Microwave-Based Motion Detection for Monitoring Circadian Rhythms in Mice

Author: Wisam Fares

Supervisory Committee: Dr. Stephen Arce, Dr. Kevin Otto, and Dr. Karyn Esser

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Abstract

Sleep is an important component of any animal's life, including human beings. Therefore, scientists who focus their research require a variety of techniques to understand causes and effects of circadian rhythms of their test subjects. Circadian rhythms encompass a variety of biological processes, but sleep is a major component of circadian rhythms and changes in sleep directly affect other components of circadian rhythms, such as eating schedule, daily activity, and awareness. A large part of funding for this type of research is dedicated to clinical applications; however, many preliminary studies are required before reaching this stage. For this reason, it is typical to start with murine models, as they are relatively easy to manage and allow for larger sample sizes compared to larger animal and clinical studies.

A primary metric used by scientists investigating circadian rhythms is daily activity. For murine models, this typically involves monitoring wheel running activity. However, this only measures the amount of time the mouse spends on the wheel, rather than total daily activity. Therefore, continuous monitoring of mice would provide more accurate representations of data. Using our microwave-based motion detector will allow for continual monitoring, while being less costly than previous methods, such as video tracking which requires extensive processing and analysis. Although our motion-detector has small current errors, it shows promise as an addition methodology for monitoring circadian rhythms in mice.

Introduction

All animals require sleep to function properly, and for this reason it is important to understand the causes and effects of irregular sleep. Investigations involving sleep typically focus on circadian rhythms which involve physiological and behavioral changes that occur throughout a daily cycle. For example, when animals sleep, wake up, eat, and so forth. Small changes in an environment or eating behavior can have drastic effects on circadian rhythms, for example being exposed to light continuously, rather than typical light-dark cycles the earth experiences can cause disruptions in sleep patterns. Disruptions in sleep can be detrimental to an animal's behavior and physiology. For this reason, researchers are inclined to investigate the extent an animal's behavior can be changed by external factors, such as change in diet or exposure to light, as previously mentioned. It is also important to understand the effects lack of sleep has on subjects, as they can often lead to a vicious feedback cycle where lack of sleep causes physiological changes that in turn cause more lack of sleep, so on and so forth.

Due to the complexity of circadian rhythms, there are a variety of methods utilized for investigation, ranging from simple techniques, such as measuring temperature changes on different areas of the body, to more complex techniques such as analyzing electroencephalographs (EEGs) [1]. However, some of these techniques are invasive or may affect sleep due to irregularity, for example having sensors attached to a subject's body. Therefore, it has been more common place to utilize non-invasive sensors that monitor motion of subjects. This is especially true in the case of murine investigations, since a minimal number of sensors is required because of the small cage size relative to larger animal models. Previously, mouse wheels were used to monitor the amount of activity mice by measuring the amount of distance was run on the wheel (Figure 1) [2]. However, this does not provide an entire log of activity, for example if the mice were active off the wheel.

Other methods include continual observation techniques, such as video-tracking and vibration sensing. Video-tracking requires video analysis, which is often time-consuming or requires dedicated software, while vibration sensing is less accurate and therefore provides less reliable data and interpretations. Using continual monitoring using motion detectors will allow for more accurate representations of mice activity while simultaneously providing a simpler data set to compile and compare, unlike video-tracking which may be subjective to software or user interpretation. This will prevent unintentional bias and lead to more consistent experimental data.

Figure 1: Mouse wheel with sensor attached to monitor amount of spontaneous activity on wheel by mouse [3].

Continual monitoring using motion detectors is not a new concept. Previously, specialized cages with built-in sensors were utilized; however, their cost was often to large to justify their use. For this reason, this project will utilize a previously proposed design for a cost-effective motion detector [4] for monitoring circadian rhythms in mice. If successful, this will provide a cost-effective monitoring system that could be mass produced for an even smaller cost, making continual motion-detection systems standard in research and allowing for comparable data between different labs.

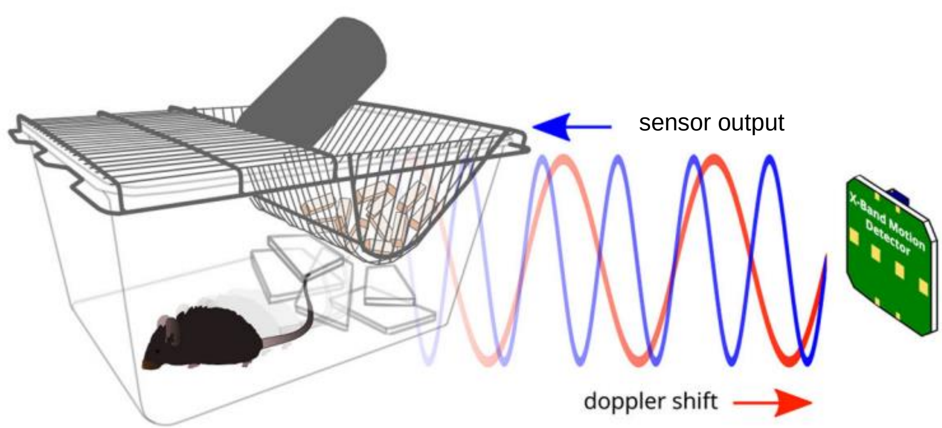

Figure 1: Illustration depicting doppler shift measurement by X-Bad Motion Detector [4].

The specific motion-detection system tested for this project utilizes the doppler shift phenomena of microwaves that correspond to changes in position of objects, in this application, of motion in mice. When a mouse moves, a microwave will reflect off it, causing a change in frequency known as a doppler shift. This change can be measuring using specialized sensors that transmit a microwave of a fixed frequency and detecting miniscule changes in the frequency of the reflection. Using this measurement, programs can correlate this frequency difference into positional changes, albeit in one dimension. To counteract this, multiple motion detectors are used to capture 3D motion and interpolate 3D position.

Materials and Methods

This project involves the two major components, namely the construction of the microwave-based motion detector and then the testing of the device. The construction of the device took most of the semester, and therefore will be the focus of this paper. Nonetheless, the testing of the device is arguably the more important and interesting portion of the project.

Materials

Listed below is the complete component list, as well as the vendors that distributed each component (Figure 3). Components listed here will be discussed as necessary when describing their roles in particular

PRODUCT #	DESCRIPTION	VENDOR	QUANTITY
32213	X-Band Motion Detector	Parallax Inc	6
952-2264-ND	3-pole, 2.54 mm, header	Digi-Key Electronics	10
P814-ND	electrolytic capacitor 22µF, 25V	Digi-Key Electronics	20
1N4148FS-ND	1N4148, 100V, 300mA	Digi-Key Electronics	20
56-0535	LED, 3 mm, 1.85V, red	Rapid Online	20
296-3707-5-ND	SN74LS423N	Digi-Key Electronics	10
952-1786-ND	4-pole, 2.54 mm, socket	Digi-Key Electronics	20
751-1055-1-ND	TEMT6000 Light Sensor	Digi-Key Electronics	3
A126332CT-ND	10 kΩ, SMD 0805	Digi-Key Electronics	25
A106060CT-ND	2.2 kΩ, SMD 0805	Digi-Key Electronics	20
A126350CT-ND	220 kΩ, SMD 0805	Digi-Key Electronics	20
5-103960-3-ND	4-pole, female, 2.54 mm	Digi-Key Electronics	20
A34222-ND	4-pole, male, 2.54 mm	Digi-Key Electronics	20
70638060	0.71mm Transparent PTFE Cable Sleeve; 5mLength	Allied Electronics	1
70637992	3.05mm Transparent PTFE Cable Sleeve; 5mLength	Allied Electronics	1
RT-11417 ROHS	Arduino Stackable Header Kit - R3	Sparkfun	6
1141	Adafruit Assembled Data Logging shield for Arduino	Adafruit	3
A000066	Arduino Uno Rev3	Arduino	3
A106055CT-ND	10Ω, SMD 0805	Digi-Key Electronics	20
541-51.0KCCT-ND	51 kΩ, SMD 0805	Digi-Key Electronics	20

Figure 3: Material list for motion-detector

Microwave-Based Motion Detector Construction

The construction of the microwave-based motion detector was done by following an outlined a previously published paper [4] with slight modifications. These modifications, which will be discussed later in this section, were made mostly based on availability of components, but were chosen to ensure minimal effects on the overall performance of the device. Overall the microwave-based motion detector assembly consists of three subassemblies (We) the motion detector shield, (ii) a data logger shield, and (iii) an Arduino Uno microcontroller board. The combination of all three subassemblies allows for the user to measure and record data. Furthermore, the circuitry used is relatively basic, and requires minimal experience to construct and collect data efficiently.

Motion Detector Shield

The motion detector shield is the major component of this project and therefore required the most work to ensure functionality. The motion detector utilizes a Printed Circuit Board (PCB) printed by OSH Park, a community circuit board printing service recommended and utilized by the previous researchers [4]. The boards are printed under standard manufacturing parameters: 1.6 mm thickness, electroless nickel immersion gold finish, clearance >160 um, trace width >160 um, 240 um drill size, and two-layer FR4 [4]. The PCB has multiple components soldered to it, including diodes, light sensors, light-emitting diodes (LEDs), electrolytic capacitors, and integrated circuits. Furthermore, surface mounted device (SMD) resistors were utilized. SMD components allow for smaller components (especially true for the resistors in this case) and therefore a higher component density. This also reduces the number of holes that need to be drilled into a PCB, increasing its manufacturing cost and production time. The six X-Band motion detectors are connected directly to this PCB and integrate each of the signals to be stored in the data logger shield (see next section).

Data Logger Shield

The data logger shield was manufactured by Adafruit. As the name implies, the data logger shield allows for measured values to be saved to an SD card for later analysis. The data logger communicates directly with the motion detector shield, receiving data from each one of the six motion detectors, returning a value of 1 (when motion is sensed) and 0 (otherwise). The data logger shield required little soldering work, as the only connections required were those that allow cross-communication between the motion detector shield and the data logger shield.

Arduino Uno Microcontroller Board

Arduino Uno is produced by Arduino, a company that specializes in creating simple circuits tailored towards beginners and experts a like due to their easy-to-master setup. The Arduino Uno is responsible for interpreting Python code provides instructions for the data logger shield to follow, such as how to save the data acquired.

As mentioned previously, some slight modifications were made to the design to accommodate restrictions that were faced. These modifications include: (We) different brands of resistors and (ii) a different DC power source. The reasoning behind these changes as well as possible consequences are discussed below.

Brand of Resistors Modification

When searching for 10Ω SMD resistors manufactured by the company Vishay as noted in the previously published paper [4], they were currently out of stock. For this reason, we decided to using 10Ω SMD resistors from the manufacturer Susumu. The reason these were chosen as a replacement is that they had a stricter tolerance of 0.5% compared to the Vishay's tolerance of 5%. Therefore, it was guaranteed that these resistors would be within the same operating range. Although the cost of the Susumu resistors was slightly higher than their Vishay counterparts, the difference in cost of a single resistor was only three cents (3¢) resulting in a total increase of 18 ¢ to the budget, which is negligible when compared to the total cost of the device.

DC Power Supply Modification

Since the previously published research was conducted in Europe [4], different DC adapters were required. However, after choosing a DC adapter that converts AC into a constant 10 V source, little to no difference was observed. Although no problems were expected from this change, it is important to note that our project did deviate from the original paper in this manner.

Testing

Testing of the device involved two experiments: (We) static conditions and (ii) dynamic conditions followed by static conditions. Rather than using actual mice in these tests, we opted to using tennis balls (with mice faces drawn on them) due to their similar size and availability.

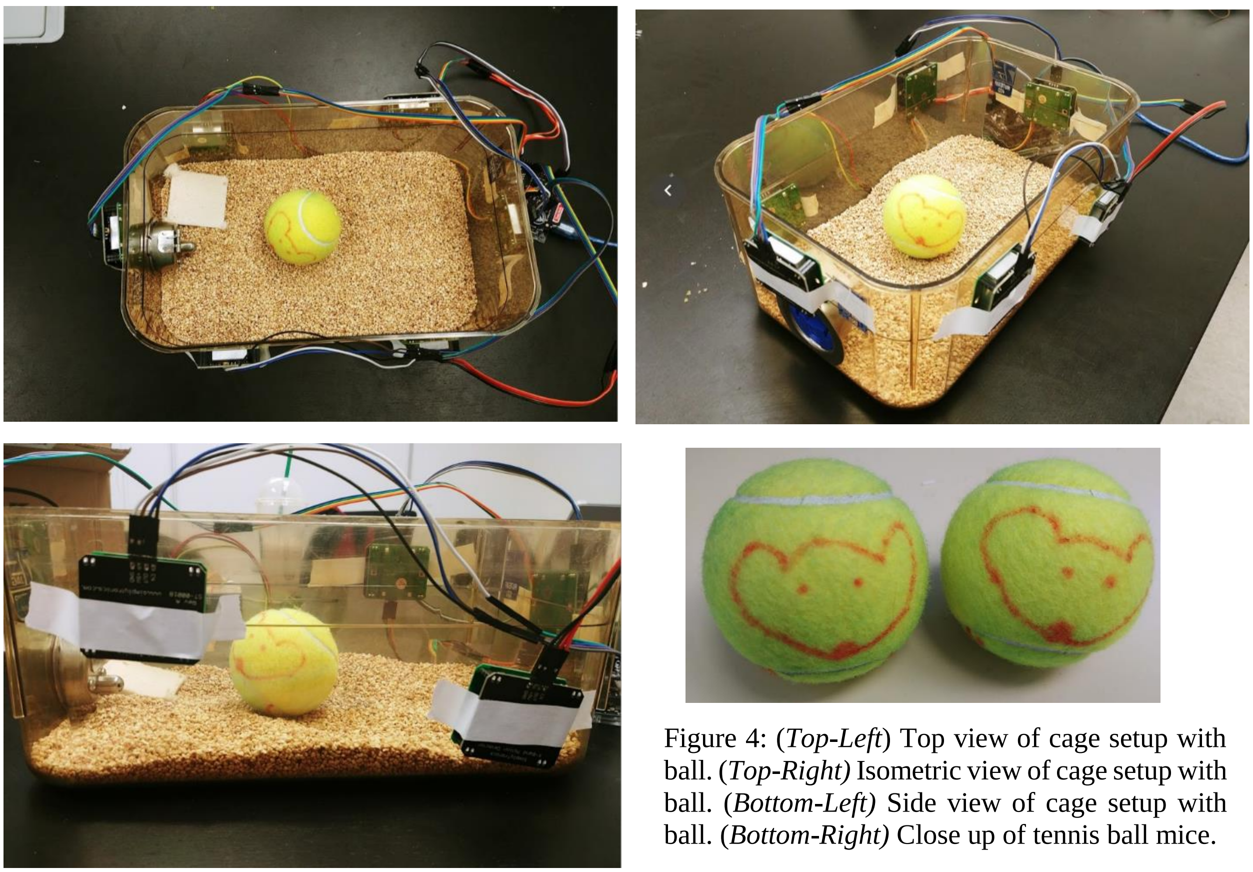

Figure 4: (*Top-Left*) Top view of cage setup with ball. (*Top-Right)* Isometric view of cage setup with ball. (*Bottom-Left)* Side view of cage setup with ball. (*Bottom-Right)* Close up of tennis ball mice.

Static Conditions

To determine a baseline of static conditions, we allowed the tennis balls to sit in the position observed in Figure 4 for 35 minutes. The ball was placed in the middle of the cage to ensure that the ball would be in the microwave beam emitted by most of the microwave sensors. After recording this data, the data logger was shut off to begin the next experiment involving motion detection.

Dynamic Conditions

To ensure that our motion detector set up was working on an elementary level in the sense that it could distinguish between a moving and non-moving object, we ran a short test over the course of 45 seconds. In this experiment, the ball was moved randomly for 15 seconds and then returned back to static conditions for 30 seconds. Analysis of the data gathered from these experiments are noted in the Results section below.

Statistical Analysis

Student t-tests were run to determine if a difference was measurable between the dynamic conditions and static conditions. This was done using SAS/JMP Software.

Results and Discussion

Static Experiments Results (Figure 5)

The following pages consist of data gather from the previously described experiments. Figure 5 shows the experiment involving 35 minutes of static conditions with the ball placed as shown in Figure 4. Over the 35 minutes, 34, 189 data points were collected at approximately 101±22 ms apart from each other. Notice that under static conditions all the graphs remain fairly constant, although the fact that Channel 3 and Channel 6 display a constant value of 1 is cause for concern since a value of 1 is indicative of motion being detected. Given the consistent nature of the error, rather than sporadic spikes, it can be hypothesized that the error arises from consistent stimulus or problems within the sensors themselves. Consistent stimulus seems most likely since Channel 3 and Channel 6 are across from each other and are emitting at similar, if not the same frequencies. This could possibly result in the sensors on each of the detectors to give a false positive.

Another possible reason for this error could arise from faulty circuits. A way to rule out this possibility would be to test each sensor individually to prevent sensor-sensor influences. After ruling this out, the coding should also be checked to ensure no errors were made resulting in a negation of the signal.

Figure 5: Channel outputs over 35 minutes of static activity, ball shown at position in Figure 4. The output here is binary, in other words, 1 if motion is detected, and 0 if motion is not detected. Channel 3 and Channel 6 have a constant output of 1 at almost every sample, indicating problems with either the motion detector or the set-up. The x-axis represents the sample number acquired, each sample was acquire approximately 101±22 ms apart.

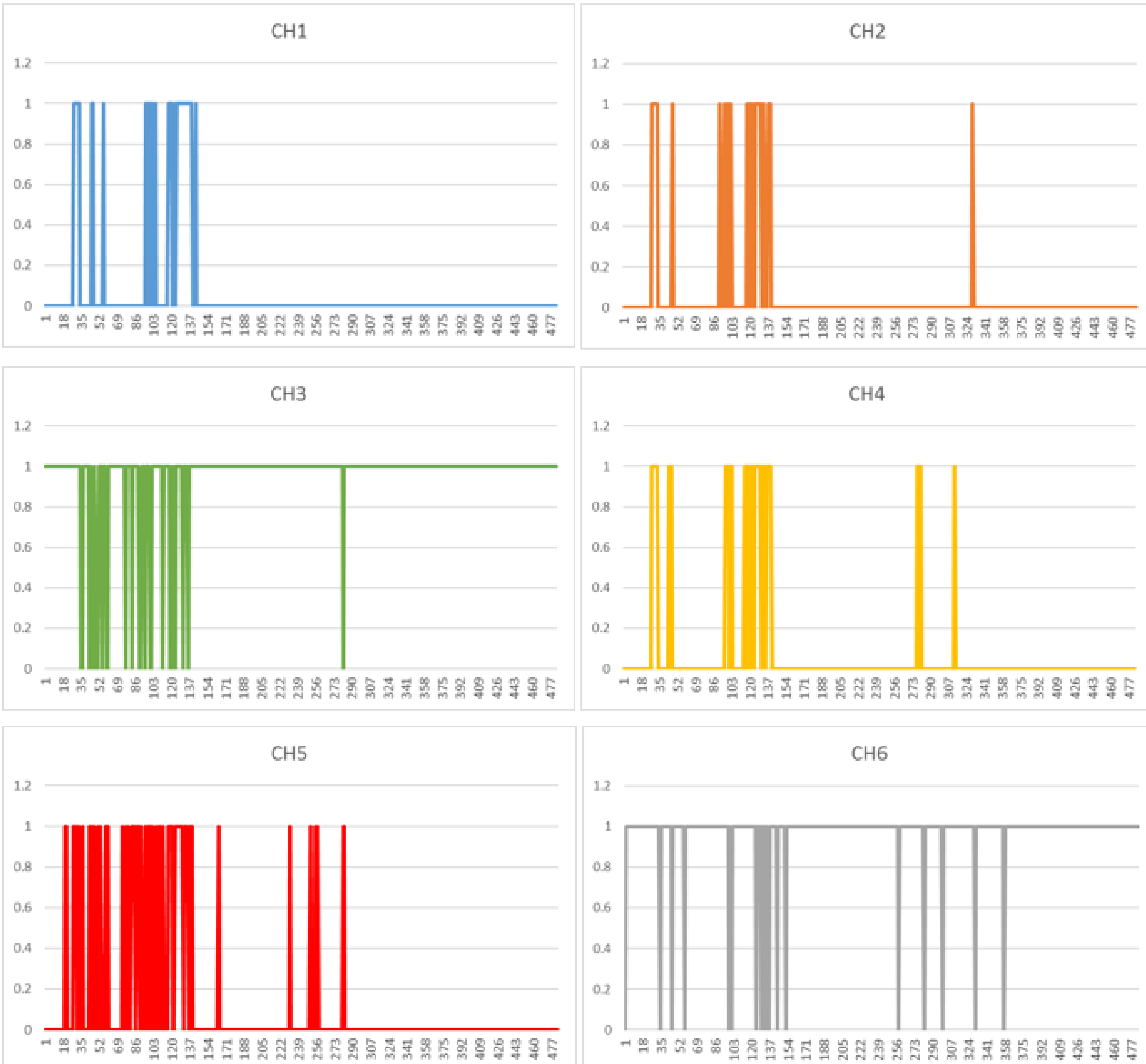

Figure 6: Channel outputs over 45 second interval, with the first 15 seconds involving sporadic activity followed by 30 seconds of stasis. The x-axis represent the sample number, each sample was acquired approximately 50±20 ms apart.

Dynamic Experiments Results (Figure 6)

As stated in the Methods section, the dynamic experiments were ran for 45 seconds long, with the first 15 seconds being dynamic motion and the last 30 seconds being static motion as previously observed. As with the static experiments, the data for Channel 3 and Channel 6 seem reversed, with 1's being expected when 0's appear and vice versa.

A students t-test was used when comparing the first 15 seconds, which equate to the first 145 data points to the last 332 (a total of 477) generated during the last 30 seconds, again with a data point being taken every 101±22 ms. The null hypothesis used for this t-test was that the means of the sets were equal.

After running the students t-test on the data sets, it was concluded that for CH1, CH2, CH4, and CH5 that the null hypothesis was to be rejected with a p-value less than 0.0001. A similar result holds for CH3 despite the apparent negation in logic since disruptions caused by the motion of the ball caused significantly many differences in the signal. Finally, CH6 a similar result of rejecting the null hypothesis, although it must be noted that the p-value for CH6 was less than $p < 0.0005$, rather than the $p < 0.0001$ for the other channels. Nonetheless, this result is significant, but there is certainly room for improvement to get CH3 and CH6 to similar outputs as CH1, CH2, CH4, and CH5.

Conclusions and Future Works

Overall, the results show, at the very least, that the microwave-based motion detector system has great potential. However, errors must be correct before moving forward. Especially errors pertaining to Channel 3 and Channel 6, so that data is homogenous in interpretation. The cause of the error can be discovered by using a variety of quality control tests, such as investigating each motion detector individually with limited external influences, specifically those resulting from nearby sensors.

After correcting these errors, more controlled dynamic experiments will be run, for example by using a pendulum, to test for the similarities in data sets expected when a repeated action is performed. After completing these preliminary tests multiple times and ensuring consistency between experiments, it would be appropriate to utilize live mice and compare data with pre-existing activity monitoring systems, such as wheel running, video tracking, and vibration sensors.

After success under controlled conditions, the ideal next step in the project would be to utilize the devices in actual data acquisition for research purposes. Hopefully, these microwave-based motion detectors will allow for easily comparable data between different experiments and laboratories around the world and become a well-established tool in murine investigations among the research community.

References

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