Pursue: Undergraduate Research Journal

Volume 4 | Issue 1 Article 2

2021

A Zugunruhe Data Collection System Using Passive Infrared Sensors

Ryan Terry
Texas A&M University, terry@tamu.edu

Luis E. Ramirez
Texas A&M University, luisramirez13@tamu.edu

Carol Carrera
Texas A&M University, carolcarrera@tamu.edu

Abigail Kimmitt
Texas A&M University, akimmitt@bio.tamu.edu

Kira Delmore
Texas A&M University, kdelmore@tamu.edu

See next page for additional authors

Cover Page Footnote

Acknowledgments This project started as part of the Capstone course series in the Electronic Systems Engineering Technology (ESET) Program at Texas A&M. This project was funded by Dr. Kira Delmore and Dr. Ana Goulart's research incentive accounts. Also, we are grateful to Professor Mike Willey who advised the students in their Capstone project and suggested the idea of using telecom cables to improve the wiring in the second prototype. About the Authors Luis Ramirez and Carol Carrera worked in this project as part of their senior design (Capstone) courses. Carol was enrolled in ESET 420 (Capstone II) course in the Fall of 2019 and Luis completed his ESET 420 course in Spring of 2020. Carol developed the first prototype and Luis maintained and documented the prototype during the data collection in the first months of 2020. Ryan Terry was an undergraduate research student in the ESET major, who graduated in December 2020. Ryan completed and installed the second prototype of the Zugunruhe data collection system and is working at a company that makes sensors in Austin, TX. Abigail Kimmitt was a post-doc researcher in Dr. Kira Delmore's biology laboratory. She validated the sensors using the infrared cameras and worked with Dr. Delmore in the data collection. Dr. Kira Delmore is an assistant professor in the biology department at Texas A&M University. Dr. Delmore has a Ph.D. in Zoology from the University of British Columbia, and did the post-doctoral research at the Max Planck Institute for Evolutionary Biology in Germany. Dr. Ana Goulart is an associate professor in the electronic systems engineering technology (ESET) program at Texas A&M University. Dr. Goulart's research interests include telecommunications and real-time data monitoring.

Authors

Ryan Terry, Luis E. Ramirez, Carol Carrera, Abigail Kimmitt, Kira Delmore, and Ana Goulart

A Zugunruhe Data Collection System Using Passive Infrared Sensors

Ryan Terry[1], Luis Enrique Ramirez[1], Carol Carrera[1], Abigail Kimmitt[2], Kira E. Delmore[2], Ana Goulart[1]

[1] Engineering Technology and Industrial Distribution Department
[2] Department of Biology
Texas A&M University
College Station, TX, 77843

Corresponding Author:
Ana E. Goulart

Electronic Systems Engineering Technology (ESET) Program;
Engineering Technology and Industrial Distribution Department;
Texas A&M University College Station, TX, 77843;
goulart@tamu.edu

Abstract

Introduction: To help scientists answer questions related to *zugunruhe* and the genes underlying migratory behavior, this paper presents the design and implementation of a zugunruhe data collection system to study the Swainson's thrush—a migratory songbird that breeds in North America. Our goal is to share how custom-off-the-shelf (COTS) devices and existing technologies were used in this project. **Methods:** Passive infrared motion sensors, telecom cables, custom printed circuit boards (PCB), and a data acquisition system using LabView® software (National Instruments) were combined to monitor bird movements. We also discuss how the learned lessons from our first winter of data collection, in which we monitored 30 bird cages, led to improvements to scale the system to support the monitoring of 60 birds in the second year. **Results:** Samples of the collected data show that the system works, which was validated by comparing our data with the images obtained using an infrared camera. Some of the challenges of maintaining the system are also discussed. **Conclusion:** This paper provides an example of an interdisciplinary, undergraduate-driven, applied research project that is still on-going. We hope it can inspire other researchers and undergraduate students to get involved in interdisciplinary research.

Key Words: zugunruhe, migratory behavior, bird movement monitoring, motion sensor, electronics data acquisition

Introduction

Figure 1. The Swainson's thrush.

Migratory songbirds have seen massive declines in the last decades, and climate change has already affecting their behavior (Rosenberg et al., 2019). One key for understanding how they will respond to these changes is if they possess the genetic variation required for adaptation. Researchers have known for decades that there is a genetic basis to seasonal migration (Helbig, 1996), but the actual genes underlying this behavior remain elusive (Liedvogel et al., 2011; Delmore and Liedvogel 2016). The Swainson's thrush (Figure 1) has emerged as a model for studying this topic; it is possible to track thrushes over the entire year in the wild, a considerable number of genomic resources have been developed for the species, and they can be maintained in captivity.

The word "zugunruhe" is German and means "unrest." It is often used in the context of migratory birds, as they become restless at night, inside their cages, during their migratory period (Gwinner and Czeschlik, 1978; Gauthreaux, 2019; Van Doren et al., 2017). When does zugunruhe start? It usually starts when the weather becomes cold and the days shorter, but it varies for different bird species. Moreover, global warming has caused changes in zungunruhe's timing, which made it even harder to predict. Another question is about genetics: is there a specific gene or a group of genes that cause birds to migrate?

The biology department at Texas A&M University is maintaining a colony of Swainson's thrushes in a laboratory to conduct research on the genetics of their migratory behavior. The researchers are investigating the genetics and migratory behavior of these birds. For the Swainson's thrushes, zugunruhe exhibited at night, as they are nocturnal migrants like most other songbirds.

Day length, or photoperiod, is the primary cue used by migratory birds to time their annual life history events (i.e., migration, breeding) (Dawson et al., 2001). The transition to nocturnal behavior is stimulated by changes in photoperiod and temperature inside the laboratory where the birds are located. The laboratory environment emulates seasonal changes in daylight and weather. Photoperiod begins to increase following the winter solstice and then decreases following the summer solstice. Increasing day length cues birds to undergo changes to prepare for migration and breeding (Dawson et al., 2001). This cue is so important to a bird's physiology that it can be simulated in captivity by number of hours that lights are on to activate behaviors of interest in the birds (Rowan, 1928).

To detect *zugunruhe*, or the transition from diurnal to nocturnal behavior, several methods have been documented in the literature. A good review of different technologies for detecting *zugunruh*e is provided by Evans (2019). Typically, video cameras (Muheim et al., 2014) can document this transition; however, they require a lot of time from the researchers to analyze the recorded images, and an automated process is needed. Video observation using infrared cameras seems to be the state-of-the-art method for monitoring bird movements in captivity. Another previous research employed motion-activated microphones to detect *zugunruhe* behavior (Eikennaar et al., 2014), which is similar to the idea of using motion sensors as we used in our system.

The infrastructure we present in this paper is integral to continuing work on the genetics of migration in Swainson's thrushes and can be applied to other questions and species. Our goal is to identify a simpler, more automated, efficient way to collect and analyze the movement data from birds.

Methods

We developed and installed an automated *zugunruhe* data collection system that records bird movement information for 10-minute intervals throughout 24 hours, for as many days needed. The initial prototype consisted of 30 motion sensors - one sensor per bird, one bird per cage - wired to a central computer using a Data Acquisition Card (DAQ) from National Instruments (NI).

We also provided near-to-real-time data collection (timestamp, movement frequency) and a graphical user interface (GUI) to view and download the data through comma-separated value (CSV) files. These data files are constantly analyzed by the researchers to determine when the thrushes transition into the migratory period or when they become nocturnal. Next, we explain the hardware and software design of the initial prototype system. Then we explain how the initial prototype evolved to a more scalable system that can monitor 60 birds.

Initial Prototype

These are the requirements for the *zugunruhe* data collection system:

- Sensors should detect bird movements at high frequencies.
- Sensors should detect movements inside the 24"x12"x14" metal birdcage.

- Sensors should output digital values, such as digital high and low signals.
- System should have no visible lights and should be discrete for birds.
- System should have a GUI to monitor birds.
- System should enable users to download the data for analyses and research purposes.
- System should provide power at 5 Volts over 500 mA for the sensors.

With these requirements, we designed a system similar to the one shown in the conceptual block diagram in Figure 2. It shows the *zugunruhe* data collection system that has motion sensors in each birdcage. These sensors are wired to a central unit using a NI-USB-6509 DAQ, which sends them to the computer through a universal serial bus (USB) connection. The computer runs our LabView® code (Fairweather and Brumfield, 2011), which counts the number of times the sensors are active and saves the raw data in a CSV file. It contains information such as an identification number, movement count, and a timestamp for each bird. The counting restarts every 10 minutes, and a new entry is saved in the CSV file.

In our first prototype with 30 sensors, the signal and power lines of the motion sensors were connected to a protoboard that provides power to the sensors through a power supply and relays the output of the signal lines to the DAQ. A protoboard is an off-the-shelf printed circuit board (PCB) that allows us to quickly assemble and test electronic components by soldering them to their pre-set holes. To save time, the wires from the birdcages to the DAQ were quickly assembled in this protoboard.

However, a custom PCB is preferable, which we designed for the second version of our system. Before describing the new system, we must first explain how the motion sensors work, how the software collects the sensors' data and the mechanical enclosure. All these are practically the same for both versions.

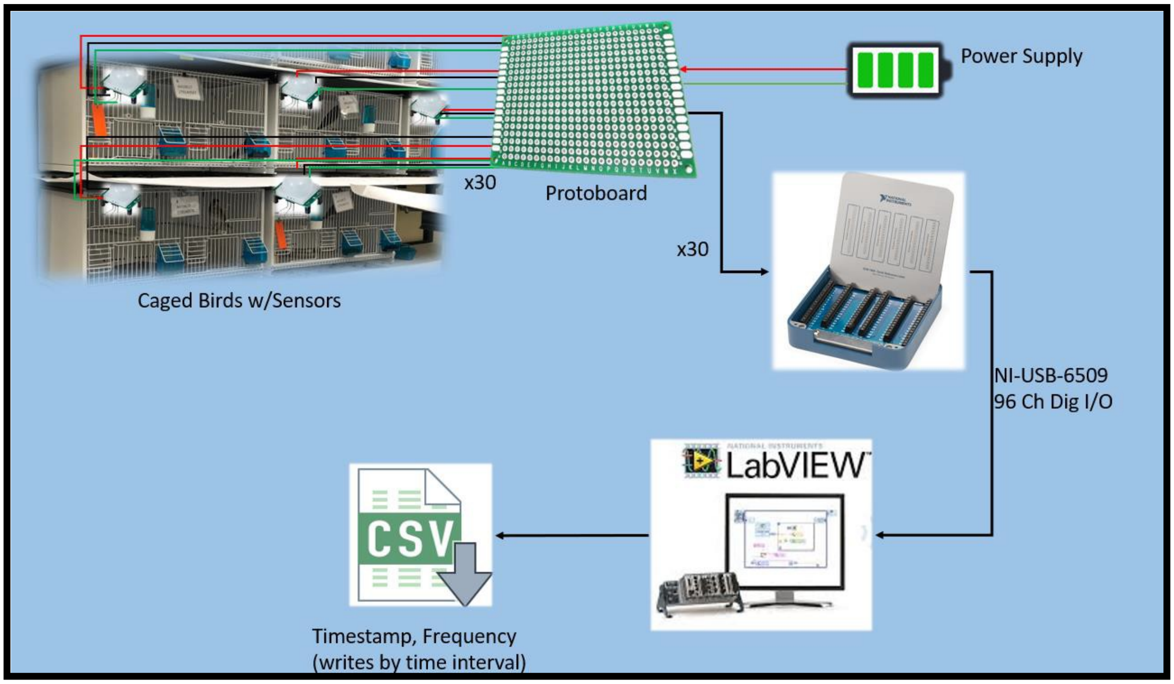

Figure 2. Zugunruhe data collection system's conceptual block diagram (first prototype).

Sensors

A passive infrared sensor (PIR, Figure 3) works by detecting warm objects. All warm objects radiate heat as well as an invisible light called infrared light. The PIR sensor is passive, meaning that it only reacts to a change. When a bird moves, the sensor detects the change in infrared light (Karvinen and Valtokari, 2014) and changes the output to a digital high state.

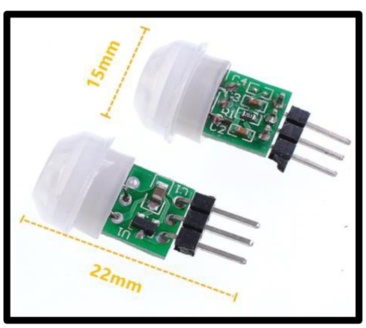

Figure 3. AM312 passive infrared sensor

To test the PIR sensor, we need to let the sensor adapt to its environment for at least 30 seconds. In this case, the environment is a birdcage, and we tested the sensor by powering it with a direct current (DC) power supply and connecting it to a light-emitting diode (LED). Once the sensor is triggered by a movement, such as a hand-wave, the sensor outputs a digital "high" signal as long as there is movement. Once the sensor registers the movement, it sends that signal as a voltage level to the LED. When the hand passes over the sensor, the LED lights up, which shows that the sensor is active. We did this as we moved the sensor along different areas of the cage to test for its optimal placement in order to detect a broad range of bird movement within the cage and to not pick up movements outside of the cage. Figure 4 shows our preliminary test to evaluate the sensor's placement.

After the initial tests, we selected the AM312 PIR sensor, shown in Figure 3. It is small enough to fit between the bird cage's bars to allow the sensing element to be inside while the rest of the device is outside. The sensor detects motion and sends a digital "high" signal on the output pin for three seconds.

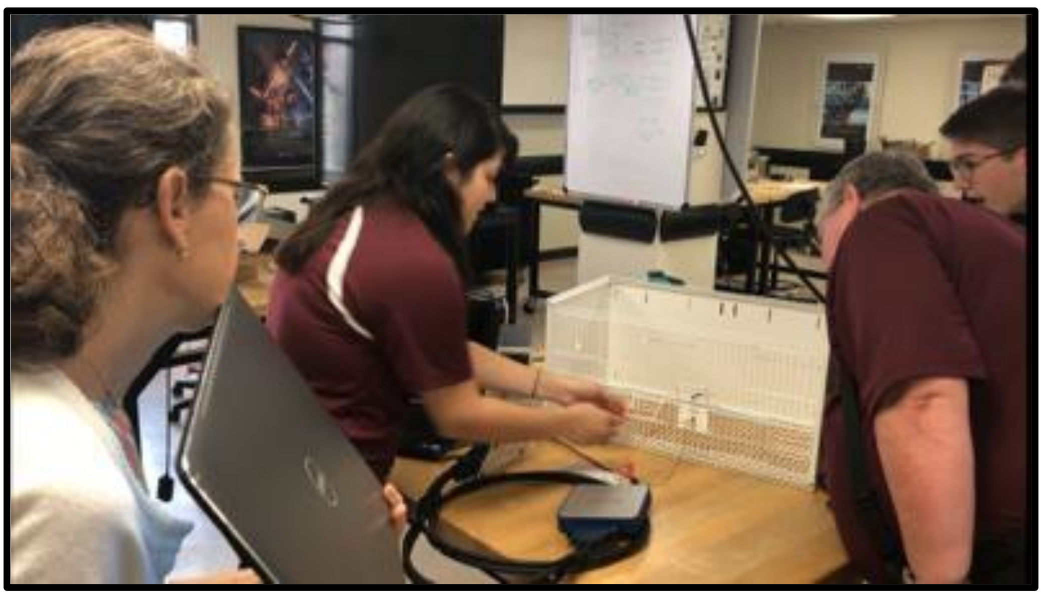

Figure 4. Initial tests of the PIR motion sensor in the birdcage.

Thus, when a bird is moving inside the cage (i.e., a slight jump on top of its perch or a short flight from one side of the cage to the other), multiple movements are recorded. The AM312 PIR sensor's output stays in digital "high" mode, without changing state, by simply holding the current state an additional three seconds after each new bird movement.

We chose the AM312 PIR sensor after testing other sensors, such as the E18-D80NK infrared photoelectric switch sensor that had an immediate time response with practically zero delays. This immediate response feature was better than the three-second delay of the AM312 PIR sensor. Still, the E18-D80NK infrared photoelectric switch sensor had a very limited, laser-like narrow beam of detection, which failed to capture the full degree of movement exhibited by the birds as we needed to detect the entire 24" x 12" x 14" cage and not one point. Another issue was that the cages were white, and their walls reflected the laser-like beam. To overcome this problem, this E18-D80NK infrared photoelectric switch sensor was also tested by placing it on the side of the birdcage and installing a black background to avoid any light reflecting the sensor; however, the results were not satisfactory, and the introduction of additional material to cover the cage walls was impractical.

In summary, the selected sensor – the AM312 PIR sensor – has a wide sensitivity range, but as a drawback, it has a three-second time delay after the detection of movement. Additional specifications of the AM312 sensor are listed in Table 1.

Table 1. AM312 PIR Sensor Specifications.

AM312 PIR Sensor	Description
Voltage	DC 2.7-12V
Current	< 0.1mA
Delay time	3 seconds holding time after movement is detected
Sensing range	≤ 100-degree cone angle, 3-5 m
Working temperature	-20 to + 60 °C
Size	Approximately 15 mm x 22 mm

Software Design

To interface the AM312 PIR sensor with its three-second holding time, the LabView program counts the number of seconds that the sensor is active instead of state transitions. To help explain this, we present here two scenarios.

First, Figure 5 shows a scenario with two bird movements at 0 and 4 seconds. The sensor's output goes to "high" when a bird moves at time 0, returns to "low" three seconds later, then at time 4 goes to "high" again. In this case, if we count the number of signal transitions, i.e., the signal changed from "low" to "high," the result is two movements. If we count the number of seconds the sensor is active, the result is 6 seconds, which divided by a 3 corresponds to 2 movements as well.

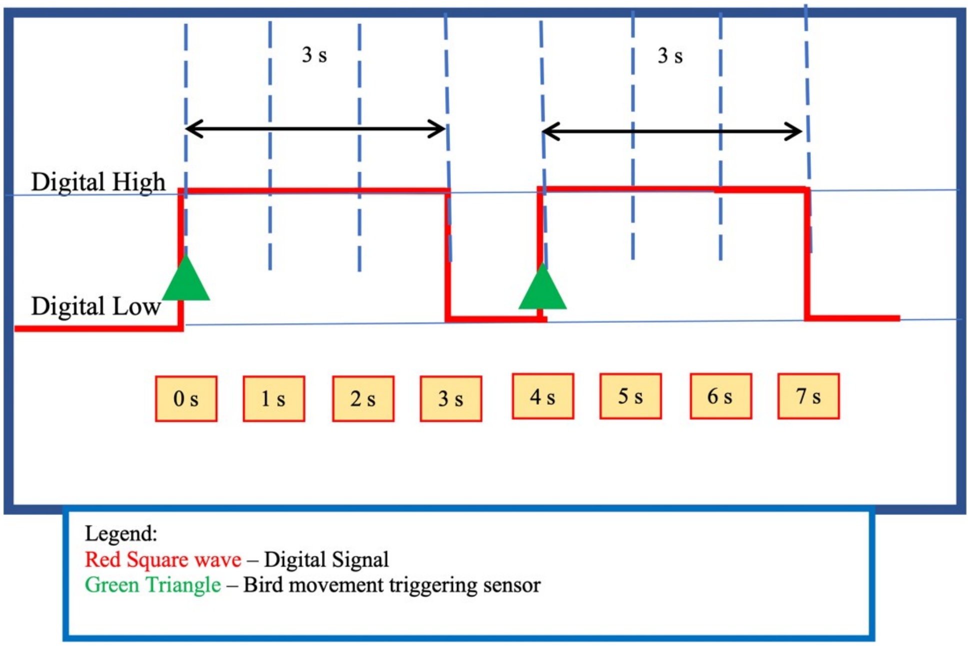

Figure 5. Scenario 1: A bird moves at intervals larger than three seconds, and two movements are detected by counting transitions from "low" to "high" or counting how long the sensor is active.

Another scenario with faster transitions is shown in Figure 6, in which birds are moving at times 0, 1, and 3 seconds. After every new movement, the sensor adds a 3-second delay and does not transition to the "low" state. If we count the number of transitions, that gives us 1 movement only. However, if we count the seconds that the sensor is active, the result is 6 seconds. If we divide 6 seconds by the 3-second holding delay, the result is 2 movements. Although it did not detect all three movements of this scenario, it provided a better result than counting the state transitions.

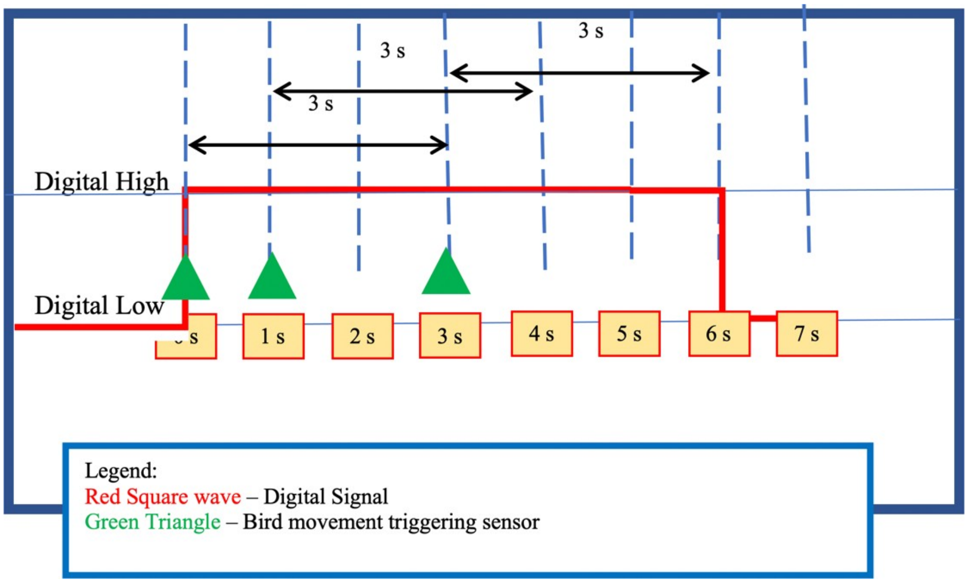

Figure 6. Scenario 2: A bird moves more frequently, and the sensor's output remains "high." Counting the number of seconds is a better measure than counting signal transitions.

Therefore, the LabView software measures the number of seconds that the PIR sensor is active. When the birds move at intervals lower than three seconds, it will record at most 60 seconds of active (digital 'high') state in a 1-minute interval. This divided by 3 results in 20 movements per minute, which we report as the highest activity that the *zugunruhe* system can detect per minute. Although the system does not count exactly the number of bird movements, the system records an approximate number of movements, which can be used to represent the level of a bird's "restlessness" within a 10-minute interval.

The flowchart in Figure 7 illustrates how our LabView program works. First, it initializes the DAQ ports and starts with 0 or no movement. A variable-time segment can be adjusted by the user to any desired time frame. In this case, we set it to 10 minutes. Then, the program reads the sensor data every second. If there is sensor movement (output is 'high'), it adds this movement to the counter. To store the movement counter at every second, registers are used at each input port and incremented at every active state. If the time interval of 10 minutes is reached, the program saves the value of each register in the CSV file and resets the counter. The

LabView code provides an easy-to-use GUI (Figure 8) and displays the status of each DAQ channel, a configurable time interval, and a file path to store the CSV file.

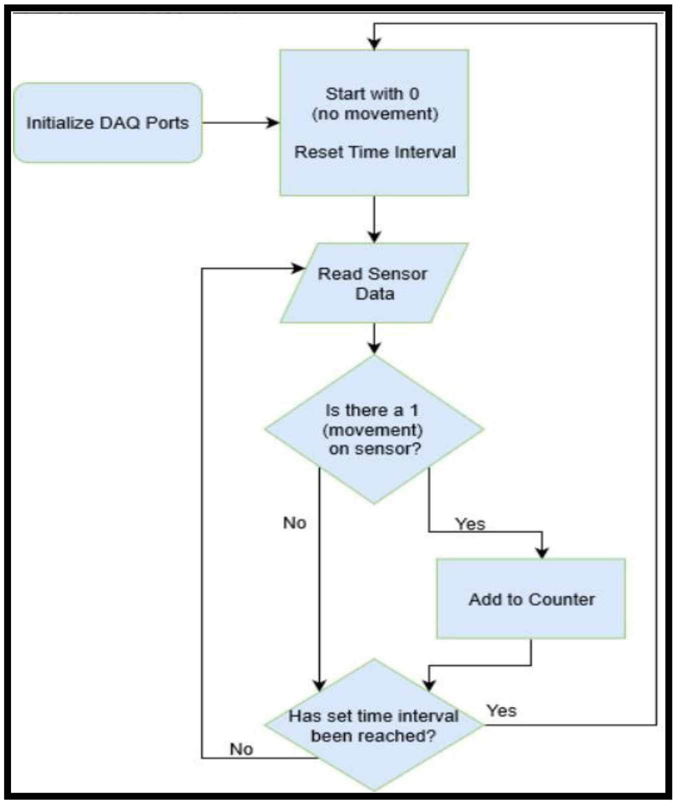

Figure 7. Flowchart of LabVIEW Code.

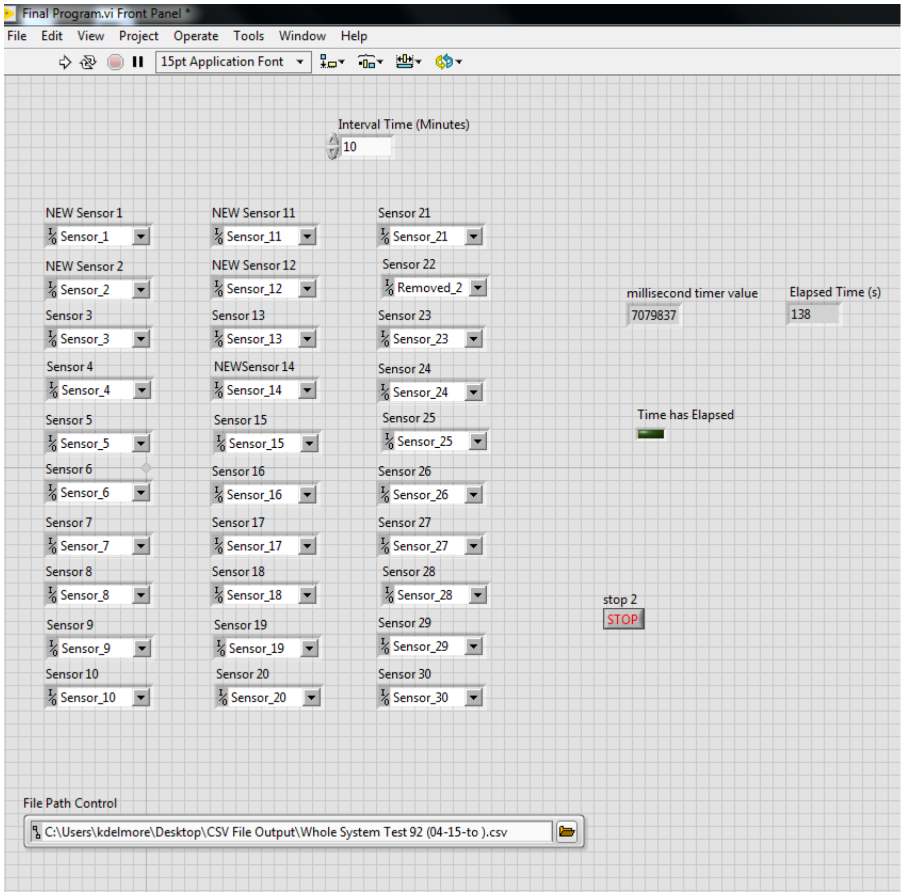

Figure 8. The graphical user interface of the LabView program. - Mechanical Design of Sensor Enclosures

For the mechanical design phase, prototyping, brainstorming, and sketching by hand were essential to optimize the design needed to mount the sensors onto the bird cages. We designed a plaque with a central hole to fit the PIR sensor and four smaller holes at each corner of the plaque to tie it onto the birdcage (Figure 9). The 3D modeling of this design was done using Solid Works® software (SolidWorks). First, we 3D-printed a few sets of these plaques to test them in the birdcages.

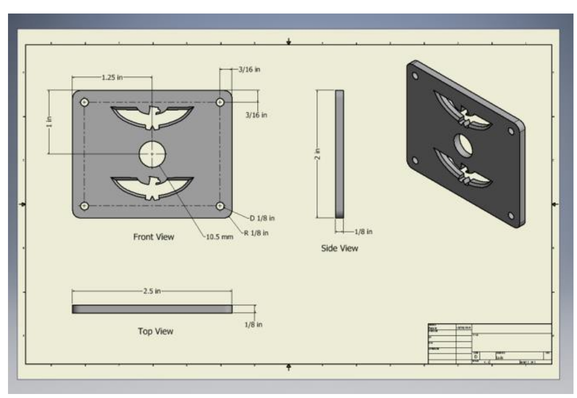

Figure 9. Passive Infrared Sensor enclosure design.

Then, we converted the design from Solid Works to AutoCAD (AutoDesk) to use a laser cutting machine for a rapid manufacturing process.

Second Prototype

After the *zugunruhe* data collection system was operational during the winter of 2019-2020, we designed and built a new system which is operational since December 2020. The goal of the new system is to be more scalable and easier to maintain with more robust wiring. The previous hardware design that uses the protoboard had many loose wires (Figure 2), and it was difficult for the researchers to move the birdcages within the laboratory. Sometimes a bird needed to be moved to a warmer place in the laboratory. When the wires were reconnected, they were accidentally connected with different polarities, and the sensor was damaged. Also, all the available pins of the protoboard were used, and the system was not scalable. The researchers planned to double the number of birds, from 30 to 60, which arrived in the laboratory in the fall semester of 2020.

Ideally, we wanted to design the system using wireless communications, such as Zigbee wireless modules (Elahi, 2010), which would remove the need for wires. However, a large number of metal birdcages in the laboratory could interfere with the wireless signals. Also, the wireless modules emitted light, which worked against the requirement of sensors being discrete with no visible light.

The principles of operation of the new data collection system are the same, but the new hardware design consists of a customized PCB that connects the sensors to the DAQ and central computer, which we call "master PCB." Our solution was to use old technology, i.e., telephone cables with RJ-11 connectors and a harmonica adapter, that helped create a star topology, similar to switches in an Ethernet network. A small PCB was designed for each cage to allow the RJ-11 connector to be plugged into the sensor. The sensors are connected using RJ-11 cables to the harmonica. The output of the harmonica is connected to the master PCB using a large telecom cable.

Figure 10. Sensors are connected using RJ-11 cables (left), which go to 12-port harmonica adapters (right). On the back of the harmonica adapter we can see the telecom cable connector.

The master PCB is shown in Figure 11. The five telecom cables are the inputs, which come from the harmonica adapter, with 12 sensors each. The output is a connector based on NI's cable pin diagram (NI # 777778-01) that allows the DAQ to be plugged directly into the master PCB.

Figure 11. Master PCB is connected to five harmonica adapter using telecom cables. This system can grow to support a total of 96 sensors.

Results

In this section, we describe the results of our first year of data collection and show that the system is accurately capturing the birds' movements. We also discuss our current experience with the second prototype.

Validation

First, benchmark testing was performed. The results of the *zugunruhe* data collection system were compared with the results of infrared (IR) cameras (D-link, DCS-932L Day/Night Network Surveillance Camera) that were installed in the laboratory and examined for nighttime activity.

We used IR cameras to collect behavioral data from a subset of 21 birds. Camera recordings were observed for five minutes every two hours between 6 P.M. and 6 A.M (i.e., seven time points) for one week. Any movement during each time point (e.g., whirring, jumping) was noted as an "active" time point, and data were recorded as the number of active time points, with a maximum record of seven time points. The PIR sensors were running continuously in 10- minute increments. Any 10-minute increment in which the bird exhibited greater than or equal to 20 movements was considered an active increment. We then calculated overall activity from the sensor as the proportion of the night that the bird was active.

We used a generalized linear model to test if there was a correlation between the activity recorded from PIR sensors and IR cameras. Since we were testing the accuracy of the PIR sensors, we used IR camera activity as the predictor variable and IR sensor activity as the response variable. We also used individual bird identification as a random factor, which accounts for repeated measures for the same individual. Activity data from PIR sensors and IR cameras were highly correlated, as shown in Figure 13.

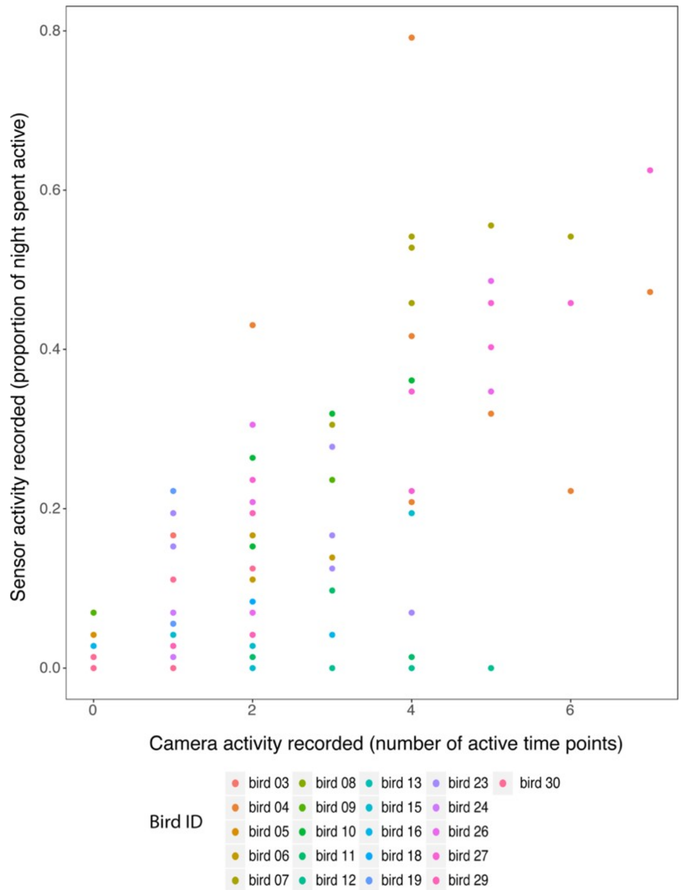

Figure 13. Activity measurements from PIR sensors and IR camera logs over one week (January 1 through January 7) were highly correlated (Generalized Linear Model, n= 20 Birds, Random Factor= Bird ID, X^2=137.04, $p < 0.0001$). Sensor data is Presented as the percentage of the night the birds were considered active. Camera activity is presented as the number of active time points observed

Data collected with the initial prototype

The first version of the *zugunruhe* data collection system was installed in the laboratory in December 2019. It recorded behavior for 30 birds for 123 days. Researchers were able to download data into a CSV format daily to check the migratory status of each bird.

An example of activity data for one bird between the Days 104 and 113 is shown in Figure 14. Night-time, when lights are off in the laboratory, is indicated with gray bars with a moon at the top for the first day. Daytime hours, when lights are on, are indicated with yellow bars and a sun for the first day. The high number of total movements when lights are off, especially after Day107, indicates the bird was exhibiting migratory behavior during this time.

In this project, we simulated a short-day photoperiod typical of winter until we were ready to measure migratory behavior. After Day 53, we gradually increased the number of hours that lights were on, reaching a long-day photoperiod of 16 hours of light: 8

hours of darkness (16L:8D) on Day 95. Figure 15 shows the total nocturnal activity of one individual bird between Day 53 and Day 122. After the photoperiod has reached a long day length (~Day 95), the bird exhibits greater nighttime activity, or "migratory restlessness."

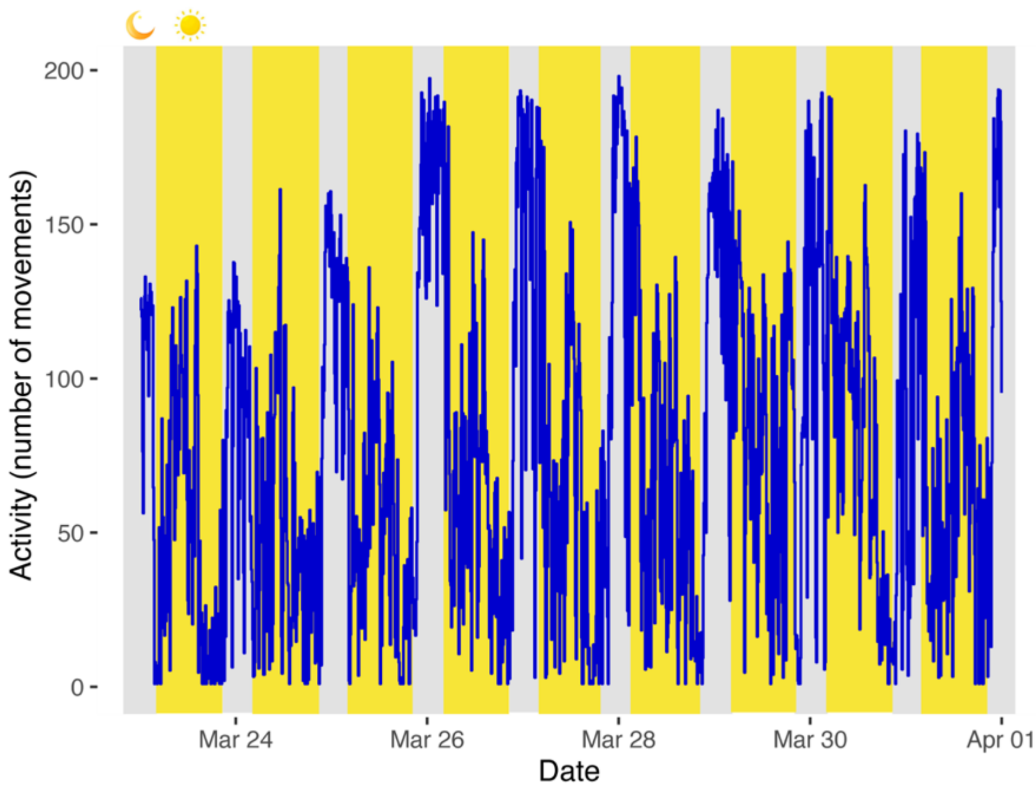

Figure 14. The activity log of one individual between Day 104 and Day 113. Lights were on during the day (yellow bars) and off at night (gray bars) based on day length typical on the breeding grounds of the bird (16 hours light: 8 hours dark).

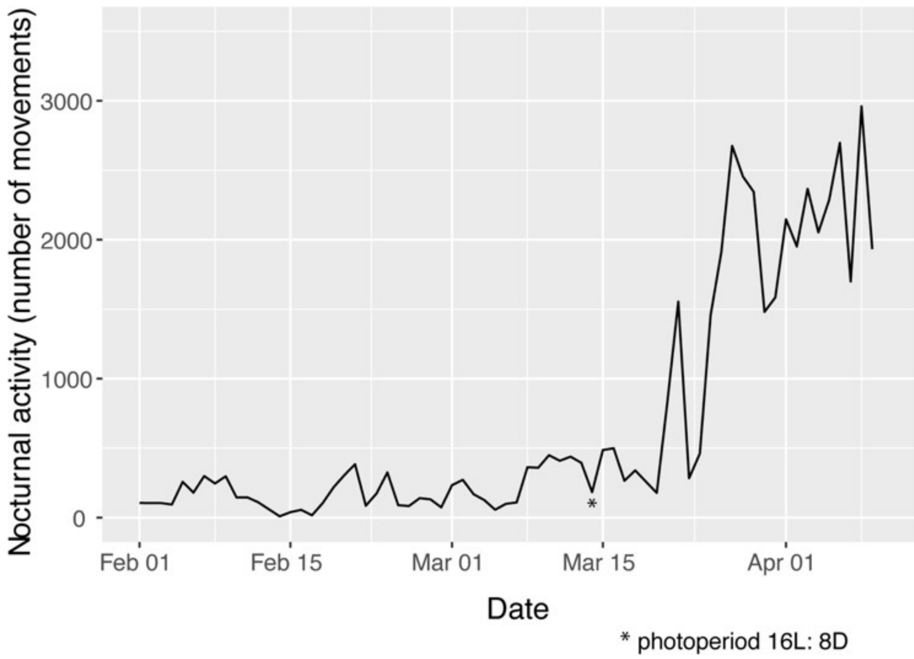

Figure 15. The total nocturnal activity was recorded between Day 53 and Day 113 for one bird. The asterisk shows when the day length reached 16 hours of light and 8 hours of dark (16L:8D), which is considered a long day length that can be used to stimulate nocturnal migratory behavior.

Experimenting with the second prototype

At the end of 2020, the second prototype of the *zugunruhe* data collection system was installed to monitor 60 birds. Although the system became more scalable and the wiring in the laboratory more organized, with the help of the RJ- 11 cables, harmonicas, and master PCB, we experienced new problems.

First and foremost, we confirm that the data collected is reliable. In one cage, the data indicated no movement, and death was suspected; however, upon inspection, the bird was alive and moving inside its cage. This happened in a few other cages as well. Many sensors had to be replaced, and we provided the researchers with extra parts for the sensor PCB and RJ-11 cables. Second, the wiring was not as robust and immune to changes as we planned. When the researchers moved cages around, they were disconnecting the sensor PCB from the PIR sensor pins instead of unplugging the RJ-11 cable. We learned that the changes we made had some trade-offs. For example, the loose wires in the first prototype were easier to test and inspect than the RJ-11, telephone-like cables, of the second version. The new mechanical enclosures were not as tight as the older units, and the sensors were loose and had to be glued one by one. Also, we tied the cables to the cages with plastic ties that were sometimes too tight and difficult to move. These new issues had to be addressed quickly, especially during the winter holidays. This was a timely project, and every detail was important to support the researchers.

As described in Section 3.1, to confirm that the data collected is reliable, the researchers used IR video cameras to compare the videos with the data collected using our prototype for a few selected cages. Now, in the winter of 2021, the data collection is ongoing.

Conclusion

In conclusion, we designed an automated system to monitor migratory restlessness for Swainson's thrushes. The direct application of this resource is to study the genetic basis of migration, but this infrastructure can have other applications. For example, many research laboratories study migratory behavior, and migration is important for many fields (e.g., ecology, conservation, neurobiology, physiology). Many researchers beyond those studying migration require information on daily activity schedules (e.g., researchers studying circadian rhythm or foraging behavior).

Two versions of the system have been built, and this is the second winter of data collection. We know that the system can be further improved, as this is a work-in-progress. In the future, we envision replacing the AM312 PIR sensor and developing a custom PIR sensor that can fit nicely in the bird cages, using a solid enclosure that is immune to moving birds and cages around. After all, the laboratory is a dynamic environment, and the *zugunruhe* data collection system should be flexible, robust, and scalable.

Finally, the interdisciplinary nature of this project has been a valuable learning experience for undergraduate researchers and faculty members. The engineering students have often communicated and interacted with students in the biology department. Moreover, they have learned how to interpret the requirements from a different discipline and turn them into a functional prototype, contributing to the research on the genetics of migration and potentially other research projects.

Acknowledgments

The authors would like to thank Professor Mike Willey, who teaches the final semester of the Capstone course series in the Electronic Systems Engineering Technology (ESET) program (ESET 420). Prof. Willey's industry experience and practical advice were essential to the development of this data collection system. We are also grateful to Barbara Earnest who trained the engineering students and supervised them in the birds laboratory. Additionally, we would like to thank other undergraduate student workers who helped test the system, such as Ashley Alario and David Ross Baldridge.

Literature Cited

Dawson, A., King, V. M., Bentley, G. E., & Ball, G. F. (2001). Photoperiodic control of seasonality in birds." *Journal of Biological Rhythms*, *16*(4), 365-380.

Delmore, K. E., & Irwin, D. E. (2014). Hybrid songbirds employ intermediate routes in a migratory divide. *Ecol. Lett*, *17*(10), 1211–1218.

Delmore, K. E., & Liedvogel, M. (2016). Investigating factors that generate and maintain variation in migratory orientation: a primer for recent and future work. *Frontiers in Behavioral Neuroscience*, *10*, 3.

Eikenaar, C., Klinner, T., Szostek, K.L., & Bairlein, F. (2014). Migratory restlessness in captive individuals predicts actual departure in the wild. *Biology Letters, 10*, 20140154.

Elahi, A., & Gschwender, A. (2010). *Zigbee wireless sensor and control network*. Prentice Hall.

Evans, H. (2019). *Study of captive songbird migratory restlessness,* zugunruhe*, by direct and video activity observation before, during and after the autumnal migration period* (Master thesis). American University, Washington, D.C.

Fairweather, I., & Brumfield, A. (Eds.). (2011). *LabView - A Developer's Guide to Real World Integration* (1st ed.). Chapman and Hall/CRC.

Gauthreaux, S. (2019). *Encyclopedia of Animal Behavior* (2nd ed., Vol. 1). Reference Work.

Gwinner, E., & Czeschlik. D. (1978). On the significance of spring migratory restlessness in caged birds. *Oikos*, *30*, 364–372.

Helbig, A. (1996). Genetic basis, mode of inheritance and evolutionary changes of migratory directions in Palaearctic warblers (Aves: Sylviidae). *The Journal of Experimental Biology*, *199*(Pt 1), 49–55.

Karvinen, T., Karvinen, K., & Valtokari, V. (2014). *Make: Sensors - Projects and Experiments to Measure the World with Arduino and Raspberry Pi* (1st ed.). Make Community, LLC.

Liedvogel, M., Åkesson, S. & Bensch, S. (2011). The genetics of migration on the move. *Trends in Ecology & Evolution*, *26*(11), 561–569.

Muheim, R., Henshaw, I., Sjöberg, S., & Deutschlander, M.E. (2014). BirdOriTrack®: a new video-tracking program for orientation research with migratory birds. *Journal of Field Ornithology*, *85*(1):91–105.

Rosenberg, K. V., Dokter, A. M., Blancher, P. J., Sauer, J. R., Smith, A. C., Smith, P. A., Stanton, J. C., Panjabi, A., Helft, L., Parr, M., & Marra, P. P. (2019). Decline of the North American avifauna. *Science*, *366*(6461), 120–124.

Rowan, W. (1928). Reproductive rhythm in birds. *Nature*, *122*,11-12

Van Doren, B. M., Liedvogel, M., & Helm, B. (2017). Programmed and flexible: long-term *Zugunruhe* data highlight the many axes of variation in avian migratory behaviour. *Journal of Avian Biology*, *48*(1), 155-172.