figure 5. Temperature Vs Distance of Loomis Roof

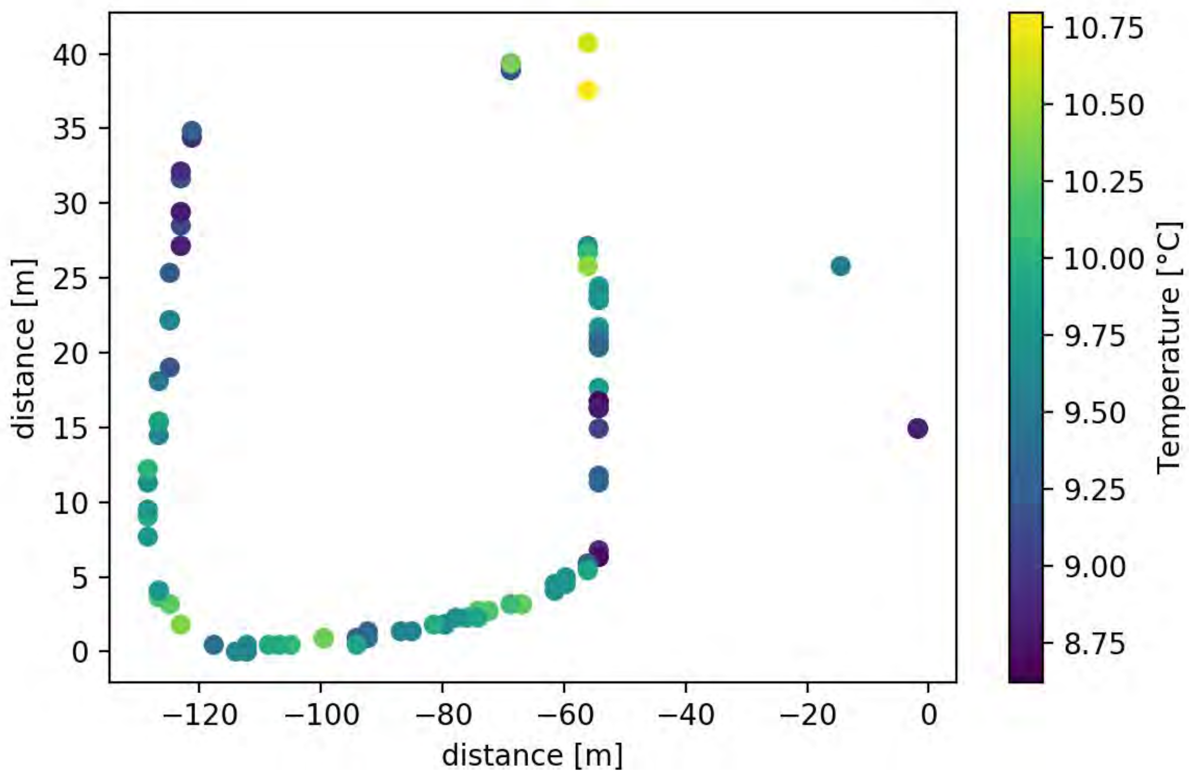


Figure 6. Looms Roof Temperature (9-11°C) 20th Nov at 10 am

We see a similar temperature pattern in Figure 6 as from the Nov 18th flight. The sun was out at this time thus the rooftop temperature was slightly warmer than on the previous flight. Notice the particularly warm spot in the northeast corner of the building. At this time the drone was still above the rooftop from evading the obstacles on the northern stretch and was not directly measuring the rooftop surface. We then flew three iterations fifteen minutes apart on November 22nd with an ambient outside temperature of 4 °C. These flights are represented by Figures 7,8, and 9 respectively. By inspection, the northeast corner is again colder in agreement with the flight on the 18th. A shadow had been cast on the north side at this time but all other segments of interest were in direct sunlight. We notice in all three consecutive flights that the same temperature increase is indicated on the southern and western sides of the roof. This reproduced evidence may further support an indication of rooftop heat leakage.

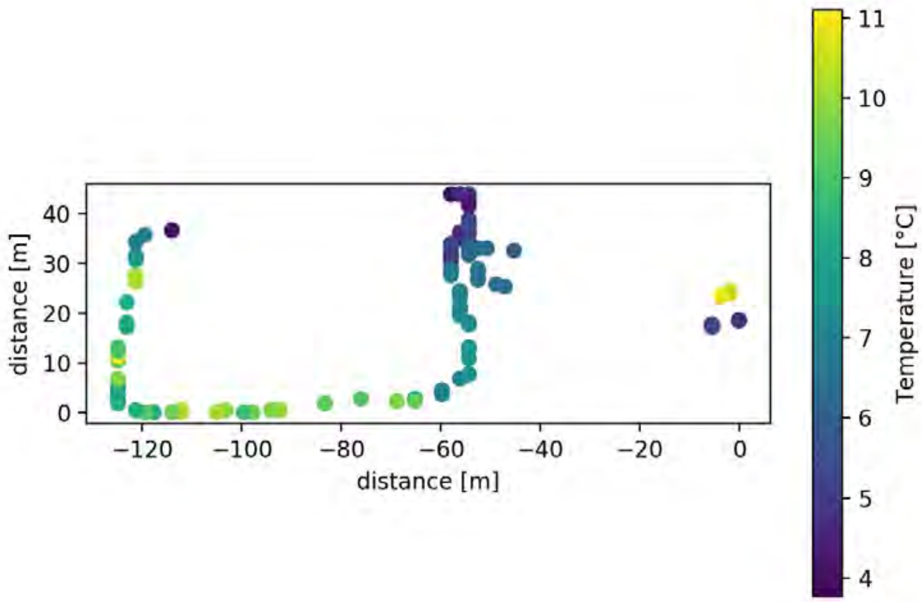


Figure 7. Loomis Roof Temperature (4-11°C) 22nd Nov at 2 pm

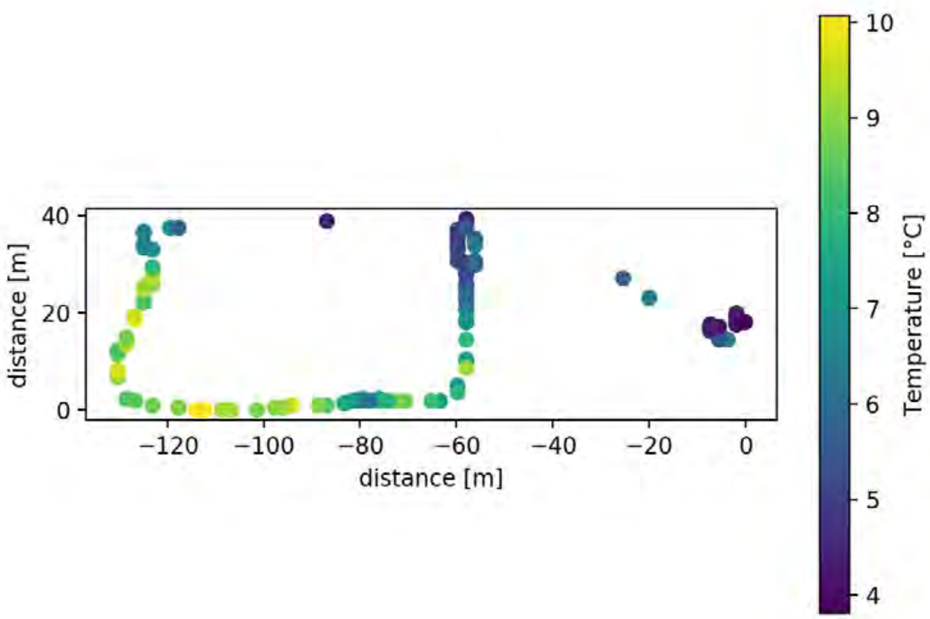


Figure 8. Loomis Roof Temperature (4-10°C) 22nd Nov at 2:15 pm

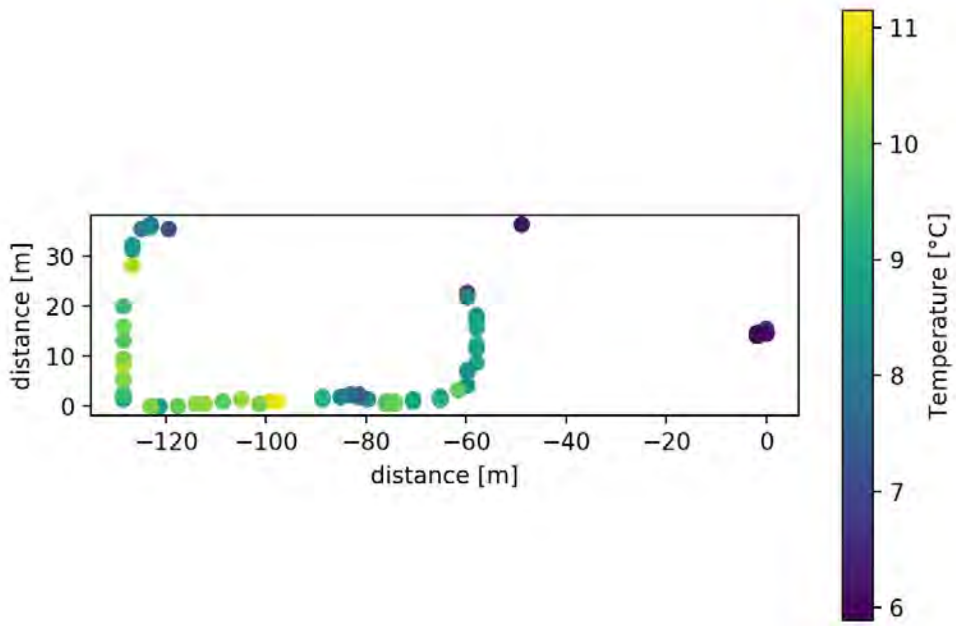


Figure 8. Loomis Roof Temperature (6-11°C) 22nd Nov at 2:30 pm

Conclusion

Our biggest takeaway from our results is that the method we have used is valid for measuring temperatures of surfaces with considerable accuracy. When carrying out the various phases of tests for this experiment we had numerous issues gathering useful data. These included errors in developing the code for the adalogger, the issues with the VLX distances maxing out. Once we gathered a reasonable amount of substantial data, we were able to validate our method and begin to look for the leakage we had originally hypothesized.

Our most recent and most successful scans of the rooftop of Loomis Lab has presented us with a very useful set of data to analyze. For the majority of the run, the data points show a consistent temperature around the perimeter of the rooftop (see Figure 3). However, there are a few points that show an increase in temperature. We cannot say conclusively that these spots represent notable heat leakage from the roof, as this may just be a source of increased temperature on the inside of the building. What we can conclude from this is what was previously stated, in that we have devised a valid method for analyzing rooftops and potentially other surfaces for notable temperature changes.

Overall, we would conclude that our experiment was a success and that our method is appropriate for what we are trying to accomplish. In order to further cement our conclusions we would need to perform additional trials, and make sure we get more repeated results to further reinforce our results.

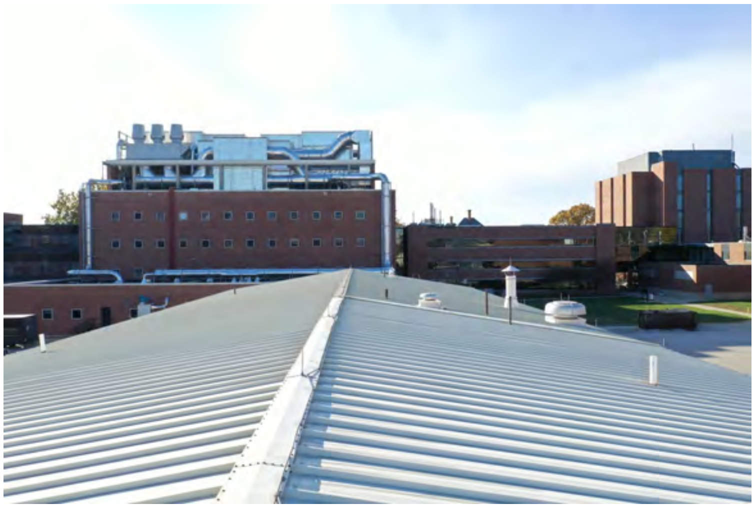
Future Work(s)

Upon gathering accurate data, and seeing that we are capable of measuring changes in temperature via our method, we can expand our work in various ways. The clear next step would be to perform measurements on various other buildings around campus, with interest being in some of the older buildings such as Noyes Lab of Chemistry. If significant heat leakage is found throughout campus, we would hope to advise the appropriate departments of the findings.

The ultimate goal could be to create a low maintenance mount and sensor package for a drone and then program it with AI to carry out these measurements automatically via Bluetooth communication. By creating a system that can carry out these tasks automatically, the entirety of the campus could be measured easily as well as other places around the Champaign-Urbana area. The end goal would be for the project to be used as an efficient way of determining if heat loss is a problem in all varieties of buildings.

Appendix A

Drone Photo Gallery



(a) Aerodynamics Research Building Rooftop

(b) Drone Launch Pad

(c) Farmhouse Rooftop With Heat Vents (431 County Rd 700 N Sadorus, IL)

(d) Northwest Corner of Loomis Laboratory Rooftop Facing Southeast

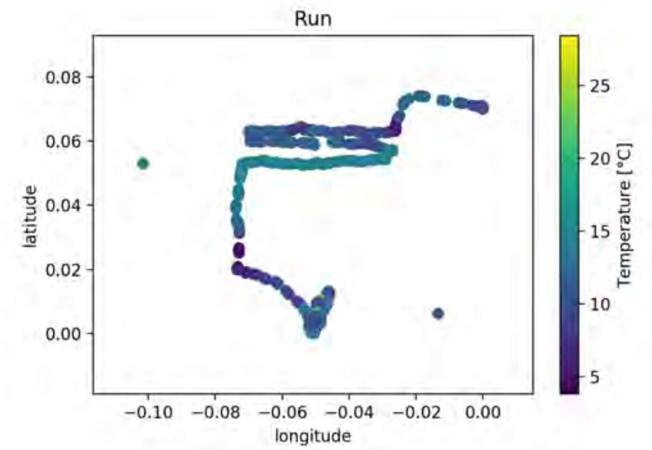
(e) 90 Degree Farmhouse Heat Vent

(f) Southeast corner looking north of Loomis

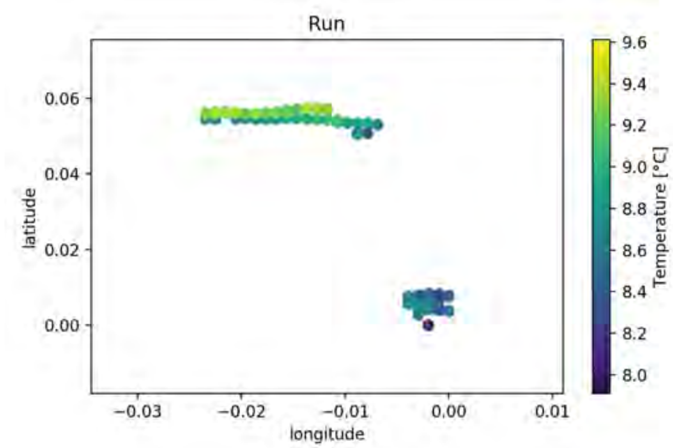
(g) Avoided raised central section of Loomis

(h) Southeast corner looking west of Loomis

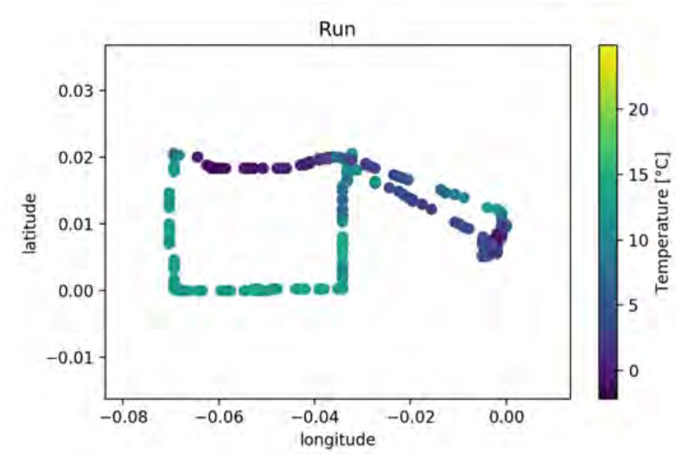
Appendix B
Test Building Trials



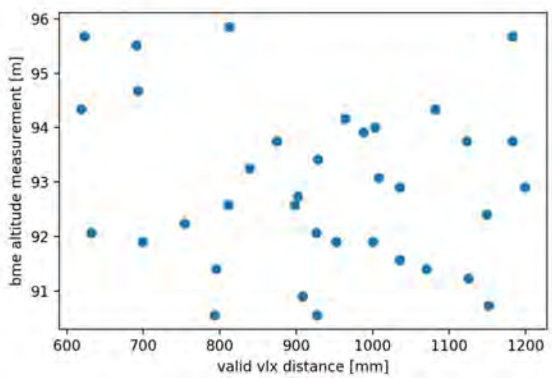
(a) Aerodynamics Research Building Multiple Pass Flight



(b) Farmhouse Multiple Pass Flight



(c) Loomis Laboratory Test Flight



(d) Measured BME680 altitude vs measured VL53L0X distance to the object. Measurement taken on the rooftop of Loomis.

References

1. Heat Loss Facts
   https://www.phpsd.com/blog/the-two-part-secret-to-minimizing-energy-loss-on-your-co
   m
   mercial-rooftop
2. MLX 90614 Datasheet/Information
   https://www.melexis.com/-/media/files/documents/datasheets/mlx90614-datasheet-melex
   is.pdf
3. Ultimate GPS Datasheet/Information
   https://cdn-learn.adafruit.com/downloads/pdf/adafruit-ultimate-gps .pdf
4. LSM Accelerometer Datasheet
   https://www.st.com/resource/en/datasheet/DM00103319.pdf
5. VL5310X IR Distance Sensor Datasheet
   https://www.st.com/resource/en/datasheet/vl53l0x.pdf
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