LIGHT SEEKING BRAITENBERG VEHICLE

A Design Project Report

Presented to the School of Electrical and Computer Engineering of Cornell University

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Masters of Engineering, Electrical and Computer Engineering

Submitted by

Tangia Sun

M. Eng Advisor: Doctor Van Hunter Adams

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ABSTRACT

Masters of Engineering Program

School of Electrical and Computer Engineering

Cornell University

Design Project Report

Project Title:
Light Seeking Braitenberg Glider

Author:
Tangia Sun

Abstract:
Braitenberg vehicles originated as a thought experiment to imagine intelligent behavior in insects; inherent sensor-to-actuator coupling in robotic systems to generate complex emergent behaviors. This project expands upon sensor-actuator circuitry without programmable logic. All “computation” will take place in the design of the circuit, relying on analog circuits to generate emergent behavior. A small glider will adjust its ailerons through photoelectric components to steer it towards a light source. We will characterize the behavior through its ability to follow a light probe and the strength of the adjustments in the aileron. This is most immediately relevant in data collection projects involving launching and scattering objects from low orbit, such as data collecting PCBs in deep forests or collecting atmospheric data. Analog boards can be significantly cheaper than functionally similar digital boards, which means advancements in quantity-based analog chips would trade off quantity, instead of cost, for low mission risk.

1 Executive Summary

Valentino Braitenberg introduced a thought experiment on how insects and bugs can exhibit emergent behavior, such as phototaxis, without higher level thinking. It imagined directly controlling actuators with sensors, generating different actuator behavior with the different magnitudes of sensor output. Translating to technical parallels, intelligent behavior is accomplished through microcontroller code, which is the equivalent of “higher level thinking”. However, if the behavior is predetermined and fixed, generating this through analog circuits could be a cheaper, more reliable, and more power efficient substitute. The motivation behind the project involved sending a swarm of gliders into low atmosphere at a specific time of day so the gliders will orient themselves towards the sun. The light-seeking behavior can be used to send a large collection of gliders in a general direction and cover a large area. This means the glider needs to differentiate brighter sources of light in a bright ambient environment, and have nuanced control over the turning radius.

This project built a glider with ailerons controlled by photo sensors to accomplish the aforementioned emergent behavior. Design characterization and physical demonstration was simulated through a controllable LED ring. The circuit needs to be designed so the logic required to generate the desired behavior is all contained within the hardware. The glider is split into roughly two parts that correspond to the ailerons, and the signal strength of the circuit is an indicator for the intensity of the light from that side of the glider.

The physical actuators needed to be controllable through an analog signal, and the actuation mechanism used was a commercial 12 layer PCB inductor with a magnet, so the inductor creates different magnetic field magnitudes depending on the current. Combining this with a 3D printed aileron and mount to control the movement of the magnet, a device was developed to move the ailerons a specific angle depending on the magnitude of the current passed through the inductor.

The inductor required an analog, high current, differential driver amplifier. This driver design is effectively a dual sided audio amplifier, and when taken differentially, could generate both a positive and negative high current signal. The driving and light detecting capabilities are successful, and without consideration for the complex aerodynamic forces of a plane, will move the ailerons in a way where it will move the glider towards the brightest source of light.

2 Background

In the current state of data collection for sending objects into low atmosphere and beyond, the primary philosophy surrounding developing technology has followed similar to the K-reproductive strategy, where all resources are invested into single vehicle which is fine tuned and engineered to succeed. However, an equally viable strategy that is underexplored is the R-reproductive strategy, where a statistically large amount of spacecrafts are sent up with an expectation that a significant amount will die, but enough will remain for mission success. Cost is a large factor in this, as mass manufacturing PCBs with microcontrollers for navigation becomes expensive, especially if each microcontroller needs to be flashed. Using analog circuitry circumvents this problem, as the PCB will be "preprogrammed" with the analog logic to generate the desired behavior.

The most traditional Braitenberg vehicle involves a phototransistor, a battery, and a motor on a simple land vehicle. Behavior is generated through the phototransistor permitting different amounts of current to the 2 motors on either side of the vehicle. Different intensities of light will control the speed of each side's motor, and depending on the wiring, could cause behavior like phototaxis or even circling the light. This has been adapted with the prior motivation to create a glider, as it is more aerodynamically feasible than an airplane, with aileron actuators instead of wheels.

3 Design Requirements

The requirements for this project can be split into two major parts; the Braitenberg sensor signal circuit design, and the mechanical glider design. The analog sensor processing needed to output a voltage, where the incident light level detected by that circuit needs to be reflected in the magnitude of the signal. This needs to adjust to the incident light in real time, and should have some consideration for both sides of the glider so there is some level of a differential signal to account for bright ambient light.

3.1 Detector Circuit

The detector circuit requirements were not hard defined, but needed to use photo-transducers and purely analog circuitry. This was under the constraint of some eyeball requirements; there needed to be an analog signal generated from these components, with as little power used as possible. Within the magnitude, there should also be information implicitly included about the angle of the brightest light. Following the original inspiration, this should be operable in daytime, which means there needs to be some form of signal "isolation" to differentiate brightest from bright. This should be constrained within a reasonable voltage, which was determined to be from 0V - 5V.

3.2 Actuator and Driver

The initial intention was to create a full glider that would exhibit the behavior in an experimental flight. However, as the year progressed and more was understood about the actuators available to us and my glider engineering knowledge, I realized I needed to abandon the idea of an actual flight and shift to an intuitive, model version of what I wanted to create. There are mechanical designs partially implemented to show a proof of concept, but the physical realizations of these were not possible in the timeframe of this project.

Assumptions made of the "showcase" ailerons needed to visually follow the same requirements as a realistic aileron. This means it needs to move so the light side will pivot up, and the dark side will pivot down. It also needs to be adjustable in how far the aileron actuates so the longitudinal pivot angle can be controlled. The circuit driver needed to control the actuator with some meaningful level of control.

3.3 PCB Design

In order to follow the original motivation as closely as possible, a design requirement was to include as much of the design into the PCB as possible. The original idea was to include some form of flex and copper PCB hybrid, where the flex portion could be used to either control the aileron or serve as a flight guider. However, this became unrealistic in the time constraint and with the design of the actuator, so the requirement shifted from the glider being able to "fly out of the box" to the glider PCB needing some assembly, but having everything contained on the PCB.

4 Implementation

4.1 Detector Circuit

After experimenting with different photo-transducer and logic circuits, the conclusion drawn was that phototransistors were the best at generating large signals, and these signals could be tuned with the flexibility of photoresistors. A big challenge was to achieve a bit more nuanced control over the light, but this became a partially solved problem based on the phototransistor's active angle, where the strength of the signal is already indicative of where the strongest signal comes from. The phototransistor circuit turned out to be a simple common collector with the phototransistor as a substitute for a BJT (Figure 1). This would be placed in a balanced location where the intensity of light would most reasonably impact the flight of the glider.

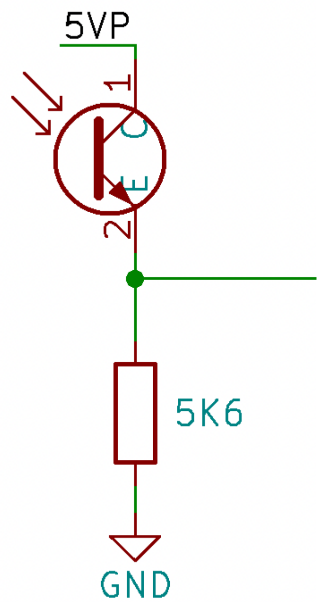

Figure 1: Phototransistor light detector circuit

The further processing for a more nuanced signal comes from the desire to pivot the glider more as the glider is further away, without massively influencing the signal. This came from photoresistors, who respond less dramatically to light, but are convenient because they function like variable resistors. This means they can be designed into operational amplifiers to adjust the gain as the light passes by. Since the determined range for the input goes from 0V to 5V, a noninverting amplifier was necessary, and the gain was adjusted by photoresistors (Figure 2). This meant the intensity of light from different angles could adjust the impact of the phototransistor. 0Ω jumpers were used so there was room for adjustments after assembly..

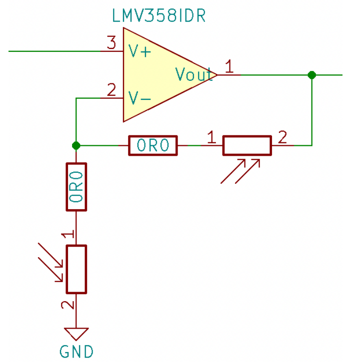

Figure 2: Analog signal small scale tuning

4.2 Actuator

The actuator is an inductor, a magnet, and a 3D printed part. The 3D printed part is made to look like an aileron on the PCB, and has mounts so standoffs could fit and pivot the aileron around a fixed range of angles. There are 3 parts to the 3D print; one side of the mount, the other side of the point with the rotation bar, and the aileron itself (Figure 3.1). These combine together on the PCB to create a pivoting mechanism. The magnet provides the weight to move the aileron upwards, the magnetic field of the inductor - or in the case of Figure 3.2 the lack of a weight - will move the aileron down. (Figure 3.2).

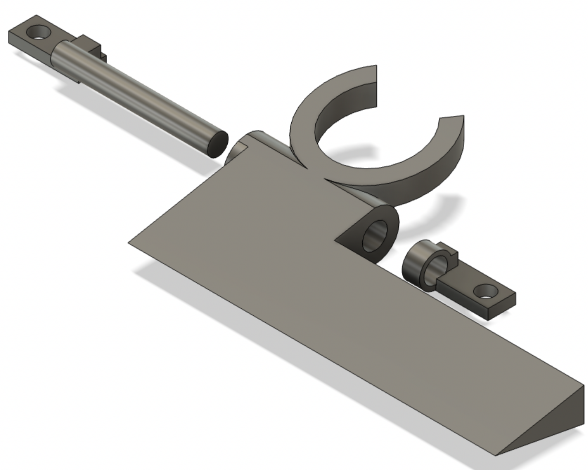

Figure 3.1: 3 Part aileron designed in CAD.

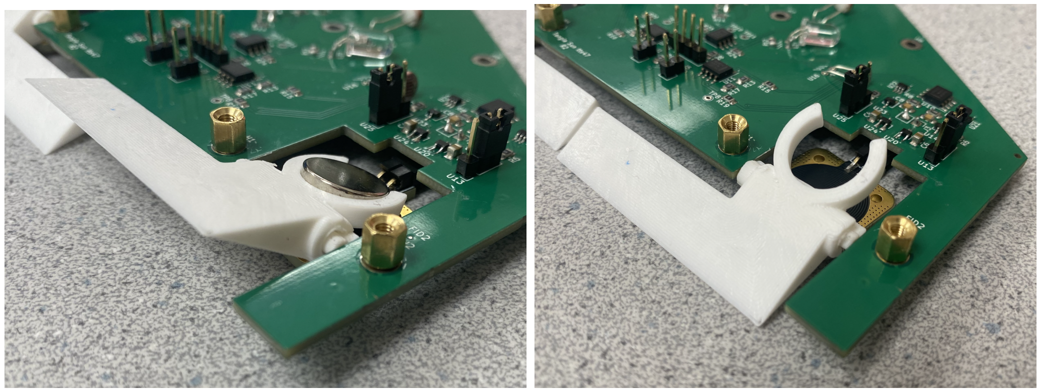

Figure 3.2: Range of motion for aileron on a physical assembly

The design is made so the center pivoting angle is aligned with the PCB, and the aileron is held by standoffs, which are possible because of the inherent ruggedness of 3D prints. No special threads were needed, as the screws of the standoffs could create their own fit into the filament.

To generate the magnetic field to repel the magnet, a Flexar 12 Layer PCB [1] was used for an inductor. This was also considered in the design, and would be mounted to the PCB through a 2 pin right angled female connector.

It's important to note this would likely not stand to significant forces in a real aerodynamic environment. The force causing the aileron to actuate upwards is the weight of the magnet, and the force counteracting gravity is the strength of the magnetic field. This means there is no feedback on the real position of the aileron, which means there is no way to stabilize or keep it in a fixed position. This is a shortcoming of the design and my mechanical knowledge.

4.3 Driver and Differential Circuit

The actuator was effectively a low impedance inductor which required high currents to be effective. The simplest form of a driver is an inverter audio amplifier, which can convert an analog signal to a high current analog signal. However, the shortcomings for these are that they are limited to positive voltages. Although this is enough to accommodate the "concept" actuators, I wanted to leave room for designing more realistic ailerons. The driver I wanted to design needed to handle both positive and negative high current amplification, which led to the design in Figure 4.1. This driver circuit requires a differential signal as inputs, which is generated by the circuit in Figure 4.2.

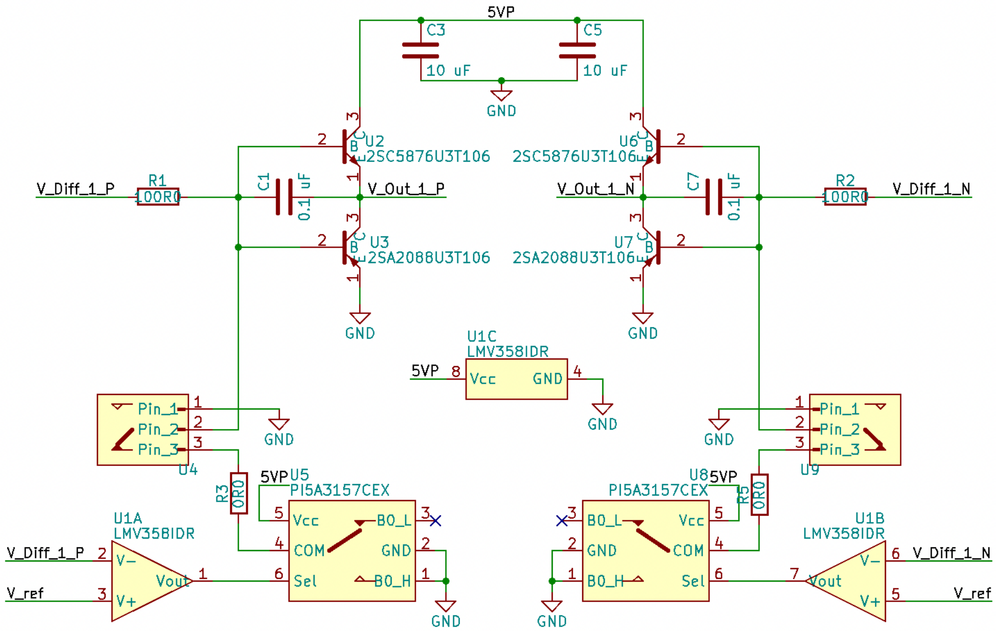

Figure 4.1: High current differential driver circuit.

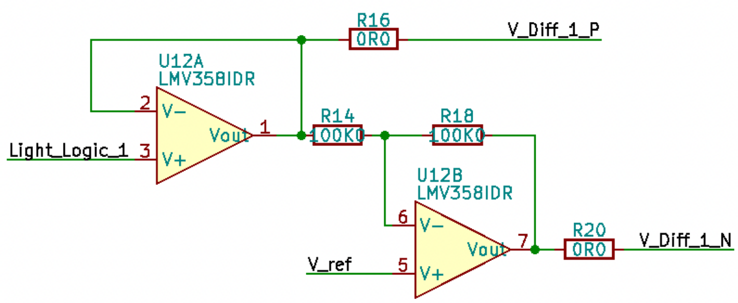

Figure 4.2: Differential Circuit

The main driving amplifier part of this is still based on an inverter amplifier, but has the capability to set the other side constant. When the signal is positive across a reference voltage, it should act as an amplifier through one side, and the other side has to be constant for the inverter to be effective. As the signal goes negative, the purpose of the two sides should switch, which combined, creates a differential signal as the input signal flips around a reference voltage. This is accomplished through relays at the input to the inverter. The desired behavior on the driver input is to have a rectifier that instead of shifting the negative to the midpoint, or synonymously the threshold, shifts it to the bottom (Figure 5.1). This means when the voltage will drive the driver when it is above the threshold, and pull the transistors down to a certain voltage when it is below the threshold (Figure 5.2).

Differentially, this will create a positive and negative swinging, high current signal (Figure 5.3)

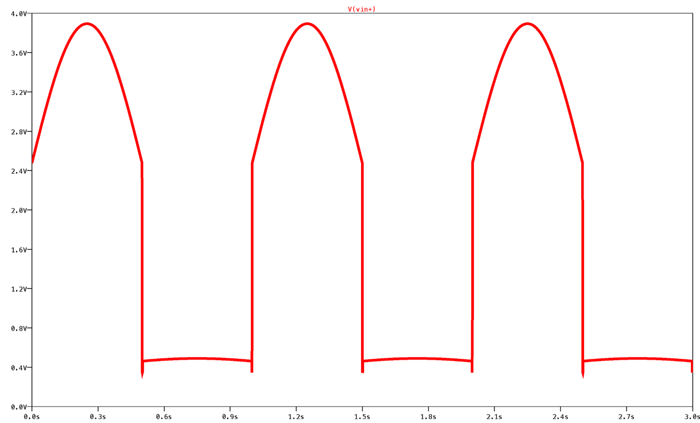

Figure 5.1: Pull-down rectifier input signal on a circuit simulation

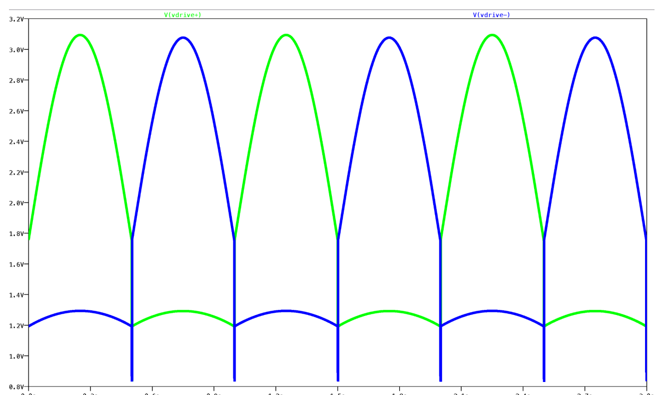

FIgure 5.2: Corresponding driver output signals on a circuit simulation

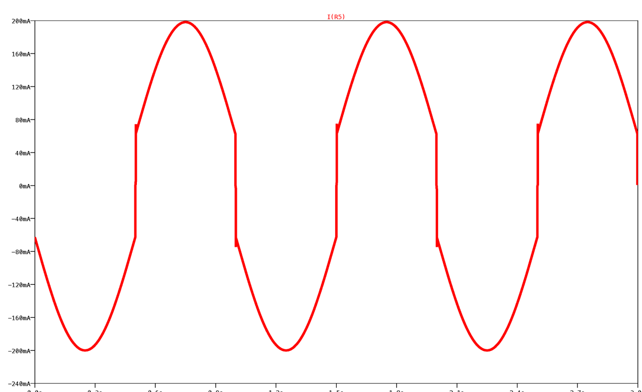

Figure 5.3: Current through a 9Ω load on a circuit simulation

In Figure 4.1, there is also a set of 3 pin headers labeled U4 and U9. These serve as modifications to accommodate the actuators. Due to the flaw that the actuators are only height controlled by the magnitude of the magnetic field generated, there is no purpose in having a magnetic field generated in the opposite direction. Generating a magnetic field to repel the magnet produces the desired behavior, but generating one in the opposite field would attract the magnet, but serves no purpose as it would immediately be pulled down as far as it can go. This is adjusted for by the 3 pin header, which would have a 2 pin connector across to short one side to ground (Figure 6). This created an easily adjusted single pole double throw switch. By grounding the relay logic on one side and opening the logic on another, a one sided, normal inverter can be created. This means the strength of the magnetic field will only repel the magnet, and is tunable across the full range. This is made for demonstrative purposes.

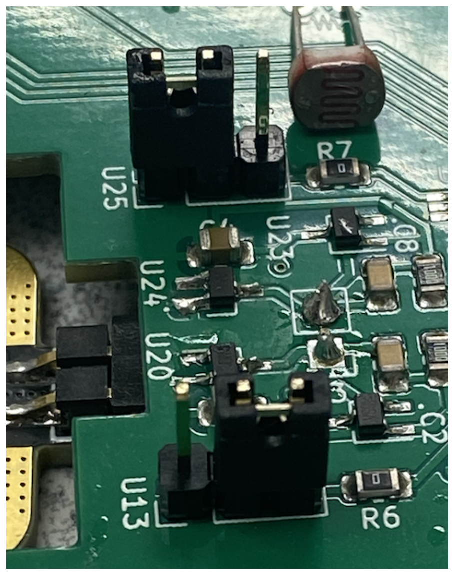

Figure 6: 3-pin male headers with a 2 pin connector to short.

4.4 PCB Design

The PCB is designed to contain all the relevant circuit designs, but was also made with the physical requirements originally stated. This meant everything needed to be self contained, either coming out of the factory or post assembled. A roughly visually aerodynamic design was chosen, and physical considerations for how photosensors were considered (Figure 7).

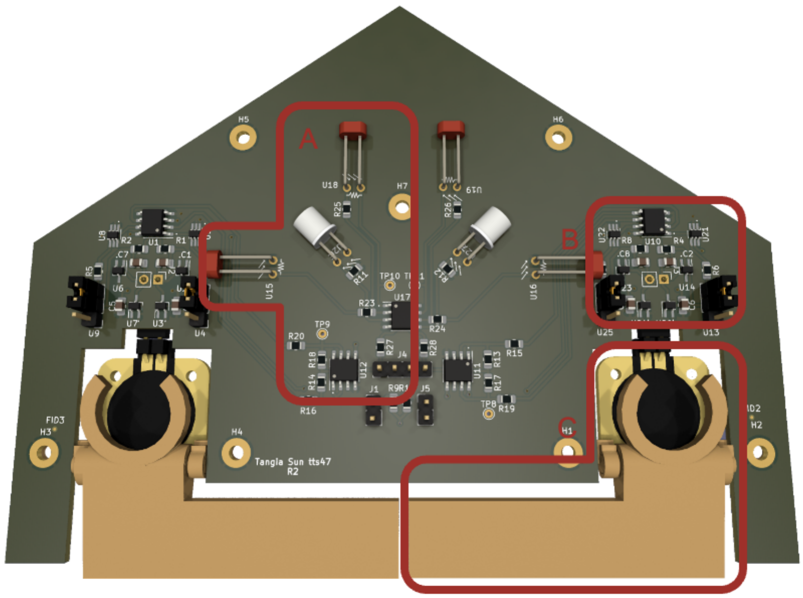

Figure 7.1: Full render of glider PCB.
A: the light detector logic. B: driver circuit. C: actuator

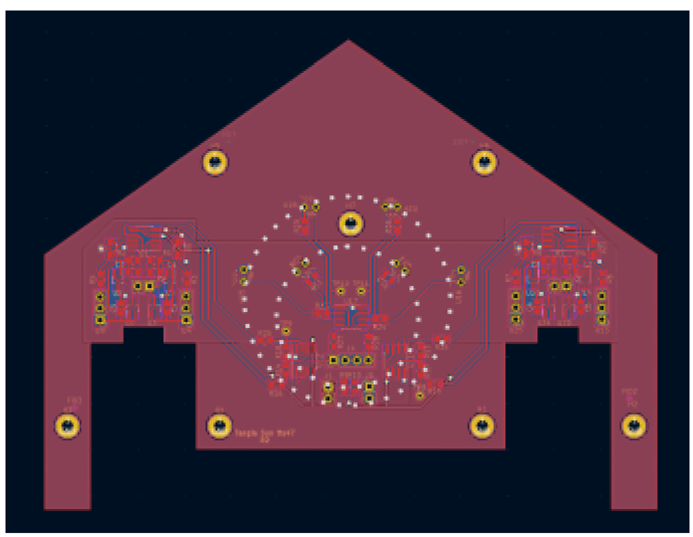

Figure 7.2: PCB view of the layout, with inserted rings for the photo transducers

For the driver circuit, it needed to be designed just to fit, which meant following traditional layout conventions. The light detector circuit needed to be fit so the design of the circuit matches with the desired light behavior. This meant making the through hole footprints fit in a radius so the light analysis is equal on both sides of the glider. The unique cutout of the PCB comes from needing to fit the actuator onto the PCB, with the mounts and cut out specifically designed so the aileron could fit.

6 Validation and Testing

6.1 Light Detector Circuit

The light detector circuit was characterized through an LED ring (Figure 8). This was built and 3D printed to create an environment where a controlled source of light could move around the glider and the voltage relationships could be characterized. An LED strip was attached, and using a microcontroller, could be used to plot a voltage against the angle of the most intense source of light. This was immensely helpful in testing different variations and designs.

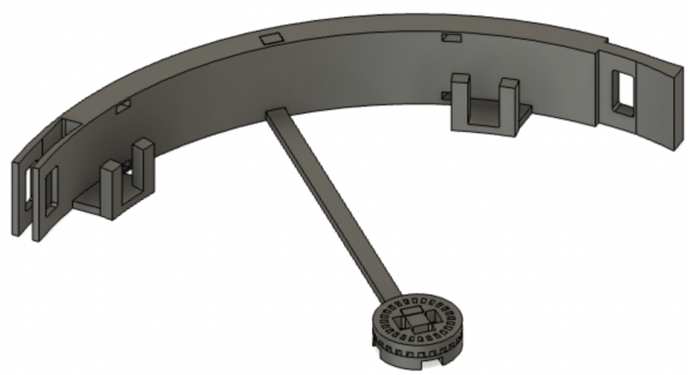

Figure 8.1: A quarter of the LED ring testing setup.

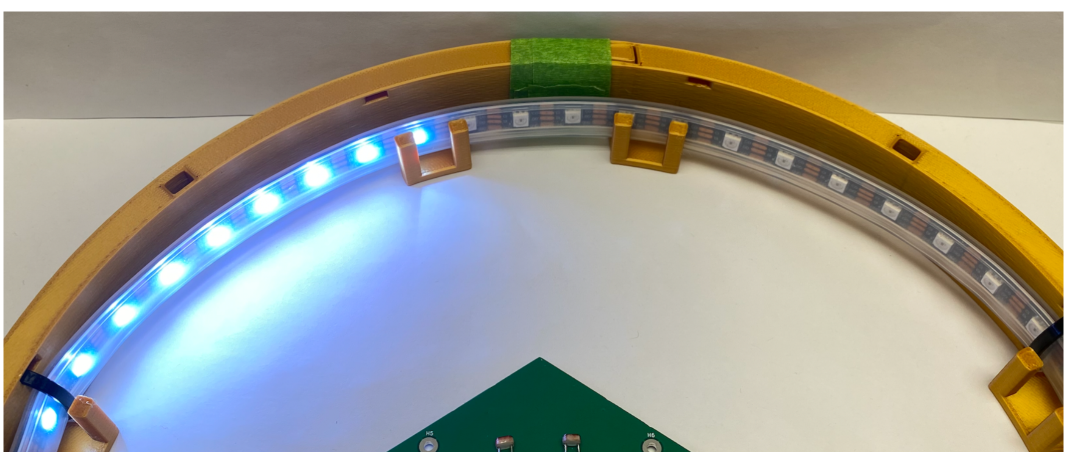

Figure 8.2: Center source of light shifting around in a ring.

The simple phototransistor based design for the light detector circuit in Figure 1 became one of the most significant design decisions. The resistor became a very simple and easy way to adjust the strength of the circuit and adapt to different lighting conditions simulated from the LED ring. A significant problem also came from the phototransistors peaking, so the gain of the system could be adjusted by tuning the constant resistors as part of the non inverting amplifier in Figure 2. Interestingly, the phototransistor did not seem to saturate too often, and problems were often caused by the amplifier circuit that followed, which meant including the option to modify the constant resistance values proved to be valuable for changing conditions. After tuning the resistor values in the circuit, the complete output for each side is taken from an oscilloscope (Figure 9).

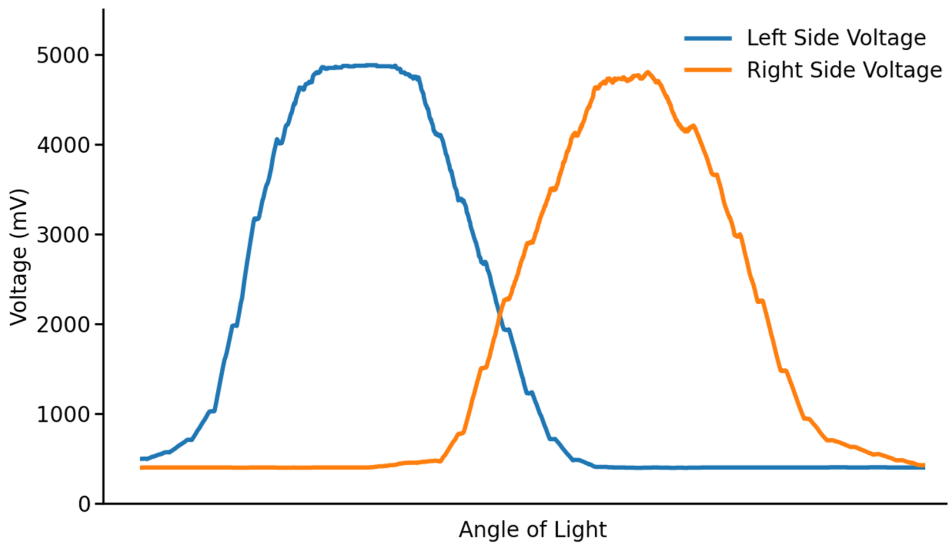

Figure 9: The voltage given on each side of the glider in response to the LED ring

This data shows that as the light travels around the glider, each respective side is able to adjust its voltage to represent how strongly that side perceives the light.

6.2 Analog Amplifier Driver Circuit

The aileron driver circuit was first simulated in LTSpice to determine its viability. Response to the voltage from the shifting light proved difficult to graph, so the substitute was to directly insert a sine wave into the input of the differential signal generator in Figure 4.2 and read across the output. This was used so the transfer function could be seen more accurately. The output voltage can be seen in Figure 10.1, and the corresponding differential current going through a 9Ω load can be seen in Figure 10.2.

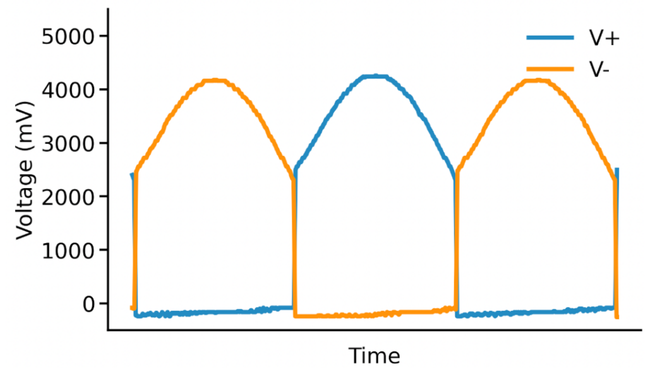

Figure 10.1: Measured voltage and the positive and negative output leading to the actuator

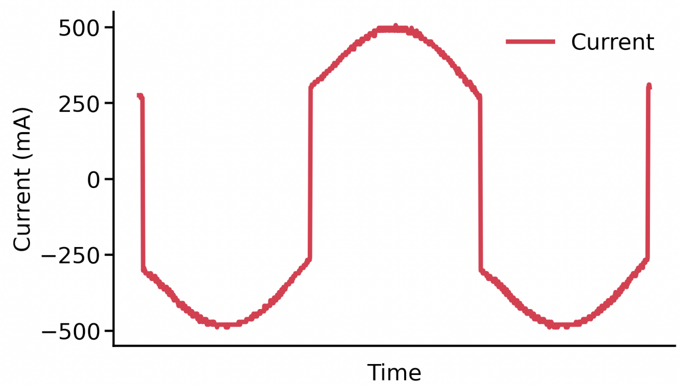

Figure 10.2: Measured differential current received by the actuator across a 9Ω load

The results shown demonstrate the circuit's ability to amplify a sine wave into a high current differential signal, which in this project was used to drive an inductor. These can be compared with the graphs in Figure 5.

6.3 Aileron

The testing with the ailerons was reduced to whether they served their purpose. The primary requirements were to make sure they rotated smoothly enough to demonstrate functionality, and whether their range of motion was acceptable (Figure 11). Different magnet sizes, quantities, and strengths were briefly tested, but it was quickly determined that the weight of the magnet was insignificant as long as it was light enough to be pushed up.

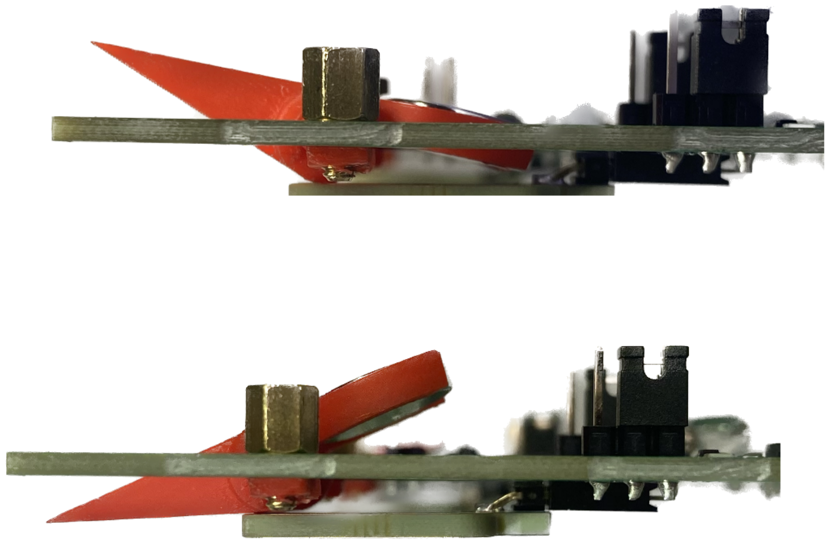

Figure 11: Aileron full range of motion

7 Conclusion and Future Work

7.1 Conclusion

Combining everything created, the final PCB glider was able to adjust its ailerons as the light shifted around the glider (Figure 12). This meant the idea of a Braitenberg glider is possible at a PCB scale. The aileron movements indicate the glider is able to move towards the direction of light.

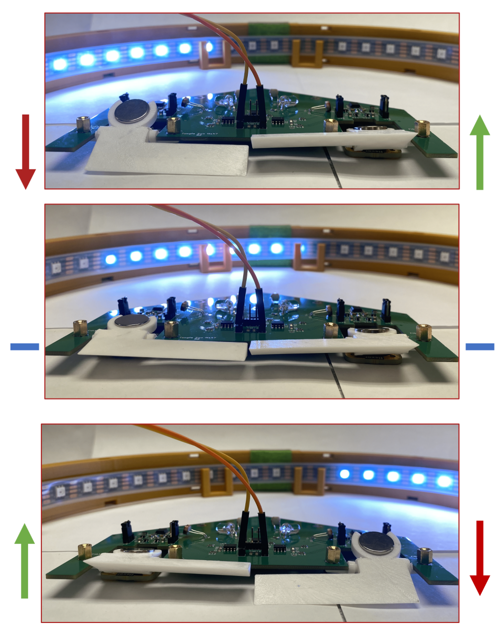

Figure 12: Aileron movements as the light circles the glider

7.2 Future Work

This project opens up a part of a fascinating study of swarm behavior [2]. Swarm behavior is the tentative term describing technological ventures into the R-reproductive strategy, but a major shortcoming in this area has been the need to mass produce the data collecting objects to create an adequate number needed to statistically carry out a successful mission. Another pillar of swarm behavior is that these individual objects need a guidance mechanism, whether to an environmental stimulus or to each other. This project demonstrates that a guidance mechanism using analog circuitry can be much cheaper and easier to mass produce than a digital circuit.

To further push this project into a closer version of what swarm projects could physically use, there are some improvements and characterizations that are needed.

The light detector circuit may be sufficient in a closed environment, but will require development in an area where lighting is more ubiquitous and there are very subtle increases in light intensity. This would mean developing the circuit so it rejects common light better and creating an analog signal that is more comprehensive of both sides of the glider.

Further characterization, and development, is required in the aerodynamics and physical flight engineering of the PCB. This would likely need to change the shape and the size of the PCB, which means adjusting the actuation mechanism as well, but provided with the right background, is entirely possible.

8 Appendix

8.1 Flexar Specifications

Figure 13a: Flexar actuator

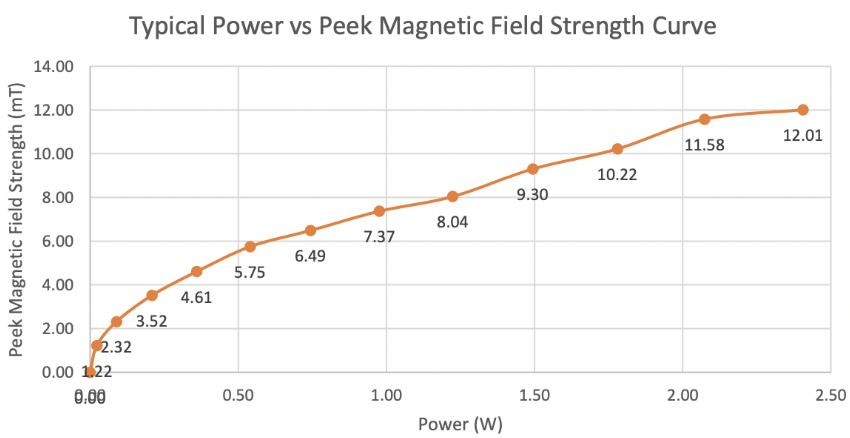

Figure 13b: Magnetic field to power curve

Coil Specifications	
Track (Thickness/Pitch)	8/8mil
Turns	200 turns
Resistance	9.4Ω ± 1
Inductance	180uH ± 2
Recommended Maximum Constant Power	1.5W
Absolute Maximum Constant Power	2.4W
Absolute Maximum Operating Constant Voltage	6V
Maximum Operating Temperature	140°C
Peek Magnetic Field Strength	12mT

Figure 13c: Coil specifications

References

[1] “PCB Actuator (Flexar),” Microbots, https://microbots.io/collections/all-kits/products/copy-of-pcb-actuator

[2] Defay, J., Niles, Q., Petersen, K. (2022). “Collective Behavior of Braitenberg Vehicles,” Unpublished manuscript.