Bird-Friendly Electrochromic Windows

ECE 445 Final Report – Spring 2023

Project # 48

Phoebe Chen, Mary Rose Farruggio, Owen Thamban

Professor: Olga Mironenko
TA: Abhisheka Mathur Sekar

Abstract

Fatal bird-window collisions pose a significant conservation concern. Current solutions are aesthetically unappealing and therefore have low adoption rates by both homeowners and architects. The goal of our project is to create a bird-friendly window prototype using electrochromic panels that turn opaque once birds are within a certain distance threshold of the window. We aim to minimize and prevent fatal collisions while maintaining the aesthetic appeal of the window.

Contents

Introduction

2.1 Problem

Each year, roughly one billion birds in the U.S. die due to collisions with windows [1]. Even birds that are only temporarily stunned and fly away often die later due to bruising and internal bleeding in the brain or other vital organs. For some species such as the ovenbird, window collisions cause more fatalities than any natural predator [2]. During the day, windows often reflect the sky and outdoor foliage which can seem inviting to birds. Birds that see through the glass are frequently attracted to houseplants or other vegetation within the home. In the evenings the glass of windows becomes invisible to birds. Making matters worse, many nocturnal migrants (including most songbirds) are attracted to the artificial light in homes, pulling them off course, causing confusion, and significantly heightening their risk of a fatal window collision. In the Spring months collision rates also rise due to territorial behavior in many species that can cause them to attack their own reflection in the glass [3].

All of the solutions currently available on the market (tightly spaced markings, mosquito netting, decals) involve a significant and semi-permanent change to the aesthetic appeal of a building. Despite the benefits to local wildlife, many homeowners and architects are unwilling to make this compromise. Hence, a new solution is needed to prevent bird-window collisions while maintaining the aesthetic appeal of large windows.

2.2 Solution

In response to this problem, we created a bird-friendly window that prevents bird-window collisions while maintaining the aesthetic appeal of large windows. The essential concept is to make birds aware of the presence of a hazard before a collision occurs, giving the birds time to react and change course. Our design relies on electrochromic materials that can transition between transparent and opaque depending on the voltage applied across them. At rest, the electrochromic panels will be in a transparent state. Our system is designed to detect a bird's approach using ultrasonic sensors and image processing. The ultrasonic sensors are attached to a frame, which extends a sufficient distance from the window to detect and react to a bird early enough to allow a direction change. When a bird is detected by either the ultrasonic sensors or the image processing, the electrochromic panels will transition to or remain in an opaque state, making the birds aware of the hazard in front of them. This system should allow birds to respond to windows as a hazard and avoid potentially fatal collisions.

2.3 Visual Aid

The ultrasonic sensors have a 15 degree angle of detection [4] and are pointed across the sides and front of the frame as seen in Figure 1, such that any bird entering the area in front of the window must pass through one of the areas detected by the ultrasonic sensor. The ultrasonic sensors are connected to the microcontroller, which times the delay between sending out a pulse and receiving the echo. By dividing the time it takes the ultrasonic sensor to return an echo by the speed of the ultrasonic wave, our microcontroller can determine the distance from the ultrasonic sensor to the object immediately in front of it. In the horizontal direction, our threshold distance will be 45 cm, the distance from Frame Part 1 to Frame Part 2 minus the wingspan of the smallest bird we are targeting (See Figure 2). In the vertical direction, our threshold will be 15 cm, representing the inner side length of Frame Part 2 minus our margin of error. If the microcontroller computes a distance from one of the ultrasonic sensors that is less than the threshold distance, it follows that another object entered the area immediately in front of the window. The microcontroller then tells the Raspberry Pi to initiate image processing using the thermal camera to determine whether the object detected by the ultrasonic sensors is a bird. If the object detected is a bird, the Raspberry Pi will continue to track the object's location relative to the frame and tell the microcontroller to turn the correct electrochromic panel opaque based on the bird's location. If the object detected is determined not to be a bird or the bird leaves the area, the system will return to a rest state (all electrochromic panels will be transparent). The frame holds four electrochromic panels in a square arrangement, and an ultrasonic sensor is mounted in the center of each side of the square (Figure 1). There are also two additional ultrasonic sensors directed downwards across the front of the frame as mentioned previously. The thermal camera is mounted at the center of the electrochromic panel configuration as shown in Figure 1.

2.4 High Level Requirements

To consider our project successful, our window system must fulfill the following:

- When the system is at rest, the panels must be kept in their transparent state. The system is considered at rest before a bird is detected or after a bird has exited.
- The system must be able to successfully detect an object of length ≥ 11 cm and width ≥ 19 cm (minimum length and wingspan of the seven birds with the highest rates of window collisions [2]) entering or exiting through the front of the 24 cm x 24 cm x 58 cm rectangular prism encompassed by the frame traveling at 7.6 m/s or less in ≥ 80% of trials.
- When the system determines that an object has been detected entering the frame-encompassed area, it must successfully transition one or more of the electrochromic panels from transparent to opaque.

These requirements are based on several key assumptions based on our research:

- The majority of fatal bird-window collisions are head-on.
- The system will only have to consider one bird entering or exiting the system at a time.
- Our system is designed to protect the seven species most likely to experience fatal bird-window collisions, not every shape, speed, and variety of bird. According to our research, the bird species at highest risk cannot fly upside down or perpendicular to the ground.

While these assumptions are slight simplifications of the system, we believe they are reasonable given the context and size of our proposed application.

2.5 Block Diagram

The System Block Diagram (Figure 3) is available for reference in the Appendix.

2.5.1 Control Subsystem

The Control Subsystem is responsible for interacting with the ultrasonic sensors in the Object Detection Subsystem, the Raspberry Pi in the Object Classification Subsystem, and the electrochromic panels in the Bird Interface Subsystem. It controls the trigger input to each of the ultrasonic sensors and calculates the distance detected by each ultrasonic sensor based on the echo output. If an object is detected going into the 3D frame, the microcontroller signals the Object Classification Subsystem to turn on the IR Thermal Camera, with a focus on the block(s) where the object was detected as entering. Making the Control Subsystem responsible for initiating our image processing helps determine whether we need our IR thermal camera and real-time video processing to be running at any given time. Since the Control Subsystem also supplies the Object Classification/Video Processing Subsystem with information on which ultrasonic sensor detected a change in distance, this setup also helps more specifically identify where the entering object should be within the 2D thermal frames of our IR camera. The Control Subsystem also receives information from the Object Classification Subsystem on which electrochromic panels have the warm-blooded object in front of them. Based on this classification information, the Control Subsystem can signal the Bird Interface Subsystem about which electrochromic panels should be opaque. The Control Subsystem consists of the ATMega32U4-MU microcontroller. The Control Subsystem requirements are as follows:

- The Control Subsystem must be able to calculate distances correctly based on input from the ultrasonic sensors. For measured distances below 20 cm, the accuracy of the calculated distances should be within 5 cm. For measured distances between 20-60 cm, the accuracy of the calculated distances should be within 10 cm. These standards should be met in 90% of trials.
- The Control Subsystem must be able to signal the electrochromic panels to change opacity once an object is detected. I/O pins controlling the opacity should transition to a high voltage (2.7-5.5 V) and low voltage (0-2.75 V) correctly in 90% of trials.
- The Control Subsystem must be able to initiate image processing in the Raspberry Pi. The interrupt pin of the microcontroller feeding into the Raspberry Pi must go high (2.7-5.5 V) when an object is detected in 90% of trials.

2.5.2 Object Detection Subsystem

The Object Detection Subsystem is responsible for detecting where warm-blooded animals have entered or exited the 3D frame in front of the electrochromic panels. This subsystem consists of 6 ultrasonic sensors which communicate with the Control Subsystem via the trigger-echo protocol. (See Figure 1 for where the ultrasonic sensors are placed along the 3D frame). When the Control Subsystem sets the trigger pin to high, the corresponding ultrasonic sensor sends out 8 ultrasonic pulses. The ultrasonic sensors then utilize the echo pin to signal to the Control Subsystem how long it took for the pulse signals to be reflected back from objects detected within their 2-400 cm beam range. Using the time between when the ultrasonic sensors emit their pulse and the time the pulse is reflected back, we can divide by the known speed at which the pulse traveled (343 m/s), to determine the distance between the sensor and the closest object in front of it. The Object Detection Subsystem requirements are as follows

- For measured distances below 20 cm, the accuracy of the calculated distances should be within 5 cm of the measured distance in ≥ 90% of trials. For measured distances between

20-60 cm, the accuracy of the calculated distances should be within 10 cm in ≥ 90% of trials.

- The ultrasonic sensors must be mounted on the frame in such a way that they can accurately determine which electrochromic panel zones the detected objects are entering/exiting within the 3D frame area in ≥ 90% of trials.

2.5.3 Object Classification Subsystem

The Object Classification Subsystem is used to determine whether a detected object that has entered or exited the 3D frame is warm-blooded, as well as track a classified warm-blooded object within the 3D frame. It receives information from the Control Subsystem on where an object has entered or exited the 3D frame, in terms of the 2 x 2 electrochromic panel grid. Depending on the temperature and size of the object in the specified region, the subsystem determines whether or not the object is warm-blooded. The subsystem then keeps track of which electrochromic panels the warm-blooded object is in front of, and sends this information back to the Control Subsystem. The Object Classification Subsystem includes an IR Thermal Camera and a Raspberry Pi 3 Model B+ single-board computer. The Raspberry Pi controls the IR Thermal Camera via the I2C communication protocol, and receives video data through the SPI communication protocol for our image/video processing. The requirements for the Object Classification Subsystem are as follows:

- The image processing can correctly identify warm blooded objects within the 24 cm x 24 cm x 58 cm frame space in ≥ 80% of trials.

2.5.4 Bird Interface Subsystem

The Bird Interface Subsystem consists of four 10 x 10 cm panels of electrochromic material. The electrochromic panels will become transparent given a 7.7 V and 60 Hz AC voltage. The Power Subsystem will supply the current to the panels while the Control Subsystem will use a digital switch to turn the panels off and on. The requirements for the Bird Interface Subsystem are as follows:

- The opacity must visibly transition between transparent and opaque in response to the microcontroller.

2.5.5 Power Subsystem

The original design of the Power Subsystem contains a barrel jack power supply connecting our PCB to a wall outlet and supplying a constant 5V to the microcontroller, Raspberry Pi, ultrasonic sensors, and voltage regulator. The second primary component is the voltage regulator we use to step down from 5V to 3V. The DC to AC converters feeding our electrochromic panels take the 3V output of the regulator. There is an additional voltage regulator within the Raspberry Pi that supplies the IR camera with 3.3V. Because the system was moved from the PCB to a breadboard for the final presentation, the final implementation of the power subsystem used a voltage supply in place of the voltage regulator due to lack of components. The requirements for the Power Subsystem are as follows:

- The barrel jack power supply must provide a steady 4.5-5.5 voltage at all times the system is operating.

- The voltage regulator must supply a DC input voltage of 2.5-3.5V to the DC to AC converters feeding into the electrochromic panels at all times the system is operating.

Design
3.1 Design Procedure
3.1.1 Control
Since the Control Subsystem consists only of the microcontroller, the primary design decision involved was selecting an appropriate microcontroller for the application. The project required a microcontroller with enough pins to communicate with the ultrasonic sensors (12 pins), Raspberry Pi (9 pins), and the digital switches (4 pins). The larger number of I/O pins required narrowed the selection of microcontrollers significantly. While there were still many commercially available microcontrollers available with a sufficient number of pins, the team chose the ATMega32U4-MU because it was recommended on the course website, several team members already had experience with the corresponding coding language and IDE, and there were many resources available online to support working with that family of microcontrollers.
3.1.2 Detection
One major design decision for the Object Detection Subsystem was the number of ultrasonic sensors mounted to the frame. The team went through many iterations of sensor number and placements in an effort to find the optimal configuration that would ensure no birds could pass into the frame without triggering at least one of the ultrasonic sensors. After deciding on the two-part frame design depicted in Figure 1, the system needed sensors on both the sides and front of the frame-encompassed area. One early design used 22 ultrasonic sensors to cover the entire surface area of the rectangular prism encompassed by the frame in an effort to ensure that no birds could enter the system without being detected. However, further research showed this was likely to cause interference between the sensors and introduce significant error into the calculated distances. Furthermore, the more sensors used, the longer it would take to cycle through checking each sensor in the microcontroller code, which would have a negative impact on the system response time. More sensors also draw more current, which decreases the available current the microcontroller can supply to other subsystems. Additionally, covering the entire surface area of the rectangular prism encompassed by the frame is unnecessary, as any bird entering the system must have some real-valued height, length, and wingspan. Therefore, it was advantageous to decrease the number of sensors to the minimum number necessary to ensure detection. Using the wingspan and length of the smallest species of bird targeted by the project, the team was able to decrease the number of sensors down to 6, placed such that no gaps were large enough for a bird to pass through the front of the frame undetected. Final placements can be seen in Figure 1.
3.1.3 Classification
The classification subsystem consists of a FLiR Lepton Thermal Camera and a Raspberry Pi B+ for image/video processing. The Raspberry Pi controls the IR Thermal Camera via the I2C communication protocol, and receives video data through the SPI communication protocol, for image/video processing.

We initially planned to implement the image/video processing code from scratch, which was way too complex for the scope of this class. Thus, we turned to using OpenCV in Python instead, with which we can test out different computer vision algorithms more easily, knowing that the library's provided high-level functions are efficiently implemented, and would satisfy our timing requirements better. As shown in the image/video processing flowchart below (Figure 11), there are two main functions: classifying detected objects, and tracking classified warm-blooded objects.

For both the classifying and the tracking functions, we first set frame pixels with values corresponding to temperatures within our desired range to white (255), and the remaining frame pixels to black (0). This allows us to more accurately find contours/blobs, and simplifies tracking. One thing to note is that we adjusted the desired contour/blob temperature range to that of humans', because functionality testing was done with human hands.

Due to the assumption that at most one warm-blooded object is within the 3D frame, an object would be classified as warm-blooded only if it is the only contour/blob with an area, bounding box width, and bounding box length within the desired size, width, and length range.

After changing environments, we realized that the temperature thresholds needed to be changed whenever we moved the thermal camera to a new environment, due to…..This means we would have to test/calibrate outputs of the thermal camera before using our bird-friendly window in a new environment. (This does not take long, though.)

Originally, for the classifying function that gets invoked during an "object detected" interrupt, we wanted the boundary points of the warm-blooded object to cover exactly the set of grid blocks specified by the Controls Subsystem. However, after testing with human hands, we found out that fingers potentially have lower temperatures than the palm's/the desired temperature range. This made us realize that bird feathers/legs could also be detected by the ultrasonic sensors, but not show up as part of the contour/blob when we set the pixels to white or black (depending on their values' corresponding temperatures) at the beginning. Therefore, our classifying function now decides to classify the detected object as warm-blooded if the boundary points of the contour/blob covers at least one of, or at most the set of specified grid blocks.

A Kernelized Correlation Filter (KCF) was originally considered for the tracking function. It has sufficiently fast throughput and accuracy, and can stop tracking when the tracked object is lost. When we get the region of interest (ROI) output per new thermal frame, we could go over each of its pixels and determine which of the 4 grid blocks have white pixels (meaning that the warm-blooded object is in front of it). However, we later realized that simply re-finding the contour/blob in the thermal frame and then going through its boundary pixels to determine which of the 4 grid blocks have white pixels, just as we do for the classifying function, would theoretically be more time and space efficient than using a KCF. (*Note: we deal with the exception/case of having more than one blob within the desired temperature and size ranges by considering the tracked object as "lost").

3.1.4 Interface

The Bird Interface Subsystem consists of the electrochromic panels and DC to AC converters. The team needed to decide how many electrochromic panels to use, the size of the panels, and the arrangement of panels. The team decided to use four electrochromic panels. Four was chosen as a sufficiently large number to demonstrate that the panels could be independently transitioned from transparent to opaque in response to the warm-blooded object's location without adding unnecessary system complexity. For practical reasons such as portability and budgetary restrictions, the team decided to use 10 x 10 cm panels. While commercially available panel sizes range from a few centimeters to several meters, larger panels were not necessary to demonstrate the concept behind the technology. The team decided to arrange the panels in a 2 x 2 grid because this arrangement most closely resembled a common arrangement of panes in a window.

3.1.5 Power

The team decided to use a barrel jack to supply power to the system because the barrel jack allowed larger total current draw than could be supplied by the microcontroller alone, the system did not need to be portable, and connecting to a wall outlet was a more reliable power source than batteries. Because most subsystems required a 5V input and the DC to AC converters alone required a 3V input, it seemed logical to add a 3V voltage regulator fed by the DC barrel jack to supply power to the DC to AC converters. While alternatively a second power supply could have been added, the connection for this second power source would have taken up unnecessary space on the PCB.

3.2 Design Details

Exact component values and circuit layout can be found in the schematic, listed in the Appendix as Figure 4. PCB Layout can be found in the Appendix under Figure 5.

3.2.1 Physical Design

For reference, the physical dimensions of the system are displayed graphically in Figure 2 of the Appendix. Each of the electrochromic panels is 10 cm by 10 cm. The model ordered for the project is an easy to apply "peel and stick" with an adhesive on one side which was attached to the frame. To ensure that there is sufficient overlap between the electrochromic panels and the frame, each opening of Frame Part 1 is 8 x 8 cm so that 1 cm of adhesive can be used to attach the panels to the frame along each side. The central beams in the horizontal and vertical direction of Frame Part 1 are each 2 cm wide, and the outer beams of Frame Part 1 are 3 cm wide. Frame Part 2 is a simple rectangular frame with a width of 3 cm. The four ultrasonic sensors attached to Frame Part 1 are mounted such that their beams are perpendicular to both frames and align with the center of each side of the square. The two ultrasonic sensors attached to Frame Part 2 are centered 6 cm away from the inner edge of the frame and each other. Frame Part 1 and Frame Part 2 are placed 58 cm apart.

Additionally, as seen in Figure 6, the 15 degree ultrasonic sensor beams cover most of the open 3D frame's surface area, and thus are able to detect bird-sized objects passing through.

3.2.2 Ultrasonic Sensor Code

The ultrasonic sensor code written on the microcontroller checked the distance detected by each sensor sequentially, with the basic outline shown in Figure 7. If an ultrasonic sensor detected a distance below the threshold, this indicated to the system that there was an object entering or exiting the frame. The microcontroller would then initiate image processing in the

Raspberry Pi by setting the interrupt pin to high. If the I/O pins of the microcontroller receiving feedback from the Raspberry Pi indicated that image processing had detected a bird, the microcontroller output a low voltage to the digital switches, disconnecting the electrochromic panels from power and causing the panels to turn opaque.

Verification

The verification process started with testing the accuracy of each ultrasonic sensor by looking at the distance it returned on the serial monitor of an Arduino versus the actual distance measured with a ruler. This was done in increments of 5 cm for distances 5-80 cm. The results are shown for all ultrasonic sensors in Figures 8 and 9. The sensors are accurate within 10% for every measured distance before 55 cm, and the error was within the acceptable margin to meet all high level and subsystem requirements. It was also necessary to test the opacity transitions of the panels and output of the DC to AC converters. All possible combinations of panels and DC to AC converters were tried with successful transitions in all cases. In an effort to quantitatively measure the opacity changes of the panels, a lux meter was used to measure the light detected through the panels from a controlled lights source when the panels were in both opaque and transparent states. The results can be seen in Table 1 of the Appendix. Additionally, the output of one of the DC to AC converters is shown in Figure 10. The last stage of verification for the integration of the Object Detection Subsystem, Control Subsystem, Power Subsystem, and Bird Interface Subsystem, was to place a hand in front of each sensor to make sure that the specific panels corresponding to each sensor would turn opaque at the correct distance threshold. This was successful for three of our four panels, as the last panel's functionality failed due to a broken DC/AC converter. The nonfunction DC/AC converter worked in initial testing, but was damaged due to a wiring error during system integration.

Although the final system was not fully integrated, the output of the Object Classification Subsystem was verified using LEDs to indicate which panels the subsystem believed to contain a warm-blooded object. By holding a hand in front of the thermal camera, capturing an image, and observing which LEDs were turned on based on the image captured, it was possible to verify that the image processing was correctly finding and tracking warm-blooded objects within the field of vision of the thermal camera. The Object Classification Subsystem had greater than 95% accuracy, which was more than sufficient to meet our high level requirements. More detailed requirement and verification tables for each subsystem can be found in the Appendix.

Costs

Since Group 48 consists of three Seniors in Electrical and Computer Engineering at UIUC, a realistic estimated approximate cost per hour of labor is $45/labor. Including the soldering of components, the programming of communication between the microcontroller and Raspberry Pi, the image processing of the thermal camera images, the integration of the UV sensors and electrochromic panels, the estimated total amount of labor is 150 hours. This comes out to $6750 for labor and an additional $143.98 for materials (excluding the Lepton Thermal Camera Breakout) as detailed in the table below.

Description	Manufacturer	Quantity	Total Price	Links
22pF Capacitor	KYOCERA AVX	2	$0.20	Link
1uF Capacitor	TAIYO YUDEN	2	$0.30	Link
MBR0520 Diodes	Micro Commercial Co	2	$0.40	Link
USB Mini-B Connector	Tensility International Corp	1	$1.32	Link
IDC Connector Header for AVR-ISP-6	Wurth Elektronik	1	$0.48	Link
Barrel Jack Connector	Wurth Elektronik	1	$1.02	Link
1x4 Molex Connectors (EG Control, EG Gnd, RPI, US0…5)	Molex	9	$3.15	Link

1x2 Molex Connector (RP Power)	Molex	1	$0.21	Link
1x5 Molex Connector (RPO)	Molex	1	$0.41	Link
22Ohm Resistors	Bourns Inc	2	$0.20	Link
10k Resistor	YAGEO	1	$0.10	Link
Atmega-32u4-m	MICROCHIP	1	$4.92	Link
TC1108-3.0VDBTR	Microchip Technology	1	$0.70	Link
MIC2091-1YM5-TR Power Distribution Switches	Microchip Technology	4	$1.04	Link
20kOhm Resistors	YAGEO	4	$0.40	Link
16MHz Crystal	Abracon LLC	1	$0.36	Link

Description	**Manufacturer**	**Quantity**	**Total Price**	**Links**
Ultrasonic Distance Sensor - HC-SR04	Adafruit Industries LLC	6	$23.70	ECE Supply Center

32 GB SD Card (for Raspberry Pi)	SanDisk	1	$7.49	ECE Supply Center
Thermal Camera (Lepton Thermal Camera Breakout) - KIT-13233 ROHS	FLiR	1	(Retired Product)	Link
Raspberry Pi - Raspberry Pi 3 Model B+	Raspberry Pi	1	$35	Link
Raspberry Pi Power Supply	Raspberry Pi	1	$19.99	Link
Electrochromic Windows - HOHOFILM 10cmx10cm Smart Film PDLC Magic Switchable Transparent Color Film	HOHOFILM	4	$34.44	Link
MTA-100 2 Pin Connector	TE Connectivity AMP Connectors	2	$0.44	Link
MTA-100 4 Pin Connector	TE Connectivity AMP Connectors	18	$4.86	Link
MTA-100 5 Pin Connector	TE Connectivity AMP Connectors	2	$0.78	Link

Barrel USB Power cable	Grid Connect Inc	1	$14.95	Link
USBASP Programmer with Adaptor	SparkFun Electronics	1	$18.50	Link
USB A to USB Mini-B Cable	Monoprice	1	$1.49	Link
Lux Meter	Cheffort	1	$19.95	Link

Conclusions

Although the final version of our system was not fully integrated, each of the individual subsystems were working and met the requirements set out at the beginning of the project. The main barrier to integration was the lack of a functioning microcontroller, which in a longer-term development would not pose a major issue. While more development is needed, this technology has potential to help solve a significant conservation concern in an aesthetically appealing and cost effective way. The Power, Control, Bird Interface, and Object Detection subsystems were all integrated successfully, and the Object Classification Subsystem was functional with high accuracy. With the availability of a new microcontroller, successful integration of a fully functional system is highly probable. Moving forward, we would recommend a larger application of the project to take advantage of economies of scale (fewer sensors would be needed per square foot as the perimeter to area ratio decreases), testing with live birds, waterproofing the system for outdoor applications, optimizing the image processing algorithm for max efficiency, and adding a median filter for the output of the ultrasonic sensors to prevent flickering in the panels. We would also have to account for different extreme weather conditions such as high humidity atmospheres/rainy environments, as this will affect the distances read by our ultrasonic sensors and adjustments will need to be made. We would also need to take into account the versatility of bird species across different regions of the world, which means wingspan ranges in our specific requirements might change. Overall, this project serves as a successful exploration of this technology's potential.

6.1 Ethics and Safety

Overall, our proposed solution poses minimal safety concerns to humans or wildlife. There are no moving parts to cause injury and all voltage and current levels are mostly below the lethal range. Since any field applications of the system would be installed outdoors, the components used in our prototyping of the product would need to be replaced with waterproof equivalents (i.e. the ultrasonic sensors) or thoroughly insulated from the environment in a field installation.

One possible safety risk is the emission of infrared radiation from our thermal camera. Although there are always some health risks associated with radiation exposure, the limited time and intensity of exposure make the health risks minimal.

Another concern is the safety of potential test subjects. Should we choose to test the system with real birds by encouraging them to approach the window and then observing whether they are appropriately repelled, any system failure could lead to injury or death. Consequently it is vital the system is thoroughly tested beforehand in the lab prior to any field applications or testing.

To protect the privacy of others as mandated by the IEEE Code of Ethics [5], the images of pedestrians or other persons whose image may be captured by the thermal camera will not be stored in the system after the cycle of image processing for the current image is complete. Images will not be exported or extracted from the system to any secondary device or database.

While all new technologies are always vulnerable to misuse and abuse, the applications in which this technology could be used to cause individual, societal, or environmental harm are, to the best of our knowledge, little to none. Should any possible misuses of our design come to light, we would greatly appreciate being made aware of the problem and will revise our design accordingly.

References

[1]

S. Loss, S. Loss, P. Marra, T. Will, "Bird–building collisions in the United States: Estimates of annual mortality and species vulnerability," *The Condor*, vol. 116, no. 1, n.p., January 2014. [Online Serial]. Available: https://academic.oup.com/condor/article/116/1/8/5153098. [Accessed Jan. 25, 2023].

[2]

R. Fritts, "These Seven Bird Species are Most Likely to Collide with Windows," *American Bird Conservancy*, 2022. [Online]. Available: https://abcbirds.org/blog/frequent-colliders/#:~:text=Common%20Yellowthroat,-This%20masked%20songbird&text=Collisions%20with%20windows%20and%20communications,Ovenbird. [Accessed Jan. 26th, 2023].

[3]

"Why Birds Hit Windows–And How You Can Help Prevent It," *The Cornell Lab*, 2017. [Online]. Available: https://www.allaboutbirds.org/news/why-birds-hit-windows-and-how-you-can-help-prevent-it/#:~:text=In%20daylight%2C%20birds%20crash%20into,they%20fly%20into%20lighted%20windows. [Accessed Jan. 25th, 2023].

[4]

"Ultrasonic Distance Sensor - 3V or 5V - HC-SR04 compatible - RCWL - 1601," *Digikey*, 2019. [Online]. Available: https://media.digikey.com/pdf/Data%20Sheets/Adafruit%20PDFs/4007_Web.pdf

[5]

The Institute of Electric and Electronic Engineers, "IEEE Code of Ethics," *The Institute of Electric and Electronic Engineers*, 2023. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed Feb. 9th, 2023].

[6]

GroupGets LLC, "*Pylepton: A Pure Python Interface to the Lepton FLIR Imaging Sensor Module*," GitHub. [Online]. Available: https://github.com/groupgets/pylepton. [Accessed: May 3, 2023].

8. Appendix

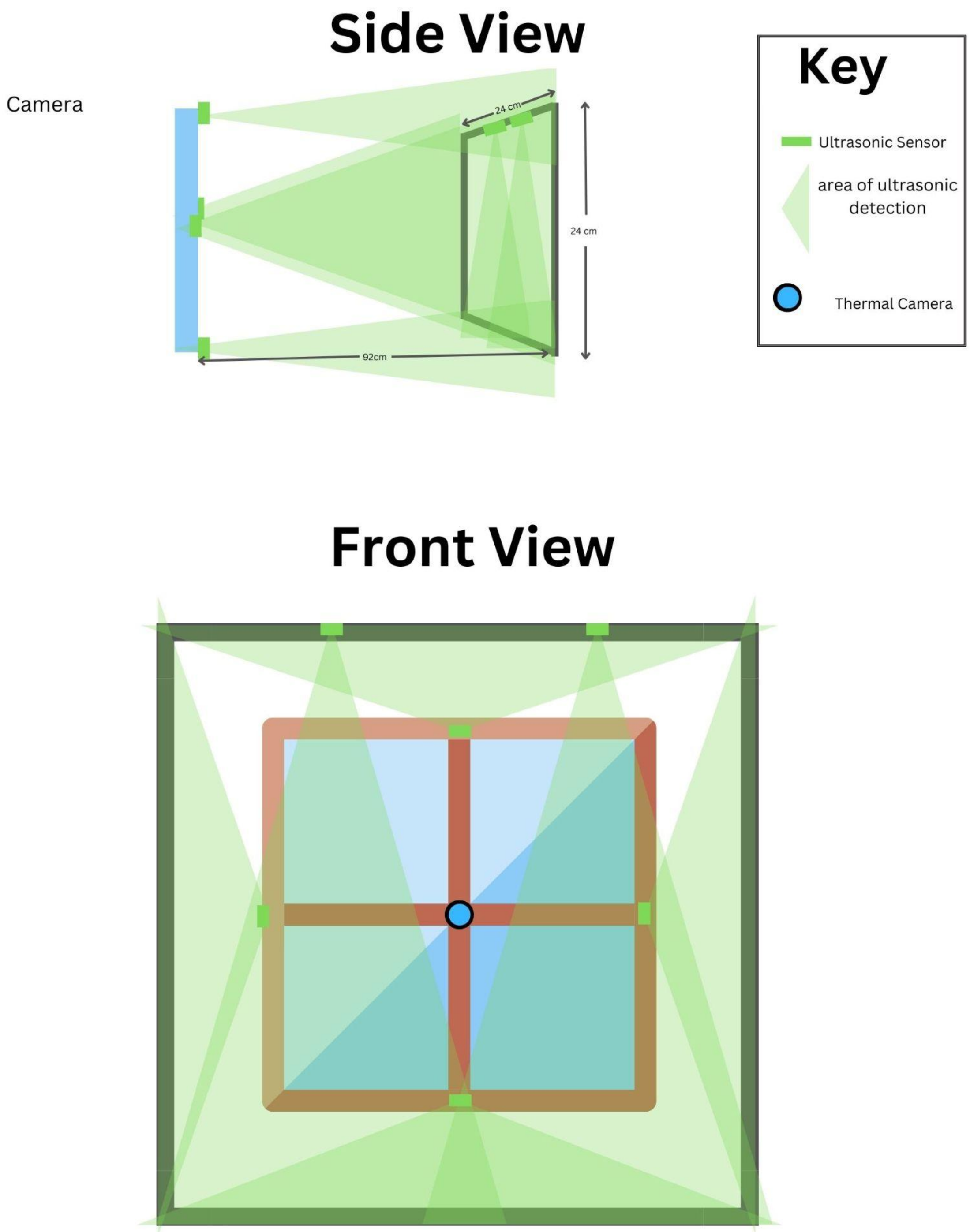

Figure 1: Our proposed arrangement of panels and sensors to avoid bird-window collisions

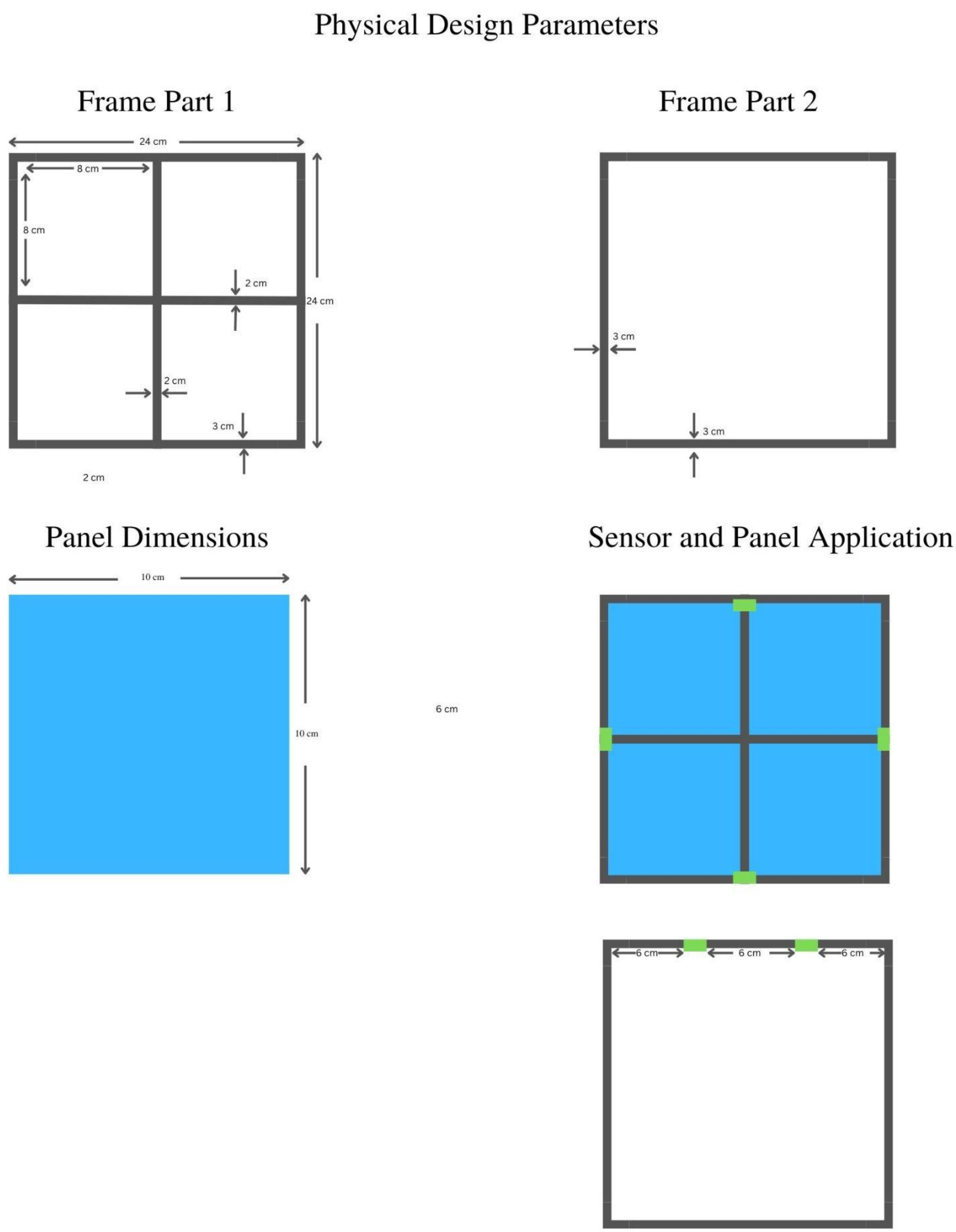

Figure 2: Physical Dimensions of System

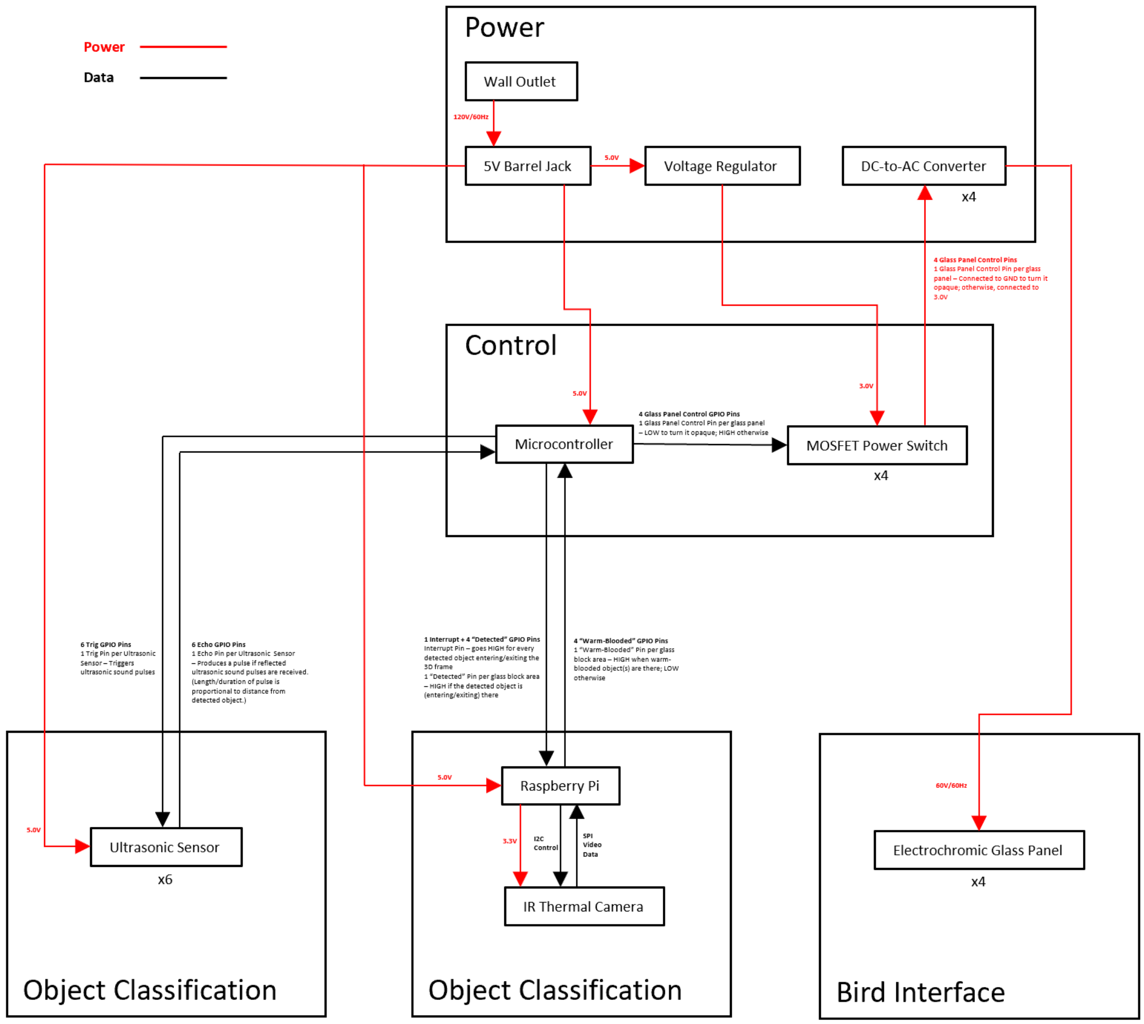

Figure 3: Block Diagram

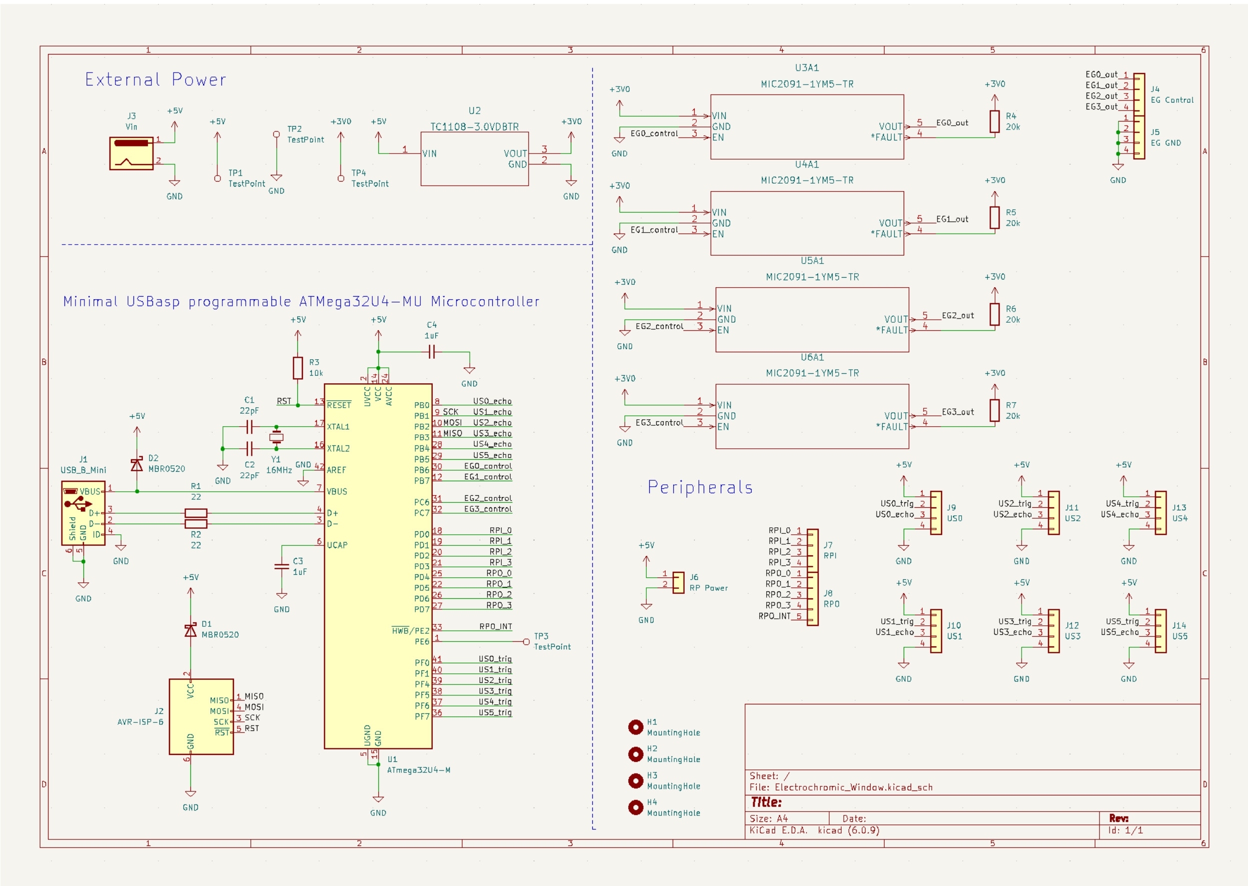

Figure 4: PCB Schematic

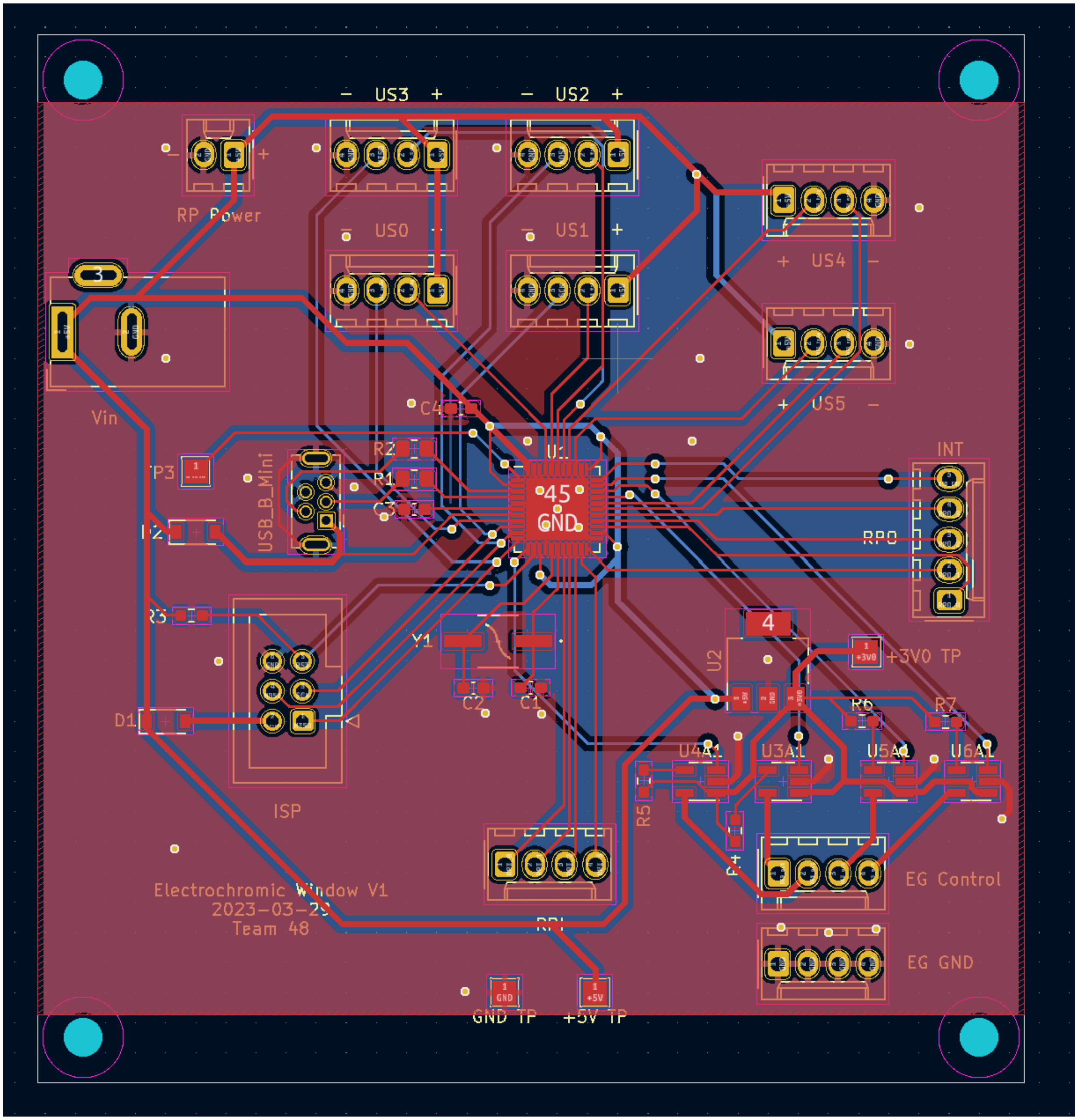

Figure 5: PCB Layout

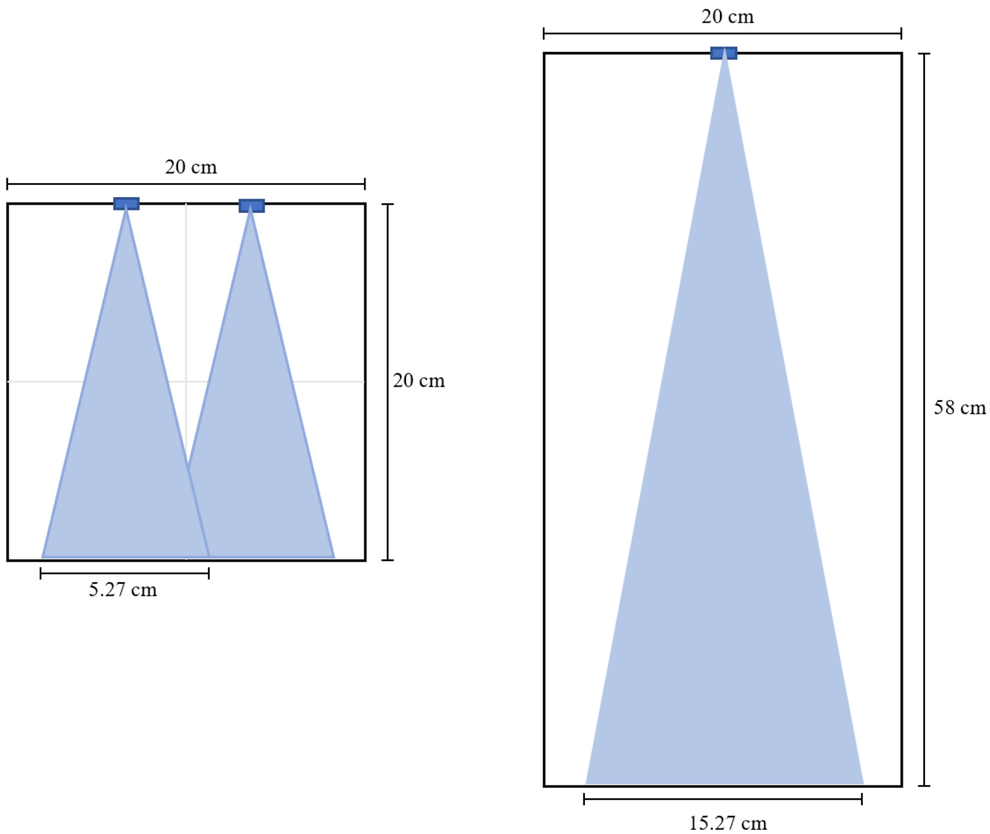

Figure 6: 15° Ultrasonic Sensor Beams along the Open 3D Frame’s Surface

```
digitalWrite(TRIG_5, LOW);                               // clear trigger pin
delayMicroseconds(2);
digitalWrite(TRIG_5, HIGH);                              // send out trigger pulses
delayMicroseconds(10);
digitalWrite(TRIG_5, LOW);                               // stop sending trigger pulses
distance5 = pulseIn(ECHO_5, HIGH) * 0.01715; // 0.0343/2 // read in the time it takes to return the pulse
                                                         // and calculate the distance by dividing by the
                                                         // speed of sound * 2
Serial.print("Distance 5: ");
Serial.println(distance5);
if(distance5 < threshold){                               // check whether the detected distance is less than
                                                         // the threshold distance
  intercept5 = true;                                     // mark that an object was detected at ultrasonic sensor 5
  digitalWrite(RaspPiInt, HIGH);                         // send an interrupt to the Raspberry Pi
  t5 = millis();                                         // record the current time
}
else{                                                    // mark that an object was not detected by ultrasonic
  intercept5 = false;                                    // sensor 5
}
```

Figure 7: Code for One Ultrasonic Sensor

Ultrasonic Sensor 1			Ultrasonic Sensor 2		
Ruler-Measured	Sensor-Measured Distance (cm)		Ruler-Measured	Sensor-Measured Distance	
5	5		5	4	
10	10		10	9	
15	17		15	16	
20	21		20	21	
25	25		25	28	
30	29		30	29	
35	34		35	32	
40	38		40	41	
45	43		45	45	
50	48		50	49	
55	52		55	55	
60	42		60	58	
65	x		65	64	
70	x		70	69	
75	x		75	78	
80	x		80	76	

Figure 8: Ultrasonic sensor measurements 1 and 2

Ultrasonic Sensor 3			Ultrasonic Sensor 4			Ultrasonic Sensor 5		
Ruler-Measured	Sensor-Measured Distance		Ruler-Measured	Sensor-Measured Distance		Ruler-Measured	Sensor-Measured Distance	
5	4.8		5	5.44		5	4.27	
10	10.41		10	11.78		10	9.23	
15	15.8		15	15.64		15	15.62	
20	20.94		20	19.47		20	21.68	
25	25.04		25	25.67		25	25.14	
30	29.36		30	31.52		30	30.08	
35	36.62		35	35.57		35	36.2	
40	39.03		40	42.19		40	38.95	
45	44.09		45	42.19		45	40.46	
50	48.32		50	49.48		50	48.21	
55	49.63		55	49.55		55	49.48	
60	50.01		60	56.08		60	X	
65	50.11		65	42.21		65		
70	X		70	X		70		
75			75			75		
80			80			80		

Figure 9: Ultrasonic sensor measurements 3-5

Table 1: Opacity Testing of Panels

	Light Measured with AC Voltage Applied (lumens)	Light Measured with No Voltage Applied (lumens)
Panel 1	4347	1222
Panel 2	9717	1178
Panel 3	4424	1725
Panel 4	8267	1504

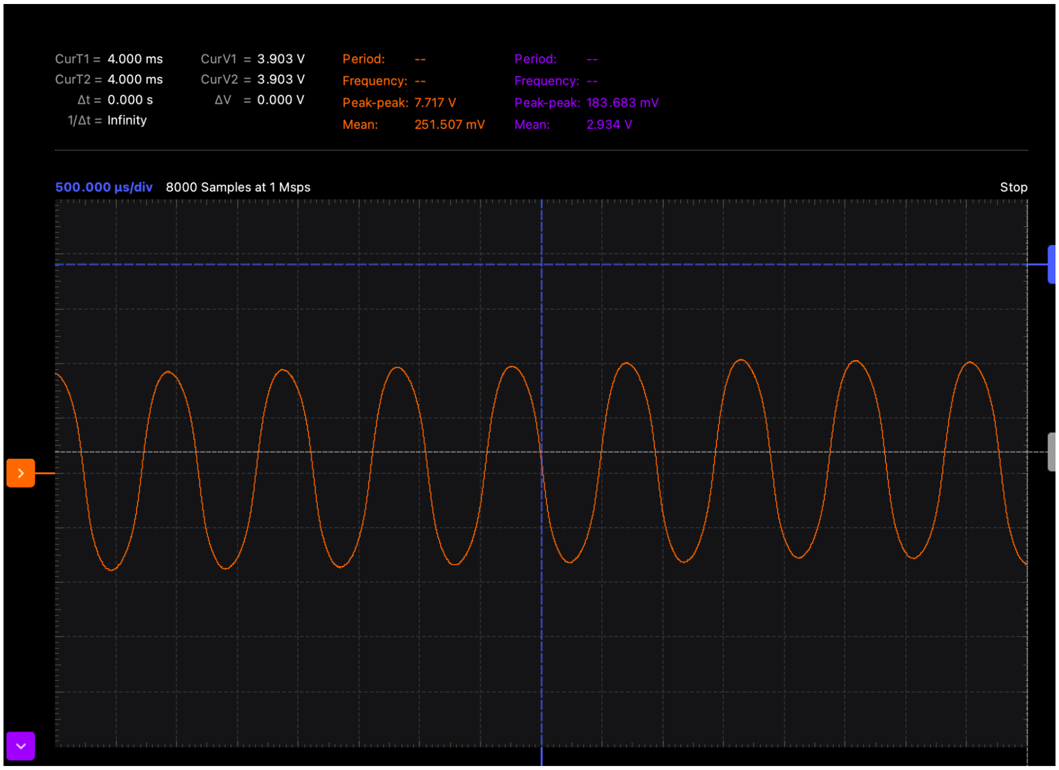

Figure 10: Sample DC to AC Converter Output

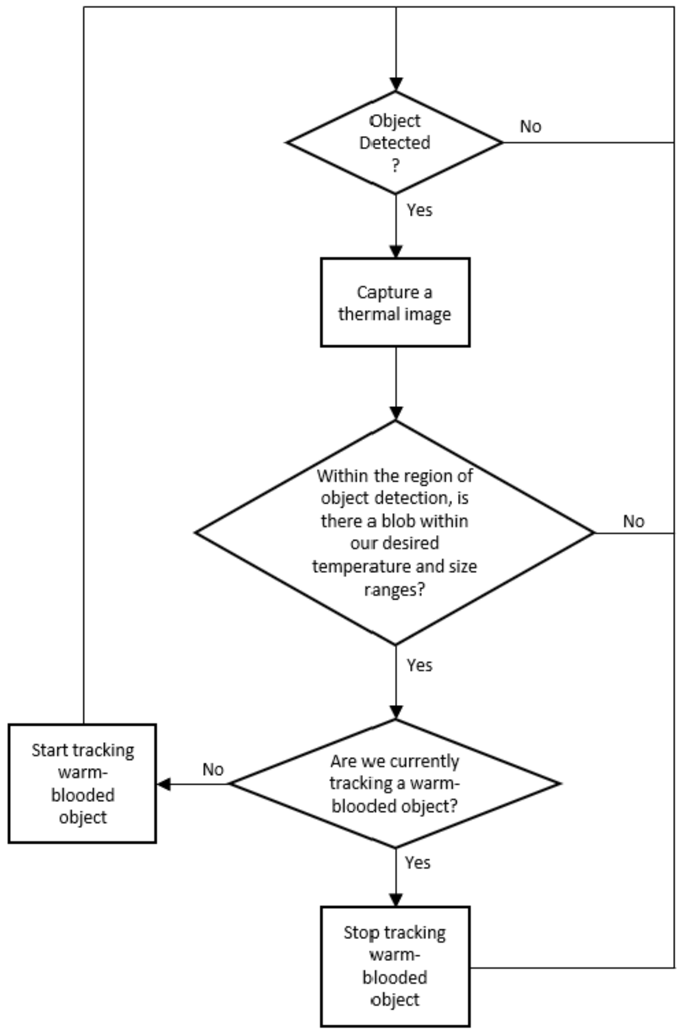

Figure 11: Thermal Image/Video Processing Flowchart

Table 2: Requirements and Verifications for Control Subsystem

Requirement	Verification
The control subsystem must be able to calculate distances correctly based on input from the ultrasonic sensors. For measured distances below 20 cm, the accuracy of the calculated distances should be within 5 cm. For measured distances between 20-60 cm, the accuracy of the calculated distances should be within 10 cm. These standards should be met in 90% of trials.	We will place objects at known distances from the ultrasonic sensors and compare the calculated distance with the distance measured in the lab.
The control subsystem must be able to signal to the electrochromic panels to change opacity once an object is detected. I/O pins controlling the opacity should transition to a high voltage (2.7-5.5 V) and low voltage (0-2.75 V) correctly in 90% of trials.	The changes in opacity can be observed visually by the experimenter. I/O pin values will be measured using one of the multimeters provided in lab
The control system must be able to initiate image processing in the Raspberry Pi. The interrupt pin of the microcontroller feeding into the Raspberry Pi must go high (2.7-5.5 V) when an object is detected in 90% of trials.	The voltage output by the interrupt pin of the microcontroller feeding into the Raspberry Pi will be measured using either one of the multimeters or oscilloscopes provided in the Senior Design Laboratory, depending on the speed of the system's response.

Table 3: Requirements and Verifications for Object Detection Subsystem

Requirement	Verification
For measured distances below 20 cm, the accuracy of the calculated distances should be within 5 cm of the of the measured distance in ≥ 90% of trials. For measured distances between 20-60 cm, the accuracy of the	We will place objects at known distances from the ultrasonic sensors and compare the calculated distance with the distance measured in the lab.

calculated distances should be within 10 cm in ≥ 90% of trials.	
The ultrasonic sensors must be mounted on the frame in such a way that they can accurately determine which electrochromic panel zones the detected objects are entering/exiting within the 3D frame area in ≥ 90% of trials.	For each 24 cm x 58 cm side of the 3D frame, we will place objects in the unique plane of the given sensor's area of detection and confirm that no other sensors have detected a distance below their programmed threshold. For the 24 cm x 24 cm side, we will place objects in each of the 9 electrochromic panel combinations (4 for each panel individually, 4 potential pairs along each side of the frame, 1 combination for when an object is detected in the center of the frame with overlap across all four panels) and confirm that each of these combinations can be identified uniquely.

Table 4: Requirements and Verifications for Object Classification Subsystem

Requirement	Verification
The image processing can correctly identify warm blooded objects within the 24 cm x 24 cm x 58 cm frame space in ≥ 80% of trials.	During the debugging phase, we will use the LED on the Raspberry Pi to determine when the system believes it has identified a warm-blooded object in the frame space, and can verify whether such an object is actually present via inspection.

Table 5: Requirements and Verification for Bird Interface Subsystem

Requirement	Verification
The opacity must visibly transition between transparent and opaque in response to the microcontroller.	Opacity changes can be easily confirmed via visual inspection.

Table 6: Requirements and Verification for Power Subsystem

Requirement	Verification
The barrel jack power supply must provide a steady 4.5-5.5 voltage at all times the system is operating.	We can confirm that the output of our barrel jack is within the acceptable range using a multimeter.
The voltage regulator must supply a DC input voltage 2.5-3.5V to the DC to AC converters feeding into the electrochromic panels at all times the system is operating.	We can confirm the output of our voltage regulator is within the acceptable range using a multimeter.