Detect and Analyze the 3-D Head Movement Patterns in Marmoset Monkeys using Wireless Tracking System

by

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ABSTRACT

Head movement is a natural orienting behavior for sensing environmental events around us. Head movement is particularly important for identifying through the sense of hearing the location of an out-of-sight, rear-approaching target to avoid danger or threat. This research aims to design a portable device for detecting the head movement patterns of common marmoset monkeys in laboratory environments. Marmoset is a new-world primate species and has become increasingly popular for neuroscience research. Understanding the unique patterns of their head movements will improve its values as a new primate model for uncovering the neurobiology of natural orienting behavior. Due to their relatively small head size (5 cm in diameter) and body weight (300-500 g), the device has to meet several unique design requirements with respect to accuracy and workability. A head-mount wireless tracking system was implemented based on inertial sensors that are capable of detecting motion in the Yaw, Pitch and Roll axes. The sensors were connected to the encoding station, which transmits wirelessly the 3-axis movement data to the decoding station at the sampling rate of ~175 Hz. The decoding station relays this information to the computer for real-time display and analysis. Different tracking systems, based on the accelerometer and Inertial Measurement Unit is implemented to track the head movement pattern of the marmoset head. Using these systems, translational and rotational information of head movement are collected, and the data analysis focuses on the rotational head movement in body-constrained marmosets. Three stimulus conditions were tested: 1) Alert, 2) Idle 3) Sound only. The head movement patterns were examined when the house light was turned on and off for each stimulus. Angular velocity, angular displacement and angular acceleration were analyzed in all three axes.

Fast and large head turns were observed in the Yaw axis in response to the alert stimuli and not much in the idle and sound-only stimulus conditions. Contrasting changes in speed and range of head movement were found between light-on and light-off situations. The mean peak angular displacement was 95 degrees (light on) and 55 (light off) and the mean peak angular velocity was 650 degrees/ second (light on) and 400 degrees/second (light off), respectively, in response to the alert stimuli. These results suggest that the marmoset monkeys may engage in different modes of orienting behaviors with respect to the availability of visual cues and thus the necessity of head movement. This study provides a useful tool for future studies in understanding the interplay among visual, auditory and vestibular systems during nature behavior.

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DEDICATION

There are absolutely no words to express my gratitude towards my family, my mother, father, brother and grandmother for having confidence in me and motivating me in every walk of life. I am very lucky to have them in my life. Thank you!

Lastly, I would like to thank my room-mates and my close friends, who have come to become a family away from family. Their constant support has made this journey a lot more fun. Thank you!

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CHAPTER 1: INTRODUCTION

This thesis studies head movement patterns of a new-world primate – the common marmosets. The goal of this thesis was to develop a self-contained, lightweight, inertia-sensor based motion tracking system that could detect and transfer motion data wirelessly in real time.

In natural environments, many animals move around in response to visual and auditory signals as they search for food and escape from predators or other threats.

Accurately characterize the head/body movement is important to our understanding of naturally occurred orienting behavior such as gaze and self-motion and eventually the neurological basis of natural behavior. In the previous work done in our lab (Simhadri, 2014), it was noted that the common marmoset monkeys can make fast head turns in the laboratory settings. However, due to the use of a single Infrared-based camera, the movement could be detected only in horizontal plane. Also, since the motion tracking system was developed on imaging-based technique, it was difficult to record continuous data as the stimulus are applied, particularly when the stimulus evoked fast head-turns. This present work is a follow-up study and aims to develop a motion tracking system that is capable of continuously monitoring the rotational information of the rapid head-turns in all three axes, namely, Roll, Pitch and Yaw.

The importance of fast head turns has been noted in the previous human studies. In addition to the orientation behavior, head movements play an important role in forming an accurate representation of auditory and visual scene during spatial hearing and navigation. For example, Leung et. al, reported the relation between head turns and internal auditory space representation (Leung, Alais & Carlile, 2008). Unrestrained head position is shown to help sound localization with improved discrimination and acuity, especially when the source of stimulus is out-of-sight. Research on contribution of head movements in sound localization have been a subject of interest from as early as 1800's (Munsterberg & Pierce, 1894). The study conducted by Wallach in 1940, provided evidence about head movements help minimize the front-back confusion as a result of similar binaural sound localization cues of sources from the frontal and back directions. (Wallach, 1940).

Since then, many studies followed that observed the importance of quantification of head movements in terms of translational and rotational motion to understand the underlying mechanism of movement patterns. Subsequently, various attempts have been made to develop motion tracking system that can track movement information of humans, non-human primates and other species, in an efficient manner. Several techniques have been developed to detect and track the head movements such as infrared red based imaging to detect movement in humans (Brimijoin, Boyd, & Akeroyd, 2013; Thurlow, Mangels & Runge, 1967). Additionally, analysis of head movement is also important in research related to determining the inter relation of head and eye movement for gaze and self-motion (Cullen, 2014; Freedman & Sparks, 1997; Tomlinson & Bahra, 1986).

Many behavioral studies has also been done to investigate the response of owl barns in response to sound stimuli to investigate the head movements in an attempt to perform behavioral studies and mapping of auditory cortex (Wagner, 1993). Furthermore, studying head movement trajectories also play an important role in the investigations involving the effect of neck muscles in head movement, and eye-coordination in gaze stabilization, as described in (Zangemeister & Stark, 1981). In such researches, the intent is to study the correlation between the activity of the neck muscle and the resultant head movement. All these investigations share a similar focus on characterizing the head movements Thus, it is quite clear that it is important to quantify the head movement patterns in a measurable unit.

To further research in this direction, this thesis investigated the use of inertial sensor based wireless motion tracking device to track the head and body movements. This system is used to examine the head movements of common marmosets (Callithrix jacchus). Marmoset is a small-bodied New World monkey specie that rely heavily on visual and vocal communication. In particular, voice communication play an important part in response to any unexpected or threatening situation. Being small-bodied, they are in general, very alert of their surroundings and they use different types of vocal calls to alert the colony from an external danger, mate attraction or location of a lost member [18]. All these characteristics make marmosets, an excellent subject for sound-localization and head- movement kinetics study.

Marmosets share the same hearing range and structure of auditory cortex as the other primates and has become an emerging model for auditory system and vocal communication studies (Wang, X., 2000; Reser, Burman, Richardson, Spitzer & Rosa, 2009). Also, they have become an attractive model for physiological as well as behavioral studies (Bugnyar &Huber, 1997; Johnson, Santina & Wang, 2012). The ability of tracking head/body movements will greatly increase the values of this model in neuroscience with regard to the neural basis of real-world listening experience. Previous work from our laboratory has shown that on presentation of auditory or visual stimuli, in body restrained conditions, marmosets respond by making rapid head turn movements. The angular velocity can reach as high as 1000 degrees per second and additionally marmosets produce quite jerky movements (Simhadri, 2014). These fast head turns were detected using infrared based imaging techniques. While these methods are efficient in detecting human head movements in 2-D, there are many additional design constraints in designing a motion tracking system for marmoset monkeys. Their small head diameter (approximately 5 cm), fast head turns (more than 1000 degrees per second) and small body weight (300g-500g), raises a need for a system that is fast, compact, self-contained and capable of detecting these movements in Roll, Pitch and Yaw axis with significant reliability.

The objective of this thesis is to develop a wireless detection system that can track the head motion of marmoset monkeys and reduces the motion artifacts significantly without compromising the high sampling rate. Another goal was to design a self-contained, portable and light-weighted system, which can be carried easily by the marmosets. The primary parameters of interest is angular velocity of these head turns, along with the angular acceleration and angular position, in response to visual, vocal and alert stimulus. This thesis aims to overcome the primary challenge of small head/body size of the marmoset and achieve the following goals: (1) A small and compact, battery operated system suitable for placement on the head diameter as small as 5cm. (2) High sampling rate in the range of 150 Hz-300 Hz, to track the fast head turns with significant reliability. (3) Highly accurate motion sensors (95-98% accuracy) to detect the smallest head movements (4) A Continuous and real-time tracking system that can detect the movement patterns as the stimulus is applied. (5) Design of experiments that involved multiple stimuli system, so as to elicit the desired response that actively engages the subject.

The methods used to track translational and angular motion parameters, in particular the angular velocity and rotational angle of the head, are explained in Chapter 3. The design of accelerometer-based system and IMU-based system are also explained. Experimental setup and data analysis techniques are discussed in Chapter 4. The results are shown in Chapter 5. The conclusion and future directions are summarized in Chapter 6. The outcome of this research may provide critical information about heading and turning behavior of the marmoset monkey species for both neurophysiological and behavioral research.

CHAPTER 2: BACKGROUND

2.1 HEAD MOTION

In the Figure 1, the coordinate system used in this study is shown. This is the standard coordinate system used in a previous study conducted in our lab and also in most of the sound localization experiments. The horizontal plane is the plane through the head and parallel to the ground, the frontal plane is parallel to the face and perpendicular to the ground and the median plane cuts through the nose and perpendicular to the face and ground.

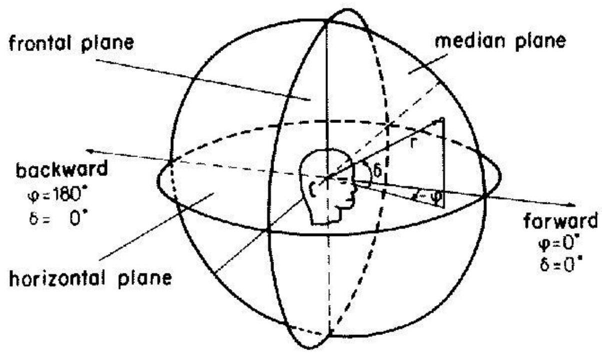

Figure 1: Head coordinate system used in auditory spatial experiments [10].

2.2 CURRENT METHODS

There have been many sensors developed to track head and body movements in non-human primates and other species. In this section, a brief analysis of these methods have been provided to understand the various approaches used in tracking of an object, in order to realize the best approach suitable to track the head movements of marmosets in three axes, which is the objective of this thesis.

In this thesis, the inertial sensor based motion tracking system is implemented. Since the research interest is head movement analysis, there are different sensors, which use different transducing mechanism to detect movement and can be used to measure the rotational and translational motion parameters, as described in this section.

2.2.1 ACCELEROMETER-BASED SYSTEMS

Accelerometer is the electromechanical device that is used to measure the acceleration forces. Most of the accelerometers use the static force of the gravity as a reference to calculate the acceleration induced in the body due to certain force acting on it [6, 7]. A three dimensional accelerometer can measure forces acting in three axes, (X, Y and Z) as indicated in Figure 2

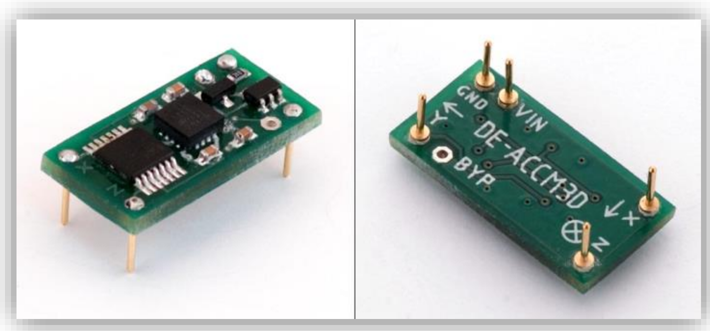

Figure 2: A 3-axis accelerometer (DE-ACCM3D) with the arrows pointing in the direction of the positive axis of application of force [6].

Accelerometers-based motion tracking system are capable of computing the linear position and translational movement information with the help of dynamic acceleration as calculated by the accelerometer. There are many types of accelerometers available in the market. Broadly they work on two principles: 1) Piezoelectric Effect, or 2) Capacitive change. In the former case, the acceleration is measured by the deformation in the tightly packed microscopic crystal structures that get stressed by the accelerative forces, and generate the voltage. This voltage change is then related linearly to the acceleration generated. In the second type of accelerometers, the accelerative forces, cause a capacitive change that in turn causes a change in voltage. Again, this voltage is linearly related to the acceleration generated on the body. Apart from that, mostly for the ease of programming, analog accelerometers are preferred, when the acceleration range is within 5 g.

2.2.2 GYROSCOPE-BASED SYSTEMS

Gyroscopes are the inertial sensors that measure the angular rate at which a certain object rotates around X (Roll), Y (Pitch) or Z (Yaw) axis as shown in Fig 3. They form a key components in most of the motion detection system due to their ability to provide latency-free measurement of rotation without being affected by any external forces, including magnetic, gravitational or other environmental factors [22].

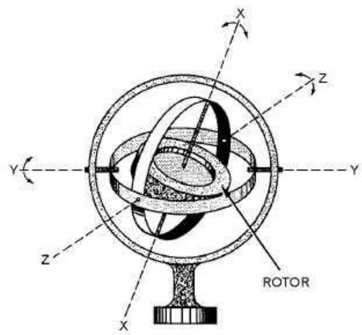

Figure 3: A 3-axis gyroscope with the arrows pointing in the direction of the positive axis of application of the torque. [9]

There are two main categories of gyroscope: 1) Electromechanical Gyroscopes 2) Micro Electro-Mechanical Systems (MEMS) based Gyroscope. MEMS-based gyroscopes are the most preferred choice in the applications where the compact size and low power consumptions are the factors of utmost importance [22]. These devices offer the integration of digital interface in an affordable a package and the size of a few square millimeters, which has greatly accelerated the use of these devices in many fields, including the motion detection and tracking applications. These gyroscopes utilizes the Coriolis Effect to detect the angular rate of motion as described in figure 4.

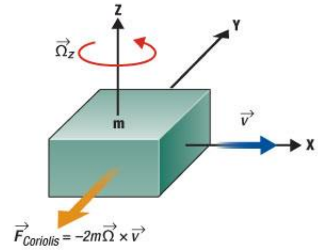

Figure 4: Coriolis Effect as applicable in MEMS based Gyroscopes [22].

Where m is the mass of an object travelling in v→ direction. When a rotational velocity of Ω→ is applied, the object experiences a Coriolis force $F_{Coriolis}$ in the direction as specified in Fig 3. The resulting physical displacement thus caused is read as a change in the voltage generated by the capacitive sensing structure. This change is proportional to the angular rate, and is thus manifested as the output voltage in case of analog gyroscopes and Lowest Significant Bit (LSB) in case of digital gyroscopes. Most MEMS-based gyroscope works on the concept of tuning fork configuration, in which two masses move and vibrate constantly in opposite direction, such that when an angular velocity is applied, the Coriolis forces are generated in opposite directions. This results in change in the capacitance. On the other hand, on application of linear acceleration, the Coriolis force is generated in same direction and therefore there is no change detected Therefore this systems are more robust to linear acceleration such as tilt, shock and vibration [22]. This phenomenon is described in Fig 5

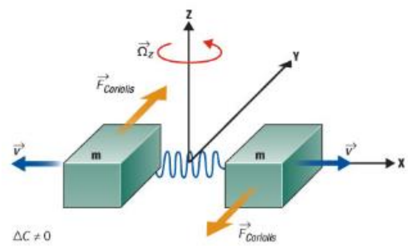

Figure 5: Tuning fork phenomenon as applied in MEMS-based Gyroscopes [22].

2.2.3 INERTIAL MEASUREMENT UNIT (IMU)

IMU's are the new age inertial sensors which are capable of measuring the linear as well as the angular motion with the help of integrated gyroscopes, accelerometers and, in some cases, magnetometer in a single self-contained system [32]. Fig 6 shows an IMU with six degrees of freedom, capable of measuring the angular rate and linear acceleration in three dimensions each. The obvious advantage of IMU's is that they offer more degrees of freedom and, with the integrated magnetometers, they can be made sensitive to magnetic fields, thereby making them excellent actuators.

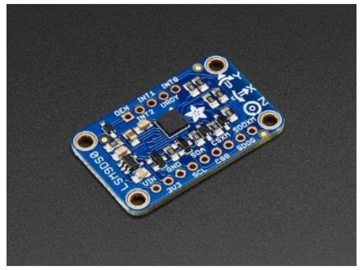

Figure 6: IMU chip [23].

The accelerometers and gyroscopes integrated works on the same principles already discussed in this section.

2.3 WIRELESS TECHNQUES

In the interest of reducing the motion artifacts and enabling the real-time processing, it is important to have a wireless communication setup between the sensor and the data processing unit. Here is a brief summary of existing types of wireless systems which can be implemented in the motion detection system.

2.3.1 INFRARED (IR) TRANSMISSION

Infrared waves act as a carrier signal. They operate with the help of a Light Emitting Diode (LED) acting as the source that transmit the IR waves in the frequency range of 300 GHz to 400 THz. At the receiver end, there is a photoreceptor that receives and converts this signal into electrical signal, which can then be decided to obtain the information. One of the major short-coming of this system is that the sender and receiver should be aligned in the line-of-sight with each other and there should be nothing obstructing in the path, otherwise the signal will be lost [16].

2.3.2 RADIO FREQUENCY (RF) TRANSMISSION

RF transmissions works in the range of radio waves, which corresponds to 3 kHz to 300 GHz. To enable the communication between the two stations, RF modules need to be used. They are transmitter-receiver pair that operate on the same frequency, and are enabled with a tuner to capture the signal from the same module. Also, to facilitate the long distance communication of the order of 10 meters or above, an external antennae needs to be used. One of the major advantages of using RF transmission is that through this transmission, communication can be established between two stations, not necessary on the line-of-sight. There are many short-range wireless techniques based on this module including Bluetooth and ZigBee. Bluetooth operates in the range of within 10 meters and generally at the operating frequency of around 2.4 GHz. ZigBee requires lower power consumption as compared to Bluetooth. However, it also has lower data rate as compared to ZigBee [20].

2.4 OTHER METHODS

2.4.1 IMAGING-BASED MOTION TRACKING

The imaging-based motion tracking techniques mainly involves an array of cameras kept in the chamber to capture images of the object at different angles. In order to detect the motion in three dimensions, multiple camera may be used. The image captured from all the cameras is thus processed to obtain the estimation on the orientation of the object. This system delivers accurate position information. However, there are a number of limitations of such a system. Firstly, the object needs to be in the area defined by the multiple cameras, any motion out of the range of the camera wouldn’t be captured. Secondly, most of the times, these systems require multiple markers to be worn by the subject, which is not possible with marmoset monkeys, due to small body. Also, it is not possible to have a real-time motion tracking with this kind of system.

2.4.2 MAGNETIC SENSOR-BASED MOTION TRACKING

This is an interesting system in which magnetic coils are used to detect the motion information. A magnetic field is set up in a closed chamber and a sensor is placed on the object of interest. In some cases, an electrical sensor is placed, which generates change in voltage according to the change in magnetic field. A similar kind of system was used in a study conducted to detect movement of blowflies (Van Hateren & Schilstra, 1991). Another implementation of such system can be mounting a magnetic coil on the object of interest, in addition to the rotational magnetic field set-up in the chamber to detect the movement. Such a system was implemented to study the head rotation in owls (Wagner, 1993). The advantage of such system is that they offer low sampling time

(~1 ms). However, these systems are highly susceptible to the news noise generated from vibration, or external magnetic field, which pose a major limitation.

CHAPTER 3: HARDWARE AND SOFTWARE DESIGN AND CALIBRATION

This chapter explains the design principles and algorithms based on which the motion tracking system has been developed. The small head diameter (approximately 5 cm), fast head turns, and small body weight, raises a need for a system that is compact, self-contained and capable of detecting these movements with significant reliability. Taking these design constraints in consideration, two systems are designed for head movement tracking in marmoset monkeys.

3.1 Block diagram of the wireless motion tracking system

The basic block diagram of the systems is explained below. All systems were designed based upon this framework.

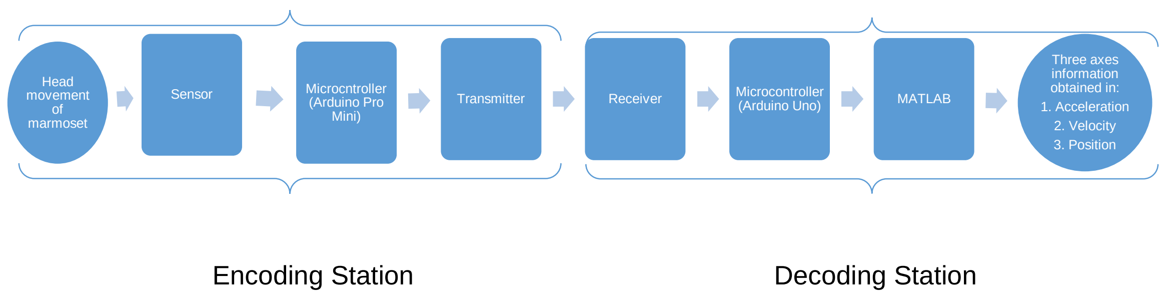

Figure 7: Block Diagram of the Wireless Tracking System

To quantify the head movements two approaches are developed. First approach involves the use of accelerometer–based system that processes the raw head movement data into the translational motion quantities, i.e., linear acceleration, linear velocity and linear position. Second approach involves the use of inertial motion unit (IMU), to obtain the head movement information in terms of rotational motion parameters, i.e., angular acceleration, angular velocity and angular position information. The detailed information on the system is described in the following section.

ENCODING STATION

Encoding station comprises of all the elements involved in sensing the movement, converting the information in a quantifiable electric signal and transmitting this information to the decoding station. The main components involved in this process are further described below.

Sensor: This is the unit in physical contact with the marmoset head. It is instrumental in transducing the rotational and translational motion information obtained through the head movement in an electrical signal. Inertial sensors are implemented to detect the marmoset head movement due to their ability to convert the movement information into the voltage change. In particular, the use of accelerometer-based system and IMU-based systems are investigated, the details of which are explained in the coming sections.

Microcontroller: A microcontroller is a self-contained system with peripherals, memory and a processor that can be used as an embedded system. For this application the family of microcontrollers Arduino, is used. Arduino is an open-source electronics platform based on easy-to-use hardware and software. It comprises of Arduino Board and Arduino Software. Arduino board processes the information obtained from the sensor, and encodes this information so that it can be transmitted further. Arduino Pro Mini is used at the encoding station due to multiple reasons. The foremost reason is the physical design constraint present due to the small head diameter of the marmoset (5 cm). Being a small chip with the dimensions as 17.78 X 33.02 mm [1]. Arduino pro mini is optimal for this application. In addition to this, it has multiple input/output digital as well as analog pins (14 Digital I/O pins and 6 analog inputs), which gives an abundant flexibility in designing and use of different sensors. The clock frequency of 8 MHz offers an appropriate encoding rate required for a high data transmission rate. Also, the output voltage of 5 V is ideal to drive the sensor unit as well as the transmission unit, thereby eliminating the requirement of an additional external battery. The Arduino pro mini itself can be reliably driven using one 9V battery, which helps in making the encoding station compact and self-contained [1]. It also offers a huge room for flexibility in programming, designing and encoding due to being a reprogrammable device using the Arduino software that is built up on C platform. It can be easily programmed using Arduino programming language and using the Arduino development environment.

Transmitter: The most important aspect of designing the motion detection system, is the ability to send the movement information wirelessly from one station to another. Particularly in the applications such as this, where the movements can be very rapid and can even reach an angular acceleration as high as 1000 degrees per second (Simhadri, 2014), it is extremely important to implement a wireless communication system to reduce the motion artifacts, and enable a reliable transmission of data. RF transmission module is selected for this application due to its ability to transmit and receive the signals not necessarily in the line-of-sight. A crucial part of encoding station is the transmitter, which reads the signal from the Arduino pro mini and transmits that information across to the receiver at the decoding station. Different options of transmitter-receiver pairs were explored, to be discussed in the coming section.

DECODING STATION

Receiver: The same RF module was implemented at the decoding station to receive the signals relayed by the transmitter at the encoding station. The information was then written on the digital input port of the Arduino Uno, from which it is conveyed further for the data processing. The RF modules are programmed in such a way that the information is transmitted and received in the real-time.

Arduino Uno: This is the reprogrammable micro controller belonging to the same family as Arduino pro mini, except that it is based on a prototype board, for the flexibility of designing. Arduino Uno was selected based on the features such as it has multiple input/output digital as well as analog pins (14 Digital I/O pins and 6 analog inputs), which gives the flexibility of designing. The TTL to USB converter provides a good interface for Laptop/Desktop connections [2]. In addition to this, Uno gives an output voltage of 3.3V and 5V both, which is sufficient to run the receiver unit. Other features include 16 MHz clock frequency, which enables 115200 bits per second of data rate, making the system perform at a higher speed (Arduino.cc). Another similar features such as reprogrammable unit makes Arduino Uno an ideal selection for the microcontroller at decoding station. The basic function of Uno at the decoding station is to program the receiver unit to receive data reliably and accurately from the transmission unit and transmit this data to the computer for further data analysis.

MATLAB

The Arduino Uno is connected to the computer/laptop through Universal Serial Bus (USB) connection. The data is written on the serial port by Arduino and this information is read using Matlab programming. Further analysis is done to obtain information about the position and acceleration and respective plots are obtained. The sampling frequency varies from 140 Hz to 400 Hz, depending on the sensor used.

3.2 System Information

3.2.1 System 1: Accelerometer-based Motion Tracking System

For the system 1, the use of a tri-axis analog accelerometer DE-ACCM3D is investigated. The accelerometer provides the translational acceleration data in three axes, with the sensing range of 3g in both the directions, which is sufficient to measure the highly rapid head movements of the marmoset. The accelerometer also offers the sensitivity of 360 mV/g, which means that it can detect the acceleration as low as 2.7mm/s^2, which is low enough to track the slightest head turn information. In addition to this, the sensor can be run on a 5V power supply, provided by the Arduino pro mini, making the system self-contained. Most importantly, the compact size of the sensor with the dimensions of 10 X 21 X 8 mm dimensions, made it the ideal choice, provided that the sensor needs to be in the physical contact with the marmoset head. The sensor can detect the change in acceleration with the accuracy of 95% and relay this information to the transmitter unit [6].

For the transmission unit, initially TWS BS Transmitter using RF module was selected. The primary reasons to select the transmitter were compact size, easily programmable, robustness and high range of input voltage adaptability. The dimensions of the transmitter are 15.25 x 10.45 mm, ideal for small head diameter of marmosets. The input voltage range of 1.5 V 15V is suitable as the output voltage Arduino mini can drive the transmitter and there is no need of an additional power source. Also, the transmitter uses ASK modulation, which makes the sensor easily programmable and easy to use [31].

The Receiver unit, RWS-371 Receiver using RF module, is the compatible counterpart of the transmitter unit. The features offered are similar to those offered by the transmitter unit, and the selection was based upon that [30].The data thus received is transmitted to the Arduino Uno for further processing. The sampling rate offered by these transmitter-receiver pair is 60 Hz, which was found to be quite low for the reliable tracking of head movements of the marmosets. Hence the use of another RF module of nRF24LO1 Single-chip 2.4GHz Transceivers was investigated. The selection of the transceivers was done based on the high on-air data rate of 2 Mbps, which brought in the multi-fold increase in the overall sampling rate. The low power requirement in the range of 1.9V to 3.6V made these transceivers easily driven on the output voltage obtained from Arduino pro mini at the encoding station as well as Arduino Uno at the decoding station, thereby making the system self-contained [17]. The compact size of the dimensions of 4 X 4 mm met the physical design constraint. In addition to this, these transceivers are easily programmable and thus gives flexibility in design. Due to these features, transceivers are used in the both encoding and decoding stations. The increase in the sampling rate was observed to be more than six times, from 60 Hz to 400 Hz, which is sufficiently high to reliably obtain the head movement information from the marmosets.

System Evaluation

There were several steps taken to evaluate the performance of the accelerometer-based system. The evaluation was done in two levels; hardware level and software level.

Hardware Evaluation

Initially, it was found that the TWS and RWS series of transmitter-receiver pair offered around 60 Hz of sampling frequency, which was too less for relaying the head movement information reliably. Hence there was a need to change the RF modules.

Also, there was an inconsistency in the transmission system observed which resulted in the loss of data. On further investigation, it was found that, although datasheet of nRF24LO1 mentions that the transceivers are tolerant to input voltage ranging from 2.6 V-3.6V, in observation it was found that the transceiver works the best at the input voltage of 3.3 V. So, a regulator was employed to maintain the input voltage of 3.3V. Also there was a problem in communication due to fluctuation in the input voltage due to connections. This was overcame by introducing a capacitor between the input voltage and ground to remove any AC component from the input voltage. This enables us to achieve the sampling rate of 400 Hz which was significantly higher than that of transmitter-receiver pair previously used.

Software Evaluation

There was an issue of drift observed in translational acceleration, which was also carried forward in velocity and position information, since these quantities were derived from acceleration information. Although algorithms in Matlab were employed to reduce the drift, it was still observed in the velocity and position data.

Setup Evaluation

Drift induced due to motion artifacts was also observed. This was removed by increasing the distance between the device and axis of rotation, so that the effect of motion artifact becomes inconsequential.

The accelerometer based wireless head movement tracking system thus designed had many attractive characteristics, such as, compact size of 12 mm x 12 mm x 2 mm makes it easy to be used on the marmosets. The system is self-contained with a 9V battery sufficient to run the whole system reliably. The high sampling rate of 400 Hz, the sensitivity of 370 mV/g and the high accuracy of about 95% makes this system ideal for tracking the translational motion information of the head movement. However, although the rotational information can still be obtained from translational motion information, to overcome the problem of drift, the use of different sensor was investigated.

3.3.2 System 2: IMU-based Motion Tracking System

The only difference between this system and the previous system is the sensing unit. A new family of inertial sensors, called Inertial Measurement Unit (IMU), is investigated. These are MEMS-based programmable unit with integrated accelerometer, gyroscope and magnetometer, and hence can detect the information about the translational motion, rotational motion and position information in three axes, using the integrated sensors respectively.

The IMU module LSM9DS0 is used as the sensor, which includes a 3D accelerometer, 3D gyroscope and 3D magnetometer integrated in a single chip [23]. The full scale linear acceleration sensing range can go as high as 16 g in both directions and it can be easily programmed to work in the dynamic range of 2g in both directions for all the three axes which was sufficient to detect the translational motion information of head movement. The dynamic range of angular velocity can be programmed to be 245/500/2000 degrees per second (dps) in either directions. This quantity was programmed at the highest value offered, i.e., 2000 dps in both directions, for all the three axes which was sufficiently high to detect the rapid head turns of the marmosets. The input voltage requirement was in the range of 2.4-3.6 V which is compatible with the output voltage offered by the Arduino pro mini. In addition to this, the compact size of 4 X 4 X 1 mm dimensions, made it the suitable for detecting the head movements of marmosets [23]. The IMU was programmed to detect the rotational information, which was given in form of angular rate. Rest of the features and components are maintained same as that of the accelerometer-based system.

System Evaluation

There was decrease in the sampling rate which was reduced to 110 Hz. After employing algorithms in Matlab and Arduino programming, the data rate was increased to around 140 Hz. Although the sampling rate was lower than that offered by the accelerometer-based system, there were many attractive features offered by the IMU-based system such as:

1. There is the issue of drift successfully removed and the accurate data is obtained.
2. The sampling rate is still sufficiently high to reliably capture the motion information of the head rotation and almost real-time tracking is obtained. The accuracy offered by the system is 98% and it can detect angular position change as low as a 1^{o}.

3.3 Software

3.3.1 Flowchart for System 1

Detailed Algorithm

Encoding Station

1. Battery is connected to the encoding unit and the power is switched on
2. The channel parameters are set at 115200 bps serial communication baud rate and sensitivity is 360mV/g
3. The information in form of voltage is read by Arduino pro mini from the analog inputs A0, A1 and A2 corresponding to X, Y and Z axis respectively.
4. The information about the difference in voltage for three axes is concatenated in one string of 9 Bytes for transmission.
5. The data is converted into digital signal and written on port 13 of Arduino from where it is relayed to the transceiver.
6. Transceiver modulates this signal using RF module and transmits this information to the decoding station

Decoding Station

1. The Arduino Uno is connected to the computer using the USB connection.
2. The channel parameters are set at 115200 bps serial communication baud rate and sensitivity is 360mV/g
3. The data is received by transceiver and written at the port 13 of the Arduino Uno.
4. The data from port 13 is written on the serial port by Arduino Uno.
5. M-file is loaded in the Matlab and the program starts running
6. Matlab reads each string of the length of 9 Bytes and stores this information in a temporary buffer. The data in this buffer is then broken in three strings and stored in three different buffers corresponding to three different axes. Each string is converted into a numerical value.

The acceleration is calculated by dividing sensitivity predefined as 360mV/g from this voltage information and after multiplying with acceleration due to gravity, the unit is obtained in terms of m/s^2.

7. Smoothing function is applied to the acceleration thus obtained so that the drift is reduced.
8. Linear acceleration is integrated to obtain linear velocity in three axes.
9. Linear velocity is integrated to obtain linear position data in three axes.
10. The plot of linear acceleration, linear velocity and linear position are obtained in three axes with respect to time.
11. The data is saved
12. Matlab program is stopped.

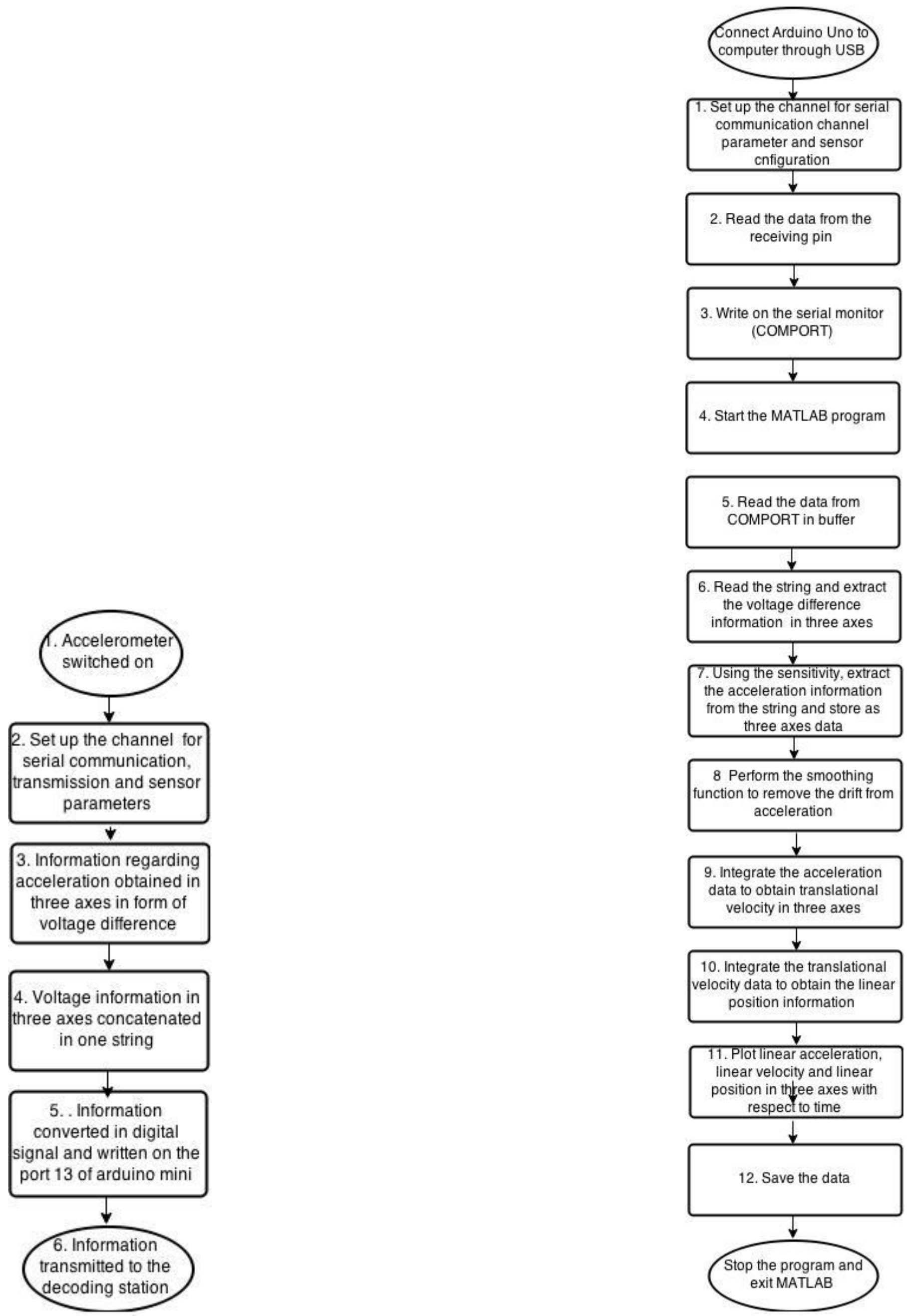

Figure 8: The flowchart of the encoding station for system 1 on the left; and the flowchart of the decoding station on the right

3.3.2 Flowchart from System 2

Detailed Algorithm: Encoding Station

1. To upload the code, FTDI chip needs to be connected with the Arduino mini. Once the code is uploaded, disconnect the chip and connect the battery.

2. The code sets up the channel configuration as transmission rate as 115200 bps and dynamic range for angular velocity as 2000 dps in both directions for all the three axes.
3. Read the data from the gyroscope sensor through the port A5. To reduce the size of the string, range is shifted. The data is collected for all three axes separately.
4. The data is concatenated in a single string and converted into the unsigned 8 bit integer, after which it is written at port 13. It is read by the transceiver and transmitted across using the channel parameters set previously.

Decoding Station

1. At the decoding station, the USB needs to be connected the Arduino Uno to the computer using the Universal Serial Bus (USB). Set up the channel parameters similar to that at the encoding station, to start the communication between the two transceivers.
2. The data is configured to be received at pin 13. The data is read from pin 13
3. The data read is then written on the serial port COM6 using the println () command. The data is read in form of one single string and at the rate of 115200 bps.
4. Load and run the m-file in Matlab.
5. The experiment is supposed to be running till the duration specified by the user. The program checks for each time instance whether the duration of the experiment is less than the input value given by the user. If so, data is continued to be saved otherwise, data collection is stopped.
6. The concept of two buffers is employed, to reduce the processing time in Matlab. Using this approach, the plots are obtained with a delay of 50ms, which is sufficiently fast to obtain instantaneous plots. This delay is not the delay in communication, but merely the time taken by the Matlab to reads the data from the serial port and plot. In this approach of two buffers, Matlab reads the data written on the serial port from one buffer, while plotting the data stored in another buffer simultaneously, exploiting the ability of Matlab of parallel processing. This is managed using the flag status. Flag status is turned 1 immediately if buffer 1 is empty and the data from the serial port is saved in buffer 1, for a fixed block size

already predefined in the program. Once data from buffer 2 is plotted, it is emptied out, and flag status is turned to 10, signifying the availability of buffer 2 to save the data. In this manner, the state of flag is checked every time. If flag is set to 1, buffer 1 is to be filled and data is plotted from buffer 2, otherwise buffer 2 is filled and data is plotted from buffer 1.

7. Data is read from COMPORT 6 to the buffer 1 or buffer 2, depending on the state of the flag.
8. Angular velocity is calculated by shifting the range back to the original.
9. The angular velocity, thus obtained is plotted once the data is written in the buffer.
10. The state of flag is set to indicate the availability of the buffer, once the plotting is done.
11. The buffer is emptied out. And the pointer goes back to check whether the duration for which the experiment has run so far is less than the duration specified by the user.
12. Once the experiment is over, other parameters such as angular acceleration and position are calculated. These parameters are not calculated along with the angular velocity in the interest of live plotting of angular parameter, which is the parameter of interest. To calculate the acceleration, angular velocity is differentiated over time and to calculate the position, the angular velocity is integrated over the time.
13. Once these parameters are obtained, the acceleration and the position data is plotted and the experiment stops.

3.4 Calibration

The calibration of the system 2 was done using the rotational chair, which was made to rotate at a constant known velocity and the results were obtained using the system 1 and system 2. The sensor and the encoding station were placed on the chair and the chair was rotated at a constant angular velocity and the plots were obtained at the decoding station. The offset was included in the algorithm.

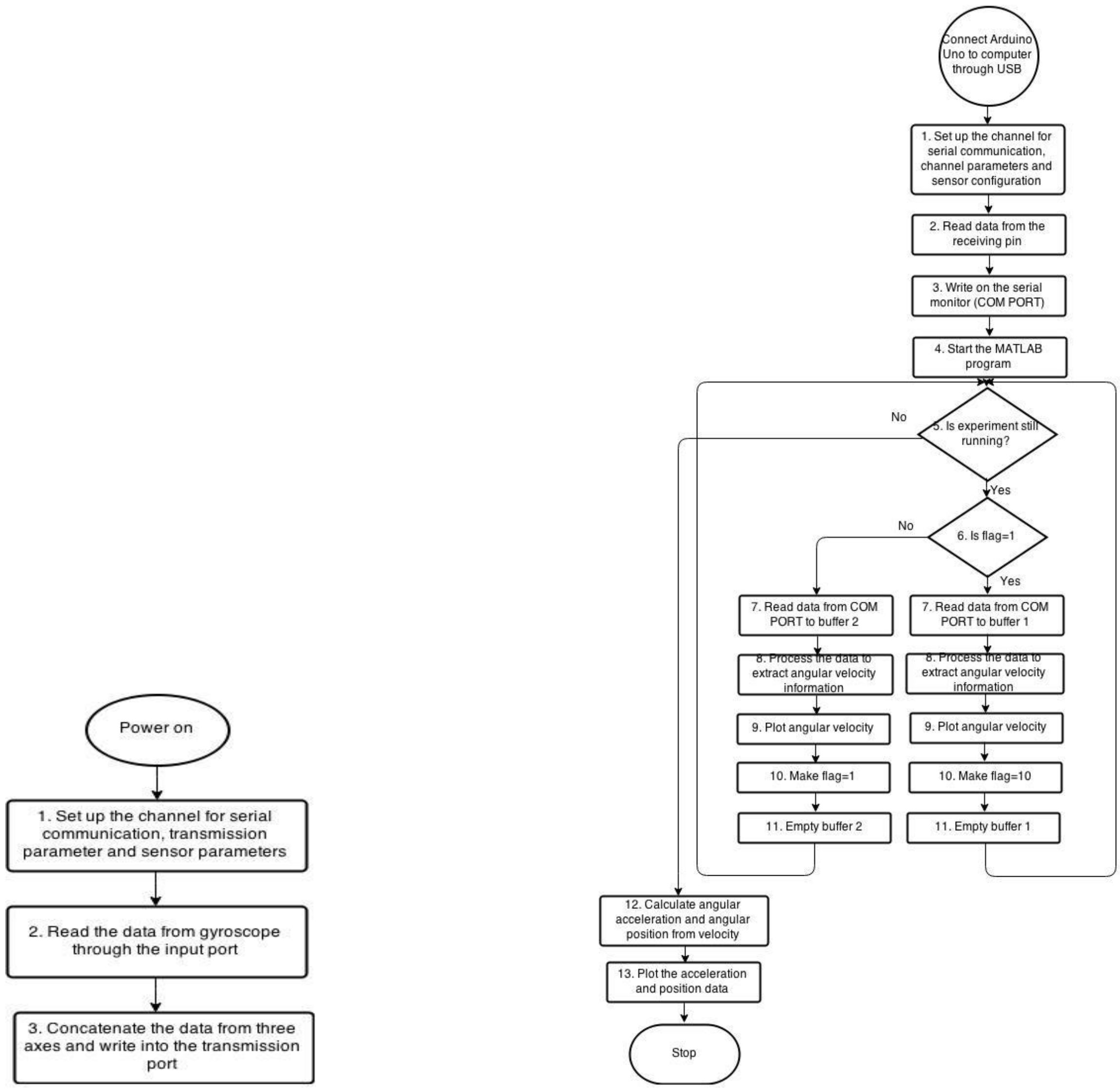

Figure 9: The flowchart of the encoding station for system 2 on the left; and the flowchart of the decoding station on the right

CHAPTER 4: EXPERIMENTAL SETUP AND ANIMAL POSITIONING

4.1 Animal Preparation and Positioning

All the experiments were conducted in awake common marmoset and followed the same procedure as approved by the Institutional Animal Care and Use Committee of the Arizona State University following NIH (National Institutes of Health) guidelines. The safety of the animal as well as that of the experimenter were ensured using the handling procedure as described in this section.

The animal was transported from the colony to the experiment chamber using a transport carrier. All the animals were trained to get in the transport carrier and chair, prior the experiments. The experiment chamber had the dimensions of 7’x7’x6.6’. A custom-made chair installed in the chamber was used to secure the animal such that the body of the animal is constrained but the head of the animal is free to move. Once secured in the chair, the comfort of the animal was ensured before the start of the experiment. Since this experiment involves securing an external device on the head of the animal, this experiment is conducted on the animals already having a head implant. Before handling the animal, the experimenter was trained according to the training procedure developed in the lab. During the handling and conducting of the experiment, the experimenter wore the Personal Protective Equipment (PPE) and paid great attention and care. At the end of each experiment, a detailed description of the trial procedure is recorded and maintained in the lab book. After the experiment, the monkey is returned to the colony using the transport carrier.

4.2 Experimental Setup

Figure 10 shows the schematic of the testing room. This testing room is same as that used in a previous study conducted in our lab in which the details of the experiment chamber are described (Simhadri, 2014). The experiment chamber is double-door sound attenuated sound booth. Two loudspeakers were placed in the left and the right corner of the room, and located at the angle of 45 degrees from the center of the chair. The lighting inside the chamber can be switched on and off, and the chamber is also equipped with an acoustically transparent 33cm x55 cm screen and low-noise Pico projector to provide visual stimulus to the monkey.

Figure 11 shows the schematic of the experimental setup. The sensor was securely fastened onto the top of the animal head using an elastic tape. The connecting wires between the sensor and microcontroller were supported by a hook suspended from the ceiling. The wires were left loose enough to allow free head movement of the animal. The sensor was placed as parallel to the transverse plane of the animal head as possible. Figure 12 shows the placement of sensor on the head of one subject.

The marmoset monkey sat at the primate chair which is positioned in the center of the acoustic chamber. While its body was constrained, a marmoset could move his/her head in all three axes at will. Head movements of a subject in relation to the alert stimulus (door open and close) were recorded in each session using an infra-red camera and the movie was then used to count the percentage of stimulus-driven head movement in data analysis. The head movement results obtained by the sensory was monitored in real time and saved through a graphical-user interface (GUI) as shown in Figure 13. The GUI enables an experimenter to record the subject information and stimulus conditions for each experiment.

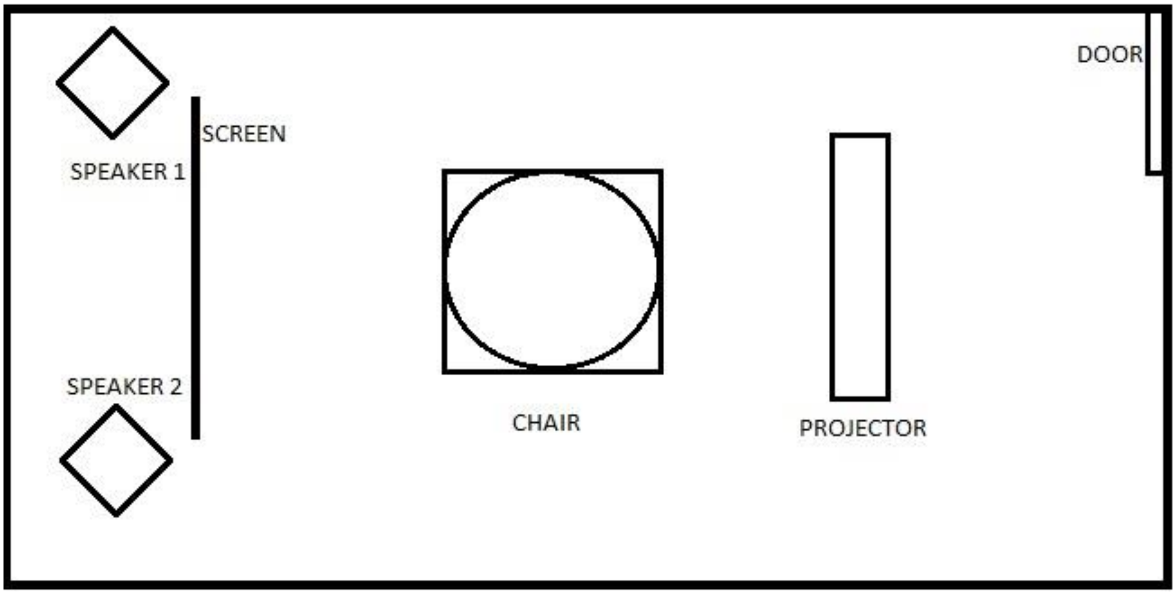

Figure 10: The schematic diagram of the testing chamber

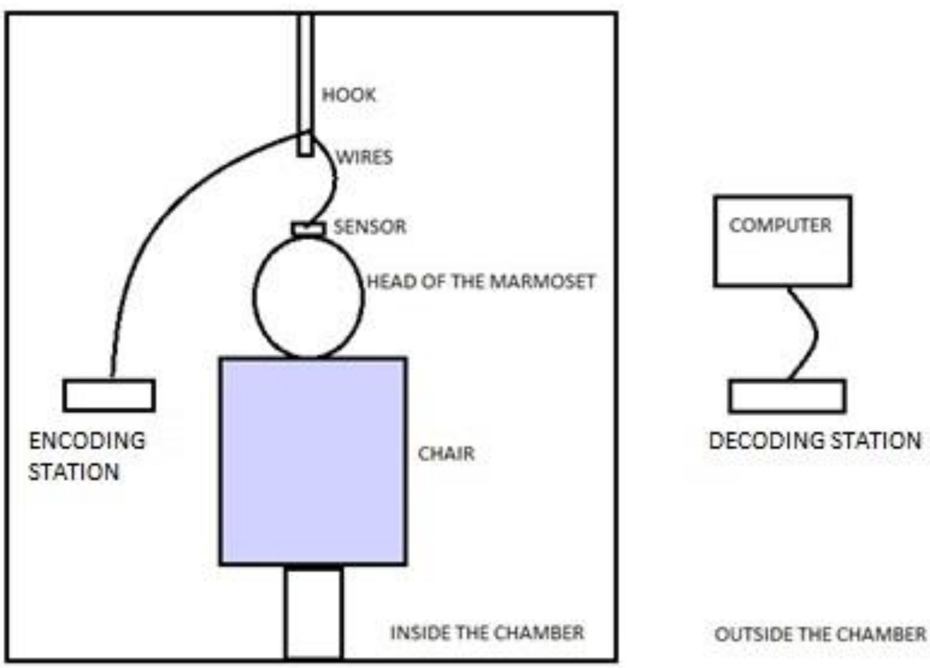

Figure 11: The schematic diagram of the experimental setup

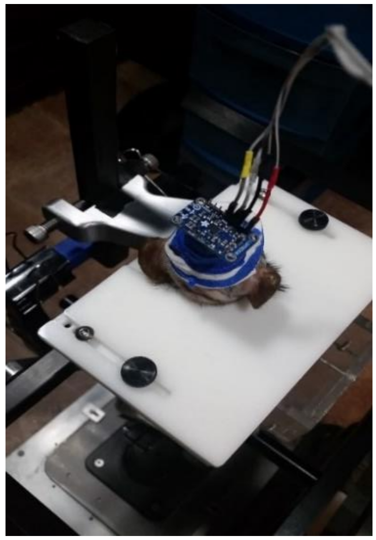

Figure 12: Sensor placement on the head of marmoset.

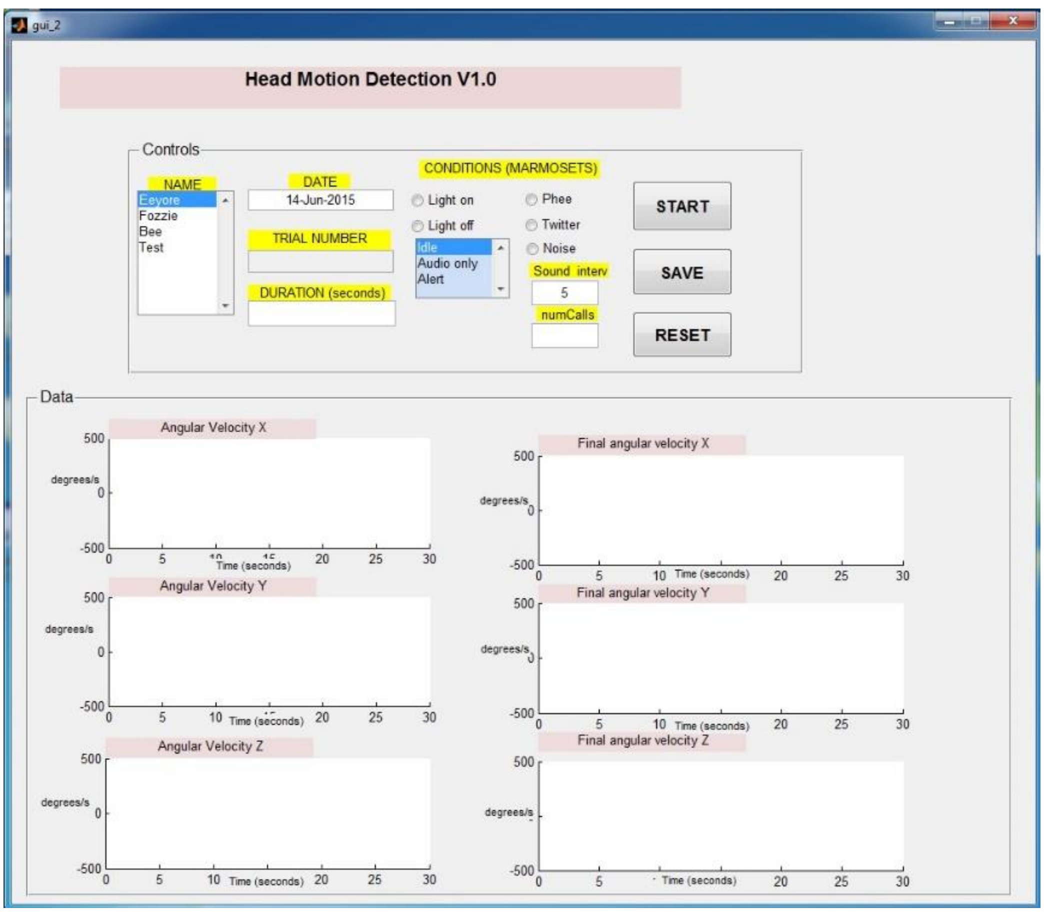

Figure 13: Graphical-User Interface for the experiment

4.3 Experimental conditions and types of stimulus

Three types of stimuli were used to evoke head movement of a marmoset. Each stimulus was repeated for house light-on and light-off situations, thus rendering a total six of stimulus conditions.

1. Alert Stimulus: previous work in our lab (Simhadri, 2014) reported consistent fast head turns when the sound chamber door was abruptly opened. This stimulus was emphasized in this research. Note that door opening/close is an ecologically viable stimulus as it is often associated with immediate action of an experimenter, such as offer the monkey reward, or change of environments, such as return to the colony.
2. Idle: In this condition, no stimulus was presented. Subject simply sat in the chair with the chamber door closed.
3. Sound only: A sound was presented from one or both of the speakers. The signal was selected from a batter of sound files including marmoset vocal calls (twitter and phee calls), bird chirps, forest sounds, and human whistling sounds.

The trial for the idle condition lasted 30 sec, while those of alert and sound-only conditions lasted 120 sec. An animal was rewarded with flavored milk between trials. Each experiment lasted between 30 and 60 minutes and only one experiment was performed per day.

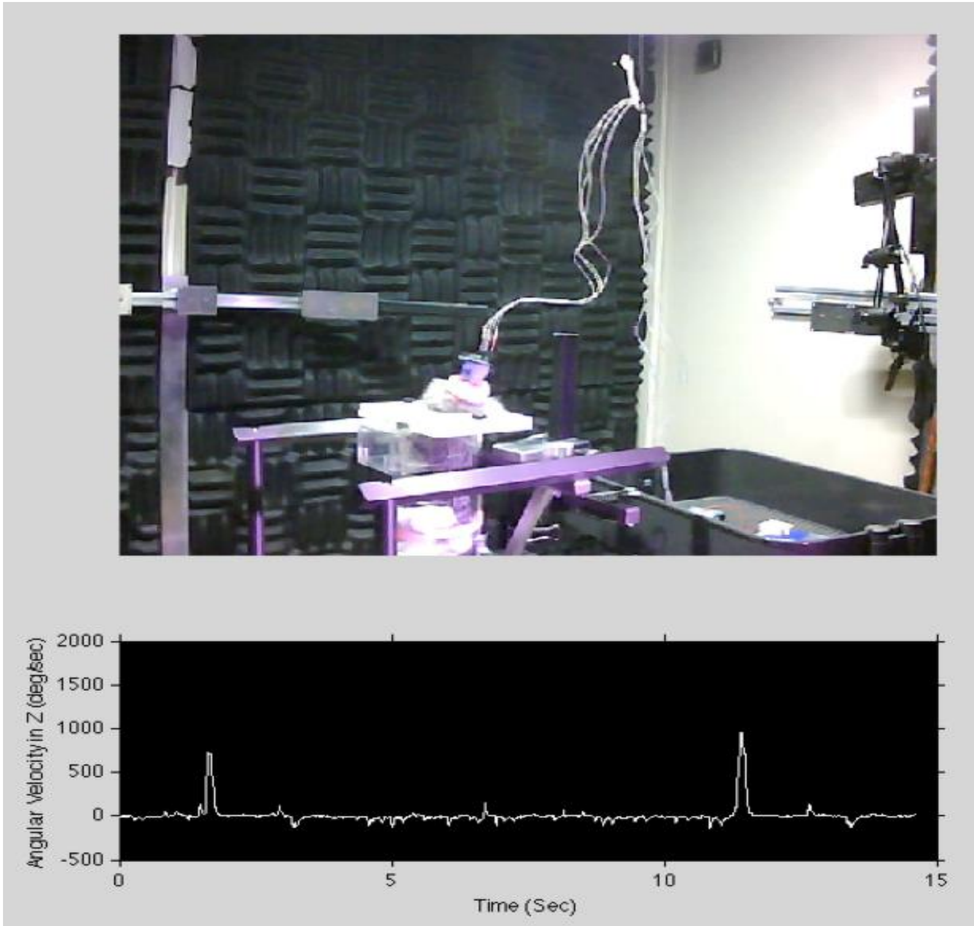

Figure 14: The video recording of the head movement (above) and corresponding velocity plot (bottom)

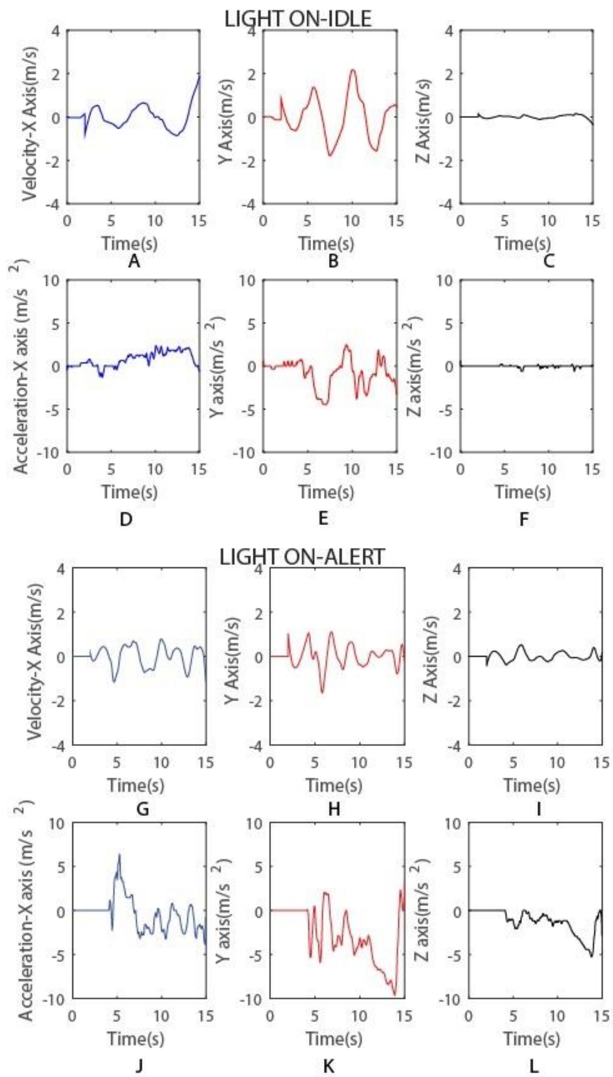

Figure 15: Translational Velocity plots as measured using System -1 (accelerometer-based). Panel A, B and C show the velocity plots in X, Y and Z axis respectively, for Light on/Idle condition. Panel D, E and F show the acceleration plots for X, Y and Z axis, in Light on/Idle condition. Panel G, H and I show velocity plots in X, Y and Z directions for Light-on/Alert condition. Panel J, K and L show acceleration plots in X, Y and Z directions for Light-on/Alert condition.

Figure 15 shows example results of marmoset head movement obtained from System 1. Since the accelerator sensor signals were analog based, considerable amounts of drift were found in the acceleration and subsequently velocity measures, which were the integration of acceleration over time. The problem of drift futher amplified in the linear displacement measures, which integrate linear velocity over time. Because of the drift issues, System 2 (gyroscope-based) was primarily used to characterize the angular rotation velocity and angular displacement in the Yaw axis.

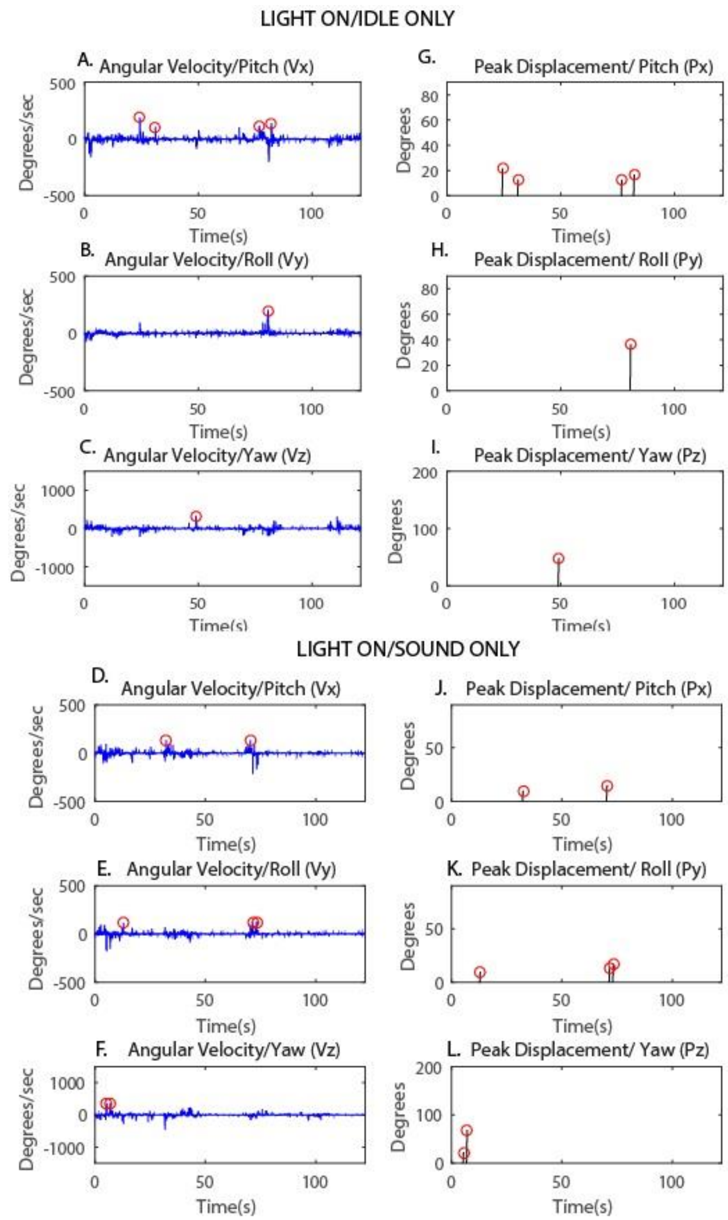

Figure 16: Example results of angular velocity and angular displacement for Light on condition for Idle and Sound only stimuli.

Figure 16 shows the example traces of marmoset head movement using System 2 (gyroscope based). It was found that the maximum amplitude of the velocity of head-turns in the Yaw direction was about 300 degrees/sec in idle condition and around 400 degrees/sec in sound-only condition. Furthermore, the peak angular displacement never crossed 50 degrees in idle condition and 70 degrees in sound-only condition.

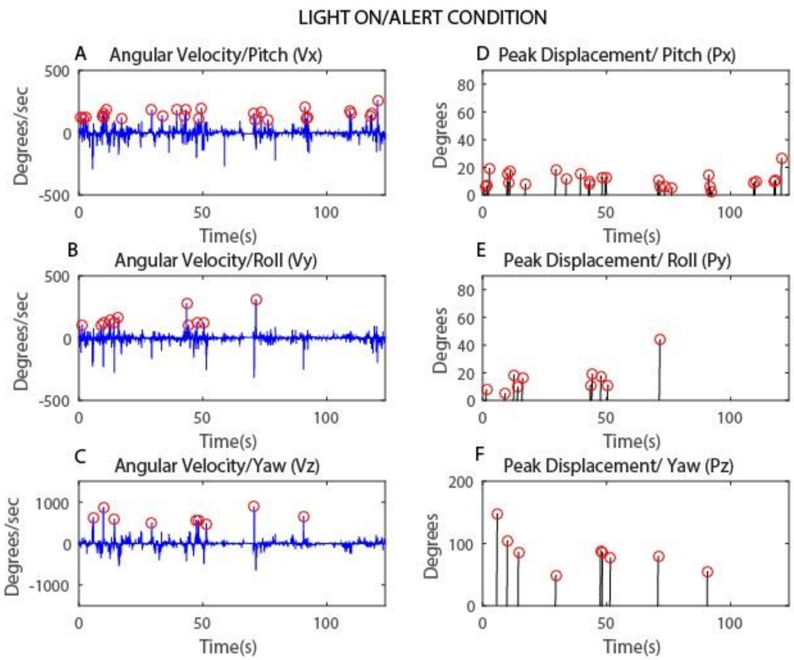

Figure 17: Angular Velocity plots and angular displacement plots for Roll, Pitch and Yaw in light-on/alert condition. The peak velocities are marked in red circles for each axis. Peak displacments are marked in the red circles for each panel. These plots rae for light on/alert condition.

As shown in Figure 17, different head turn kinetics weref found for the same light on condition, but when the alert stimulus was given. Marmoset monkeys made fast and large head turns and reached the peak angular velocities as high as 1200 degrees/sec, and peak angular displacements as high as 150 degrees in the Yaw axis.

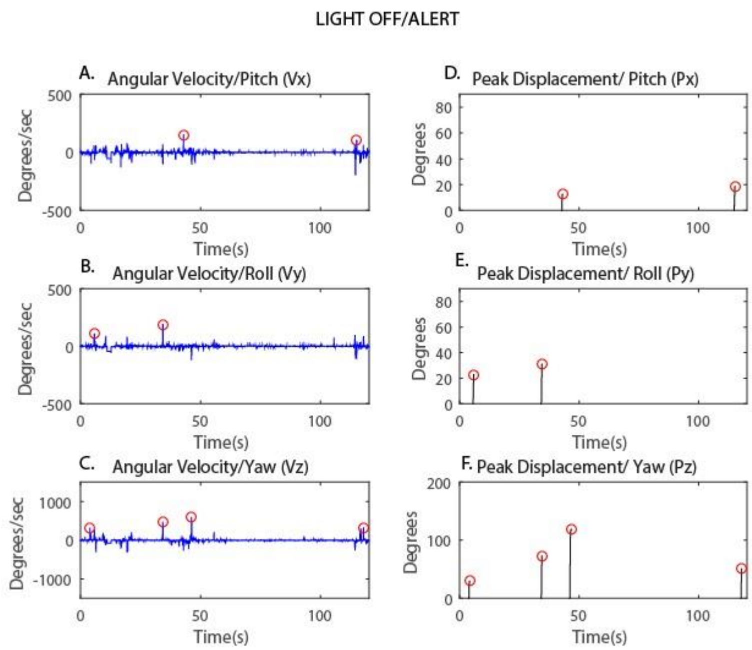

Figure 18: Angular Velocity and angular displacement plots for Roll, Pitch and Yaw in light-off/alert condition. The peak velocities are marked in red circles for each axis. Peak displacments are marked in the red circles for each panel.

It can be seen in Fig 18 that the peak velocities as well as the number of fast head turns decreased significantly in the light off condition as compared to the light on condition. Also, unlike those in Fig. 17, the range of the angular displacement rarely exceeded 90 degrees . Since the maximum peak velocities are mostly obtained in the Yaw direction, further analyses were conducted to examine the kinetics of fast head turns in this direction.

To further analyze the difference in the peak velocity and peak displacement in light-on and light-off condition, the profiles of angular velocity that exceeds 300 degrees/second were extraced and the corresponding angular displacement were calculated. Figure 19 shows the the raw traces for each metric (gray) and averaged of peak velocities and displacments (red) for head motion in the Yaw direction. There were striking difference in results found for the light-on and light-off conditions. The mean of maximum peak velocities for light-on condition was found to be 650 degrees/sec, whih was significantly higher than the mean of maximum peak velocities for light-off condition, which was 400 degrees/second. Similar observation was made for the peak angular displacements, where the average maximum was 95 degrees for the light on and 55 degrees for the light-off condition.

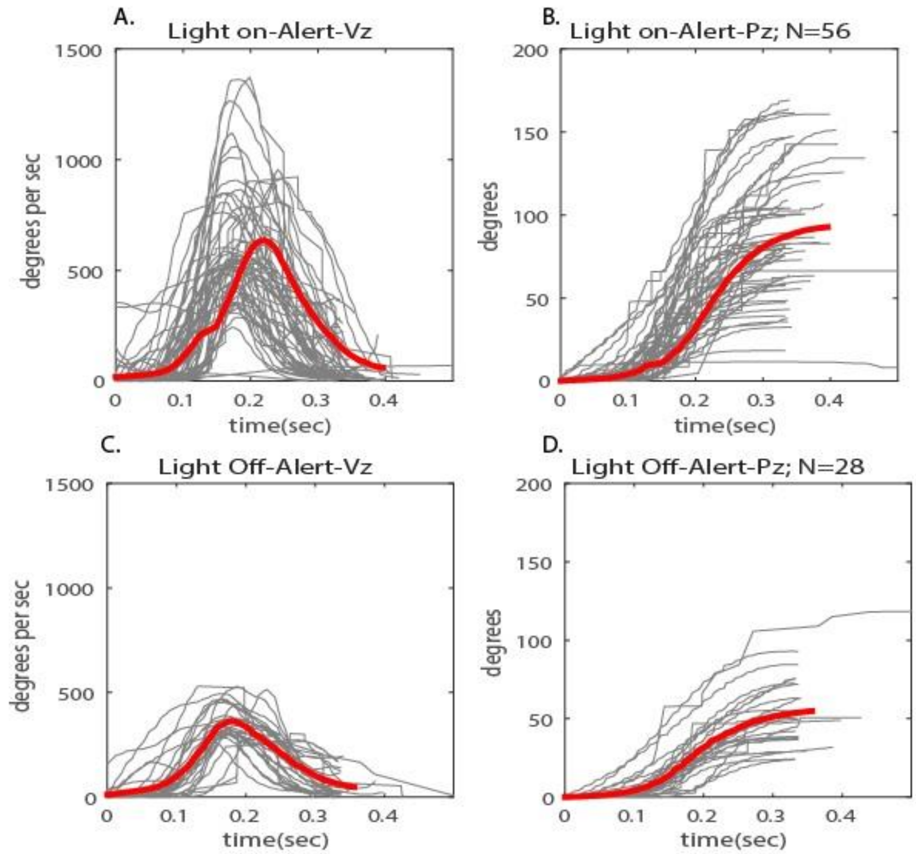

Figure 19: Velocity profiles for the peak angular velocities and peak angular displacements. Panel A and B show the mean of the peak velocities and mean of the peak displacements, respectively, in light on/alert condition. Panel C and D show the mean of the peak velocities and mean of the peak displacements, respectively, in light off/alert condition

To further understand the relationship between the peak velocities and peak displacements, main sequence were plotted in both conditions in Figure 20. Evidently, the main sequence shows a steeper slope for the light-on condition as compared to the light-off condition. The linear fit suggests that fast head movement of the marmoset monkeys is driven by ballistic mechanisms and larger displacement of head is associated with greater velocity. These findings are similar to the saccade eye movement (Mitchell, Reynolds &Miller, 2014), suggesting head saccade behavior in marmosets.

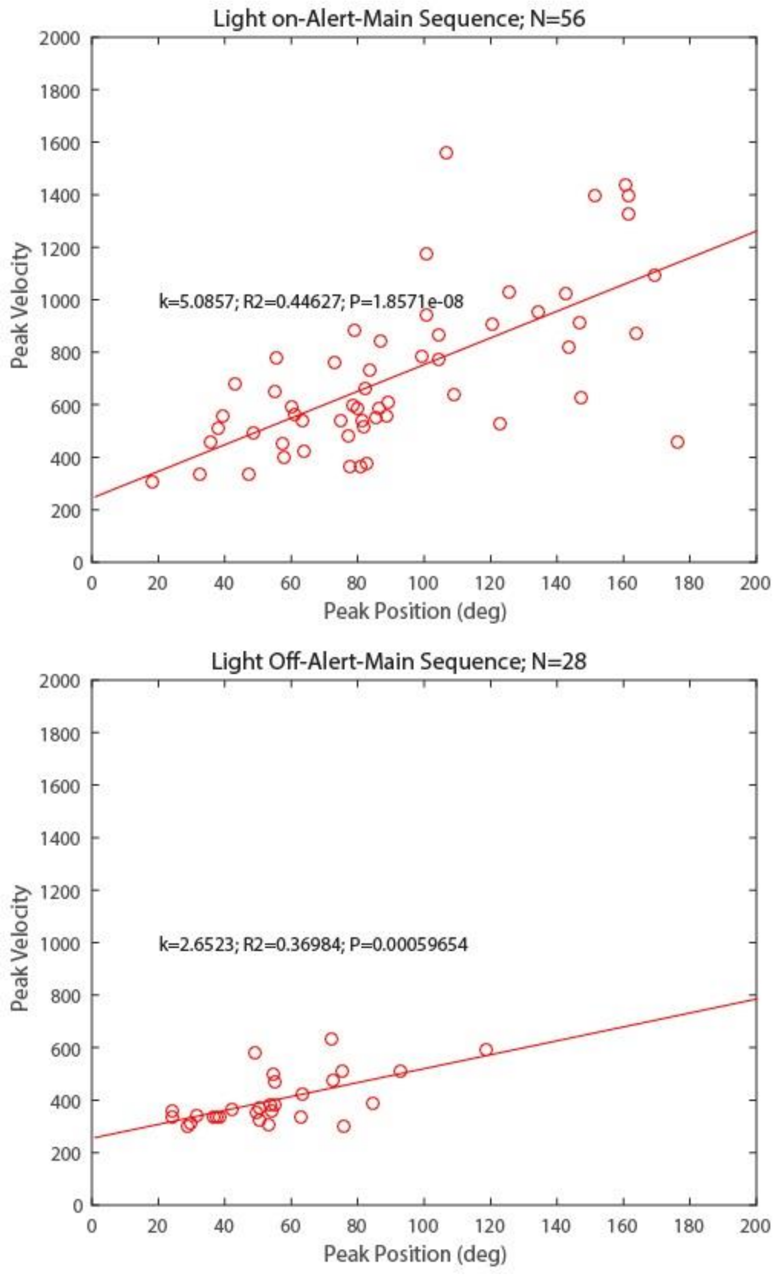

Figure 20: The Main Sequence plots in light-on/alert and light-of/alertf conditions.

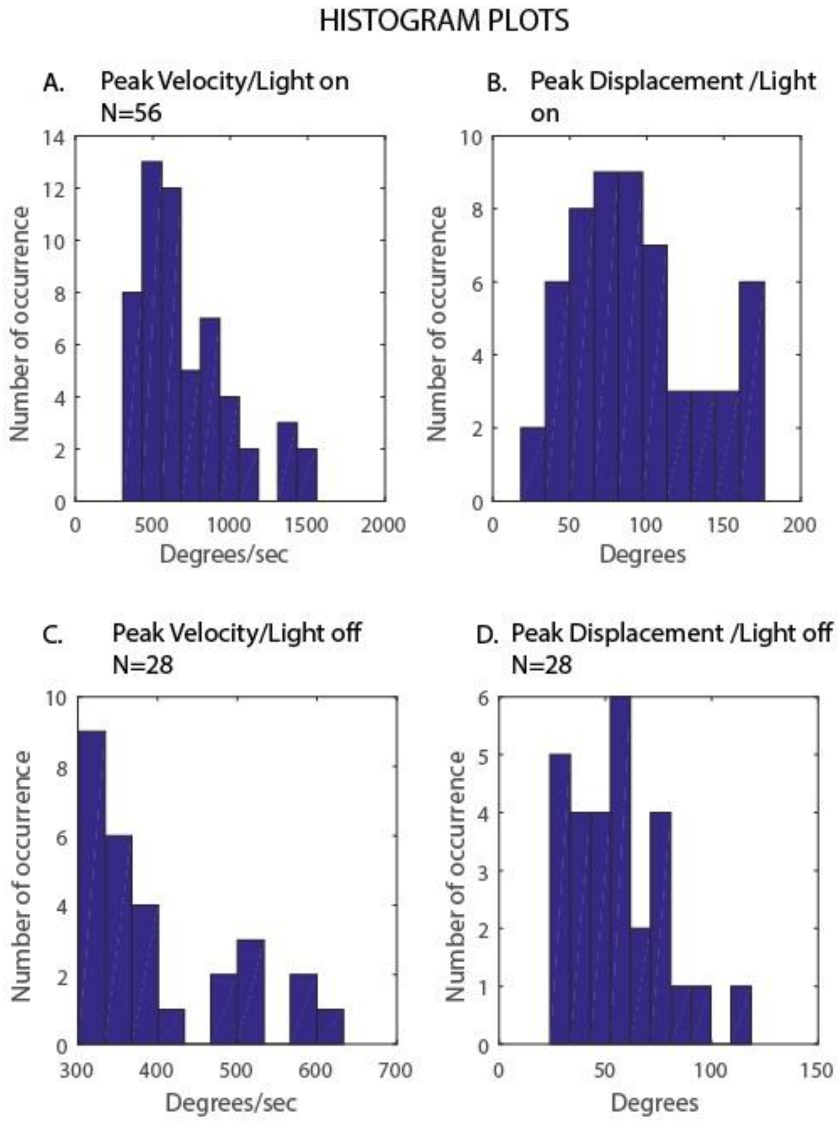

Figure 21: Histogram plots of peak velocities and acceleration in light on/alert and light off/alert conditions.

Figure 21 summarized the distributions of peak velocity and peak displacement of head rotation in the Yaw axis. A great number of fast head turns were obtained in the light-on condition as compared to the light-off condition. The amplitudes of the peak velocities and peak displacements achieved in the light on condition are significantly high as compared to the light-off condition. On conducting a Wilcoxon Rank Sum Test in Matlab on the peak velocity distribution in light on and light off conditions, p-value of 4.9047e-06 was obtained, which rejects the null hypothesis that both the velocities follow the same distribution.

Finally, Table I summarizes the number of head saccade achieved by the marmoset in the light-on and light-off conditions. Head saccade is determined when a monkey made a complete turn with no hesitation towards the door. The initial head direction for each head saccade was given as well.

Conditions	Total number of Alert Stimulus	Total number of Head saccade	Initial head positions of the head saccade relative to the door position
Light on	57	44 (77.19%)	Same side (37) Opposite side (7)
Light off	55	17 (30.90%)	Same side (14) Opposite side (3)

Table I. Head saccades and initial head positions for both light-on and light-off conditions

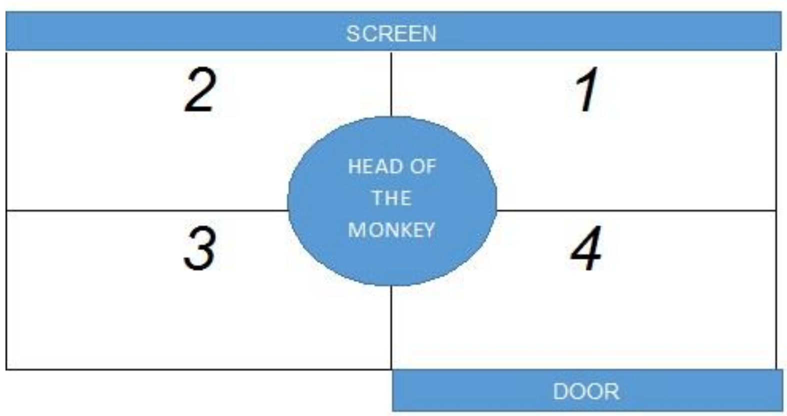

Figure 22: Head Position Quadrants.

As shown in Fig. 22, the initial head positions in 1 and 4 quadrants were considered in the same side as the door, while that in 2 and 3 quadrants were considered in the opposite side of the door. The head positions were determined through the video recordings of each alert trial in light-on and light-off conditions. The results show more instances of head saccades in the light-on than the light-off conditions. In addition, the head saccades were more easily evoked when the initial head position was on the door side, suggesting that the peripheral vision may play a role in initiating fast head movement in these experiment in addition to the sound made by door opening.

CHAPTER 6: DISCUSSION AND FUTURE DIRECTIONS

A motion tracking device was successfully developed and implemented to address all the design constraints as discussed in Chapter 1 and Chapter 2. To summarize, a real-time, wireless head tracking system was developed with a sensor that weighed only 5 grams. The tracking system can be easily mounted on the head of the marmoset monkey. The tracking system can track the head movement of a marmoset in all the three directions, namely Roll, Pitch and Yaw. In addition, this tracking system is self-contained, powered by a 9 V DC battery, and capable of detecting and encoding motion signals within an integrated circuit on the encoding station. The decoding station was easily interfaced with the computer for recording and further data processing. The sampling rate achieved was around 175 Hz which is sufficiently high to obtain a detailed head movement information of marmosets.

Fast and large head turns in the Yaw axis were observed in response to the door-opening alert stimulus as compared to the sound only stimulus and idle condition. This result agreed with the result obtained in the previous work done in our lab (Simhadri, 2014). The door opening is an ecologically behavior-driven stimulus, as it mostly indicates a significant event to the monkey, such as the completion of the experiment, or delivery of reward. Detail analysis of the results further revealed that the number of fast head-turns was higher in the light-on (N=56) than the light-off condition (N=28), in response to similar numbers of alert stimuli (N=57 and 55, respectively). This result indicates that the marmosets were more responsive and aware of their surrounding in the light-on condition than the light-off condition. In addition, the mean peak velocities and mean peak displacements in the Yaw direction were higher in the light-on condition (mean peak ~ 700 degrees/sec) than the light-off condition, thereby suggesting that marmosets made fast and large head turns when they detect an alert stimulus. Marmoset monkeys may employ different orienting mechanisms in the presence and absence of the visual cues, which can be indicative of the interplay of Sound, visual and vestibular system to respond to a stimuli.

The main sequence analysis show that the peak velocity and peak displacement of marmoset head movement follows a linear relationship, similar to that of the saccade eye movement (Mitchell, Reynolds & Miller, 2014).

One of the limitations of this system is that to secure head-stage, it needs to be mounted on the head of monkey who has be implanted with a head-cap. This limits the number of animals who can participate in this experiment (N=2). The other non-implanted naïve monkeys were untrained to an external device placed on their head and therefore did not focus on the task. For these animals imaging-based technique seem to be more efficient. With the right training, however, the wireless motion tracking system can potentially be used, even for the naïve monkeys.

In future, there can be multiple sensors employed to track the head as well as body movement. The modified system with combined accelerator and gyroscope has the potential to track the head/body movement pattern of marmosets in free-roaming behavior. Such a motion-tracking system may provide insight into how the marmoset monkeys respond to different stimuli in a less constrained environment and allow studies of the locomotion patterns of the marmosets with controlled stimulation.

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